CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	Depicting energy service demands as a mitigation lever in energy systems models
Authors	Gaur, Ankita Singh
Publication date	2024
Original Citation	Gaur, A. S. 2024. Depicting energy service demands as a mitigation lever in energy systems models. PhD Thesis, University College Cork.
Type of publication	Doctoral thesis
Rights	© 2024, Ankita Singh Gaur. - https://creativecommons.org/licenses/by/4.0/
Download date	2026-11-15 14:53:28
Item downloaded from	https://hdl.handle.net/10468/16972



UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Ollscoil na hÉireann, Corcaigh

National University of Ireland, Cork



Depicting energy service demands as a mitigation lever in energy systems models

Thesis presented by

Ankita Singh Gaur, B.Tech., M.Tech.

for the degree of

Doctor of Philosophy

University College Cork

School of Engineering and Architecture

MaREI Centre, Environmental Research Institute

Supervisors: Prof. Hannah Daly
Prof. John Curtis

Head of School: Prof. Jorge Oliveira

May 2024

Contents

List of Figures **v**

List of Tables **viii**

Acronyms **ix**

Nomenclature **xiii**

Author's declaration **xiii**

Acknowledgements **xiv**

Executive Summary **xvi**

1 Introduction **1**
1.1 Motivation and background 1
1.1.1 Climate change imperative: A call to urgency and the role of models 2
1.2 Literature review 4
1.2.1 Challenges in current modelling practices: Limitations in representing demand-side interventions 4
1.2.2 Challenges in current modelling practices: The Global South oversight 10
1.2.2.1 Passenger mobility in South Asia: challenges and opportunities 12
1.3 Thesis aim & key research questions 16
1.4 Thesis in brief 17
1.5 Role in collaborations 18
1.6 Thesis output 20

Part 1: Role of demand in Ireland's decarbonisation plan **23**

2 Energy service demand modelling in TIMES-Ireland Model **24**
2.1 TIMES-Ireland Model 24
2.1.1 TIMES Model generator 25
2.1.2 Model architecture 26
2.1.3 Time & Geography 28
2.2 Drivers of energy service demands in the TIMES-Ireland Model 28
2.2.1 Population 29
2.2.2 Economic growth 29

2.3 Energy service demand projections . . . 29
2.3.1 Transport . . . 30
2.3.2 Residential . . . 31
2.3.3 Industry . . . 31
2.3.4 Services . . . 32

3 Low energy demand scenario for Ireland 35
3.1 Introduction . . . 36
3.1.1 Rationale for low energy demand pathway . . . 39
3.1.2 Reducing energy service demand: options and modelling . . . 40
3.2 Review of low energy demand scenarios . . . 42
3.3 A Low Energy Demand pathway for Ireland (ILED) . . . 49
3.3.1 Background . . . 49
3.3.2 TIMES-Ireland Model and ILED Scenario Description . . . 50
3.4 Results . . . 56
3.4.1 Impact on costs . . . 58
3.4.2 Impact on energy consumption and technology uptake . . . 62
3.4.3 Impact on CO_2 emissions . . . 64
3.5 Discussion . . . 66
3.5.1 Key insights . . . 66
3.5.2 Limitations and future work . . . 67
3.5.3 Policy implications . . . 68
3.6 Conclusion . . . 69

4 Impact of dispersed settlement pattern on net-zero transition in Ireland 70
4.1 Introduction . . . 71
4.2 Background and literature review . . . 73
4.2.1 Spatial settlement and density as a driver of energy demand . . . 73
4.2.2 Modelling the drivers of Low Energy Demand pathways . . . 75
4.2.3 The role of density on low carbon infrastructure in the Irish context . . . 76
4.2.3.1 Electric grid . . . 77
4.2.3.2 Active modes and Public transport infrastructure . . . 77
4.2.3.3 District heating network . . . 77
4.2.4 Ireland's climate commitments and challenges . . . 78
4.3 Analysis and results . . . 80
4.3.1 Data . . . 80
4.3.2 Exploratory data analysis . . . 81
4.3.2.1 Residential Buildings . . . 82
4.3.2.2 Passenger Transport . . . 87
4.3.3 Energy demand and carbon emissions intensity . . . 92
4.3.3.1 Residential space heating . . . 92
4.3.3.2 Passenger kilometres- journeys to work/school/college . . . 95
4.3.3.3 Kaya identity . . . 96
4.4 Discussion . . . 97
4.4.1 Key insights . . . 97

4.4.2 Policy implications . . . 99
4.4.3 Modelling insights . . . 100
4.4.4 Limitations . . . 101
4.5 Conclusion . . . 102

5 Implications of heating sector electrification on the Irish power system 104
5.1 Introduction . . . 105
5.2 Methodology . . . 109
5.2.1 Model Description . . . 109
5.2.2 Data and Assumptions . . . 110
5.2.3 Scenario Description . . . 111
5.3 Results . . . 112
5.3.1 Power system impacts of current policy regarding electrification of heat 112
5.3.2 Alternative policy options: Optimal spatial electrification of heating . 115
5.3.3 Alternative policy options: Impact of decarbonisation policy versus renewable policy . . . 117
5.3.4 Spatial comparison of demand and supply under RES-E vs emissions policies . . . 120
5.4 Discussion . . . 122
5.5 Conclusion and Policy Implications . . . 124

***Part II: Sustainable development strategies for passenger transport in Global South* 126**

6 Mobility scenarios for the Global South: Developing an evidence-based framework for a large-scale IAM 127
6.1 Introduction . . . 128
6.1.1 Motivation . . . 128
6.1.2 Why South Asia? . . . 131
6.1.3 Overview of approach and key contributions . . . 133
6.2 Mobility related phenomena relevant to Global South . . . 134
6.2.1 Growth and development . . . 135
6.2.2 Infrastructure . . . 135
6.2.3 Disruptive technology . . . 135
6.2.4 Behavioural, lifestyle & socio-cultural practices . . . 136
6.2.5 Interacting phenomena . . . 137
6.3 Representing phenomena in an Integrated Assessment Model . . . 137
6.3.1 Integrated Assessment Model . . . 138
6.3.2 Translating phenomena to IAM parameters . . . 138
6.4 Passenger mobility demand model . . . 141
6.4.1 Daily travel passenger demand model . . . 142
6.4.2 Long-distance passenger travel demand model . . . 142
6.4.3 Projecting mobility demand using dimensionality of model . . . 143
6.5 Sustainable mobility and decarbonisation scenarios . . . 148
6.5.1 National Policies in South Asia (NP) . . . 149

6.5.2 Best mobility practices in Global South (BP) . . . 150
6.5.3 Transit Oriented Development (TOD) . . . 151
6.5.4 Technology focus (TECH) . . . 151
6.6 Results . . . 151
6.6.1 Outcomes of passenger mobility demand model . . . 152
6.6.1.1 Passenger distance travelled . . . 152
6.6.1.2 Share of modes in passenger distance travelled . . . 154
6.6.1.3 Balanced vs concentrated development . . . 156
6.6.2 Outcomes of phenomena interactions in scenarios . . . 157
6.6.2.1 Passenger distance travelled . . . 157
6.6.2.2 Share of modes in passenger distance travelled . . . 159
6.7 Discussion and conclusion . . . 165
6.7.1 Key insights . . . 165
6.7.2 Limitations . . . 167
6.7.3 Future work . . . 168

7 Conclusions, Insights & Recommendations 169
7.1 Methodological contributions . . . 169
7.2 Key insights: Answers to research questions . . . 171
7.3 Policy insights . . . 176
7.3.1 Policy impact . . . 178
7.4 Recommendations for future work . . . 178

Appendix 181
A. Supplementary material Chapter 5 . . . 181
A.1 Mathematical formulation of the Electricity Network and Generation INvEstment (ENGINE) model . . . 181
B. Supplementary material Chapter 6 . . . 185
B.1 Detailed description of definition of each phenomenon . . . 185
B.2 Share of urban population in each area type for each country in 2011 186
B.3 Daily travel model estimated using Indian Census 2011 . . . 186
B.4 Long distance travel estimated in all countries in 2011 . . . 187
B.5 Trends in mode composition of growth in daily travel . . . 188

Bibliography 191

List of Figures

1.1 Mapping approaches to embed behavioural and demand-side dynamics in IAMs and ESOMs (Berg et al., 2019; Luh et al., 2022; Keppo et al., 2021) . 7
1.2 Countries in South Asia with percentage of urban population in 2022 13
1.3 Overview of the thesis structure 19

2.1 Simplified representation of reference energy system in TIM 27

3.1 Evolution of CO_2 emissions in the illustrative pathways featured in SR 1.5 where S1, S2 and S5 are based on ?? SSP1, SSP2 and SSP5 respectively (Riahi et al., 2017; Rogelj et al., 2018; Gidden et al., 2019) 37
3.2 Drivers, options and enablers of reducing energy service demands along with direct and indirect impact interactions 41
3.3 Comparison of narratives of two global low energy demand scenarios 44
3.4 Categorisation of options to reduce energy service demands in LED pathways into Avoid-Shift-Improve framework (adopted from (Berg et al., 2021)) . . . 48
3.5 Schematic representation of reference energy system (RES) in the newly developed TIMES-Ireland Model (TIM) 51
3.6 Comparison of historical freight tonne kilometres per capita in various countries and future projections for Ireland in BAU and ILED pathways 52
3.7 Comparison of historical passenger kilometres per capita for various countries and future projections for Ireland in BAU and ILED pathways 53
3.8 Historical passenger transport mode share and total passenger kilometres in Ireland (O'Riordan et al., 2022) 54
3.9 Comparison of type of residential dwellings in BAU and ILED scenarios . . . 55
3.10 Decarbonisation trajectories modelled in TIM and carbon budget outcomes (Scenario EX- CO_2 Emission reduction by X% in 2030 relative to 2018 where X= 32, 51 and 61) 59
3.11 Average marginal abatement cost of per kilo tonne of CO_2 for every 5 years between 2025-2050 59
3.12 Total undiscounted annual energy system cost in addition to the No_mitigation scenario. Includes annual investments, fixed and variable costs, and excludes network and infrastructure costs 60
3.13 Difference in energy system costs (fixed, investment and variable) between BAU ESD and ILED pathways in 2030 and 2050 61
3.14 Annual per capita personal investments in residential (retrofits) and transport sectors (new private car) in addition to the No_mitigation scenario 61
3.15 Final energy consumption per capita and resultant fuel mix 63

3.16 Novel technology uptake between 2020 and 2050 64
3.17 Cumulative sectoral CO_2 emissions between 2020 and 2050 65
3.18 Cumulative BECCS needed between 2020 and 2050 65

4.1 Percentage of population living in each group calculated at Electoral Division level 82
4.2 Average new dwelling size by type (CSO, 2020a). 'All new dwellings' indicates the weighted average size of all new dwellings constructed in that year 83
4.3 Share of type of dwelling in each population density group for 2006 and 2016 Census years 83
4.4 Comparison of Spearman correlation matrix for population density and dwelling type calculated at County level 84
4.5 Spearman coefficient of correlation between population density and occupancy by dwelling type for 2016 84
4.6 Share of dwellings by central heating fuel type in each population density group (CSO, 2017) 85
4.7 Spearman correlation matrix of population density and central heating fuel types in Census 2016 85
4.8 Percentage of one-off houses in each population density group (CSO, 2020b) 86
4.9 Planning permission for all dwelling types between 2001 and 2021 86
4.10 Comparison of car ownership rates in urban versus rural areas in 2006 and 2016 Census years 87
4.11 Pearson Coefficient of correlation between car ownership and population density calculated at Electoral Division level 88
4.12 Comparison of mode choice in urban versus rural areas for 2006 and 2016 Census years 88
4.13 Comparison of Pearson correlation matrix for population density and mode choice calculated at Electoral Division level 89
4.14 Population density versus number of public transport stops calculated at Electoral Division level for 2016 (Geofabrik, 2018) 90
4.15 Population density versus average frequency of service at nearest public transport stop 90
4.16 Pearson Coefficient of correlation between frequency of bus services and population density 91
4.17 Population density versus distance to public bus stop at county level (CSO, 2020) 91
4.18 Comparison of Pearson correlation matrix for population density and commute distances calculated at Electoral Division level 91
4.19 Distribution of journeys by distance in each group (2016 Census) 95
4.20 Kaya identity decomposition of passenger transport emissions for each population density group 97

5.1 Description of the ENGINE model 109
5.2 Candidate connection nodes of renewable and storage investment 110
5.3 Change in costs with respect to Base_RES 113

5.4 Change in regional generation mix (MW) with respect to Base_RES in 2030 114
5.5 Renewable curtailment . . . 115
5.6 System losses . . . 115
5.7 Change in costs with respect to Base_RES . . . 116
5.8 Renewable curtailment . . . 117
5.9 System losses . . . 117
5.10 Objective function components . . . 118
5.11 Cost components . . . 118
5.12 Generation mix in 2030 . . . 119
5.13 Changes in transmission capacity for renewable versus carbon reduction scenario 120
5.14 Optimal electrification level in every region in 2030 . . . 121
5.15 Regional distribution of generation capacity in RES-E and emission target cases in 2030 . . . 122

6.1 Overall workflow of approach describing various steps involved (dotted arrow line indicates future work- Step 7) . . . 134
6.2 Passenger mobility demand model inputs and the adjustable dimensions . . . 143
6.3 Trip rate trajectories in each country (calculated using GDP per capita values from SSP2 projections) . . . 145
6.4 Trajectories of distance (in kilometres) in each trip distance category . . . 145
6.5 Changes in daily travel mode share trajectories for India (SSP2) . . . 147
6.6 Total passenger kilometres per capita in all countries in South Asia for SSP2 152
6.7 Trends in GDP per capita and PDT per capita (values indexed to 2011) . . . 153
6.8 Total passenger kilometers disaggregated by area type for SSP2 . . . 154
6.9 Resultant mode shares in all mode share trajectories defined for both travel types (SSP2) . . . 155
6.10 Urban PDT in each country for balanced and concentrated types of urbanization 156
6.11 Daily travel passenger kilometres by area type and long distance travel at national level in all scenarios in 2011 and 2050 . . . 158
6.12 Passenger distance travelled in billion passenger kilometres (Bpkm) in every country and scenario . . . 160
6.13 Resultant mode shares in all scenarios and mode share trajectories defined for both travel types (SSP2) . . . 162
6.14 Share of modes in daily travel PDT . . . 164

B1 Share of modes in daily travel PDT . . . 188
B1 Share of modes in daily travel PDT . . . 189
B1 Share of modes in daily travel PDT . . . 190

List of Tables

2.1 Population 29
2.2 Number of dwellings by type ('000) 32
2.3 Energy service demands in TIM 33

3.1 Passenger transport modal share in the ILED scenario 54
3.2 Comparison of energy service demand values in BAU and ILED scenario . . 57
3.3 Main assumptions and sources for reduction of energy service demands in 2050 in the ILED pathway 58

4.1 Number of dwellings in each population density group in 2016 Census 92
4.2 Summary of central heating fuel share by dwelling type in each population density group (CSO, 2020) 92
4.3 Dwelling space heating demand, $\alpha_{T,F}$, $(kWh/house/yr)$ for dwelling archetypes and per fuel 93
4.4 Emission factor for residential space heating fuels (SEAI, 2023) 94
4.5 Residential energy service demand and space heating emissions per capita (2016) 94
4.6 Assumptions for mode share and average distance (O'Riordan et al., 2021) . 95
4.7 Emission factors 96
4.8 Passenger kilometres and CO_2 emissions per capita in each population density group (2016) 96

5.1 Comparison of payback periods of heat pump systems 108
5.2 Description of cases analysed 112

6.1 Representation of phenomenon in MESSAGEix-Transport 139
6.2 Parameter values for each phenomena 139
6.2 **Continued:** Parameter values for each phenomenon 140
6.3 Combination of phenomena considered in scenarios 149

B1 Modelling approach for each phenomenon in the framework 185
B2 Distribution of population between urban area types in 2011 186
B3 Daily travel demand model 186
B4 Long distance travel estimated in billion passenger kilometers 187

Acronyms

ASHP . . . . . Air-source heat pump

ASI . . . . . Avoid shift improve

AV . . . . . Autonomous vehicle

BAU . . . . . Business as usual

BECCS . . . . . Bioenergy with carbon capture and storage

BER . . . . . Building energy rating

BES . . . . . Battery energy storage

BRT . . . . . Bus rapid transit

CAGR . . . . . Compound annual growth rate

CAP . . . . . Climate Action Plan

CCGT . . . . . Combined cycle gas turbine

CCS . . . . . Carbon capture and storage

CDR . . . . . Carbon dioxide removal

CGE . . . . . Computable general equilibrium

COF . . . . . Car Oriented Future

CREDS . . . . . Centre for Research into Energy Demand Solutions

CSO . . . . . Central Statistics Office

EKC . . . . . Environmental Kuznets Curve

EPC . . . . . Energy Performance Certificate

ESD . . . . . Energy service demand

ESOM . . . . . Energy System Optimisation Model

ETS . . . . . Emission trading scheme

EU . . . . . European Union

EV . . . . . Electric vehicle

GDP . . . . . Gross domestic product

GHG . . . . . Greenhouse gas

GNI* . . . . . Modified Gross National Income

GVA . . . . . Gross value added

HP . . . . . Heat pump

I3E . . . . . Ireland Environment, Energy and Economy

IAM . . . . . Integrated Assessment Model

ICE . . . . . Internal combustion engine

ICT . . . . . Information and communication technologies

IIASA . . . . . International Institute for Applied Systems Analysis

ILED . . . . . Ireland's Low Energy Demand

IMAGE . . . . . Integrated Model to Assess the Global Environment

IPCC . . . . . Intergovernmental Panel on Climate Change

IPT . . . . . Intermediate public transport

LDV . . . . . Light duty vehicle

LED . . . . . Low Energy Demand

MAC . . . . . Marginal abatement cost

MRT . . . . . Metro rail transit

MaaS . . . . . Mobility as a Service

NACE . . . . . Nomenclature of Economic Activities

NET . . . . . Negative emissions technology

NMT . . . . . Non-motorized transport

NPV . . . . . Net present value

OECD . . . . . Organisation for Economic Co-operation and Development

PDT . . . . . Passenger distance travelled

PKM . . . . . Passenger kilometres

PSV . . . . . Public service vehicle

PT . . . . . Public transport

RECC . . . . . Resource Efficiency and Climate Change

RES . . . . . Reference energy system

SDG . . . . . Sustainable Development Goal

SEAI . . . . . Sustainable Energy Authority of Ireland

SF . . . . . Sustainable Future

SNSP . . . . . System non-synchronous penetration

SSP2 . . . . . Shared Socioeconomic Pathway 2

SSP . . . . . Shared Socioeconomic Pathway

STS . . . . . Societal Transformation Scenario

TES . . . . . Thermal energy storage

TIAM . . . . . TIMES Integrated Assessment Model

TIMES . . . . . The Integrated MARKAL-EFOM System

TIM . . . . . TIMES Ireland Model

TOD . . . . . Transit oriented development

VDT . . . . . Vehicle distance travelled

VKM . . . . . Vehicle kilometres

Nomenclature

Units

$BEUR$	Billion Euros
$CO2_{eq}$	CO_2 equivalent
GJ	Giga Joules
km^2	Square kilometres
kWh	Kilo Watt hour
m^2	Square metres
Mt	Mega tonne
MWh	Mega Watt hour
PJ	Peta Joules
tCO_2	tonnes of CO_2
TJ	Tera Joules
tkm	tonne kilometres
TWh	Tera Watt hour

Variable

α	Final energy consumption
β	Correction factor
δ	Final energy demand
η	Efficiency
AD	Average distance
CHF	Central heating fuel share
CO_2	Carbon dioxide emission
D	Distance
E	Space heating fuel consumption
EF	Emission factor
GDP_cap	GDP per capita
GDP_cap_idx	GDP per capita indexed
JS	Journey share
ND	Number of dwellings
P	Population
PDT_cap	PDT per capita
PKM	Passenger kilometres
Pop	Population
TR	Trip rate
TS	Trip share
WF	Weighting factor

Subscript

at	Area type
D	Population density group
dc	Distance category
F	Fuel type
M	Mode
m	Mode
mt	Mode share trajectory
n	Country
S	Energy service
s	SSP scenario
T	Dwelling archetype
u	Type of urbanisation
y	Year

Author's declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.

Acknowledgements

I am sincerely grateful to Hannah Daly for her supervision, motivation and support. Hannah, thank you for believing in me, especially during times I struggled to do so. You've not only been an excellent supervisor to me but also a role model. I am also thankful to John Curtis for his guidance from my early days as a research assistant at the ESRI, Dublin and into my PhD. Your mentorship has been invaluable in shaping me as researcher.

This thesis owes a great deal to the contributions of my colleagues from EPMG. Thanks to Olexandr Balyk for his patience and kindness. James Glynn, thank you for the guidance in the early days, which help set the course of this thesis. Brian O'Gallachoir thank you for your support and encouragement. Vahid Aryanpur, your friendship and trust in me have been true blessings. Jason McGuire, Andrew Smith, Fionn Rogan, Tomás Mac Uidhir and Paul Deane thank you for the collaboration opportunities, feedback and insightful conversations. I am also grateful to Muireann Lynch and Desta Fitiwi for their guidance and mentorship during my time at the ESRI. You both always encouraged me and provided excellent opportunities to expand my career as a researcher. I would like to acknowledge the Science Foundation Ireland (SFI) for funding my research in Ireland.

The mentorship of Aneeque Javaid and Paul Kishimoto has greatly contributed to the development of this thesis. Your patience, guidance, and time have been pivotal in the successful completion of the YSSP project. Thank you both sincerely.

My life as a PhD student in Cork would not have been the same without friendships: Rajas Shinde, Vera O'Riordan, Amy Hollands, Anga Hackula, Nathan Gray and many others. Anjali Jain, thank you for being my go-to academic friend since 2017. Thank you Vishal Vijaykumar for being my travel companion and listening to my rants. A decade-long friendship with Shravani Dalvi and Anand Mathew, both integral to my happiness, has served as a constant pillar of support through all my ups and downs. My siblings, Kshitij and Shaurya have been a constant source of support and love. My parents, Nandini and Aniruddh, are undoubtedly the reason why I was able to achieve this feat and made me the person I am. Thank you for your encouragement and for igniting my passion for research.

This thesis has come to fruition thanks to the persistent belief others had in me over my lifetime, sometimes exceeding my own sense of assurance.

Executive Summary

Energy Systems Optimisation Models (ESOMs) and Integrated Assessment Models (IAMs) are integral to informing climate change mitigation strategies and the associated policymaking processes. However, the techno-economic nature of these models restricts the representation of demand-side mitigation measures, which have been recognised to have substantial potential in meeting climate goals. Specifically, measures that can bring about a reduction in the level or structure of energy demand are often missing. Even when such measures *are* included—often as exogenous scenarios—they are typically not well-connected to empirical evidence and lack spatial and demographic granularity. Moreover, these demand reduction measures are more relevant to developed countries like Ireland. In developing countries, access to energy services is disproportionately low, despite the higher growth in demand for energy relative to developed countries. Further, the representation of Global South regions is generally oversimplified in large-scale IAMs, often relying on stylised assumptions based on observations from Global North. This thesis seeks to address these gaps by adopting a dual approach of addressing demand-side mitigation while incorporating a particular perspective from the Global South region.

This thesis develops bottom-up projections of energy service demand for the TIMES-Ireland Model (TIM). The baseline energy service demands are driven by growth in population and economy. TIM is set up to allow for alternate scenarios for demand drivers that result in different energy service demand projections in the end-use sectors. The thesis develops the 'Irish Low Energy Demand' (ILED) scenario where the impact of reducing and restructuring energy service demand on the whole energy systems is analysed using TIM. The results indicate that the ILED pathway is especially valuable in meeting near-term deep mitigation targets and lowers reliance on novel fuels and technologies. For policymakers, the recommendation is to expand the arsenal of mitigation measures, beyond policies that promote renewable energy deployment and energy efficiency.

It was observed that a pivotal driver of such Low Energy Demand (LED) scenarios both, at national and global level, is spatial settlement patterns. The LED scenarios heavily depend on future compact development. Hence, to improve the granularity and empirical basis of such scenarios, this thesis quantifies the relationship between population density and the

energy as well as carbon intensity of the residential and transport energy service demands. Analysis reveals that the energy and carbon intensity of populations living in dense parts of Ireland are significantly lower than those living in sparsely populated areas. The future growth of cities and town in Ireland, whether compact or dispersed, will heavily determine emissions trajectory and mitigation options. This exercise allows future modelling studies to include spatial settlement patterns as a mitigation lever.

This thesis also analyses the impact of electrifying spatially dispersed residential heating demand on the Irish power system. This analysis is particularly important for Ireland: given the lack of a district heating network, electrification is the central heat decarbonisation policy. Utilizing a generation and transmission expansion planning model, the analysis finds that the spatial distribution of demand drives the investments in the power system. This again highlights the role of future spatial settlement patterns in decarbonising the Irish energy system. Further, electrifying residential heating via heat pumps leads to greater utilization of renewable energy, when combined with thermal energy storage.

In the next part, this thesis explores the gaps and challenges associated with representing Global South regions in a global IAM. With a focus on passenger mobility in South Asian countries, this thesis develops an evidence based framework to improve the quantification of sustainable mobility scenarios in global IAMs. A comprehensive literature review is conducted to identify measured causal relationship between various phenomena, such as urbanisation and passenger mobility patterns, placing an emphasis on literature focusing on South Asia and the Global South. These phenomena are incorporated into a novel mobility projection model designed to interface with an IAM. This is an innovative and adaptable framework, that can be applied to other Global South regions and other IAMs. Using this framework, four distinct mobility scenarios are developed, each reflecting alternate visions for mobility based on explicit futures for these phenomena.

Through the various research chapters, this thesis demonstrates the value of including demand-side measures in ESOMs and IAMs. It highlights how energy service demands can be managed to reduce GHG emissions, particularly in the residential and transport sectors. Further, by incorporating empirical evidence of the phenomena that drive energy service demands, the research develops methodologies to improve the quantification of decarbonisation scenarios in ESOMs and IAMs. And lastly, the inclusion of region-specific data for the Global South is a step towards more equitable practices within IAM frameworks.

Chapter 1

Introduction

1.1 Motivation and background

This thesis explores energy service demand as a climate change mitigation option in detailed energy systems models. It develops improved methodologies for representing demand-side complexities and drivers in Energy Systems Optimisation Models (ESOMs) and Integrated Assessment Models (IAMs), in order to expand the "solution space" models depict.

This thesis progresses the ideological development from the imperative of reducing and restructuring energy demand in developed nations like Ireland to a nuanced understanding of the significance of access to energy services, particularly mobility, within the context of the Global South. It discusses different mitigation approaches, such as consumption reduction in developed countries like Ireland and the importance of fostering green growth in the Global South. Through the research chapters, the many dimensions of energy demand and its role in climate change mitigation across disparate geographical and developmental contexts are presented.

To establish an understanding of the context, this thesis begins with an exploration of the role of optimisation models in climate change mitigation planning. Subsequently, the limitations inherent in current modeling practices are discussed through an extensive literature review. This section presents the recent advancements in representing demand side mitigation options in ESOMs and IAMs, while also addressing methodological constraints. Finally, the position of the Global South within climate change mitigation modelling is discussed, highlighting the scarcity of literature, data and consequently, the focus on these countries.

Each chapter in this thesis (Chapter 2-6) addresses one or more unique research gaps and/or introduces specific modelling methods. Certain contextual details, such as those pertaining to Ireland's national Climate Action Plan or background literature are repeated across chapters, as each chapter serves as a standalone research paper—either already published or currently under review. This ensures clarity and coherence within individual studies while contributing to the overarching theme of the thesis.

1.1.1 Climate change imperative: A call to urgency and the role of models

The Earth is warming at a faster rate than ever recorded in history and anthropogenic emissions, by far, are the largest contributor to global climate change. This is supported by significant evidence assessed by the United Nation's Intergovernmental Panel on Climate Change (IPCC), confirming human activities as the cause (Masson-Delmotte et al., 2018). The Paris Agreement marked a historic milestone, uniting nations worldwide in the collective effort to combat climate change and adapt to its inevitable impacts (UNFCC, 2016). The overarching aim of the Agreement is to limit global warming to well below 2°C above pre-industrial levels by the end of this century and strive to limit warming to 1.5°C. In this context, the IPCC's Special Report (SR1.5) published in 2018 underscores the imperative of cutting global annual CO_2 emissions in half by 2030 compared to 2010 and achieving net-zero CO_2 by 2050 (Masson-Delmotte et al., 2018).

In the face of the urgent need to curtail emissions, it is evident that the focal point lies within the current energy system. This system is primarily driven by the combustion of fossil fuels and is the largest contributor to greenhouse gas (GHG) emissions. To bring about steep reductions in emissions from the energy system, it is important to examine potential pathways of system evolution, i.e., explore the possibility and feasibility of meeting climate targets through a set of technological options, economic restructuring, policy measures and societal transformation (Pye et al., 2020; Trutnevyte et al., 2019). Mathematical models such as ESOMs and IAMs serve as indispensable tools for assessing energy systems' decarbonisation pathways. They can assist policymakers in determining strategies for achieving climate targets such as reaching net-zero by 2050 (Pye et al., 2020).

IAMs model human-earth systems and adopt a wider systems view connecting energy, land-use, climate change and other social factors. In contrast, ESOMs focus more deeply on the energy system and its subsectors. IAMs are generally developed at the global level, covering a larger part of the economy and providing aggregated results, whereas ESOMs concentrate on the energy sector and offer higher resolution details (Henke et al., 2023). Essentially, ESOMs are a subset of IAMs.

Energy systems models provide a means of formalising scattered knowledge about complex interactions, allow developing scenarios of future evolution of the energy systems and help policymakers with explicit decisions on guiding the energy system in a direction that aligns with climate goals (Pfenninger et al., 2014). The increased climate ambition post-Paris Agreement has brought new modelling challenges into light, demanding rapid emission re-

ductions, especially in the near term. This necessitates including options that can bring about substantial system transformation rapidly and cost-effectively, as well as modelling social and political uncertainties and disruptive events that could significantly impact the energy system (McCollum et al., 2020; Pye et al., 2020). These challenges contribute to increasing model complexity, which is not always credible and could also potentially have negative consequences on the policymaking process (Venturini et al., 2019).

Social factors such as public acceptance or behaviours associated with energy use can serve as both drivers and barriers to energy transition. But these factors are not always linear (Plaga et al., 2024). In order to represent such factors in ESOMs, IAMs or other optimisation models, they must be linearized, which oversimplifies their impact, and modellers must assign quantitative values, which are often based on modellers' judgement (Fodstad et al., 2022; DeCarolis et al., 2017). This introduces uncertainties in outcomes that can be difficult to decipher. Further, increasing model complexity can reduce fidelity, transparency and trustworthiness, and also limit its flexibility and the research questions it can answer (Niet et al., 2022). To avoid the above issues, interdisciplinary approaches are needed such that inputs from social sciences, and humanities can be integrated into such important decision guiding tools (Li, 2017; Süsser et al., 2022). Further, instead of an overly complicated single model, ESOMs and IAMs can be linked to other 'realistic' models or consider multiple exogenous scenarios (Köhler et al., 2018; Niet et al., 2022; Süsser et al., 2022).

Recognising the importance of such models in the climate change discourse, modelling teams and practitioners have pooled their collective experiences to recommend best practices and advocate for essential enhancements related to technical, economic and societal realism within these models (DeCarolis et al., 2017; Trutnevyte et al., 2019; McCollum et al., 2020; Pye et al., 2020). Two main recommendations are firstly, expanding the mitigation option space to include demand reduction and restructuring as a mitigation option and secondly, improving the representation of behaviours and lifestyles—elements either missing or over-simplified in current models. The following section explores specific limitations related to representing demand-side interventions in ESOMs and IAMs, and discusses the above recommendations in greater detail.

1.2 Literature review

1.2.1 Challenges in current modelling practices: Limitations in representing demand-side interventions

"All models are *wrong*, but some are *useful*."

—*George E. P. Box*

While energy systems models have been developed extensively spanning decades, they have inherent limitations.

A significant limitation garnering considerable attention in recent years is the techno-economic nature of ESOMs and IAMs. While adept at representing efficiency improvements, and fuel and technology substitution, these models predominantly focus on supply-side solutions and technology upgrades in mitigation pathways (Stoddard et al., 2021; Creutzig et al., 2018; Gambhir, 2019; Creutzig et al., 2016). Notably, their capabilities to represent demand-side mitigation options are limited. Demand is generally an exogenous parameter in these models, often driven by growth in population and economy. However, the IPCC's Sixth Assessment Report (AR6) WG3 dedicated an entire chapter to the role of demand-side interventions in climate change mitigation titled 'Demand, Services and Social Aspects of Mitigation' (Creutzig et al., 2022b). Demand-side strategies have the potential to reduce GHG emissions by 40-70% by 2050 (Creutzig et al., 2022b).

The conventional perception of energy demand often revolves around quantifiable units of energy such as kilowatt hours of electricity or litres of petrol. However, as a society, our interaction with energy goes beyond its physical form; rather, it is the services and functionalities that energy can provide that shape our demands (Rinkinen et al., 2021). As famously said by scientist Amory Lovins "people do not want energy; they want hot showers and cold beers". Energy services encompassing access to work, education, and leisure activities, thermal comfort, the import/export of goods, nutrition and hygiene— referred to as energy service demands— are enabled by the provision of energy. These energy service demands are complex in nature and vary in space and time. Demand for these services is often an outcome of various interacting socioeconomic factors (such as income, age, education level, gender), practices and norms, infrastructure and material arrangements, technological advancements and policy measures (Trentmann et al., 2018; Rinkinen et al., 2021). Hence, modelling and including these complexities in the current generation of ESOMs and IAMs poses certain challenges.

The main demand-side interventions discussed in the energy systems modelling literature can be broadly categorised using the "Avoid-Shift-Improve" (ASI) framework (Creutzig et al., 2022b). The interventions categorised as "avoid" are those that effectively decrease the demand for energy services. These interventions include practices such as transit-oriented development, smaller housing units, and embracing shared economy models. The "shift" category includes interventions such as a transition to mass public transport and active modes of travel (walking and cycling), and promoting multi-family dwellings. And finally, the "improve" category encompasses interventions that decrease energy and carbon intensity of the energy service demand such as technological upgrades like electrification or fuel switching.

Among the interventions discussed above, ESOMs and IAMs are far better able to represent efficiency improvements and technology or fuel substitution endogenously. This is because these models were built to represent such phenomena explicitly via techno-economic parameters (Pfenninger et al., 2014). Moreover, efficiency improvements and cost of fuel or technology substitution are well measured concepts and hence easy to quantify. However, the qualitative and structural drivers of GHG emissions and demand-side mitigation options that are less easily quantifiable are not well represented. This is due to the "techno-economic" mindset of these models that prioritises a narrow suite of technological options and market-based solutions (Stoddard et al., 2021; Geels et al., 2017). Demand-side mitigation options include socio-cultural, behavioural and lifestyle factors, as well as institutional and infrastructural elements (Creutzig et al., 2022b). The main advantages of including mitigation options, especially those that bring about a reduction in energy service demands, in decarbonisation pathways identified in the literature are as follows:

1. Reduces system size- The final energy demand determines the size of the energy system. Lowering energy service demand reduces the size of the energy system, thereby decreasing the supply-side investments needed for decarbonisation.

2. Reduces reliance on carbon dioxide removal (CDR) technologies- These pathways have much lower requirements of CDR technologies, which are uncertain at current status of development. The alternate mitigation options also postpone the requirement of CDR (Van Vuuren et al., 2018). There are also concerns about the impact of CDR technologies on the ecosystem and biodiversity and their economic feasibility (Anderson et al., 2016; Smith et al., 2016; Hilaire et al., 2019).

3. Moderates reliance on novel fuels and expensive technologies- These pathways exhibit reduced dependence on emerging fuels like hydrogen. Additionally, the demand for

technological enhancements, such as electrification and retrofits, is significantly diminished in such pathways. This helps in overcoming the financial barriers associated with energy systems transition, as upfront consumer investments required are lower (Ven et al., 2018).

4. Near-term emission reduction- The LED pathways were found to accelerate low-carbon energy supply, especially in the near-term where technological transformations are not rapid enough to meet climate goals (Sluisveld et al., 2016).

5. Co-benefits- Moving away from private vehicles and embracing non-motorised modes of transport will reduce congestion and improve air quality in cities. The reduction in energy demand will also decrease the financial burden of adopting expensive green technologies, making the energy transition more fair and just.

These factors are generally represented through exogenous parameters in ESOMs and IAMs, although efforts have been made to represent consumer behaviour endogenously within these models.

Figure 1.1 outlines the various methodologies for incorporating behavioural aspects and demand-side dynamics into IAMs or ESOMs. The horizontal axis represents the integration approach, ranging from endogenous representation within the model to external linkage via exogenous parameters. The vertical axis represents the degree of complexity of each method, ranging from high to low. It is important to note that the depiction in the figure is more qualitative, and the actual level of complexity of these methods depends on various factors such as the number of exogenous parameters and the sophistication of behavioural dimensions involved.

Endogenous methods involve the incorporation of behavioral aspects, lifestyle patterns, and other dynamics within the model itself. These approaches encompass linking a behavioral model directly with an IAM or ESOM, integrating technology or dynamic learning mechanisms, and accounting for the evolving heterogeneity among consumers.

In the transport sector, efforts have been made by previous studies to represent mode choice in TIMES framework that captures behavioural heterogeneity (Daly et al., 2014; Pye et al., 2015; Tattini et al., 2018b; Tattini et al., 2018a). McCollum et al. (2017) and Aryanpur et al. (2022) introduce consumer heterogeneity and a disutility cost or hurdle rate associated with vehicle purchase decision within MESSAGE-Transport and the TIMES-Ireland Model (TIM) respectively. Blanco et al. (2019) soft link the JRC-EU-TIMES model with a system dynamics model to improve the representation of consumer choices in an ESOM. Similarly, in the residential sector, Cayla et al. (2015) disaggregate demand based on technical and

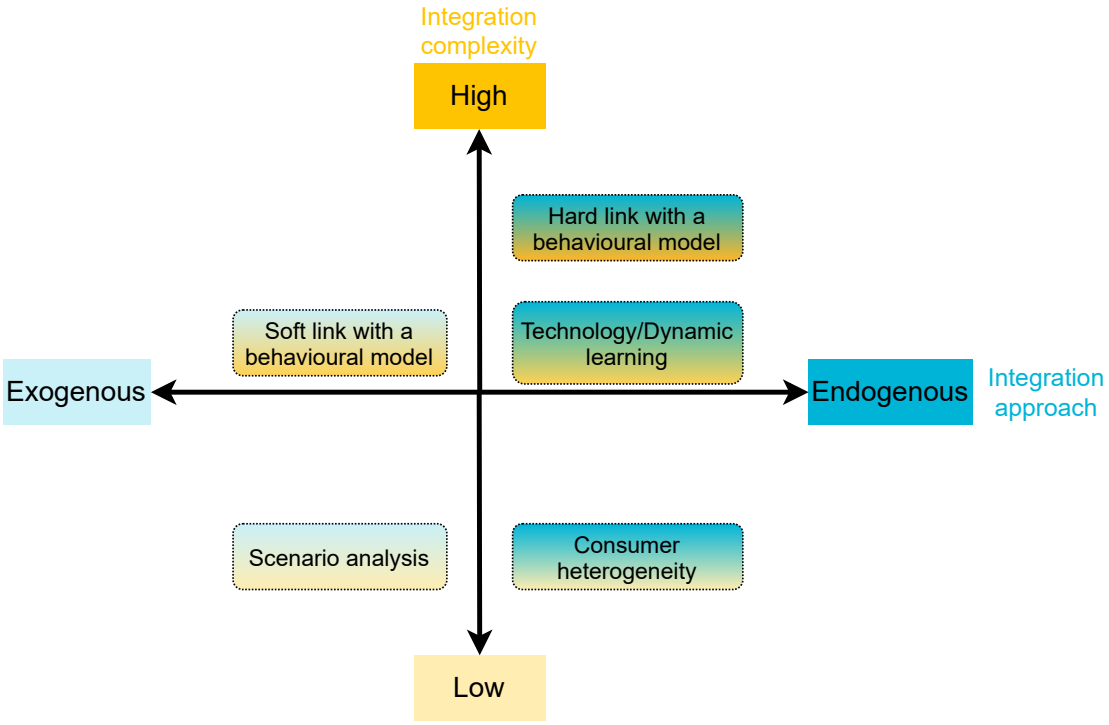


Figure 1.1: Mapping approaches to embed behavioural and demand-side dynamics in IAMs and ESOMs (Berg et al., 2019; Luh et al., 2022; Keppo et al., 2021)

behaviour-related determinants within the TIMES-Household model. Andersen et al. (2020) soft-link TIMES-DK with a computable general equilibrium (CGE) model to explore the impact of policies on the energy efficiency retrofit investment behaviour of households.

Endogenising consumer behaviour through structural changes in ESOMs and IAMs may introduce additional sources of uncertainty in the modelling process (Aryanpur et al., 2022). Further, the endogenous approach limits the range of lifestyle changes or behavioural patterns that can be represented in these models (Berg et al., 2019; Luh et al., 2022). This is because behavioural aspects, which are often non-linear and qualitative in nature, have to be converted to cost-terms to be integrated within ESOMs and IAMs. This is a non-trivial task that significantly increases model complexity, requires a large amount of data and reduces model flexibility (Berg et al., 2019; Luh et al., 2022). Soft-linking models increases computational burdens. This method is also constrained by resources required to develop and maintain multiple models.

Incorporating behavioral, lifestyle, and other aspects of societal transition through exogenous methods entails fine-tuning the parameters of IAMs and ESOMs. This tuning is either informed by insights from behavioral models or scenario assumptions, offering a nuanced approach to capture the complexity of these factors in the modelling process.

Scenarios are a valuable tool to explore the plausible evolution of complex and interacting systems in the future. They provide a means to integrate scattered knowledge on possible future outcomes of societal evolution into holistic and coherent narratives grounded in best available scientific evidence and community or societal experiences (Rasmussen, 2008; Riahi et al., 2022). Scenarios are not a single prediction of the future but a range of possible futures, determined by the underlying context (Beach, 2021). Integrating scenarios into IAMs and ESOMs is a relatively straightforward process. Rooted in narratives and storylines, these scenarios outline potential societal transitions and the anticipated impacts on the energy/economy and related systems. Despite being reliant on a set of assumptions, scenarios serve as a valuable tool for envisioning diverse futures. They are used at national and global levels to support climate change mitigation related policymaking processes (Krey, 2014). They also facilitate intermodel comparisons, a practice endorsed and recommended by the IPCC in AR6 (Riahi et al., 2022; McCollum et al., 2018; Krey, 2014).

The shared socioeconomic pathways (SSPs) are one example of quantifying and implementing structured narratives around lifestyle changes and their drivers in global IAMs (Bauer et al., 2017). These scenarios have global coverage and five vastly different futures that are consistent with the challenges to mitigation and adaptation (Bauer et al., 2017; Riahi et al., 2017). Ven et al. (2018) focus on the climate mitigation potential of behavioural changes in food, housing and mobility in the European Union (EU) through a set of assumptions. Sluisveld et al. (2016) explore the implications of lifestyle changes in meeting climate targets in an IAM which are represented through changes in level of demand and by constraining other exogenous model parameters. Similarly, Van Vuuren et al. (2018) explore the impact of alternative pathways that include lifestyle changes, rapid demand electrification and additional CO_2 reduction in meeting Paris Agreement targets.

Since such scenarios are mostly represented through exogenous parameters of the ESOM or IAM, these exogenous parameters may fall short in capturing the direct measures of various socio-cultural, behavioural, and lifestyle phenomena—even where such quantification are well-established in the literature, and certainly where not (Yeh et al., 2022; Lo Piano et al., 2023). The introduction of new transformations in energy services (novel services, disruptive technology, etc.) is inherently not well-connected to empirical evidence.

Further, these scenarios are generally aggregated at both levels, geographic and demographic (Mastrucci et al., 2023). Energy systems and societal transitions such as uptake of new technologies, sustainable development policies, and the costs and benefits of such transitions are spatially and demographically uneven (Schippl et al., 2020; Golubchikov et al., 2020; Yenneti et al., 2016). Scenarios often do not—or can not—include regional disparities and

heterogeneity explicitly, which limits the ability to model and analyse regional inequalities in access to energy services and infrastructure in an IAM or ESOM framework (Fragkos et al., 2021). It also restricts the absolute representation of policies and other effective climate mitigation levers in such models which might be important for drastic societal transition needed to meet climate goals (Trutnevyte et al., 2019; Keppo et al., 2021; Mastrucci et al., 2023).

Energy systems decarbonisation pathways are beginning to include demand reduction and restructuring as a mitigation option, both at the global and national scale (Grubler et al., 2018; Kuhnhenn et al., 2020; Barrett et al., 2021; Napp et al., 2019; Johnson et al., 2023). These Low Energy Demand (LED) scenarios are based on envisioning alternate future pathways of societal transformation that can lead to lower levels of energy service demand.

However, the underpinning drivers, such as spatial planning, of these scenarios are often missing or not well-quantified. For example, Berrill et al. (2024) find that higher population density is associated with lower private car usage in several European countries. It was also found that residential dwellings situated in remote or sparsely populated locations with less or no access to networked infrastructure such as the gas grid have limited decarbonisation options (Gaur et al., 2024). Population density as a mitigation lever is generally absent in LED-type scenarios, despite its significant role as an underlying driver in reducing energy service demand.

In acknowledging the aforementioned limitations, it is crucial to recognise that the majority of the modelling limitations are focused on the Global North context, where demand reduction is a major decarbonisation strategy (McGarry et al., 2024). However, the Global South is currently undergoing population and economic growth, leading to an expansion of their energy systems. Despite this growth, access to energy services remains unequal and disproportionately low in many of these regions. Consequently, the applicability of low energy demand scenarios in these countries may be counter-intuitive. Recognizing that the choices in energy development in these regions will have a significant impact in determining the future trajectory of GHG emissions, a closer examination of their unique challenges and opportunities is necessary. The next section discusses the current gaps in modelling energy transitions in the Global South, with a focus on passenger mobility.

1.2.2 Challenges in current modelling practices: The Global South oversight

The Global South contains about 80% of the global population and exhibits a distinct demographic and economic trajectory compared to the Global North. However, currently, the representation of Global South countries in large-scale global IAMs is oversimplified, relying on stylised assumptions that presume a developmental trajectory similar to that observed in the Global North. For example, the measured causal relationship between increasing car ownership with rising incomes in the Global North is assumed to play out in the Global South as well, despite the large differences in current mobility patterns between these regions.

The Global South continues to experience higher population and economic growth, leading to an expansion of their energy systems. It is evident that these countries are going to play a pivotal role in shaping the future GHG emissions trajectory and determining the feasibility of achieving the Paris Agreement goals. Choices made by countries in the Global South in the near future will significantly influence global efforts to mitigate climate change in the coming century.

The Global South is likely to face the disproportionate burden of severe consequences of climate change such as water and food scarcity. The disparity of resources in these countries emphasizes the need for equitable and just solutions to address climate change impacts. As unequivocally stated by the IPCC:

> "Those who contributed the *least* to climate change are often the *most vulnerable* to its impacts."
>
> —*IPCC (Lee et al., 2024)*

As economic and population growth in these countries increases, urbanization and the demand for energy services, particularly in the residential and transport sectors, are on the rise. While considerable attention has been directed toward addressing energy access and fuel poverty in households, exemplified by a Sustainable Development Goal (SDG) dedicated to universal household energy access, mobility as a form of energy access is understudied in the literature.

Mobility of passengers and goods is a fundamental phenomenon of everyday life. It is the outcome of complex interaction between socioeconomic conditions, personal choice, available infrastructure and policy measures. Amplification in mobility has increased economic activities, improved access to services and goods, and has led to the development of vast social networks (Cook et al., 2018). On the other hand, it has marginalized low income

groups—especially in urban areas, making economic disparities apparent, and has also significantly contributed to climate change (Dávila et al., 2013).

Over the past two decades, the transport sector has experienced a rapid and notable increase in energy-related CO_2 emissions, at an annual average rate of 1.7% (IEA, 2023). To be on track to meet the 2050 net-zero target, deemed necessary by the IPCC in order to limit global temperature rise to 1.5°C, transport emissions need to fall rapidly in the near-term (Masson-Delmotte et al., 2018; IEA, 2023). This can be achieved through fleet electrification, investments in low-carbon infrastructure, demand reduction, and effective policy and regulatory measures.

Policies and measures to reduce emissions from the transport sector have either proved to be ineffective or progressing at a pace insufficient to meet climate targets (Jaramillo et al., 2022). A key contributing factor is the limited depth of exploration in understanding the drivers of demand within this sector (Lamb et al., 2021). Further, as mobility patterns and transport technologies evolve, there is a mutual impact which may invalidate the extrapolation of historical mobility patterns (Daniels et al., 2022). Hence, there is a need to increase the sophistication of travel demand projections and include the impact of ongoing innovations, policy interventions and feedback effects (Yeh et al., 2022; Daniels et al., 2022; Briand et al., 2023).

The demand for mobility in global IAMs and ESOMs is often projected using measured causal relationships such as increasing passenger distance travelled (PDT) with GDP and rising private vehicle ownership with income. However, alternate trajectories of energy demand are being developed to simulate the impact of structural changes in the economy and societal transformations (Van Vuuren et al., 2018). For example, the LED scenarios by Grubler et al. (2018) and Kuhnhenn et al. (2020) transcend causal relationships that often underpin scenarios that limit global warming to 1.5°C and envision an alternate future trajectory of energy demand.

However, both these scenarios (and others) are highly aggregated geographically with only Global North and Global South regions. This categorisation oversimplifies the diversity and complexity within regions, potentially overlooking important variations in socioeconomic, technological, and policy contexts that could influence the outcomes of such scenarios (Emodi et al., 2022). Sub-national analysis of the effectiveness of various policy options for sustainable urban mobility transition is necessary to empower policymakers and urban planners to implement policies aligned with the objectives of the Paris Agreement (Winkler et al., 2023).

Moreover, these LED-type scenarios present a counter-intuitive challenge for regions in the Global South (Semieniuk et al., 2021). Cities in these regions are witnessing significant population growth and heightened economic activities, resulting in an escalating demand for mobility services. However, access to mobility services in these cities remains disproportionately low, partly due to lack of appropriate infrastructure. This gives rise to the complexity of improving access to mobility services for those at a disadvantage, either due to their location or income class, while at the same time decarbonising the transport system to meet climate goals. Further, analysis by Zhang et al. (2021b) shows that spatial organisation and structure of cities would play an important role in determining the effectiveness of transport energy policies.

The focus on the mobility needs of Global South has been limited and this could be attributed to the lack of reliable data, limited resources and policy priorities that focus on immediate development challenges. However, despite such limitations, it is crucial to emphasise the importance of improving the granularity of analysis in these countries. This is particularly significant because Global South cities are rapidly expanding and will play a critical role in shaping emissions from the transport sector. Hence, developing detailed and realistic scenarios based on empirical evidence will enable consideration of the complexities of mobility patterns and infrastructure development in these regions, supporting the design of adequate policies (Zhang et al., 2021a).

This thesis improves the quantification of sustainable mobility scenarios in global IAMs and ESOMs for the Global South to avoid bias arising from over reliance on data, literature and evidence from Global North. It also improves the representation of various demand-side mitigation options and associated behavioural, lifestyle and socio-cultural phenomena corresponding to the passenger transport sector within an IAM or ESOM framework. To develop and test the modelling framework, South Asian countries are considered as a case-study.

1.2.2.1 Passenger mobility in South Asia: challenges and opportunities

The case of South Asian countries is particularly interesting as 25% of the global population resides in these countries, of which 36.6% live in urban areas (Figure 1.2) (UNDP, 2022). Economic and population growth along with increasing urbanisation rates have driven a continuous increase in demand for mobility (passenger and goods) in these countries. These drivers are likely to continue in the region, inevitably leading to increase in demand for mobility and—without intervention—GHG emissions (ITF, 2022). Currently, South Asia stands at a pivotal juncture where the adoption of green growth policies and technologies

has the potential to enable a leapfrogging effect. This would allow steering away from car dependency and emission-intensive mobility patterns as witnessed in the Global North toward a more sustainable development pathway (Herman, 2021). Green growth can be broadly defined as economic growth that favours transition to low-carbon practices and efficient resource use while raising quality of life (OECD, 2013). As a large part of the infrastructure is yet to be built, South Asian countries can potentially bypass private vehicle dependency by leveraging demand management options, adopting cleaner vehicle technology (electrification) and developing multi-modal transport systems (Herman, 2021; Emodi et al., 2022). While there are several challenges that South Asian countries must overcome, there are also significant opportunities for them to advance sustainable mobility solutions as outlined below.

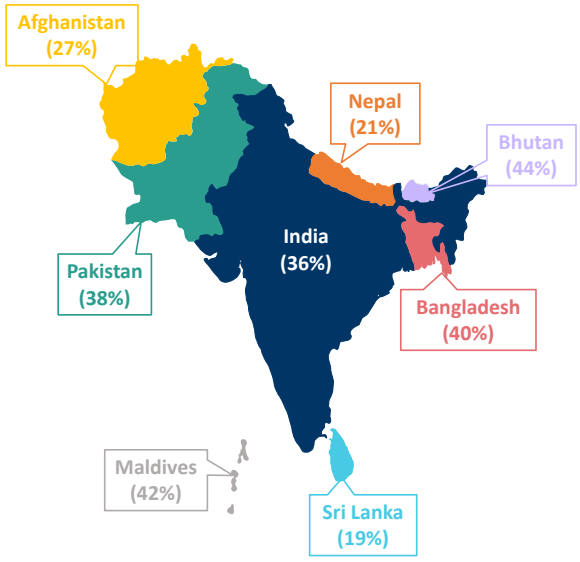


Figure 1.2: Countries in South Asia with percentage of urban population in 2022

Challenges

Firstly, the urbanisation process in South Asia diverges from norm observed in the Global North, where urbanisation typically coincides with growth in income and living standards. In South Asia, urbanisation has been rapid and haphazard, resulting in spillover of cities through creation of slums and informal settlements (Ellis et al., 2015; Badami et al., 2013). Since lower income households are forced to live in such peripheral settlements, their travel distances to access services such as employment, education, and healthcare increases (Chaudhry et al., 2023; Hamiduddin, 2023). The longer distances combined with lower disposable income reduces access to mobility significantly (IEA, 2021).

Secondly, the cities in these countries are struggling to cope with the pressure of rising

population which is evident in the lack of infrastructure and access to basic services, and the degrading environment (Ellis et al., 2015; Badami et al., 2013). Rising income levels and the lack of public transport (PT) infrastructure have led to increasing vehicle ownership rates (2-wheelers and private cars). This has not only caused a continuous increase in GHG emissions from the transport sector, but has also led to poor air quality and congestion in urban areas.

And finally, low income households are especially dependent on non-motorised (walking and cycling) modes of transport. The lack of adequate infrastructure combined with increasing motorisation rates have led to higher road fatalities involving pedestrians and raises safety concerns (IEA, 2021; Cazzola et al., 2021). The process of urbanisation in these countries is far from stagnancy, and the way it unfolds in the coming decades will heavily determine prospects of economic growth and climate change mitigation (Hasnath, 2013).

Opportunities

Urban policies centered around poverty alleviation, spatial planning and connectivity, and improving environmental quality and well-being can contribute to "well-managed" urban growth, leading to prosperity in these areas (Ellis et al., 2015; Hasnath, 2013). For example, transit oriented development (TOD) integrates land-use and transport planning, aiming to create livable communities with high density mixed land use and reduced travel distances. In the context of South Asia, where urbanisation is anticipated to rise accompanied by surge in mobility demand, TOD can assume a pivotal role as a strategic mechanism to manage traffic externalities, especially in cities where mass transit systems are already in place or being developed (Ministry of Housing and Urban Affairs, 2015; Nadeem et al., 2023). Further, compact urban development has the potential to reduce CO_2 emissions and avoid premature deaths due to air pollution (Fu et al., 2024).

The development of public transport infrastructure in South Asian countries has had a significant impact on inclusive growth (Rehman et al., 2023). India, Pakistan, and Bangladesh have either initiated or are contemplating the development of bus rapid transit (BRT) and metro rail transit (MRT) systems as a part of their sustainable transport network expansion policies (Jain, 2013). Public transport development is likely to play a key role in the region to reduce income and spatial inequalities in access to services. Bangladesh, India and Pakistan have either begun or proposed constructing high speed rail infrastructure, which will reduce intercity travel time and likely reduce the share of road-based transport and aviation.

Penetration of digital technology can also drive the implementation of various mobility solutions to improve access. Ride hailing services in South Asian cities have witnessed significant

growth since their introduction, partly to fill the void created by inadequate public transport infrastructure (Shah et al., 2022; Wadud et al., 2022). The users of such services in these cities are typically young, affluent and smartphone users (Shah et al., 2022; Raj et al., 2023; Rahman et al., 2021). While ride hailing services have led to an increase in the number of vehicles on the road and consequently resulting in higher traffic congestion and air pollution in cities (Agarwal et al., 2023), in the long run, they could lead to a reduction in private vehicle ownership (Wadud et al., 2022; Wadud, 2020).

Traffic externalities and environmental concerns have had a positive influence on the likelihood of adopting carpooling in India and Pakistan (Das et al., 2021; Goel et al., 2020a; Javid et al., 2017). Although, additional safety measures and policy mechanisms are needed to promote carpooling and reduce single occupant car use in South Asian cities (Javid et al., 2017; Meshram et al., 2020; Saxena et al., 2023). Further, many Indian cities have implemented bike-sharing schemes as a part of the Smart City Mission but their penetration is currently very limited given the inadequacy of the infrastructure (Machavarapu et al., 2022).

Mobility as a Service (MaaS) is growing in developed countries, with well-established transport systems (Hasselwander et al., 2023). Although there is initial evidence that MaaS can promote sustainable mobility in the Global South, for instance, the 'Kochi One' project in India, there is a lack of literature and validation on perceptions and willingness to adopt MaaS at a larger scale in South Asia (Hasselwander et al., 2023; Kant et al., 2023).

The prevalence of practices such as telecommuting is influenced by socio-economic factors, including household size, job nature, and the willingness of managers or employers to permit remote work. Nayak et al. (2021) identify the potential group of future telecommuters in India. The study suggests that encouraging telecommuting within this group can lead to a significant reduction in passenger transport emissions, given that these individuals are likely to own and use private vehicles. Online shopping also has the potential to reduce shopping trips, particularly because it saves travel time (Abbagani et al., 2022).

Non-motorised modes of transport such as walking, cycling and some forms of intermediate public transport (IPT) are an important part of the urban transport system in South Asia. Despite the lack of appropriate infrastructure, share of non-motorized transport (NMT) is substantially high, predominantly driven by low income households and inadequacy of public transport (Cazzola et al., 2021). However, safety is a major concern for NMT users, especially given the increasing motorization in South Asia. Further, general perception or cultural views also may hinder the adoption of NMT options, even if appropriate infrastructure is made available, and hence enhancing awareness on the benefits of using NMT (non-energy) might

be necessary (Mansoor et al., 2022).

The level of environmental awareness and motivation to take mitigative/adaptive measures against climate change in South Asia is generally low (Alvi et al., 2020). Although national policies in most of these countries recognize the need to raise awareness about climate change and its impacts, they remain underdeveloped (Mbah et al., 2022). Additional efforts have to be made, at the national and regional level to increase awareness through education programs and marketing campaigns.

In this context, this thesis develops an evidence-based framework that improves the quantification of sustainable mobility scenarios for the Global South. The process involves a literature review of mobility-related phenomena, with an emphasis on literature and data focusing on South Asia and the Global South. These phenomena are then incorporated into a new mobility projection model that can be linked to an IAM. This is a new adaptable framework that can be applied to focus on any other Global South region. And finally, four distinct mobility scenarios are developed for these phenomena based on alternate visions for mobility.

1.3 Thesis aim & key research questions

The overarching aim of this thesis is to improve the evidence base underpinning the modelling of climate change mitigation pathways in ESOMs and IAMs with a focus on energy service demands. The thesis is centred around the following research questions:

- **RQ1:** What is the value of including alternate demand futures in ESOMs and IAMs?
- **RQ2:** What benefits can demand reduction and restructuring measures, typically overlooked in decarbonisation scenarios, bring for climate change mitigation?
- **RQ3:** What is the impact of spatial settlement patterns on energy service demand? How can such drivers of energy service demand be parameterised in an energy systems model?
- **RQ4:** What is the impact of electrifying spatially dispersed household heating demand on the Irish power system?
- **RQ5:** How can the quantification of sustainable mobility scenarios for the Global South be improved to avoid biases arising from reliance on data, literature, and particular phenomena from the Global North?

- **RQ6:** How can the countries in the Global South leapfrog private car dependency towards a more sustainable development of the passenger transport system?

1.4 Thesis in brief

This thesis is divided into two parts. The first part of the thesis begins with energy service demand projections for Ireland in the TIMES-Ireland Model (TIM) driven by growth in population and economy. It then explores alternative trajectories for energy service demands, introducing the Irish Low Energy Demand (ILED) scenario. The ILED scenario represents the energy sector meeting the Climate Action Bill 2021 decarbonisation objectives through structural changes in energy service demands and de-materialising the economy along with low-carbon technology. A pivotal driver of the ILED scenario is the spatial settlement pattern, emphasizing the compact development of cities and towns. This intentional urban design is expected to yield a reduction in energy service demands within the residential and transport sectors. The next research work in this thesis quantifies the relationship between population density and the energy as well as carbon intensity of the residential and transport energy service demands. The objective is to enrich the granularity of analysis and provide empirical evidence that can underpin the development of future scenarios akin to ILED. In the following chapter, the thesis explores the ramifications of electrifying the spatially dispersed residential heating sector on the Irish power system.

The second part of the thesis focuses on developing evidence-based passenger mobility scenarios for the Global South, with a focus on South Asian countries. It transforms measured data related to various passenger mobility related phenomena into meaningful IAM/ESOM parameters. This involves the development of a high-resolution passenger mobility projections model. Using this framework, passenger mobility futures for South Asia are then developed.

The details of each chapter are outlined below and the overall structure of the thesis is shown in Figure 1.3:

- **Part I -** This part consists of four chapters (Chapter 2-5). The central theme of this part is the role of demand in Ireland's decarbonisation plan. It addresses research questions RQ1-RQ4. The chapters are summarised below:
  - **Chapter 2 -** This chapter presents the energy service demand projections methodology and the resultant output for the case of Ireland. These projections are used as baseline inputs in the TIMES-Ireland Model (TIM).

- **Chapter 3 -** This chapter presents the Irish Low Energy Demand (ILED) scenario using the TIMES-Ireland Model (TIM). ILED represents a scenario where ESDs are decoupled from economic growth by shifting travel, increasing end-use efficiency, densifying urban settlement, focusing on low-energy intensive economic activities and changing social infrastructure. The model version and results are open source and archived on Zenodo.
- **Chapter 4 -** This chapter presents a methodology to quantify the impact of spatial settlement patterns as a driver of the residential and transport ESDs in Ireland. It uses exploratory data analysis to estimate the mathematical relationship between various energy service demands and the dispersal of population. It also reviews the indirect impact of spatial settlement patterns have on climate mitigation via the viability of enabling low-carbon infrastructure.
- **Chapter 5 -** This chapter examines the power system impacts of integrating high quantities of heat pumps, in line with government targets. It provides a broad discussion of the ramifications of heating sector electrification in terms of system costs and expansion planning under renewable energy targets. It also explores alternative policy pathways to minimize impacts on the system. These include determining optimal locations for heat pump integration and a technology-neutral emission reduction target.

- **Part II -** This part consists of one chapter. The central theme of this part is sustainable development strategies for passenger transport in the Global South. It addresses research questions RQ1, RQ5 and RQ6. The chapter is summarised below:
  - **Chapter 6 -** This chapter presents a framework that incorporates various passenger mobility related phenomena into a new mobility projection model that can be linked to an IAM. The passenger mobility scenarios developed herein are based on literature and data that prioritises evidence from the Global South. This framework focuses on South Asian countries but can be applied to any other Global South region.

1.5 Role in collaborations

The majority of the thesis is my own research work. However, collaborations with various other researchers forms a significant part in the development of the chapters. This section outlines the role of others who have contributed in strengthening this thesis.

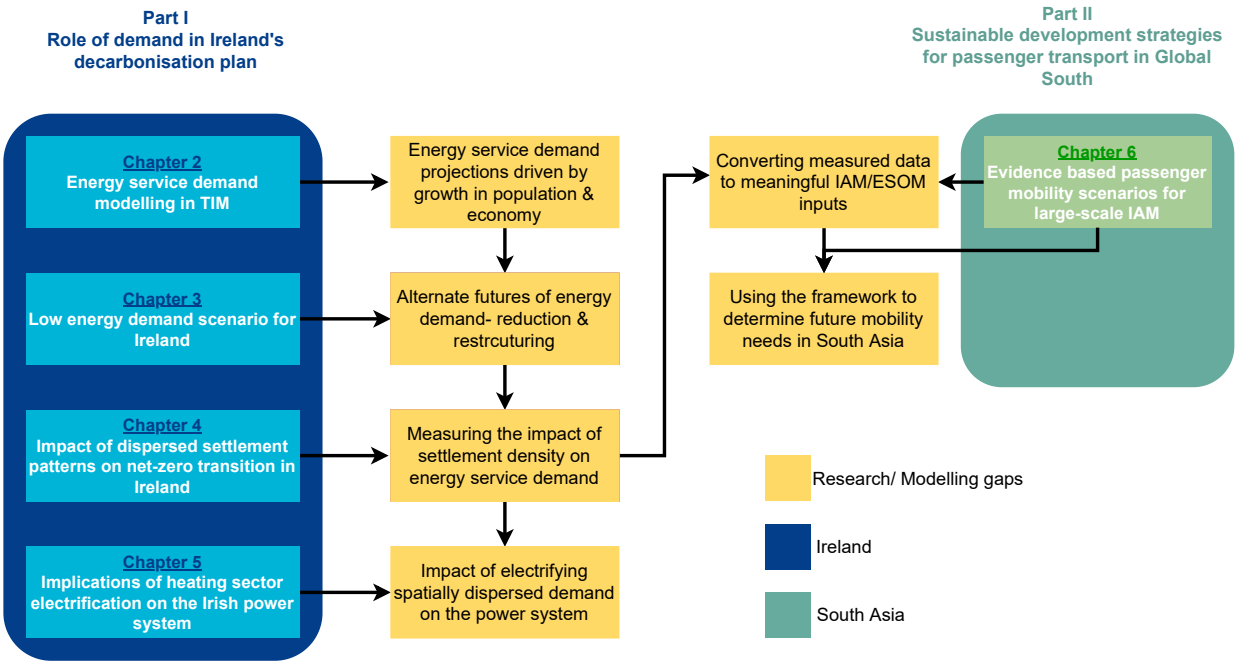


Figure 1.3: Overview of the thesis structure

Chapter 2 describes my contribution to the TIMES-Ireland model documentation paper (Balyk et al., 2022). Prof. Hannah Daly and Dr. James Glynn advised on the original methodology and reviewed drafts. This work was a part of an expert peer-review process and I received feedback on my work from Prof. John Curtis and others.

Chapter 3 is published in a peer-reviewed journal of which I am the lead author. I developed the scenario, conducted the formal analysis and prepared the draft. Prof. Daly and Dr. Glynn provided guidance on the methodology. Dr. Olexandr Balyk helped debug the model, prepared the public repository on GitHub and archived the model and results on Zenodo. All co-authors reviewed the draft.

Chapter 4 is published in a peer-reviewed journal of which I am the lead author. My supervisors, Prof. Daly and Prof. Curtis assisted me with the conceptualisation and methodology of the paper. I conducted the formal analysis and prepared the draft. Dr. Jason McGuire added text and data related to residential sector calculations (Section 4.3.3.1). Dr. Vera O'Riordan provided data for the transport sector (Section 4.3.3.2). All co-authors reviewed the draft.

Chapter 5 is published in a peer-reviewed journal of which I am the lead author. Dr. Desta Fitiwi assisted me in developing the e-heat model within ENGINE. I performed the formal analysis and prepared the draft. Dr. Muireann Lynch provided feedback and assistance with

the original draft. All co-authors reviewed the draft.

Chapter 6 is under review in a peer-reviewed journal of which I am the lead author. I developed the model, conducted the formal analysis and prepared the draft. Dr. Aneeque Javaid and Dr. Paul Kishimoto provided guidance in developing the methodology. Dr. Kishimoto also provided coding assistance for developing the model in Python. Dr. Javaid and Prof. Daly advised on advancing the model. All co-authors reviewed the draft.

1.6 Thesis output

Journal papers

Lead author

- **Gaur, A**., Balyk, O., Glynn, J., Curtis, J. and Daly, H., 2022. Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland. *Renewable and Sustainable Energy Transition*, 2, p.100024. ***-Chapter 3***

- **Gaur, A**., McGuire, J., O'Riordan, V. J., Curtis, J. and Daly, H., 2024. Dispersed settlement patterns can hinder net-zero transition: Evidence from Ireland. *Energy Strategy Reviews*, 51, p.101296. ***-Chapter 4***

- **Gaur, A**., Fitiwi, D.Z., Lynch, M. and Longoria, G., 2022. Implications of heating sector electrification on the Irish power system in view of the Climate Action Plan. *Energy Policy*, 168, p.113136. ***-Chapter 5***

- **Gaur, A**., Javaid, A., Kishimoto, P., and Daly, H., (in preparation). Mobility scenarios for the Global South: Developing an evidence-based framework for a large-scale IAM. In preparation for submission to *Transportation Research Part D: Transport and Environment* ***-Chapter 6***

Contributing author

The peer-reviewed papers presented below have been informed by my research which was undertaken either before or during the course of this thesis.

- Balyk, O., Glynn, J., Aryanpur, V., **Gaur, A**., McGuire, J., Smith, A., Yue, X. and Daly, H., 2022. TIM: modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1. 0). *Geoscientific Model Development*, 15(12), pp.4991-5019. ***-Part of this is discussed in Chapter 2***

- Mc Guire, J., Rogan, F., Balyk, O., Mac Uidhir, T., **Gaur, A**. and Daly, H., 2023. Developing decarbonisation pathways in changing TIMES for Irish homes. *Energy Strategy Reviews*, 47, p.101086. ***-Related to content presented in Chapters 2 and 4***

  - This paper presents the residential sector in the TIMES-Ireland Model (TIM). I contributed to developing the energy service demand projections for this sector. Further, I used a part of this research in Chapter 4 of this thesis. This paper is not included in this thesis.

- Hoare, C., Aghamolaei, R., Lynch, M., **Gaur, A**. and O'Donnell, J., 2022. A linked data approach to multi-scale energy modelling. *Advanced Engineering Informatics*, 54, p.101719. ***-Related to content discussed in Chapter 5***

  - This paper is a step preceding Chapter 5 of this thesis. It develops a novel framework to calculate the residential heating demand at the transmission node level for Ireland. This project was a result of collaboration within the Energy Systems Integration Partnership Program (ESIPP). I contributed to the results section which shows the application of this framework. This paper is not included in this thesis.

Conferences, Workshops and Seminars

- Gaur, A., Daly, H., and Ó Gallachóir, B., 2023. Dispersed settlement pattern can hinder net-zero transition. *41st International Energy Workshop (IEW)*, June 2023, Golden, Colorado, US.

- Gaur, A. and Daly, H., 2023. Where we live: How settlement patterns impact energy service demands and climate mitigation options. *33rd Irish Environmental Researchers Colloquim (ENVIRON)*, April 2023, Letterkenny, Donegal, Ireland.

- Gaur, A. and Balyk, O., 2022. Energy Trade in TIMES-Ireland Model. *IEA-ETSAP webinar series- Current Modelling Practices*, September 2022, Kjeller, Norway.

- Gaur, A, and Balyk, O., 2022. 'Human Dimension' Modelling Approaches in TIMES-Ireland Model (TIM). *IEA-ETSAP webinar series- Current Modelling Practices*, September 2022, Kjeller, Norway.

- Gaur, A. and Daly, H., 2022. Analysing the impact of spatial development on energy service demands to aid deep mitigation pathway development in Ireland. *Scenarios Forum*, June 2022, Laxenburg, Austria.

- Gaur, A. and Daly, H., 2022. How can lower energy demand help Ireland achieve its

climate targets? *ESRI-MaREI Seminar*, May 2022, Online event.

- Gaur, A. and Daly, H., 2022. Analysing the impact of spatial development on energy service demands to aid deep mitigation pathway development in Ireland. *40^{th} International Energy Workshop (IEW)*, May 2023, Freiburg, Germany.
- Gaur, A. and Daly, H., 2021. Modelling a low energy demand pathway in an energy system optimisation model: Case study for Ireland. *14^{th}Integrated Assessment Modelling Consortium (IAMC)*, Dec 2021, Online event.
- Gaur, A. and Daly, H., 2021. A low energy demand pathway for Ireland. *IEA-ETSAP workshop*, June 2021, Online event.
- Gaur, A. and Daly, H., 2020. Assessing the framework between macro-economic models and energy systems optimisation models. *MaREI Symposium*, November 2020, Online event.

Invited lecture

- Gaur, A., 2021. Introduction to Power System Planning. *Faculty Development Programme (FDP) on Challenges in Evolving Power Systems*, November 2021, Department of Electrical Engineering, Finolex Academy of Management & Technology, India, Online event.

Part I: Role of demand in Ireland's decarbonisation plan

Chapter 2

Energy service demand modelling in TIMES-Ireland Model

Abstract

This study presents the energy service demand projections in the end-use sectors in Ireland which are used as exogenous inputs to the TIMES-Ireland Model (TIM). The base line energy service demands are driven by growth in population and economy. TIM is set up to allow for alternate scenarios for demand drivers that result in different energy service demand projections in the end-use sectors. [1]

Keywords: Energy service demands, TIMES, Ireland, population, economic growth

2.1 TIMES-Ireland Model

The TIMES-Ireland Model produces energy system pathways for energy supply and demand in Ireland consistent with either a carbon budget or a decarbonisation target. It calculates the lowest-cost configuration of energy fuels and technologies which meet future energy demands while respecting technical, environmental, economic, social and policy constraints. Key inputs and constraints include primary energy resource availability and costs, the technical and cost evolution of new mitigation options and the maximum feasible uptake rates of new technologies. Alternatively, TIM can be used to assess the implications of certain policies, namely regulatory or technology target-setting (for example, biofuels blending obligation or sales/stock share target for electric vehicles).

[1] Excerpt from: Balyk, O., Glynn, J., Aryanpur, V., Gaur, A., McGuire, J., Smith, A., Yue, X. and Daly, H., 2022. TIM: modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1. 0). Geoscientific Model Development, 15(12), pp.4991-5019.

2.1.1 TIMES Model generator

TIMES (The Integrated MARKAL-EFOM System) is a bottom-up optimisation model generator for energy-environment systems analysis at various levels of spatial, temporal and sectoral resolutions (Loulou et al., 2016a; Loulou et al., 2016b). The TIMES code, written in GAMS and available under an open source licence (IEA-ETSAP, 2020) is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP)[2], a Technology Collaboration Programme (TCP) of the International Energy Agency (IEA), established in 1976. TIMES models can have single or several regions and typically are rich in technology detail, used for medium- to long- term energy system analysis and planning at a regional, national or global scale.

TIMES is a linear optimisation, techno-economic, partial-equilibrium model generator which assumes perfectly competitive markets and perfect foresight. Model variants enable myopic foresight, general equilibrium, stochastic programming and a variety of multi-objective function options. The standard objective function maximises the net total surplus (the sum of producers' and consumers' surpluses) which, in a perfect market with perfect foresight, equates to maximising the net present value (NPV) of the whole energy system, maximising societal welfare. Profits, taxes and subsidies are internal transfers, i.e. occurring within the economy, that do not change the NPV (albeit taxes and subsidies can be included to influence the optimisation). It calculates the energy system specification which minimises discounted total energy system costs over the model time horizon, which is the sum of investments, fixed and variable costs, fuel import costs and export revenues for all the modelled processes, less potential salvage values of investments for which whole lifetime goes beyond the model time horizon.

The user inputs the following to the model generator:

- Reference Energy System (RES), is the process-flow architecture of economic sectors and energy flows (commodity) between processes (technology), which consume and produce energy, energy service demands and/or other commodities such as environmental emissions (including greenhouse gases) and other materials. The base-year energy flows are calibrated to national energy balances.
- Energy service demands, are the physical services required by the economy and society for mobility, heat, communications, food etc., which drive energy demand.
- Energy supply curves, the quantities of primary energy resources (e.g. wind power)

[2]https://iea-etsap.org/

or imported commodities (e.g. oil, gas, bio-energy) available at specific cost points for differing quality and quantity of energy commodities.

- Techno-economic parameters of existing and potential future energy technologies: economic parameters including current and projected future investment and fixed/variable costs and efficiencies of technologies for energy supply (e.g., solar PV panels, transmission and distribution infrastructure, biorefineries, hydrogen production) and energy demand (e.g., electric vehicles, natural gas boilers, carbon capture and storage); technological parameters including transformation efficiency, availability factor, capacity factor and emissions factor.
- User constraints, which can be any combination of linear constraints (including fixed, maximum or minimum bounds on growth, investment or shares) on technologies or fuels. These are typically used to simulate real-world technology constraints or to simulate policy scenarios. A typical user constraint for decarbonisation analysis is limiting total annual or cumulative CO_2 emissions to model energy system pathways that meet a national decarbonisation target.

TIMES outputs the optimal investment and operation level of all energy technologies which meet future energy service demands at least cost, while respecting user constraints. The model also produces corresponding energy flows, emissions and marginal prices of energy and emissions flows.

2.1.2 Model architecture

Fig. 2.1 shows a simplified RES in TIM. It describes the structure and energy flows including two major parts: supply-side and demand-side. The former comprises energy resources, fuel production and conversion technologies (e.g. biorefineries, hydrogen production and different power plants), transmission and distribution infrastructure (e.g. gas pipelines and power grid). The latter covers end-use sectors (e.g. transport, residential) and the corresponding energy service demands (i.e. passenger, freight, hot water). Energy resources incorporate both domestic fossil-based fuels and renewables potentials. These fuels are processed and then distributed across country. End-use technologies consume energy commodities to meet energy service demands. GHG emissions from fossil fuel combustion and process-related emissions in industry are tracked at the fuel supply module, electricity generation technologies and sectoral-consumption levels.

The model's base year is 2018 and all energy flows, emissions and energy technology stocks are calibrated to the 2018 energy balance (SEAI, 2019).

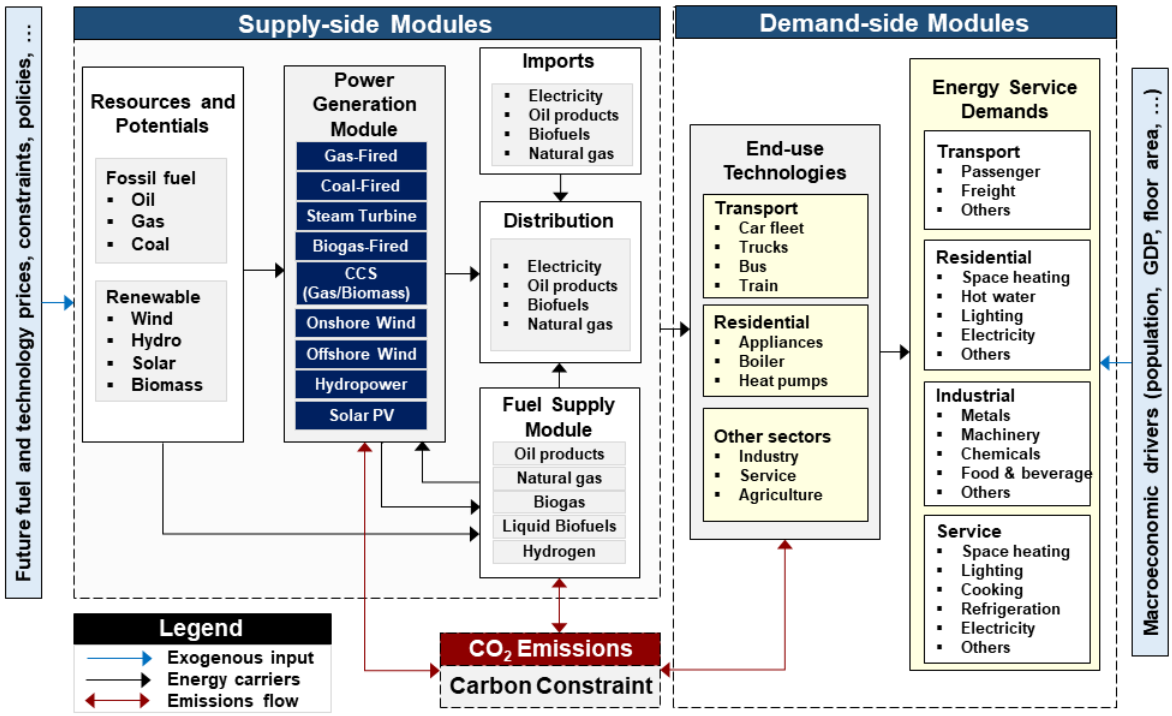


Figure 2.1: Simplified representation of reference energy system in TIM

The discount rate, the degree to which future values are discounted to the present, is a key parameter in the TIMES objective function. A social discount rate reflects how society views present costs and benefits against future ones and is lower than a financial discount rate, which is how firms make investment decisions. In appraising potential projects or investments, the Government applies a social discount rate. Broadly speaking, in an ESOM scenario with a carbon budget constraint, a higher discount rate would promote later decarbonisation and less capital-intensive technology choices. In this model, a discount rate of 4% is applied, which is based on a Social Rate of Time Preference methodology as set forth in the Public Spending Code (O'Callaghan et al., 2018). This rate is consistent with García-Gusano et al. (2016) who recommend using a maximum value of 4-5% for the social discount rate in ESOMs.

Technology-specific discount rates (also known as hurdle rates) are typically used in ESOMs to capture investment decision-making from the individual user or industry perspective, to capture market imperfections, limited finance and behavioural heuristics which limit the uptake of novel or capital-intensive investments, even when they are cost-optimal. These parameters are not used in the core version of TIM given its use for modelling long-term energy system pathways from a societal perspective. However, variants of the model can be developed to simulate real-world impacts of policies and behaviour which can include hurdle

rates (Aryanpur et al., 2022).

2.1.3 Time & Geography

TIM has been developed with a deep knowledge of the geography of the Irish energy system. A special spatio-temporal approach was taken in the RES base year specification and scenario file data structures to allow flexible regional definitions and temporal resolution in TIM. The model can run in multiple modes with multiple configurations of regional and temporal resolution ranging from a single region national model at a single annual timeslice, all the way to 26 counties at hourly resolution where supply-demand data is available at that spatio-temporal granularity (Electricity, Gas & Transport).

High spatial granularity is required to give greater policy clarity on optimal investment needs based on region- and county-specific characteristics to enable counteracting socioeconomic challenges such as energy poverty and infrastructure development within an optimisation framework (Aryanpur et al., 2021). We address this in TIM by creating model input data structures that allow specifying data and formulating constraints on both national and county level. Internal file switches, as well as user shell options, could then be used to apply TIM on either of the levels.

We have decided to focus on this data-driven spatio-temporal model setup to future-proof TIM and enable future Irish energy policy research needs as data-availability improves during TIM's lifespan.

2.2 Drivers of energy service demands in the TIMES-Ireland Model

Energy service demands in end-use sectors are driven by growth in the population and in the economy. The model is set up to allow for alternative scenarios for these drivers resulting in different energy service demand projections in the end-use sectors, e.g. as applied in Gaur et al. (2022a) and Gaur et al. (2022b). This section describes baseline driver projections with a detailed description of energy service demand projections included in the respective sector sections.

2.2.1 Population

Historical population estimates and future projections are obtained from (CSO, 2020). We use the M2F1 scenario since it represents a medium growth in population and is in line with population projections used in other national sources (Yakut et al., 2020).

Table 2.1: Population

Year	Population (millions)
2018	4.85
2020	4.98
2030	5.40
2040	5.82
2050	6.19

2.2.2 Economic growth

Economic growth projections are mostly taken from national sources to ensure internal consistency. GVA and income projections are modelling outcomes from Bergin et al. (2017) used by national sources. The following historical and projected data is used:

- Historical Gross value added (GVA) for the required NACE categories in the services and industry sectors is obtained from EUROSTAT database. Projections for GVA are from the Ireland Environment, Energy and Economy (I3E) model (Yakut et al., 2020).
- Gross domestic product (GDP), both historical and future projections, is obtained from Organisation for Economic Co-operation and Development (OECD)(OECD, 2018).
- Income, historical values of total incomes, are taken from Central Statistics Office (CSO) (CSO, 2021a). Assumptions about income growth in the future are from the National Transport Model (AECOM, 2019).
- Modified Gross National Income (GNI*) is derived from CSO's labour force scenario combined with a forecast for output per person (CSO, 2018).

2.3 Energy service demand projections

Table 2.3 lists the energy service demands in TIM along with their corresponding drivers and values for 2018 and 2050. Specifics of the methodologies for projecting each energy service demand are detailed below, for transport (2.3.1), residential (2.3.2), industry (2.3.3) and services (2.3.4).

2.3.1 Transport

Passenger-kilometres: Private Cars Future passenger car transport demand is projected based on future population growth and a growing rate of car ownership, which is in turn determined by income growth. Car ownership usually follows an S-shaped function which has three periods: slow growth during low income levels, rapid increase as income levels rise quickly and finally a saturation period. Gompertz statistical model has been found to best fit the historical relationship between car ownership and income levels, although other functions have also been used in previous studies (Lian et al., 2018). The basic Gompertz function is shown in Equation 2.1.

$$y = \alpha * e^{-\beta * e^{-\gamma x}} \tag{2.1}$$

where y is the car per adult, α is saturation level of car ownership, x is an economic indicator (income per adult in this case) and β,γ are parameters that are estimated using historical data obtained from CSO.

Projection of future car ownership levels is based on changes in income levels. The saturation level of car ownership is assumed at 875 per 1000 adults (AECOM, 2019). Car ownership (cars per adult) is projected to rise from 0.56 in 2018 to 0.69 in 2050, an increase of 23%. Passenger-kilometres are then derived using car ownership as a proxy and assuming an occupancy level of 1.492 and kilometres per car to remain constant at about 17300 per year. Total passenger-kilometres from private cars in 2050 is projected to increase by 42% from the 2018 level with a compound annual growth rate (CAGR) of 1.1%. The growth rate of passenger-kilometres from private cars was 1.35% between 2008 and 2018.

Passenger-kilometres: Other modes of transport Other modes of transport represent a much smaller share of mobility demand compared to private cars. Passenger-kilometres of large public service vehicles (PSVs) are projected using population as a driver in a log function and assuming average occupancy of 27.5. Large PSV passenger-kilometres are expected to increase by 24.2% in 2050 as compared to that in 2018 with a CAGR of 0.7%. Passenger-kilometres of other modes (luas, train, small PSVs, and motorcycles) and active modes (walking and cycling) are projected using population as a driver. The passenger-kilometres are expected to increase by 60% with a CAGR of 1.5%.

International Aviation fuel demand International aviation fuel demand is projected using number of passengers as a driver. The number of aviation passengers is projected

using damped Holt Winters function based on historical time-series data obtained from CSO (Dantas et al., 2017; Grubb et al., 2001). The number of passengers in 2050 is expected to increase by 45.5% compared to 2018. The historical fuel demand for aviation and number of aviation passengers are then used as input for a linear regression model to project the future demand for aviation fuel. The fuel demand in 2050 increases by 37% relative to 2018 with a CAGR of 1%.

Other transport fuel demand Demand for freight is projected using growth rates from AECOM (2019). The growth in tonne-kilometres of freight is expected to increase by 1.18 times in 2050 from 2018 level with a CAGR of 2.5%. Navigation fuel demand is projected using GDP as the explanatory variable. Fuel demand for navigation in 2050 is expected to increase 2.85 times compared to 2018 with a CAGR of 3.3%. Fuel tourism is assumed to remain constant at 11 PJ.

2.3.2 Residential

The residential stock projections up to 2040 are taken from Bergin et al. (2020) housing demand estimates, which utilise economic growth projections from Bergin et al. (2017). The stock is expected to increase by 40% from 2018 level with a CAGR of 2%. This results in an average of 27,600 new houses per annum between 2021-2040. Beyond 2040, population is used as a driver to project housing stock. The total housing stock obtained in 2050 is 2.57 million dwellings which implies 8% increase from 2040. Since the data on type of dwellings is limited, a simple linear regression, as shown in Equation 2.2 is used to calculate the share of the building archetype in a given year (y). The resultant dwelling stock projection by archetype is shown in Table 2.2.

$$\begin{aligned} Apt(\%) &= 7.5 \ln(y) - 56.97 \\ Att(\%) &= -2.53 \ln(y) + 19.68 \\ Det(\%) &= -4.93 \ln(y) + 37.91 \end{aligned} \tag{2.2}$$

2.3.3 Industry

Energy demand for the industrial sector is projected using GVA per capita for each nomenclature of economic activities (NACE) category and population (Yakut et al., 2020). Historical energy consumption is obtained from SEAI (2019) energy balance. The total energy demand

Table 2.2: Number of dwellings by type ('000)

Year	Apartment	Attached	Detached
2018	207	766	724
2030	355	918	833
2040	493	1003	878
2050	629	1057	890

from industry in 2050 is projected to increase by 47% from the 2018 level. Cement demand up to 2025 is projected using Department of Finance, 2020 stability program update which provides forecasts for the growth in modified investment. In 2019, 65% of the modified investment was in building and construction. Calculating a linear regression of the log of the index for output of the cement sector on the log of investment in building and construction at constant price results in an 18.6% increase in cement demand in 2025 from 2018 level. Beyond 2025, growth in cement demand is assumed to be the same as the growth in GNI*. This leads to a further increase by 17.8% between 2025 and 2050 at a CAGR of 0.7%. The energy intensity of the industry sector is expected to decline by 46.5% between 2018 and 2050 with a CAGR of -2%, reflecting historical trends.

2.3.4 Services

The end-use demand services in the service sector are estimated as million-meter square of area required for public and private sector buildings, data centre demand and public lighting units. The area is projected assuming the same growth as in GNI*. The total area is projected to increase by 61.8% by 2050 from 2018 level with a CAGR of 1.5%.

Electricity demand for data centres is obtained from EirGrid's "steady evolution" scenario (EirGrid, 2017). The demand is expected to increase by 6 times in 2030 from 2018 level. We assume no growth in data centre demand after 2030 since permission requests for new/expanding existing capacities are not available yet. Further, post-2030 demand is even more uncertain given (i) the potential for exponential data usage growth and further data centres applications vs (ii) technology improvements and whether data centres fully utilise their contracted import capacity. Electricity consumption of data centres for cooling, and their potential to supply district heat from the excess heat they generate, are represented using the methodology described in Petrović et al. (2020).

Public lighting units are projected based on Project Ireland 2040, whereby five major cities of Ireland, Dublin, Cork, Limerick, Galway and Waterford are expected to grow by 50% in 2040 (Government of Ireland, 2018). This results in a 12.5% increase in public lighting units in Ireland by 2040 from 2018 level, with a CAGR of 1%. Beyond 2040, the units are

projected to increase by 1% per annum until 2050.

Table 2.3: Energy service demands in TIM

Energy Service Demand	Unit	Driver	Value	
			2018	2050
Non-Energy Mining [05-09]	PJ	GVA per capita, Population	2.07	0.13
Food and beverages [10-11]	PJ	GVA per capita, Population	22.25	34.00
Textiles and textile products [13-14]	PJ	GVA per capita, Population	1.20	4.97
Wood and wood products [16]	PJ	GVA per capita, Population	6.69	7.65
Pulp, paper, publishing and printing [17-18]	PJ	GVA per capita, Population	0.67	2.31
Chemicals and man-made fibres [20-21]	PJ	GVA per capita, Population	10.60	13.11
Rubber and plastic products [22]	PJ	GVA per capita, Population	1.14	0.89
Other non-metallic mineral products [23]	PJ	Modified investment, GNI*	17.77	24.82
Basic metals and fabricated metal products [24-25]	PJ	GVA per capita, Population	19.54	21.73
Machinery and equipment n.e.c. [28]	PJ	GVA per capita, Population	1.29	1.69
Electrical and optical equipment demand [26-27]	PJ	GVA per capita, Population	4.27	16.37
Transport equipment manufacture [29-30]	PJ	GVA per capita, Population	0.17	0.04
Other manufacturing [31-33,12 & 15]	PJ	GVA per capita, Population	4.25	6.12
Construction [41-43]	PJ	GVA per capita, Population	4.02	5.90
Short-range passenger travels	BPKM	Income, population	14.56	21.07
Medium-range passenger travels	BPKM	Income, population	31.28	45.29
Long-range passenger travels	BPKM	Income, population	27.13	38.97
Goods vehicle for freight	BTKM	Growth rate from (AECOM, 2019)	11.54	25.14
Tourism fuel	PJ		7.72	0.00
Navigation fuel	PJ	GDP	3.51	10.04
Unspecified fuel	PJ		21.78	0.00
Aviation domestic	PJ		0.23	0.23
Aviation international	PJ	International Aviation Passengers	45.94	62.63
Residential Apartment Demand	000'	Population	206.80	628.93
Residential Attached Demand	000'	Population	766.35	1056.50
Residential Detached Demand	000'	Population	724.43	889.76
Residential Refrigeration Demand	PJ	Residential dwelling growth (total)	1.13	1.71
Residential Cooking Demand	PJ	Residential dwelling growth (total)	2.00	3.03
Residential Cloth Washing Demand	PJ	Residential dwelling growth (total)	0.77	1.17
Residential Cloth Drying Demand	PJ	Residential dwelling growth (total)	1.03	1.56
Residential Dish Washing Demand	PJ	Residential dwelling growth (total)	0.83	1.26
Residential ELC Appliances Demand	PJ	Residential dwelling growth (total)	9.22	13.98

Residential Other Applications Demand	PJ	Residential dwelling growth (total)	0.00	0.00
Services - Commercial Services	Mm^2	GNI*	28.90	47.39
Services - Public Services	Mm^2	GNI*	58.15	95.35
SRV-Commercial Services: Data centers	PJ	From EirGrid	5.63	40.30
SRV-Public Services: Public lighting	Mlamps	From (Government of Ireland, 2018)	0.48	0.58

Chapter 3

Low energy demand scenario for Ireland

Abstract

Typically, energy system decarbonisation scenarios neglect the mitigation opportunities from reducing and restructuring energy service demands (ESDs), focusing instead on technology and fuel substitutions. Models tend to be designed to factor technologies explicitly while ESDs are exogenous. However, existing literature suggests that the scale and speed of decarbonisation required to limit global warming to 1.5°C by the end of the century requires a shift in energy demands to avoid the need for large-scale negative emission technologies. This can be brought about by major structural changes in drivers of demand such as transport modal shifting, substituting emission intensive materials like cement, and reducing building heat demand through behaviour change and efficiency. Ireland, the subject of this paper, has legislated one of the most ambitious decarbonisation targets in the world: the need to understand the role of demand shift is paramount. To fill this gap, the Ireland's Low Energy Demand (ILED) mitigation narrative is developed and applied to the TIMES Ireland Model (TIM), an energy systems optimisation model. ILED represents a scenario where ESDs are decoupled from economic growth by shifting travel, increasing end-use efficiency, densifying urban settlement, focusing on low-energy intensive economic activities and changing social infrastructure. Compared to a scenario where ESDs follow 'Business-as-usual' growth, ILED enables the achievement of steep decarbonisation targets with a less rapid energy system transformation, lower capital and marginal abatement costs, and with lower reliance on the deployment of novel technologies. [1]

Keywords: Climate change mitigation, Decarbonization, Lifestyle change, Low energy demand, Net-zero, TIMES, Macro Energy Systems Optimization Models

[1] Published as: Gaur, A., Balyk, O., Glynn, J., Curtis, J. and Daly, H., 2022. Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland. Renewable and Sustainable Energy Transition, 2, p.100024.

3.1 Introduction

The IPCC's Special Report on global warming of 1.5°C (SR1.5) published in 2018 had a profound impact on international and national climate policy discussions (Masson-Delmotte et al., 2018). It emphasised the need to reduce global annual CO_2 emissions by half by 2030, relative to 2010, and to net-zero by 2050, to limit global temperature rise. The report prominently features climate mitigation scenarios and development pathways that inform the techno-economic feasibility of measures adopted to curb emissions. Pathways that limit global warming to 1.5°C this century require rapid and deep transformations in the energy and industrial systems, land use and urban infrastructure.

Energy consumption has always been strongly coupled with economic growth and if this correlation exists in the future, meeting climate goals will require unprecedented changes in energy technologies, fuels and infrastructure, requiring innovations and large-scale negative emission technologies (Masson-Delmotte et al., 2018). The 'green growth' theory or 'Environmental Kuznets Curve (EKC)', that occupies a notable position in the climate change policy discourse, asserts economic growth (measured in terms of GDP) can be decoupled from resource use and CO_2 emissions (Gill et al., 2018). However, some studies argue that existing empirical evidence does not fully support this theory, partly due to the economy-wide rebound effect (Hickel et al., 2020; Haberl et al., 2020; Brockway et al., 2021). Other concepts such as degrowth, energy sufficiency, and consumption corridors have been widely discussed in the literature but not integrated with energy transition pathways (Hickel, 2019; Millward-Hopkins et al., 2020; Kikstra et al., 2021; Sahakian et al., 2021).

With some exceptions, energy system decarbonisation scenarios tend to conform to the 'green-growth' paradigm: assuming that the drivers of energy demands will follow historical patterns, they demonstrate how mitigation targets can be met with technology and fuel switches alone.

One of the major features of the scenarios reviewed in the IPCC's SR1.5 is the role of carbon dioxide removal (CDR) through the use of negative emissions technologys (NETs) to meet the end-of-century climate goals (Masson-Delmotte et al., 2018). Most of the scenarios modelled for this report feature a temporary overshoot in the increase of the global temperature of 1.5°C above preindustrial levels, and use NETs to reduce atmospheric concentrations of greenhouse gases (GHGs) and return to the temperature target. However, there is a real risk that these technologies might not be able to deliver CDR at the scale promised and a CDR-dependent pathway might exceed the remaining carbon budgets associated with meeting the emissions and temperature goals (Anderson et al., 2016; European Academies

Science Advisory Council, 2018; Holz et al., 2018; Realmonte et al., 2019; Hilaire et al., 2019; Grant et al., 2021). Some NETs can have adverse impacts on ecosystem and questions about their feasibility in terms of cost, land availability and competition for food production, feedstock resource potential, social acceptance, and safety are yet to be addressed along with other geophysical and institutional barriers (Anderson et al., 2016; Smith et al., 2016; Hilaire et al., 2019). Hence, there is a need to explore alternate mitigation pathways that limit or do not use NETs (Anderson et al., 2019).

The SR1.5 also features a relatively new pathway called 'LED' developed by Grubler et al. (2018) wherein the future energy demand is lowered from current level. Figure 3.1 shows the CO_2 emissions in the four 1.5 °C consistent illustrative pathways featured in SR 1.5 (Masson-Delmotte et al., 2018; Riahi et al., 2017; Rogelj et al., 2018; Gidden et al., 2019). It can be clearly seen that the LED pathway has the lowest negative emissions among other featured scenarios.

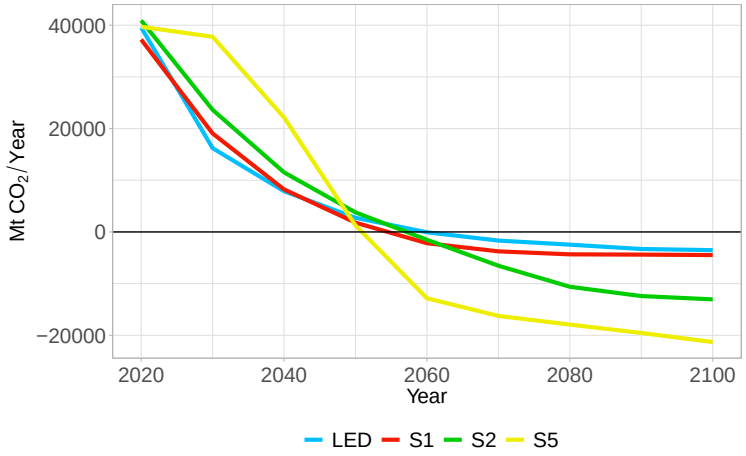


Figure 3.1: Evolution of CO_2 emissions in the illustrative pathways featured in SR 1.5 where S1, S2 and S5 are based on Shared Socioeconomic Pathways (SSPs) SSP1, SSP2 and SSP5 respectively (Riahi et al., 2017; Rogelj et al., 2018; Gidden et al., 2019)

Alternate deep mitigation pathways include the impact of technological changes, structural changes in the economy, and societal transformations on the drivers of energy demand (Van Vuuren et al., 2018; Le Quéré et al., 2019). Mitigation scenarios have traditionally focused on the supply side of the energy system while behavioural and end-use demands have received less attention (Creutzig et al., 2018). This is because the present generation of Integrated Assessment Models (IAMs) or Energy System Optimisation Models (ESOMs), which underpin global and national climate mitigation planning, typically has limited capabilities for endogenously representing new behavioural changes or social structures that can affect energy demand, whereas, representing technology and fuel switches are straightfor-

ward (Gambhir, 2019; Creutzig et al., 2016). Van Soest et al. (2019) found that the United Nation's Sustainable Development Goals (SDGs) related to human development and governance are not well represented in IAMs. Most models produce future energy mixes based on exogenous energy service demand projections driven by historical relationship between population and economic growth. Though efficiency improvements are often included such as building retrofits, electrification and fuel switching, and technology upgrades, other solutions that could either lower energy demand or shift to cleaner modes of provision such as modal shift, lowering heating temperature set-point and material recycling are relatively new that can limit climate change but are often missing (Pye et al., 2020; Kesicki et al., 2011; Grubler et al., 2018; IEA, 2021). Although full endogenisation of all mitigation options is not possible within IAMs and ESOMs, linking them through exogenous assumptions and narratives is a common approach (Van Soest et al., 2019).

There is a consensus that modelling social, economic, and political disruptions that could change the way energy is consumed is important to understand possible future levels of energy service demands (Hardt et al., 2019; Liu et al., 2020; Hanna et al., 2021; Anable et al., 2012). Better representation of demand-side policies and integrating multidisciplinary insights from social sciences, economics, and engineering could help policymakers devise effective plans for future changes (Hardt et al., 2019; Hanna et al., 2021; Brutschin et al., 2021). This is further confirmed by two recent reports at the global level from the International Energy Agency, World Energy Outlook 2020 (International Energy Agency, 2020) and Net Zero by 2050 (IEA, 2021). They emphasise that behavioural change will be an integral part of decarbonisation pathways. These reports estimate that about 1.7-2 Gt of CO_2 emissions can be avoided by 2030 if behavioural changes are implemented quickly, and about half of these emissions savings are associated with the transport sector.

The purpose of this paper is threefold: First, we argue for broadening mitigation scenarios to include Low Energy Demand (LED) pathways, which include changes in both the structure and trajectory of energy service demands[2] (ESDs) as a mitigation option. We begin by discussing the importance of considering LED pathways in climate mitigation scenarios and the role they might play in achieving the Paris Agreement temperature targets (Section 3.1.1). Then, we explore the measures through which demand could be modified along with their interdependencies (Section 3.1.2). Second, we review the LED-type scenarios available in the energy system modelling literature including scenario narratives and corresponding parameters (Section 3.2). Third, we present a case study for Ireland using the newly-developed

[2]Energy Service Demands (ESDs) include demand for activities that drive the demand for final energy consumption, such as space and water heating, cooking, washing, mobility, materials production etc.

TIMES Ireland Model (TIM) (Section 3.3). Ireland has recently committed to a legally-binding target of reducing GHG emissions by 51% by 2030 relative to 2018 and a net-zero GHG target by 2050. We develop a new Irish LED scenario (ILED) and demonstrate the impacts this has in achieving energy system decarbonisation targets. The discussion and conclusion are presented in Sections 3.5 and 3.6 respectively.

3.1.1 Rationale for low energy demand pathway

"Low energy demand" (LED) pathways are mitigation scenarios in the literature based on reducing energy service demands through changes in behaviour, increasing end-use efficiency, brought about by, for example, denser urban development, economic restructuring, and changing consumer practices. Since in LED scenarios the absolute levels of energy service demands are lower relative to a baseline or "business as usual (BAU)" case, it enables faster GHG reductions and/or lowers the need for novel fuels and technologies (Grubler et al., 2018).

A lower level of energy demand services implies downsizing of the entire energy system, compared to a BAU growth in ESDs, making it easier to decarbonise the supply side (Grubler et al., 2018; Fragkos, 2020). Along with enabling a clean energy transformation, the LED pathway requires lower deployment of CDR and biofuels (Fragkos, 2020). The most widely-modelled NET is bioenergy with carbon capture and storage (BECCS), which requires large areas of land that raises concerns about biodiversity loss, which can be avoided in the LED pathways (Anderson et al., 2016; Grubler et al., 2018; Kuhnhenn et al., 2020).

Long-term decarbonisation pathways are dependent on short-term policies, and feasible only if actions are taken sooner rather than later (Pye et al., 2017; Solano-Rodríguez et al., 2018; Vogt-Schilb et al., 2015). However, achieving the near-term (2030) steep decarbonisation targets necessary to meet the Paris Agreement goals is challenging given the slow turnover of fossil fuel technologies, leading to high mitigation costs, heavy reliance on often novel technology deployment, and increases likelihood of overshooting the carbon budgets and targets (Riahi et al., 2015; Eom et al., 2015). In such a scenario, the LED can play a crucial role in overcoming the impacts of delayed response and making near-term targets feasible (see Section 3.4).

An important point to note is that the LED pathway proposes a reduction in energy demand without compromising quality of life (Grubler et al., 2018; Kuhnhenn et al., 2020). For example, setting a lower set-point temperature can avoid over-heating homes and using smart devices to control heating zones and time can help reduce consumption. Other possible

co-benefits of the LED pathway include reduced air pollution, better indoor environment, healthier lifestyles, and lower energy bills (Grubler et al., 2018; Kuhnhenn et al., 2020). Some options in LED enable a just transition, such as modal shift to public transport helps people with no cars or low income have better access to transport infrastructure (Kikstra et al., 2021).

3.1.2 Reducing energy service demand: options and modelling

'Reducing' energy service demands is a viable option for helping to meet decarbonisation targets, especially for developed countries. However, there is a lack of detailed discussion on how this can be practically achieved (Cullen et al., 2011). Energy demand can be reduced in several ways:

- By improving device efficiency, where the same level of energy service demand is met with less energy consumed through more efficient devices, such as more efficient cars or heating systems;
- Through structural shifts in energy service demands towards more efficient processes, for example through mode switching in private transport towards public transport or active modes, or switching construction materials from carbon-intensive products such as cement to timber, or
- Through reducing energy service demands, such as reducing travel demand through compact urban development and teleworking, or reducing the size of residential homes, thus reducing the floor area of dwellings to be heated (Hammond, 2014).

If we assume car kilometres are fixed, then decarbonisation may only be delivered through changing vehicles or fuels. However, a broader perspective on mobility that includes the possibility of modal shift, ride sharing or telecommunication expands the mitigation options space. Although LED scenarios consider efficiency improvements in their narratives, it is necessary to distinguish between energy demand (kWh, MJ, litres of petrol) and energy service demands (practices and economic products, like mobility, passenger bus kilometres, tonnes of cement, value added in services, thermal comfort in buildings, materials production, etc.). Efficiency improvements and technology uptakes reduce the energy demand levels, while in the LED we emphasize decreasing the ESD levels or changing their structure. Nevertheless, modifying ESDs will need technical and social innovations such as investments in public transport infrastructure, encouraging work-from-home, building retrofit grants, planning dense urban development, etc. (Geels et al., 2018).

The enablers of modifying ESDs can be broadly classified into four categories, namely: Technological, economic system transition, behavioural and lifestyle changes, and policy interventions (Figure 3.2). The enablers are methods or changes through which end-use service demands can be reduced directly or indirectly. For instance, remote working and online shopping directly reduce passenger kilometres whereas public transport infrastructure has an indirect impact of lowering vehicle kilometres through shifting to higher occupancy modes. We acknowledge that the interactions shown in the figure are not exhaustive.

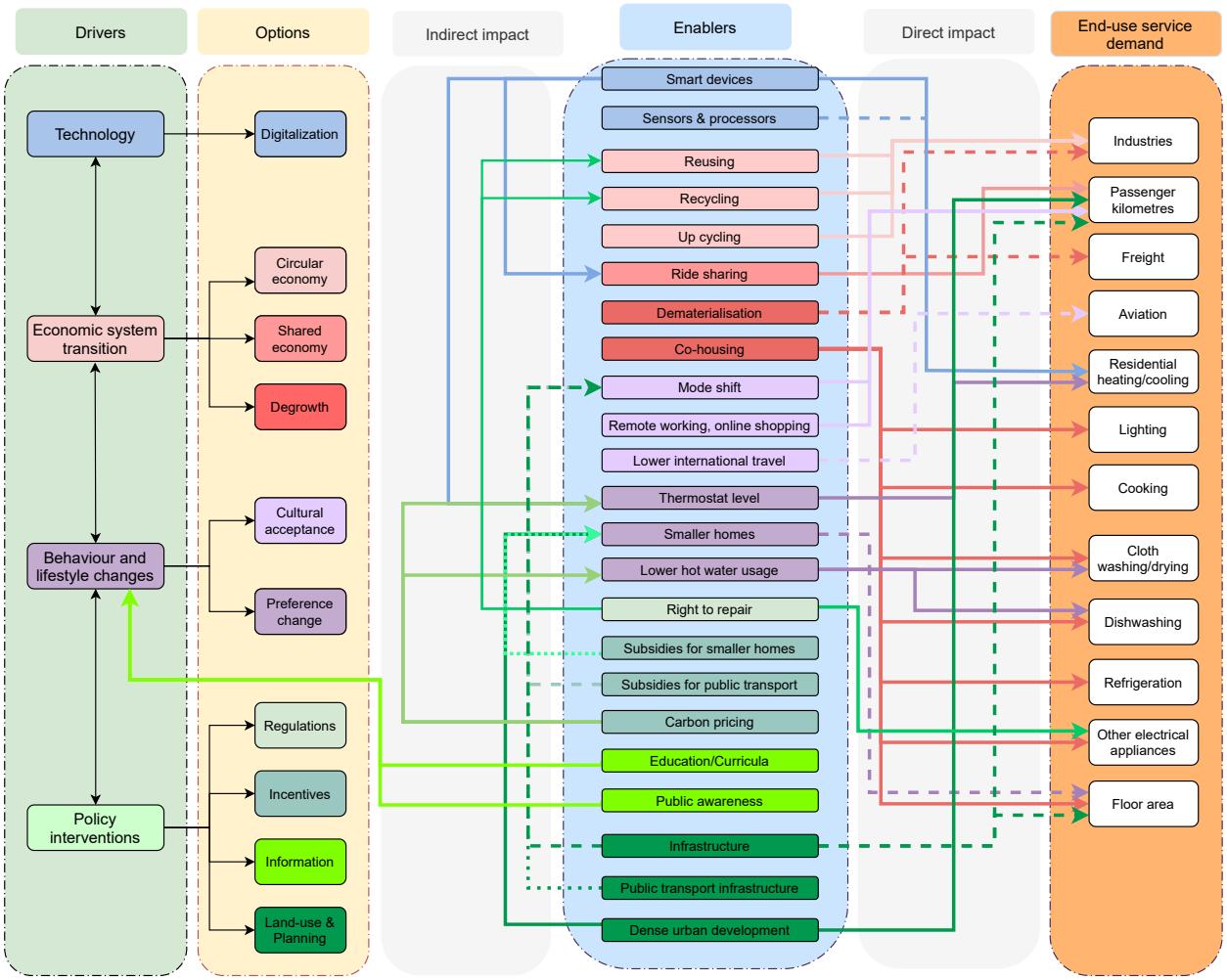


Figure 3.2: Drivers, options and enablers of reducing energy service demands along with direct and indirect impact interactions

Among the options described in Figure 3.2, IAMs and ESOMs often endogenously represent efficiency improvements and technological substitution while lifestyle changes are usually exogenous and in a stylised form in such models (Berg et al., 2019; Van Soest et al., 2019). Apart from efficiency and technology, demand reduction can be analysed endogenously in ESOMs like The Integrated MARKAL-EFOM System (TIMES) through cross-price elastic-

ities as shown by Kesicki et al. (2011).

Some studies have also incorporated behavioural constraints in IAMs and ESOMs to endogenously represent behavioural measures. For example, McCollum et al. (2017) show the benefits of incorporating behavioural features in connection with vehicle choice in an IAM framework. Their scenarios indicate that including behavioural aspects allows a more 'realistic' assessment of non-price based policies (McCollum et al., 2017). Daly et al. (2014) use the travel time budget concept and a public transport investment factor (travel time investment parameter) to enable endogenous modal choice within the TIMES framework. This concept is further extended by Pye et al. (2015) to include the rate of modal shift and maximum modal shift potential. Both these studies demonstrate that behavioural measures are an important mitigation strategy for decarbonising passenger transport. Tattini et al. (2018a) further elaborate the previous two studies and assess modal shift dynamics in an integrated energy system in TIMES for the whole country. This study shows that modal shift enables the energy and transport sectors to reach carbon-neutrality at a faster pace and at lower costs compared to the case when modal shift is not included (Tattini et al., 2018a). Tattini et al. (2018b) further improve representation of endogenous modal choice in a TIMES framework by including demand-side heterogeneity and intangible costs that vary with class of transport users. Cayla et al. (2015) develop a modelling approach to include household behaviour in terms of energy consumption and equipment purchase, and household heterogeneity in TIMES-Households model. The results indicate that unrealistic technology diffusion can be avoided if sufficient heterogeneity is considered. These studies demonstrate the value of endogenising consumer decisions within IAMs or ESOMs and how behavioural measures are an important part of decarbonisation strategies. However, a number of gaps still remain: options to 'reduce' energy service demand are missing from these studies, costs of bringing about behaviour change are typically not captured and these studies focus on sectors in isolation, rather than taking a whole-systems approach.

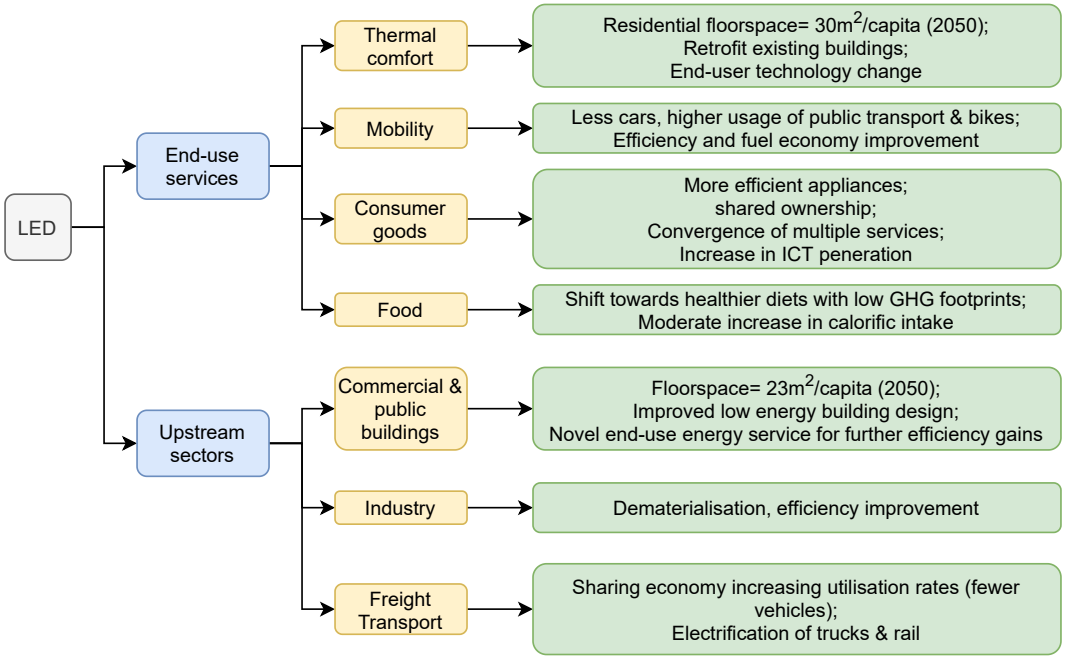
3.2 Review of low energy demand scenarios

This section reviews low energy demand scenarios identified in the literature. The previous section covered studies that focus on a single sector while the LED scenarios reviewed here encompass narratives covering multiple ESDs. We found two studies that consider the global energy system and exclusively focus on the potential for lower demand scenarios and their implications for the energy system, called 'Low Energy Demand (LED)' by Grubler et al. (2018) and 'Societal Transformation Scenario (STS)' by Kuhnhenn et al. (2020). Figure 3.3

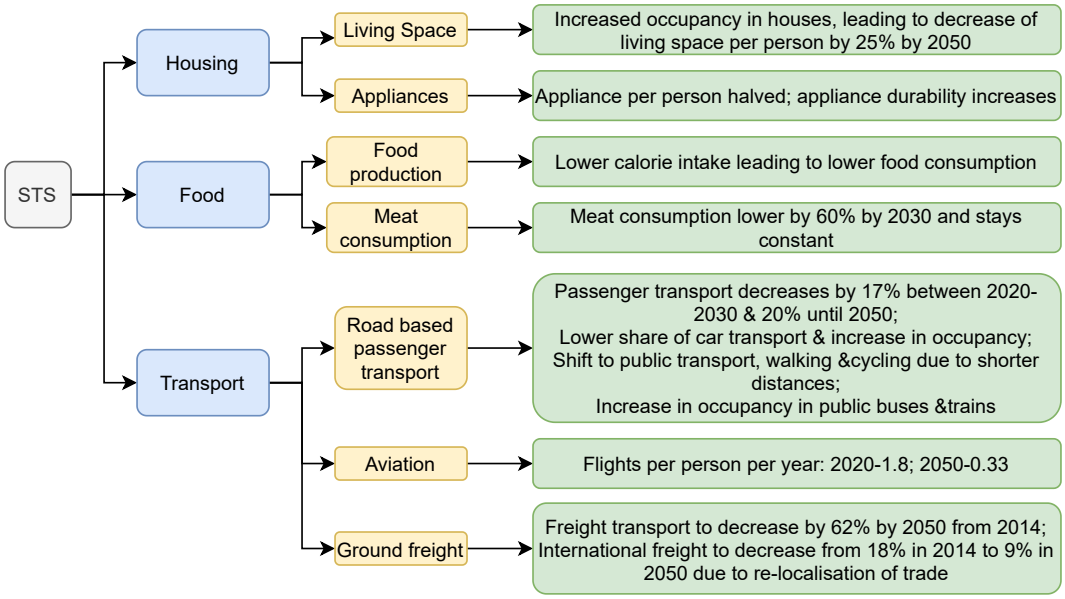
shows the layout of narratives in the LED and STS scenarios. Both scenarios broadly rely on a combination of technological innovations, economic transitions, behavioural and lifestyle changes to bring about major reductions in energy service demands. The key premise in both scenarios is to maintain energy consumption at a sufficient level for a decent standard of living for all. The studies also evaluate their impact on SDGs. These scenarios convert behavioural and lifestyle change narratives into relevant parameters and calculate demand reductions exogenously. However, there are several key differences to note. Firstly, the LED scenario is simulated using MESSAGEix-GLOBIOM (optimisation), an integrated assessment modelling framework while the STS uses Global Calculator (simulation) that is an open source model of the world's energy, land and food system. Secondly, in the LED, changing energy service demands have impacts on upstream sectors, covering a greater part of the energy and economic system while the STS is solely focused on end-use services. And finally, the LED includes nuclear power whereas STS omits this option.

The LED and STS scenarios each cover only two world regions: the Global North and Global South in the former, and Annex I and Non-Annex I countries in the latter. More regional resolution would allow consideration of socioeconomic trends and technology uptake rates (Fishman et al., 2021). As an application of the Grubler et al. (2018) LED scenario, Fishman et al. (2021) develop detailed scenario parameters for the residential buildings and private transport sectors, covering 20 global regions. Dwelling area is assumed to converge to 30m^2/capita by 2060 globally and passenger kilometres to reduce to 8434 person-km per capita in developed nations in the LED scenario. The changes are to occur through denser urbanisation, multifamily homes, modal shift, and lifetime extensions of buildings and vehicles. The material efficiency improvement potentials are determined for each of the sectors using the Resource Efficiency and Climate Change (RECC) framework and implementation strategies include end-of-life recovery, material substitution, reuse, downsizing among others.

Several other global studies have modelled low energy demand-type scenarios for particular sectors. Sharmina et al. (2021) focus on difficult-to-decarbonise sectors: aviation, shipping, road freight, and industry using Integrated Model to Assess the Global Environment (IMAGE). Demand reduction options for the various sectors are as follows: Aviation:- large scale modal shifts to high-speed trains and carbon tax to discourage flying; Shipping and road freight:- carbon tax which will provide incentives for distributed manufacturing and local storage to reduce the need for freight; Industry:- recycling of iron and steel. This study concludes that demand-side opportunities exist and need better representation in IAMs. They argue that without any demand reduction in these sectors, decarbonisation will de-



(a) Low Energy Demand scenario by Grubler et al. (2018)



(b) Societal Transformation Scenario by Kuhnhenn et al. (2020)

Figure 3.3: Comparison of narratives of two global low energy demand scenarios

pend on the deployment of CDR technologies.

Napp et al. (2019) use the TIMES Integrated Assessment Model (TIAM)-Grantham to explore the role that advanced technologies and energy demand reductions through behavioral changes can have for the global industry and transport sectors. The demand reduction po-

tential of each sector is obtained from the literature. Their results indicate that advanced technologies along with demand reduction can bring about deep and rapid decarbonisation of the energy system and reduce the reliance on BECCS by approximately 18% (Napp et al., 2019).

At the national level, two studies were found that present LED scenarios using an energy system model with exogenous energy service demand projections (Barrett et al., 2021; Oshiro et al., 2021). Barrett et al. (2021) present a comprehensive analysis of the role energy service demand reduction can play in meeting UK's 2050 net-zero goal undertaken by the Centre for Research into Energy Demand Solutions (CREDS). Their 'Transform Demand' LED scenario considers a transformative change in technologies, practices and infrastructure that bring about reduction in energy service demands along with co-benefits such as improved health and local environment, lower investment needs and lower cumulative GHG emissions. They conclude that their LED scenario has several advantages in achieving the net-zero target, which include reducing fossil-based energy production, overcoming technical challenges associated with transforming a large energy supply system, reduced overall investment and less reliance on risky CDR technologies. The LED scenario does not compromise quality of life even with a halving of energy demand in UK.

Oshiro et al. (2021) present a LED scenario for Japan called 'LoDem' scenario that considers energy service demand reduction measures such as dematerialisation, material efficiency improvement, reducing hot water usage, adjusting thermostat level, shifting to non-motorised and public transport, reducing passenger trip frequency, and lower freight demand. Implementing energy service demand reduction measures along with energy-efficient technologies could reduce final energy demand up to 37% by 2050 (Oshiro et al., 2021). These measures could also reduce dependency on carbon capture and storage (CCS) by 50% in 2050. Sectoral analysis indicates that industry is the largest contributor to reducing system costs through demand reduction followed by buildings and transport.

The industrial sector, a major energy consumer, can be difficult to decarbonise, especially due to rebound effects following efficiency improvements (Kermeli et al., 2014). We found two studies that present LED pathways exclusively for the industrial sector, one at the global level and the other at the national level for Japan (Kermeli et al., 2014; Ju et al., 2021). Globally, the industrial sector consumes 24% lower energy in 2050 in the LED scenario relative to a BAU scenario when energy efficiency improvement measures and increased recycling are considered alongside lower material demand (Kermeli et al., 2014). On the other hand, Ju et al. (2021) present climate mitigation scenarios for Japan's industries using four energy-economic models and IAMs. They present two low energy demand scenarios.

In the first scenario, lower GDP growth rates are used while in the second, energy service demands are reduced by 50% by 2050 along with lower GDP growth rates. The underlying narrative for the second scenario includes improvements in material efficiency, shift to smart devices and low carbon products, natural disasters, financial crisis, etc. The multi-model analysis shows that a low industry demand scenario reports the largest emission reduction and also reduces production and marginal abatement costs.

Passenger transport demand is driven by infrastructure, spatial settlement patterns and, socioeconomic and technological transitions. Behavioural and lifestyle changes have huge impacts on transport energy consumption enabled by public and active transport infrastructure and, planning and policy signals that favour these modes over private cars (Brand et al., 2019). Four studies, three at the national level and one at the global level, analyse a low energy demand pathway for passenger transport. Blas et al. (2020) use MEDEAS-World IAM to analyse global transport decarbonisation strategies for 2050. Among the simulated scenarios, the 'Degrowth' scenario accounts for demand reduction through behavioural and cultural change that leads to a change in mobility patterns. This scenario is based on the assumption that serious efforts will cause a shift from the present growth-oriented economy towards one which ensures sufficiency without excessive growth in energy demand. These include modal shift in passenger and freight transport, demand reduction and decrease in economic activity. The recycling rate is assumed to double between 2020 and 2050. Results show that only the degrowth scenario meets decarbonisation targets while maintaining minimum mineral reserves for critical materials.

Two studies describing passenger transport decarbonisation scenarios for Japan find that teleworking, online shopping, better public transport, carpooling and ride sharing, and efficient urban planning are factors that will lead to a decrease in passenger kilometres (Gi et al., 2020; Kainuma et al., 2017). Besides a decline in individual mobility, an ageing society leads to a decrease in total passenger kilometres despite economic growth (Kainuma et al., 2017). Although both studies have similar narratives, Gi et al. (2020) present a very detailed scenario, they capture daily life behaviour as well as megatrends such as population aging, gender equality, tertiary industrialization, and transport technology innovation, as compared to Kainuma et al. (2017).

Brand et al. (2019) present contrasting futures using a simulation model and quantitative scenarios that consider transport-related lifestyle change along with techno-economic transition for Scotland. They find that carbon budgets are achievable only in the 'Combined lifestyle and electric vehicle (EV)' (radical change in travel patterns, mode choice, high electrification and phasing out of conventional petrol and diesel road vehicles) scenario, in which

the average number of trips decrease by 55/person/year and distance travelled decreases by 1653 km/person/year by 2050 relative to 2012 (Brand et al., 2019). In this scenario, lower demand is met by modal shift which includes less private cars, more public transport, and ride sharing along with higher occupancy in vehicles, higher fuel efficiency, and new low carbon technologies (Brand et al., 2019). For the residential sector, Levesque et al. (2019) explore the potential of low energy consuming practices that include new behaviours and uptake of green technologies. Their analysis reveals that these practices could reduce energy demand from the residential sector by 61% by 2100. Some of the behavioural measures include low demand for floor space, shorter and fewer showers, adjusting thermostat levels according to the outdoor temperature, wearing the same clothes more often, using dishwashers at full load only, and reduced hot water usage.

Adopting an alternate approach, Millward-Hopkins et al. (2020) present a global energy scenario using a bottom-up modelling approach that combines activity levels and energy intensities for each end-use service and then calculate total final energy consumption maintaining 'Decent Living Standard' globally. They estimate that global energy use could be reduced to 1960 levels despite population growth, provided energy demand is reduced to sufficiency levels. It is a minimum/lower bound bottom-up energy sufficiency calculation.

Figure 3.4 summarises all the options discussed in the literature presented above. We use the "avoid shift improve (ASI)" framework to categorise all the options. Although generally used for the transport sector, this framework is now being extended to include other demand-side sectors as well (Wilson et al., 2020). This ASI framework is associated with a modified 'Kaya identity', which helps to identify how each option has the potential to reduce emissions (Berg et al., 2021). In this form of the identity, carbon emissions are decomposed into four parts namely activity, structural change, energy intensity, and fuel mix (carbon intensity). Lower activity implies lower service demand which is equivalent to energy demand 'avoided'. Any structural change in energy consumption leads to a 'shift' in energy demand e.g. modal shift, material substitution. And finally, decreasing energy intensity and reducing the carbon intensity of the fuel mix is an 'improvement' in efficiency. The 'improve' category is endogenous in IAMs and ESOMs while the 'avoid' and 'shift' categories are generally exogenous.

The literature above suggests that LED scenarios can play an important role in mapping energy system pathways consistent with limiting global warming to 1.5-2°C. The studies above demonstrate additional mitigation measures which enable more feasible technical transition and can bring co-benefits that are needed to achieve ambitious GHG reduction targets. They demonstrate the importance of diversifying and expanding the mitigation space. Without

		Activity	Structural change	Intensity	Fuel Mix
	$\frac{CO_2}{capita} =$	$\frac{consumption}{capita}$ *	% *	$\frac{energy\ use}{consumption}$ *	$\frac{emissions}{energy\ use}$
Sector	**End-use service**	**Avoid**	**Shift**	**Improve**	
Transport	Passenger kilomtres	Less cars Increase in occupancy Shorter distances Lower trip frequency	Public transport Active modes (walking & cycling)	Efficiency Fuel economy Electrification	
	Freight	Fewer vehicles Carbon tax Circular economy	Modal shift	Electrification	
	Aviation	Decrease in international travel Carbon tax	Large scale modal shift		
Residential	Dwelling	Lower per capita space Higher occupancy in houses	Multi-family homes Building material substitution	Retrofit Technology upgrade Durability of appliances	
	Comfort	Changing thermostat level Shorter & lesser showers Using washing machine & dishwasher on full load			
Industry		Dematerialisation Recycling	Material substitution Smart devices & low carbon products	Process and material efficiency	

Figure 3.4: Categorisation of options to reduce energy service demands in LED pathways into Avoid-Shift-Improve framework (adopted from (Berg et al., 2021))

considering demand sector mitigation options, the burden of decarbonising the energy sector is on NETs, which has uncertainty in its deployment.

The mitigation options above cannot be achieved through responsible behaviour alone and should be brought about by a planned socio-economic transformation. Policies must include behavioural and lifestyle changes and not just technology-dependent solutions. Strict energy efficiency regulations, cost reductions, technology improvements and planned urban design are among the few policy recommendations mentioned. The implementation of these policies will be crucial. More research and development is needed to promote such changes through effective policy designs.

However, there are very limited national studies that demonstrate a mitigation pathway including an LED scenario. Although global studies provide good examples of what the energy service demand reduction options are, the feasibility of these mitigation options can be region specific. For example, considering technology deployment potential or socio-cultural acceptance of low-carbon practices at the regional level is important to evaluate economic and political feasibility of such pathways (Brutschin et al., 2021). Further, the 'cost' of demand reduction is not discussed in the literature, and are important research questions. Although demand reduction has been a topic of discussion for a long time, its analysis and implementation have not been discussed sufficiently in the energy systems modelling literature. This study seeks to fill that gap.

3.3 A Low Energy Demand pathway for Ireland (ILED)

This study develops an Irish Low Energy Demand scenario (ILED) to demonstrate how modifying energy service demands can contribute to meeting very ambitious decarbonisation goals. Broadly, ILED encompasses a scenario with densification of settlement patterns, very significant investment in public transport and walking and cycling infrastructure, and de-materialisation of the economy, which enables large-scale modal shifts in transport, lower heat demand in buildings, and lower demands for materials such as cement. This study then applies both a business-as-usual energy demand scenario and ILED to different climate mitigation targets, including very steep near-term ambition as well as a 'net-zero' target for 2050. Most of the options to reduce ESDs in ILED are under the 'avoid' and 'shift' categories as per Figure 3.4. Models mainly have an 'improve' category, but through this scenario we are adding the 'avoid' and 'shift' options as well.

3.3.1 Background

Ireland's energy system accounted for 59% of the total GHG emissions in 2018 of which the transport (19.6%), energy industries (17%) and residential (11%) sectors had the highest shares (Environment Protection Agency, 2021). Further, the CO_2 intensity of energy supply in Ireland is 20% higher than the European average, which makes long-term decarbonisation goals a challenge (Sustainable Energy Authority of Ireland, 2020). The Irish Government has enacted the Climate Action and Low Carbon Development (Amendment) Act 2021 which sets in place a framework for legally-binding carbon budget ceilings consistent with reducing GHG emissions by 51% by 2030 relative to 2018, and to reach net-zero CO_2 by 2050 (Government of Ireland, 2021).

However, there are several challenges that Ireland must overcome to achieve these targets. Firstly, 35% of GHG emissions arise in the agriculture sector, which is dominated by beef and dairy production. The emissions from agriculture are considered more difficult to abate than energy sectors, and therefore the energy sector is likely to be required to decarbonise more than 51% to meet the overall target. The most recent Climate Action Plan (CAP) published in 2021 by the government sets out a sectoral decarbonisation range of 20-30% for the agriculture sector to 2030, which would require CO_2 emissions from the energy system to reduce by 60-70% this decade. Secondly, fossil fuels represent more than 90% of the share of energy in the transport and heating sector demands. Dispersed settlement patterns and an inefficient building stock make decarbonisation particularly challenging (SEAI, 2018). Finally, decarbonising electricity is a challenge given that nuclear energy is not adopted, and as the electricity grid is relatively isolated from mainland Europe, integrating high shares of renewables is technically challenging, though the wind resource is substantial (EirGrid, 2021).

To demonstrate how very steep decarbonisation of the energy system may be achieved, both in 2030 and 2050, this paper presents a case study on the evolution of the Irish energy system with energy service demand reduction as a mitigation pathway.

3.3.2 TIMES-Ireland Model and ILED Scenario Description

This study models the ILED scenario in an energy system optimisation model (ESOM). For our purpose, we have used the TIM, a successor to the Irish TIMES model, which has provided inputs to Irish energy policies for over a decade (Balyk et al., 2022; Ó Gallachóir et al., 2020; Deane et al., 2013; Glynn et al., 2019). This new model has been recently finalised and accounts for the changing energy system, advances in modelling methodology, and the ambitious mitigation targets for Ireland (Balyk et al., 2022). The original model (Balyk et al., 2021), as well as the version used in this study (Gaur et al., 2022a) are archived on Zenodo.

Figure 3.5 shows a simplified reference energy system (RES) in TIM. The RES consists of two main modules: Supply and Demand. The supply module consists of resources, fuel production and conversion technologies, and infrastructure. The demand module comprises the end-use sectors and their corresponding energy service demands. The base year is 2018 and all energy flows, emissions, and energy technology stocks are calibrated to Sustainable Energy Authority of Ireland's (SEAI) 2018 energy balance (SEAI, 2019). A social discount[3]

[3]In the context of climate change, social discount rate represents the value of investments today to avoid climate change impacts later.

rate of 4% is applied. TIM is set up with flexible regional and timeslice definitions, ranging from a single region national model at one annual time slice, all the way to 26 counties at hourly resolution (Aryanpur et al., 2022). We use the annual period definition, single region, and the 40 timeslice version of TIM in this study.

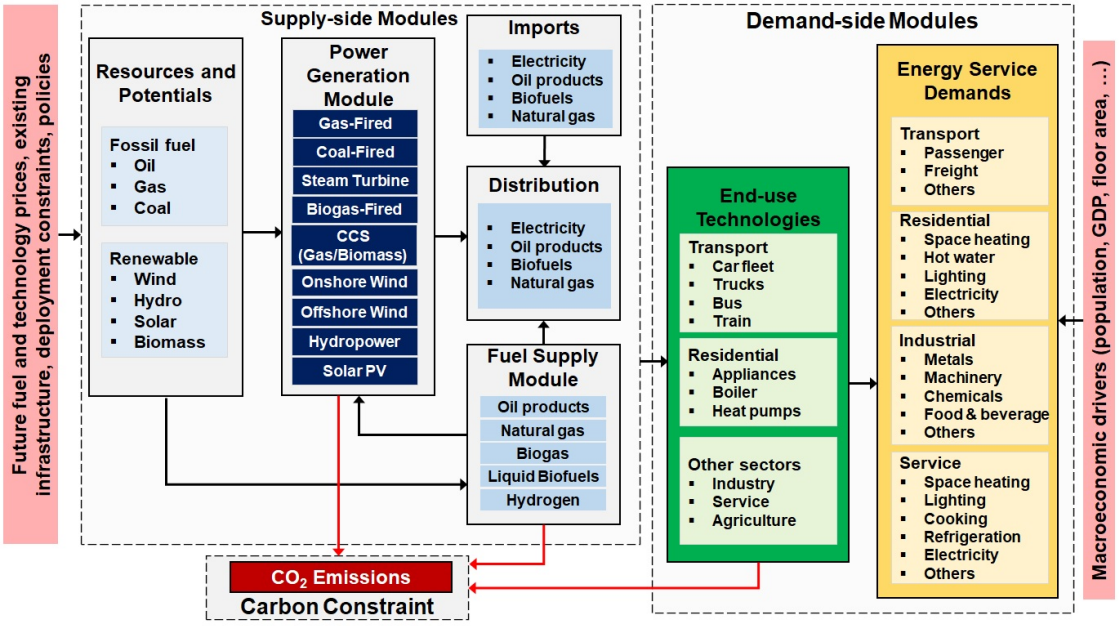


Figure 3.5: Schematic representation of reference energy system (RES) in the newly developed TIMES-Ireland Model (TIM)

The business-as-usual (BAU) ESDs in end-use sectors are driven by growth in the population and the economy. The energy service demands are sufficiently disaggregated to allow for alternative scenarios for these drivers to feed into alternative energy service demand projections, namely ILED. Further information on BAU energy service demands can be found in Section 2.2. Table 3.2 outlines the key assumptions for the ILED scenario.

The ILED pathway parameters are based on literature view, historical trends and comparison with other developed nations that lead to low energy demand. These parameters are not only based on technical details such as efficiencies but also on behavioural and societal transformations such as choosing more sustainable modes of transport or lowering internal heating temperatures in homes. The assumptions on parameter values are rather arbitrary and need additional scoping. The ILED is predominantly a "what-if" scenario that represents a future where ESDs are lower in comparison to BAU projections.

- Transport
  - Freight transport: The total road freight activity was approximately 11.5 billion

tonne-kilometres (tkm) in 2018. Road-based freight transport increased by 110% between 1995 and 2018, with current projections foreseeing a further increase of 2.18 times between 2018 and 2050. Figure 3.6 shows the historical freight tkm in Ireland in comparison to Great Britain (GBR), United States (USA), Japan (JPN) and the EU average (OECD, 2021). Freight activity in Ireland increased during the Celtic Tiger years (1994-2007) when the Irish economy grew rapidly. ILED assumes per-capita freight activity will return to the 1995 level - 1525 tkm/capita in 2050. This is a reduction of about 36% from the 2018 level of 2375 tkm/capita. The underlying narrative is that reviving local economies, better logistics and reductions in consumer demands, particularly for heavy materials such as construction materials, enables this reduction. Total freight activity is then expected to be 9.45 billion tonne-kilometres in 2050, a total reduction of about 18% from that in 2018.

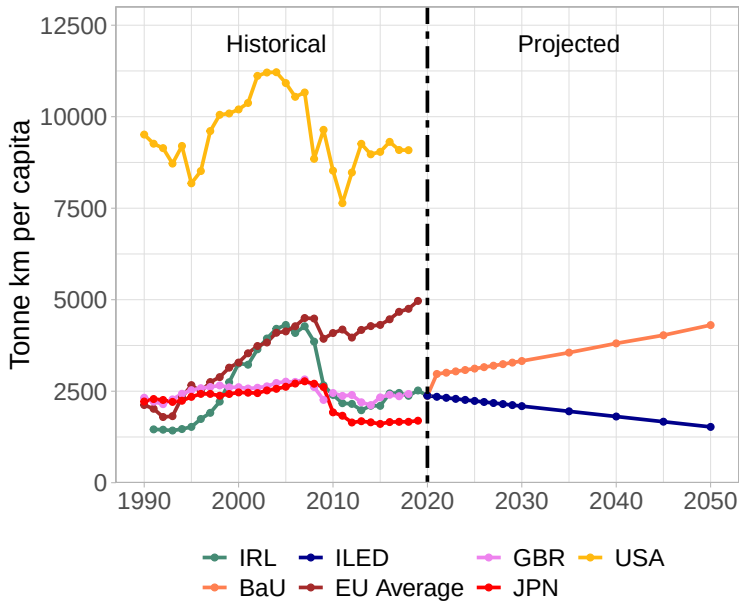


Figure 3.6: Comparison of historical freight tonne kilometres per capita in various countries and future projections for Ireland in BAU and ILED pathways

– Passenger transport: Road-based passenger transport activity (vehicle kilometres (VKM)) increased by about 36% between 2000 and 2018 (CSO, 2021). The total passenger transport resulted in about 73.7 billion-passenger kilometres (bpkm) in 2018, which is about 15,342 passenger kilometres (PKM)/capita. In BAU projections, this increases to around 17,000 pkm/capita in 2050. In the ILED scenario, we assume that the pkm/capita will decrease to 12,000 owing to shorter travel distances, increased occupancy in vehicles, and a large share of the labour

force working from home by 2050. Population assumptions are as in Table 2.1. Hence total pkm in 2050 is $12,000 * 6.19 = 74.3$ billion pkm. The long-term development strategy of the Irish government is to ensure compact growth of cities such as to reduce travel distances which is to be enabled through infrastructure and supporting amenities (Government of Ireland, 2018). In this context, we assume short distance travel (< 5km) to increase by 5% in 2050 whereas medium (5-30 km) and long-distance (>30km) journeys to decrease by 2.5% each. The 2020 passenger kilometres are adjusted for COVID-19 pandemic, accounting for the national lockdowns and travel restrictions. It is assumed in BAU that demand will recover and continue to follow the historical trajectory while in the ILED scenario we assume the recovery to be slower until 2030, and then decline until 2050.

The historical modal share of passenger transport is shown in Figure 3.8. Private cars make up about 80% of total passenger transport in Ireland. In the ILED scenario we assume a change in travel patterns that encourages more of active modes and public services, and less of private cars as shown in Table 3.1. Active modes such as walking, and cycling have a much greater share in the ILED scenario as compared to 2018. The share of private cars decreases by 21% and that of large public service vehicles (PSVs) increases by 9%.

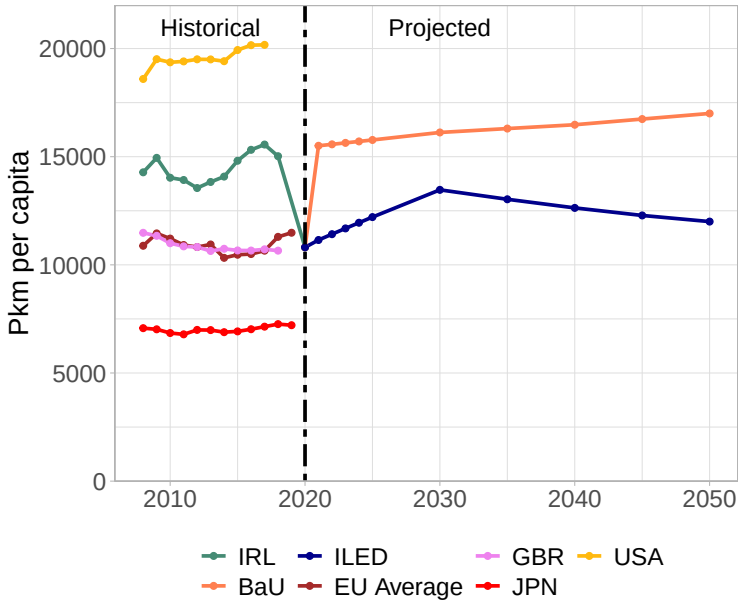


Figure 3.7: Comparison of historical passenger kilometres per capita for various countries and future projections for Ireland in BAU and ILED pathways

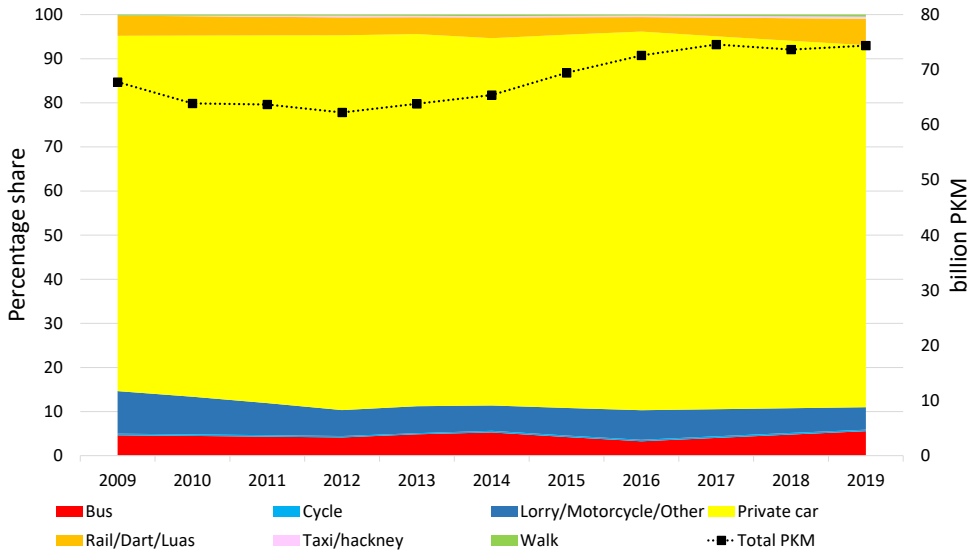


Figure 3.8: Historical passenger transport mode share and total passenger kilometres in Ireland (O'Riordan et al., 2022)

Table 3.1: Passenger transport modal share in the ILED scenario

Mode	Short distance (< 5km)		Medium distance (5-30 km)		Long distance (> 30 km)		Total	
	2018	2050_ILED	2018	2050_ILED	2018	2050_ILED	2018	2050_ILED
Private cars	51%	20%	83%	65%	74%	62%	73%	52%
Motorcycles	0%	0%	0%	0%	0%	0%	0%	0%
Small PSVs	2%	2%	2%	1%	1%	1%	2%	2%
Large PSVs	8%	13%	13%	27%	16%	24%	14%	23%
LUAS	1%	3%	1%	4%	0%	0%	0%	2%
Train	0%	0%	0%	2%	8%	13%	3%	5%
Walking	32%	49%	0%	0%	0%	0%	6%	12%
Cycling	5%	14%	0%	1%	0%	0%	1%	4%

- Residential sector: The residential sector accounted for 24% of final energy consumption and about 17.4% of CO_2 emissions in 2018. A total of 1.7 million houses and apartments were occupied by residents of Ireland according to the 2016 Census, of which 12.2% were apartments, 45.1% were attached and 42.7% were detached houses. The total housing stock is projected to grow to 2.57 million by 2050, with 24.4% apartments, 41.1% attached and 34.5% detached dwellings in the BAU case. The planned urbanisation in (Government of Ireland, 2018) talks about 50% of new dwellings to be delivered within existing built-up footprint of the five cities and suburbs of Dublin, Cork, Limerick, Galway and Waterford. And for most other urban areas it is 30%. The ILED assumes that new detached houses are upgrading and replacing existing ones, and of the new houses required, 60% will be apartments and 40% attached dwellings due to planned urbanisation (Government of Ireland, 2018). Figure 3.9 shows the comparison of dwelling types for the BAU projection and ILED. Further, behavioural and

efficiency improvements reduce the energy service demands within households. Space and water heating account for about 80% of residential energy demand. The ILED assumes that space heating demand per dwelling decreases by 20% by 2050, 10% of which is to be achieved by lowering heating temperature by 1°C (Palmer et al., 2012; SEAI, 2021). The other 10% can be achieved by encouraging boiler servicing every year. A further 4% saving in space heating is assumed for attached and detached dwellings, to be attained by using radiator valves to turn off heating in unoccupied areas. Domestic water heating demand is assumed to decrease by 30% owing to shorter showers, lower heating temperatures, insulating tanks and installing immersion timers (Electric Ireland, 2021). Energy demand for lighting and, pumps and fans are assumed to decrease by 10% each.

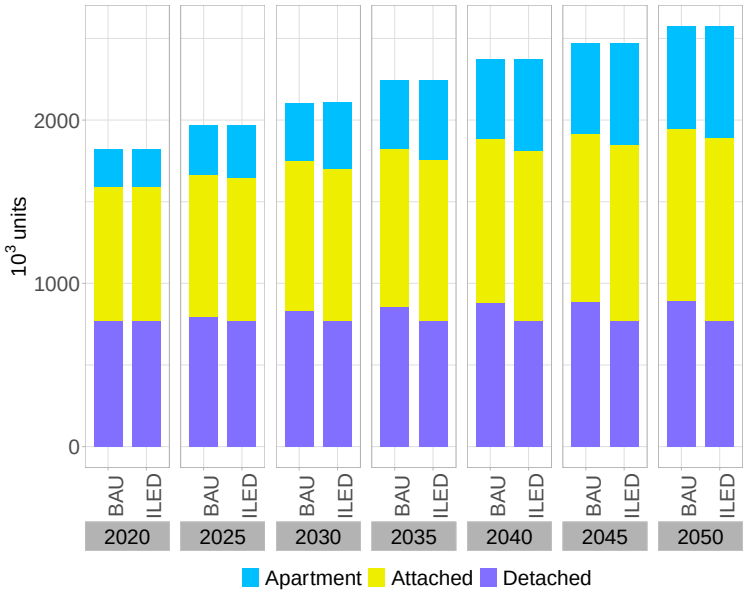


Figure 3.9: Comparison of type of residential dwellings in BAU and ILED scenarios

The ILED assumes that all refrigerators and cooking appliances will be of maximum efficiency (85%) by 2050. Clothes washing and drying, and dish washing demand is assumed to decrease by 20% relative to BAU ESD projections, the narrative being that people wear same clothes more often, make use of line drying, and load machines to their full capacity. Electrical appliances also reduce consumption by 20% relative to BAU ESD projections due to efficiency improvements and unplugging devices to avoid stand-by mode power consumption.

- Industry: The industrial sector was responsible for about 18% of the final energy consumption and about 7.7% of the total GHG emissions in 2018. The average energy intensity (energy/GDP) of industrial activity is expected to decline by 30% in the

next decade, as mentioned in the World Energy Outlook 2020 (International Energy Agency, 2020). A further decrease by 15% to 2050 is considered in the ILED scenario (in total a 45% decrease in energy intensity from current level). This can be achieved by increasing production efficiency and better usage of materials (e.g., recycling, circular economy). A 50% reduction in energy demand from the cement industry is expected by 2050, which is to be replaced by other building materials such as timber and build on existing footprint (Duffy, 2018; Government of Ireland, 2018). In total, the industrial energy demand declines by 25% in 2050 as compared to 2018.

- Commercial and public services accounted for 14% of the total energy demand in Ireland in 2018. At the current level, commercial and public service buildings amount to $6m^2$/capita and $12m^2$/capita respectively, with current projections foreseeing an increase to $7.65m^2$/capita and $15.39m^2$/capita. In the ILED scenario, we assume instead that space reduces to $5.3m^2$/capita and $10.7m^2$/capita for the commercial and public buildings by 2050. It is a 11% reduction in per capita space requirements owing to to dense urban development and work from home, teleworking, etc. (Government of Ireland, 2018). This results in a decrease of energy demand by 37% in 2050 as compared to the 2018 level. This reduction in energy demand is to be achieved through promoting work from home (less number of offices needed) and dense urban development (smaller office space). Public lighting units are assumed to remain constant at the 2040 level, in line with government plans to expand major cities up to 50% from current levels. In the ILED scenario, we assume that no further expansion takes place and lighting units remain constant at 540,000.

3.4 Results

In this case study, we explore a total of three mitigation pathways along with two demand variations for each which are enumerated below. The pathway names describe the percentage of emission reduction from the energy system by 2030 relative to 2018: E51 and E61 correspond to pathways where energy-system CO_2 emissions fall by 51% and 61% respectively between 2018 and 2030. Both pathways achieve net-zero emissions by 2050. These are consistent with the national climate target of reducing economy-wide emissions by 51% and require the agriculture sector to meet emissions reductions targets of 51% and 33% respectively. Whereas, the E32 mitigation pathway does not meet the national mitigation target but is consistent with the Climate Action Plan 2019 targets whereby Non-emission trading scheme (ETS) GHG emissions are to be reduced by 30% in 2030 relative to 2005 and by 80% in

Table 3.2: Comparison of energy service demand values in BAU and ILED scenario

Sector	Parameter		Unit	Value 2018		Value 2050_BAU		Value 2050_ILED	
Transport	Freight		tonne kilometres (tkm)	2375 tkm/capita		4307 tkm/capita		1525 tkm/capita	
	Passenger transport		passenger kilometres (pkm)	15342 pkm/capita		17000 pkm/capita		12000 pkm/capita	
Residential	Dwellings	Apartments	'000 units	206.799		628.932		686.467	
		Attached	'000 units	766.352		1056.500		1120.427	
		Detached	'000 units	724.430		889.756		768.294	
				Old	New	Old	New	Old	New
	Space heating	Apartments	MWh/dwelling	3.85	1.23	3.85	1.23	3.08	0.98
		Attached	MWh/dwelling	7.85	2.85	7.85	2.85	5.81	2.11
		Detached	MWh/dwelling	14.41	6.74	14.41	6.74	10.66	4.99
	Water heating	Apartments	MWh/dwelling	3.41	2.20	3.41	2.20	2.39	1.54
		Attached	MWh/dwelling	3.01	2.35	3.01	2.35	2.11	1.65
		Detached	MWh/dwelling	3.81	2.49	3.81	2.49	2.66	1.75
	Lighing/Pumps & fans	Apartments	MWh/dwelling	0.54	0.69	0.54	0.69	0.49	0.62
		Attached	MWh/dwelling	0.81	0.92	0.81	0.92	0.73	0.83
		Detached	MWh/dwelling	1.26	1.49	1.26	1.49	1.14	1.34
	Refrigeration		PJ	1.13		1.71		1.61	
	Cooking		PJ	2.00		3.03		2.86	
	Cloth washing		PJ	0.77		1.20		0.96	
	cloth drying		PJ	1.03		2.41		1.93	
	Dish washing		PJ	0.83		1.95		1.56	
	Electrical appliances		PJ	9.22		13.98		11.19	
Industry	Energy intensity		PJ/MEUR					45% decrease from current level	
	Cement		PJ	17.8		24.82		8.9	
Services	Commercial buildings		m^2/capita	5.95		7.65		5.3	
	Public buildings		m^2/capita	11.97		15.39		10.7	
	Public lighting units		million lamps	0.48		0.575		0.54	

Table 3.3: Main assumptions and sources for reduction of energy service demands in 2050 in the ILED pathway

Sector	Parameter	Assumption	Source
Transport	Freight	tkm/capita to go back to 1995 level	Own assumption
	Passenger transport	pkm/capita in 2050 is approximately equal to current EU average	(OECD, 2022)
Residential	Dwellings	Dense urban development and utilise existing built-area footprint	(Government of Ireland, 2018)
	Space heating	Demand per dwelling to decrease by 20%	(Palmer et al., 2012; SEAI, 2021)
	Water heating	Demand per dwelling to decrease by 30%	(Electric Ireland, 2021)
	Refrigeration	Efficiency improvement from 80 to 85% in 2050	Assumptions for future technology in TIM (Balyk et al., 2022)
	Cooking		
	Cloth washing	20% reduction in energy demand	(Grubler et al., 2018)
	cloth drying	20% reduction in energy demand	(Grubler et al., 2018)
	Dish washing	20% reduction in energy demand	(Grubler et al., 2018)
	Electrical appliances	20% reduction in energy demand	(Grubler et al., 2018)
Industry	Energy intensity	Energy intensity to decrease by 30% by 2030 and further 15% by 2050	(International Energy Agency, 2020)-2030, own assumption-2050
	Cement	50% reduction from 2018	(Duffy, 2018; Government of Ireland, 2018)
Services	Commercial buildings	11% reduction in space requirements from 2018 level	(Government of Ireland, 2018), own assumption
	Public buildings		

2050 relative to 1990. Figure 3.10 shows the CO_2 emission pathways modelled in this case study.

Each mitigation pathway is modelled with two different energy system demand scenarios: BAU (described in the previous chapter) and ILED, described in the previous section.

3.4.1 Impact on costs

Figure 3.11 shows the average marginal abatement cost (MAC) for subsequent 5-year periods between 2025 and 2050. The MAC represents the cost of mitigating the most expensive tonne of CO_2 in each scenario for the energy sector. The E61 scenario has the highest MAC between 2055 and 2030 since this is the most ambitious decarbonisation scenario among those explored in this study. The E51 scenario also has a very high MAC relative to others, implying that achieving near term ambitious climate goals will be challenging. On the other hand, scenarios meeting these mitigation targets with ILED pathways have much lower MACs as compared to their BAU ESD projection counterparts. It should be noted that the MAC drops to a minimum between 2035-2040 and then slowly increases again because cheaper options are available before the 2040s to mitigate the last tonne of carbon that drives MAC. Beyond

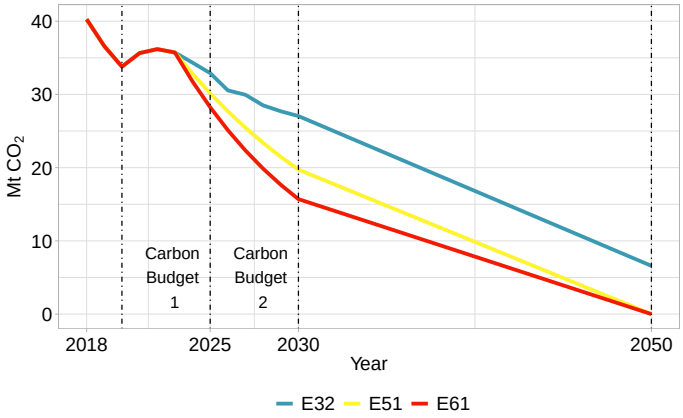


Figure 3.10: Decarbonisation trajectories modelled in TIM and carbon budget outcomes (Scenario EX- CO_2 Emission reduction by X% in 2030 relative to 2018 where X= 32, 51 and 61)

2040, the model has to invest in the most expensive options to reach net-zero, leading to an increase in MAC. Further, between 2030 and 2050, the emission trajectory is interpolated within the model which leads to lower emissions in E61 pathways (BAU and ILED) than E51 even beyond 2030. Hence, the MAC is higher in E61 and E61_ILED when compared to E51 and E51_ILED.

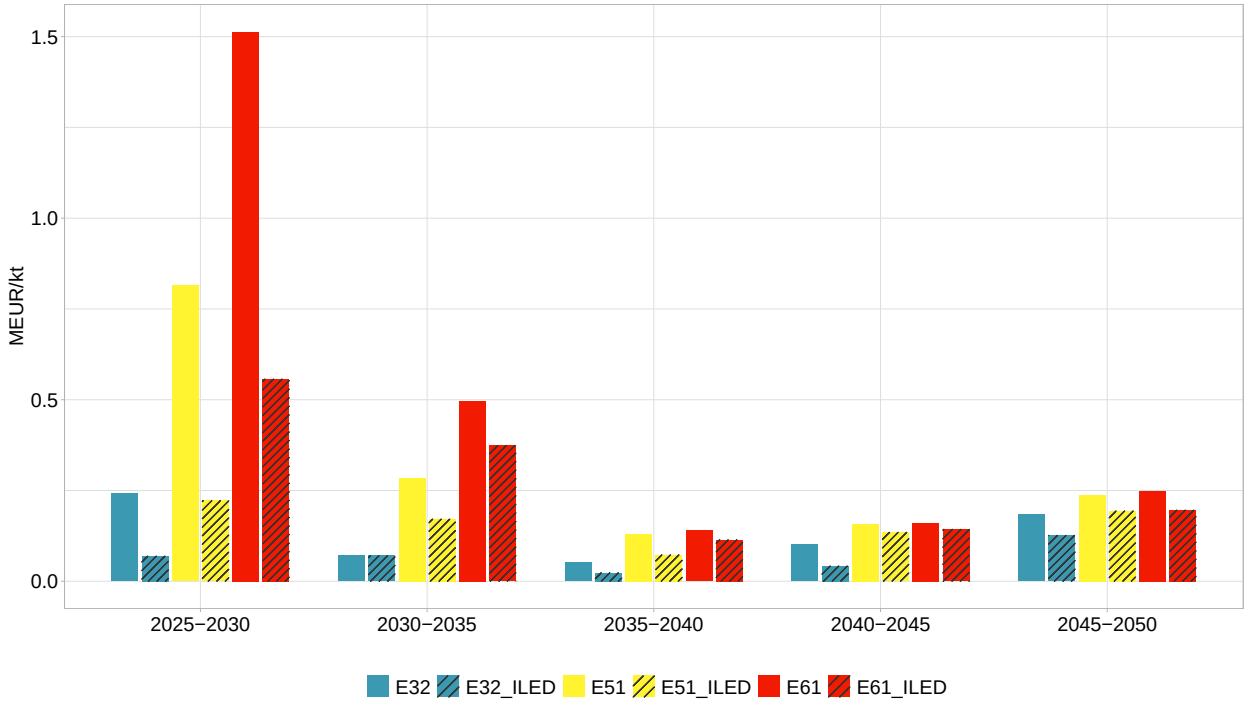


Figure 3.11: Average marginal abatement cost of per kilo tonne of CO_2 for every 5 years between 2025-2050

The total undiscounted annual system cost is shown in Figure 3.12. As discussed previously, the final energy demand determines the size of the energy system which includes size of supply side and the needed infrastructure to deliver the energy needs. In the scenarios with BAU ESD projection, the size of the energy system is large compared to that in the ILED pathway. Hence much higher investments are needed in these scenarios. E61 incurs the highest investments because of the extra work the energy system has to do to meet the targets of the climate bill. Figure 3.13 shows the total savings in fixed, investment and variable cost between BAU demand and ILED demand pathways in 2030 and 2050. There are huge savings in the investment costs in the ILED pathways, reducing total system costs in turn, particularly in 2050.

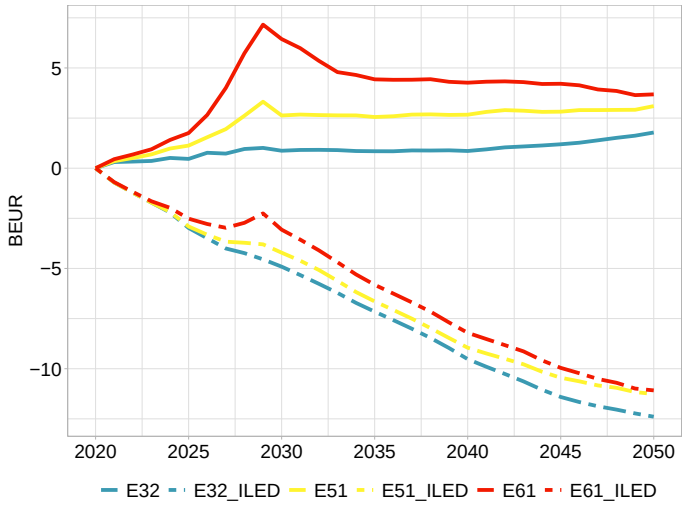


Figure 3.12: Total undiscounted annual energy system cost in addition to the No_mitigation scenario. Includes annual investments, fixed and variable costs, and excludes network and infrastructure costs

Figure 3.14 shows the personal investments per person needed in the housing and transport sectors. The cash flow needed in the ILED pathways for meeting climate goals is much less than the BAU ESD pathways.

The ILED pathways bring down the MAC considerably which shows their importance, particularly for meeting near-term decarbonisation targets. Further, the ILED pathways significantly reduce the total system costs, bringing down the costs of transforming the energy sector. They follow a low investment trajectory to deliver the energy needs and meet climate goals. And finally, per-capita personal investments are also lower in the ILED pathways. These results imply that the total cost of decarbonising the energy sector is significantly lower in the ILED pathways.

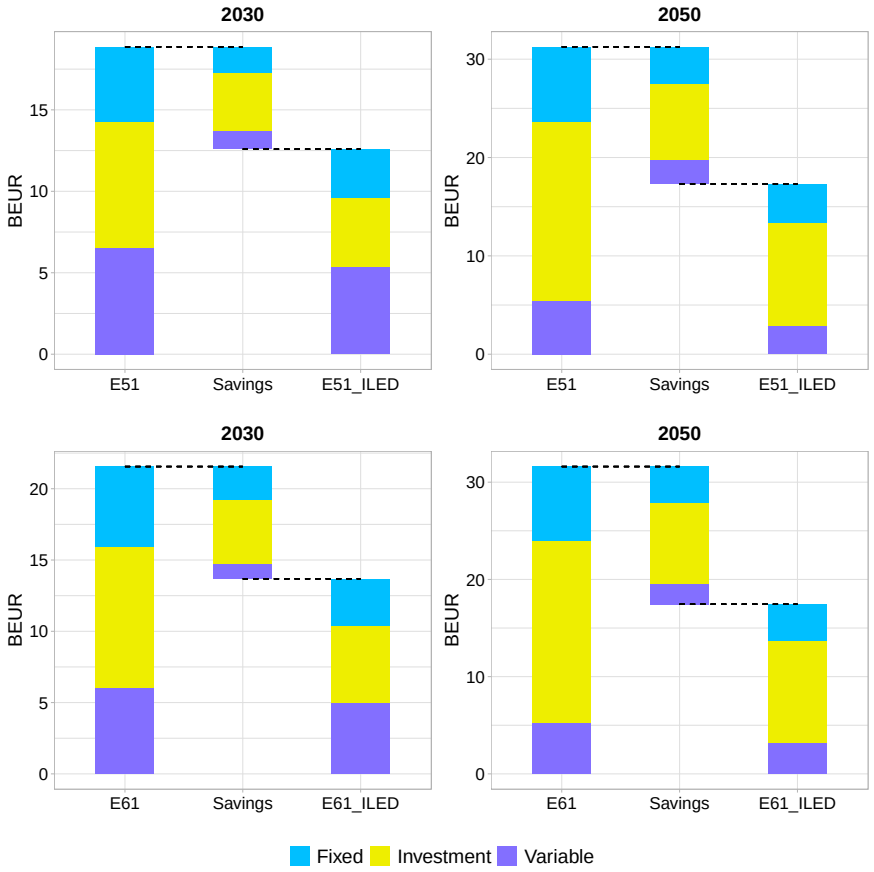


Figure 3.13: Difference in energy system costs (fixed, investment and variable) between BAU ESD and ILED pathways in 2030 and 2050

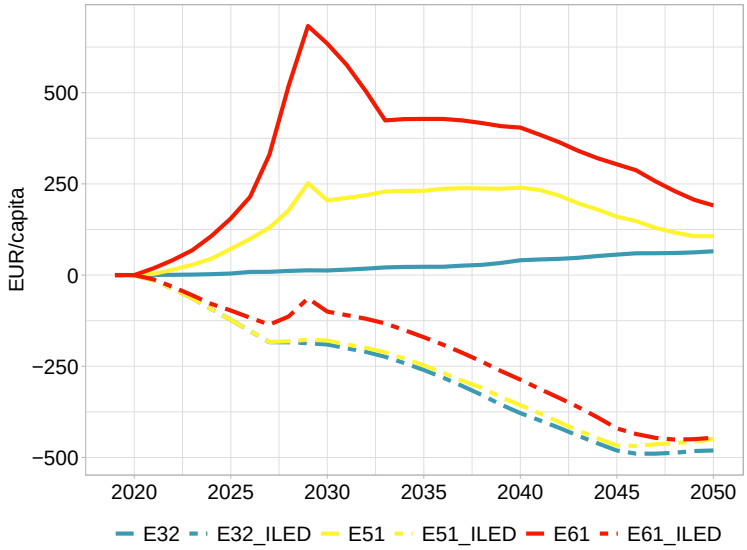


Figure 3.14: Annual per capita personal investments in residential (retrofits) and transport sectors (new private car) in addition to the No_mitigation scenario

3.4.2 Impact on energy consumption and technology uptake

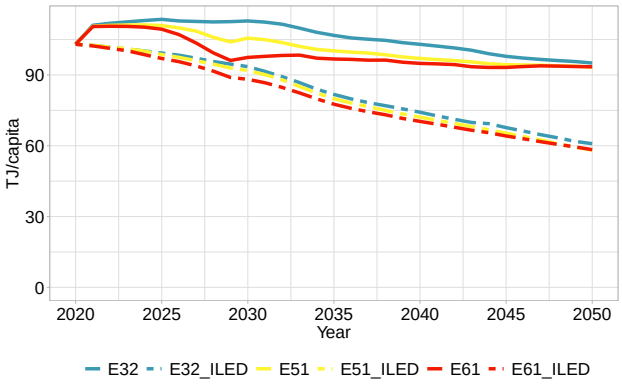
Figures 3.15 shows the per-capita final energy consumption and the percentage share of fuels in the fuel mix. In 2030, the share of electricity and other renewables is lower in the ILED pathways while that of oil and natural gas is high as compared to the scenarios with BAU ESD projection. This means that pursuing the ILED pathway allows some fossil fuels in the energy mix and does not require very significant changes in the supply-side of the energy system. Progressing towards the mid-century, hydrogen is increasing in the E32, E51 and E61 scenarios while for the ILED pathways the share is very small. In the E32_ILED scenario, the share of renewables is very small, while in the E51_ILED and E61_ILED scenarios share of biofuels is lower than BAU scenarios. The ILED pathways still have higher share of natural gas and oil in 2050.

Figure 3.16 shows the uptake of novel technologies in various sectors. The generation from offshore wind is doubled in 2050 in the BAU ESD projection scenarios as compared to their ILED equivalents. This result is especially important for 2030 (near-term) where offshore wind capacity needed is about 7.5 GW in the BAU ESD projections, which would be challenging to install from planning permission point of view, while it is 3.7 GW in the ILED pathways.

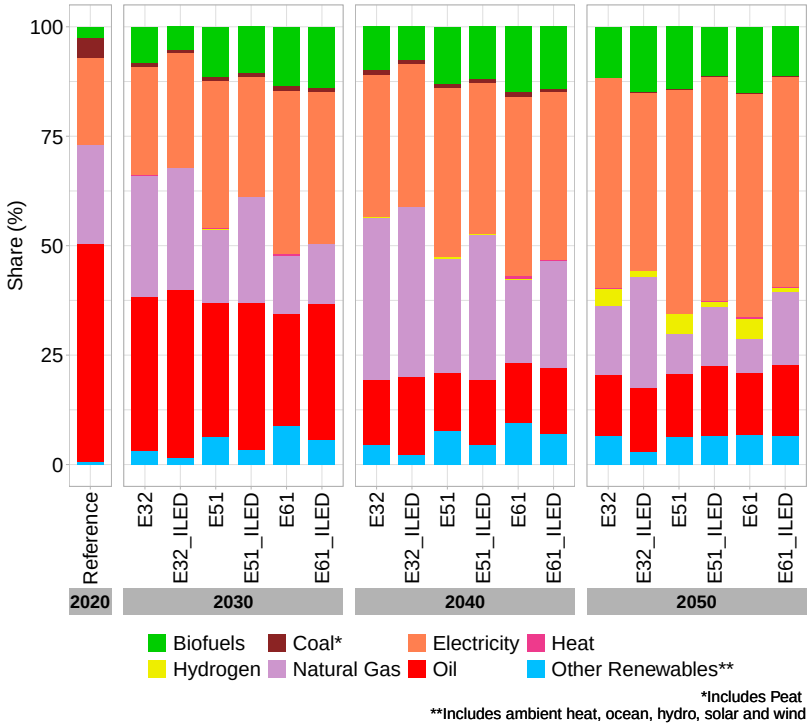
New private EV sales are much lower in the ILED pathways, particularly in E61_ILED. Around 4,000 EVs were sold in Ireland in 2020 and about 8,000 in 2021 until October (CSO, 2021b). Annual EV sales in the E61 and E51 pathways are approximately 130,000 and 49,000 respectively until 2030 to reduce emission intensity of passenger transport. However, in the ILED pathways, annual EV sales are about 8,700 until 2030, which is more in line with the current trends.

New EV and fuel cell vehicle sales for freight are also lower in ILED pathways. In 2021 (until October) around 1,000 such freight vehicles were sold in Ireland (CSO, 2021b). However, in E32, E51 and E61 pathways, about 10,000, 23,000 and 37,000 EV and fuel cell vehicles respectively are needed every year until 2030. In the ILED pathways, 4,000-11,000 EV and fuel cell vehicles for freight are needed each year until 2030. These numbers are still higher than current trends but much lower than the BAU ESD projection scenarios.

The Irish Government has set a target of upgrading about 0.5 million residential dwellings to B2 building energy rating (BER). The E51 and E61 pathways foresee 39,000 and 60,000 retrofits per year until 2030. On the other hand, about 10,000 and 39,000 retrofits per year are needed in the E51_ILED and E61_ILED pathways respectively. Lowering ESDs in residential dwellings reduces the need for upgrades. Further, quite a few retrofits are pushed



(a) Final energy consumption per capita



(b) Fuel mix which shows energy carriers that are consumed directly in the sectors

Figure 3.15: Final energy consumption per capita and resultant fuel mix

beyond 2040 in the ILED pathways.

These results indicate that the ILED pathways decrease the requirement for novel fuels and technologies. They allow fossils to remain in the fuel mix for a longer time period, while still complying with the emission constraints. The ILED pathways also foresee much lower technological transformations in power generation, decreasing the technical challenges of integrating large amounts of renewables in the grid. The pace and scale of transformation needed in the supply side of the energy system are much lower in the ILED pathways.

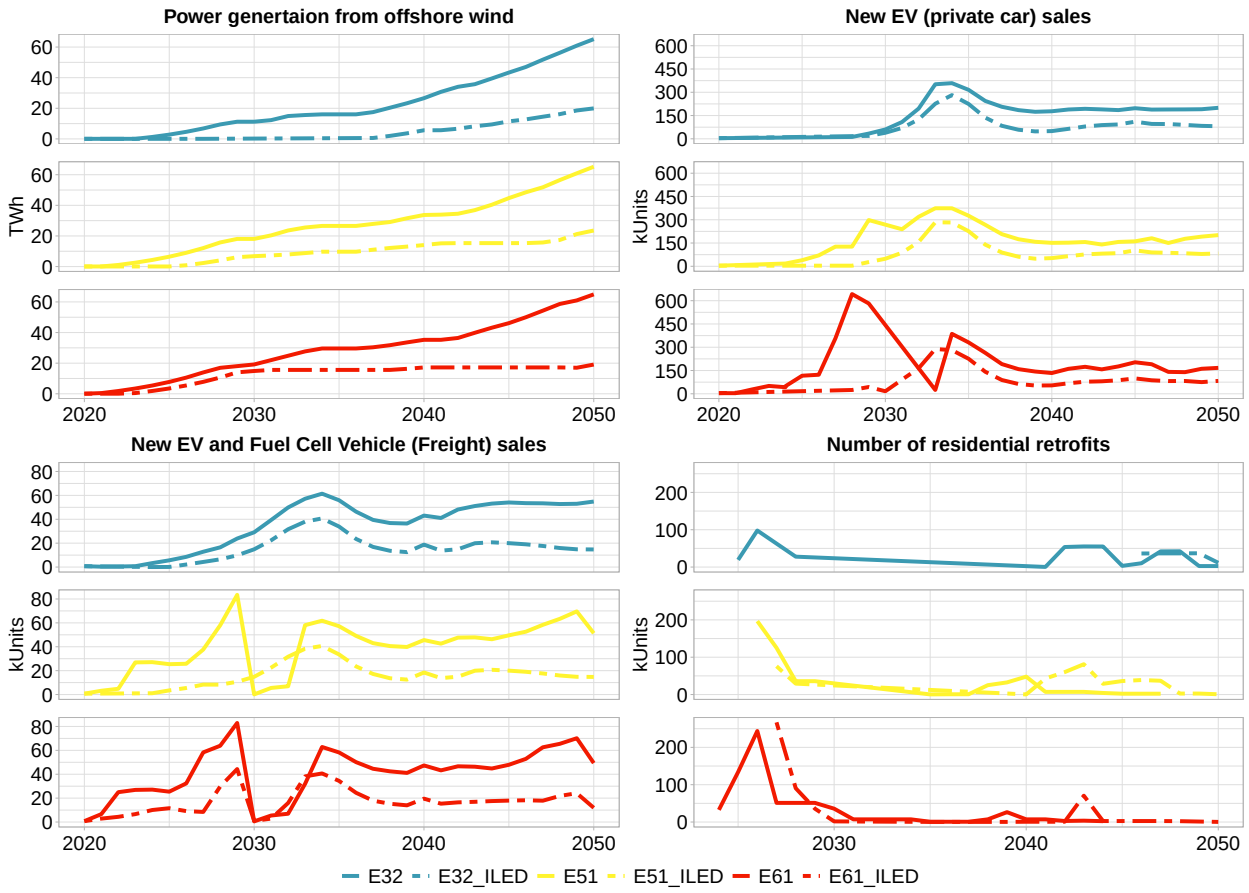


Figure 3.16: Novel technology uptake between 2020 and 2050

The ILED pathways require less rapid technology replacement. These pathways foresee lower ESDs which can be met through sustainable modes and behavioural change instead of depending on technology uptake, which is expensive. Secondly, the ILED pathways postpone the need for technology uptake, allowing a greater timeframe to achieve climate goals.

3.4.3 Impact on CO_2 emissions

Figure 3.17 shows the cumulative CO_2 emissions of every sector between 2020 and 2050. The total cumulative emissions are the same in BAU ESD projection and ILED pathways, however, there are some differences in individual sectors. For instance, emissions in the residential and power generation are higher in the ILED pathways as compared to BAU ESD projection pathways. Lower retrofits in the residential sector and greater fossil-fuel based generation in the power sector cause a lack of fuel switching which leads to slightly higher emissions in these sectors in the ILED pathways.

Figure 3.18 shows the cumulative amount of CO_2 captured from BECCS needed between

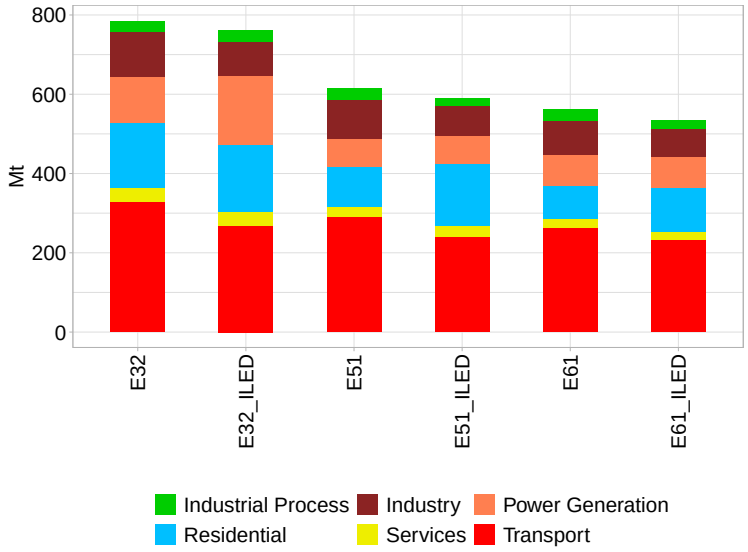


Figure 3.17: Cumulative sectoral CO_2 emissions between 2020 and 2050

2020 and 2050. E31 foresees the lowest amount of BECCS while E51 requires greatest amount. E51 needs higher BECCS than E61 because the latter does more work in terms of decarbonisation by 2030 than the former. E32_ILED pathway needs no BECCS at all, while E51_ILED and E61_ILED pathways need 38% and 23% lower BECCS as compared to E51 and E61 respectively.

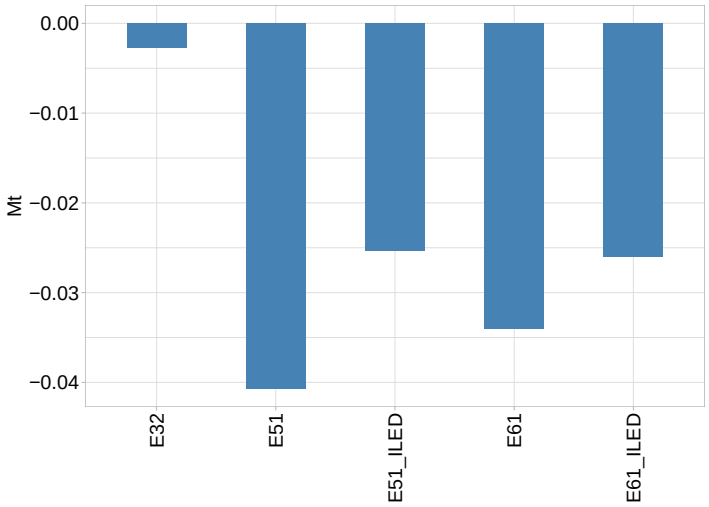


Figure 3.18: Cumulative BECCS needed between 2020 and 2050

The ILED pathways result in similar cumulative emissions as BAU ESD projection pathways, however, some sectoral differences exist. The ILED pathways reduce dependency of the energy system on uncertain and risky technologies like BECCS.

3.5 Discussion

3.5.1 Key insights

This paper presents a low energy demand scenario that considers a number of demand-side mitigation options, often missing in mainstream energy scenarios. The ILED pathway is modelled exogenously to demonstrate the impact of reducing energy service demands on the whole energy system. This scenario presents a possible future energy system evolution pathway which is often ignored in energy policy discussions. The ILED scenario parameters are based on literature review, historical trends and comparison with other developed nations.

The marginal abatement costs, in the near-term (2025-2030), are less than half in the ILED pathways relative to BAU ESD projection pathways. The investments needed to transform the energy system are about 45% lower in the ILED pathways in 2030 and about 42% lower in 2050. Personal investments as well are 45% lower in 2030 and about 34% lower in 2050 in ILED pathways compared to BAU ESD projection pathways. These results indicate that ILED pathways can help meet the near term climate change mitigation targets following a low investment trajectory. Lowering energy demand decreases the size of the energy system, bringing down the costs of transforming the energy sector.

Technology uptake rate is smaller in the ILED pathway. Power generation from offshore wind is about 34-65% less in the ILED pathways. EV sales are about 82-93% lower, especially in the near-term, in the ILED pathways as compared to BAU ESD projection. Further, the residential sector foresees fewer number of retrofits in the ILED pathways, with some retrofits postponed beyond 2040. Share of novel fuels like hydrogen is around 3.5% lower in ILED pathways. The share of novel fuels and technologies is lower in the ILED pathways, while fossil fuels and internal combustion engine (ICE) are present in the system for a longer time. These results imply that rapid deep technological transformation in the energy system will not be necessary if pursuing the ILED pathway.

The ILED pathways have a much slower rate of technology uptake and fuel switching. This gives the energy system a greater time frame for a sustainable transition to achieve the climate goals. A slow transition, however, suggests that the CO_2 emissions are not significantly lower in the LED pathway despite lower demand. In fact, for the residential and power sector, the emissions are higher due to a lack of fuel switching in these sectors. Lower energy demand is offset by fossils, resulting in slightly higher emissions from these sectors. On the flip side, cumulative negative emissions from BECCS are about 23-38% lower in ILED path-

ways, decreasing the dependency of the energy system on uncertain and risky technology to meet its climate goals.

Changing the structure and trajectory of ESDs provides a number of mitigation options that are cheaper in the short-term as indicated by the costs needed to transform the energy system to meet climate goals when such options are considered. These options are also more sustainable in the long-term as they move away from the notion that 'novel fuels and technologies are needed to meet climate goals', which may lead to an overshoot in carbon budgets if not fruitful.

3.5.2 Limitations and future work

The empirical values used in the ILED scenario should be considered in light of some limitations. In the absence of empirical data for Ireland, some values for ESDs are arbitrary (for example, assuming they will revert to values in a historical year), while others are based on international studies. Future work will involve a more detailed analysis of the actual demand reduction potential for each ESD, including the impact of drivers such as spatial settlement patterns, population density and policies.

A considerable amount of demand reduction in our study is based on expected dense urban development that would lead to shorter travel distances, and smaller houses and work spaces. However, we do not account for the investments needed in public infrastructure needed to bring about these reductions. Since ILED pathways foresee much lower investments in the energy system, those could be re-directed towards infrastructure development (Barrett et al., 2021).

LED demand reduction in passenger transport assumes an immediate saving due to sustained low transport demand following COVID. However, this is a source of uncertainty given that as of 2022, demands have recovered strongly following the pandemic. This implies that GHG and energy savings as a result of transport LED measures may be overestimated.

The ILED pathway would likely impact the Irish economy and at the same time could bring about considerable improvements in health, well-being and social cohesion. These factors are not considered in this study and are highlighted as research priorities.

Future work will also focus on decomposing CO_2 emission reduction as a factor of demand reduction, efficiency improvement and structural shifts to quantify savings from each of these measures.

3.5.3 Policy implications

Climate mitigation policy in Ireland and elsewhere has to date focused largely on technology and fuel substitution. However, rapidly-increasing urgency to mitigate climate change requires that policymakers also address high energy-intensity activities.

Ireland is an important case study for this work, given the country's "laggard" status in climate mitigation and recent increased ambition, with a legislated target of reducing overall GHG emissions by 51% between 2018 and 2030.

As discussed, this study demonstrates the very strong benefits of addressing energy demand for meeting climate mitigation targets. To meet the mitigation potential from an LED pathway, policymakers must expand the arsenal of mitigation measures, beyond policies that promote renewable energy deployment and energy efficiency. The transformation required to meet climate targets must therefore must expand beyond technologies and also encompass societal and economic domains, which has wide-ranging implications for policymakers and state institutions.

To reduce energy demand in transport, policies can promote active and public transport modes and disincentivise private car use. This requires investment in infrastructure, for example to improve bus and rail availability, speed and quality, and to make walking and cycling safe with protected road space (Thacker et al., 2019). Private car ownership and use can also be reduced by complementary measures targeting taxation, parking restrictions, road use charges and allocating road space away from private car use (Busch-Geertsema et al., 2021). Countries who raise significant revenue through vehicle registration taxes and road fuel excise duty may require measures to replace this income stream.

Spatial planning and housing are also important components of both passenger and freight transport energy demand: Affordable housing close to employment, schools and services reduces trip length and overall private transport demand, and makes alternative modes more viable. Dense urban development also improves freight logistics and lowers demand.

Spatial planning and denser development in particular can also lower heat demand by lowering floor area of both homes and offices - detached, rural homes are significantly larger than dwellings built in towns and cities, and also have higher heat loss through external walls - and also improving the feasibility of district heat networks, and use waste heat from industry.

This paper demonstrates that speed at which low carbon electricity can be rolled out will be an important bottleneck in meeting Ireland's decarbonisation target this decade. Therefore

measures targeting a moderation of electricity demand growth will support mitigation targets alongside renewables deployment, such as energy efficiency, prioritising transport demand reduction and mode switching over electrification, and moderating growth in large users of electricity such as data centres.

Such measures pose new challenges for policymakers and state institutions. Improved cooperation between local and central government, as well as, across functional areas (e.g., housing, transport, planning, etc.) is necessary to successfully implement such initiatives.

3.6 Conclusion

While the importance of limiting global warming to 1.5 °C is recognised, energy systems modelling typically fails to address systematic drivers of energy demand growth, which must be addressed to limit global warming. By presenting a case study for Ireland, this study established that the LED pathway is especially valuable to meet near-term deep mitigation targets, where technology alone cannot bring about the necessary reductions in CO_2 emissions without costly early retirement of fossil fuelled technologies. Our main results find that the LED pathway reduces dependency on capital-intensive fuels and technologies, and also reduces overall system costs due to smaller size of the energy system.

The LED pathway can also bring benefits for society, such as less congestion, more compact and "liveable" cities and towns, health benefits, and a better standard of living from active travel and more comfortable homes. "Low hanging fruit" of energy demand reduction may allow for faster mitigation action while increasing quality of life. It also improves energy security by lowering the reliance on high-energy intensive services such as private cars. The overall impact of reducing energy consumption on the economy and rebound effects have not been quantified. However, energy efficiency improvements are not paramount in our scenario assumptions and some rebound effects could be absorbed.

However, the LED pathway cannot be achieved by assuming voluntary behaviour changes from people and companies but must be enabled through sector-specific and targeted policies. Large-scale investment into sustainable mobility, better planning to allow housing densification, and public education to shift in values and norms towards lower consumption are also needed. Quantifying the cost and enabling measures to bring the LED pathway about is a high priority for future research.

Chapter 4

Impact of dispersed settlement pattern on net-zero transition in Ireland

Abstract

Limiting the growth of final energy demand helps meet the steep greenhouse gas (GHG) reduction trajectories required to address climate change, and can also bring wider sustainability benefits. Integrated Assessment Modelling (IAM) and energy systems modelling analyses are increasingly including low energy demand (LED) measures in GHG mitigation scenarios, but their granularity and empirical basis is typically low, limiting actionable insights. Here, we contribute to addressing this gap by examining the role of spatial settlement patterns as a driver of energy service demand, particularly in the transport and residential sectors. We focus on Ireland, which has enacted ambitious decarbonisation commitments in law, that are challenging to deliver partially due to a large proportion of the population living in rural one-off housing. We perform exploratory data analysis to estimate the mathematical relationship between various energy service demands and the dispersal of population, and calculate the energy service demand level and CO_2 emissions per capita at various population densities. We also review the indirect impact spatial settlement patterns have on climate mitigation, via the viability of enabling low-carbon infrastructure. We find that higher density settlement patterns are associated with lower energy service demands and greater potential for infrastructure to enable the low carbon transition. We also find that residential and transport GHG emissions are, respectively, 62% and 52% lower for populations living in the highest density regions than in the lowest. Finally, we discuss a path forward for incorporating this empirical analysis into future mitigation scenarios. [1]

[1]Published as: Gaur, A., McGuire, J., O'Riordan, V. J., Curtis, J. and Daly, H., 2024. Dispersed settlement patterns can hinder net-zero transition: Evidence from Ireland. Energy Strategy Reviews, 51, p.101296.

4.1 Introduction

One of the reasons that decarbonisation has not happened at the pace and scale needed to address climate change is due to the lack of addressing the drivers of energy demand (Lamb et al., 2021). Society and the economy do not inherently require energy in its physical form, but rather the services that energy can provide, such as access to work and education, thermal comfort, nutrition and hygiene (so-called energy services) (Rinkinen et al., 2021). Demand for these services is complex and varies in space and time. Comfort and living standards are often linked to fuel usage and infrastructure availability to access services (Trentmann et al., 2018). Energy demand is not only driven by price and the demand for energy services but also by social conventions, practices, infrastructure and material arrangements (appliances, fuel), which vary in space and time (Trentmann et al., 2018; Rinkinen et al., 2021). This complexity of energy demand makes it important to understand how social practices and spatial patterns of settlement evolve over time (Walker, 2014).

There is a consensus that to limit climate change in line with the Paris Agreement commitments, the energy sector must undergo a profound transition (Shukla et al., 2022). Integrated Assessment Models (IAM) and energy systems models often underpin climate mitigation planning and are used to create maps of energy demand futures to inform climate mitigation pathways. Relatively greater attention has been placed within these studies on technological change to drive this transition, which brings about the decarbonisation of energy through end-use electrification and renewable electricity, for example. However, decarbonisation studies are increasingly focusing attention on the role that lowering final energy demand can play in the energy transition as an important enabler of climate mitigation (Creutzig et al., 2022b). Among these, Low Energy Demand (LED) scenarios, which are based on decoupling energy consumption from economic growth, are gaining increasing momentum (Gaur et al., 2022b; Grubler et al., 2018; Barrett et al., 2021; Kuhnhenn et al., 2020). These scenarios revolve around narratives with lower consumption and simulate the impact on energy systems. However, these narratives generally represent aggregated impacts of societal transitions, and are not able to factor in specific policy levers to bring about lower energy service demands. They also typically are not granular in terms of regional analysis.

To address this gap, studies can embed a representation of the drivers of energy service demand such as social norms, culture, infrastructure, and individual preferences, which can allow models to provide new and useful insights on climate change mitigation options (Anable et al., 2012; Brand et al., 2019). This paper focuses on spatial planning, which determines the density of settlement patterns, as one driver of energy service demands (ESDs), in particular

for the residential and passenger transport sectors.

There has been relatively little attention paid to the role of spatial planning as a mitigation lever in IAMs and national energy systems models. The spatial distribution and density of settlement patterns plays an important role in determining the demand for mobility and heat, and also the viability of networked infrastructure that can enable decarbonisation, such as public transport and district heating networks.

The aim of this paper is to contribute to the ability of modelling studies to factor in energy service demand reduction as a climate mitigation option, and in particular to allow this lever of change in spatial planning, and associated policy and infrastructure, that can enable lower energy demand futures. To do this, we quantify the relationship between the dispersal of housing over time and energy service demand indicators in the transport and residential sectors. This allows future studies to parameterise Low Energy Demand scenarios on the basis of alternative spatial settlement patterns. The study focuses on Ireland, which has a large and growing housing need, very ambitious decarbonisation commitments in law and dispersed settlement. In terms of geographical extent, Ireland spans approximately 53.1425° N to 51.4272° N latitude and 11.0438°W to 6.0020°W longitude. The elevation across the country varies, with the highest point being at 1,038 meters (3,406 feet) above sea level. As of the 2022 Census, the total population of Ireland is approximately 5 million.

In this context, the contribution of this paper is fourfold: Firstly, exploratory data analysis (EDA) is used to quantify and discuss the relevance of settlement density in determining energy service demand (Section 4.3). We use Census data to determine how spatial settlement patterns impact car ownership, transport mode choice, type of dwelling, central heating fuel, and other factors that directly or indirectly affect energy demand. We also estimate the mathematical relationship between population density and energy service demands (section 4.3.2.1 and 4.3.2.2). Secondly, the empirical evidence is used to estimate the energy service demand level at various population densities. Thirdly, we review and discuss the role of dense settlement patterns in the infrastructure required to enable the energy transition needed to meet decarbonisation goals (Section 4.2.3). The mathematical relationship and energy demand density will determine the future energy service demand levels and elucidate the associated infrastructure costs such as distribution of pipelines for district heating or natural gas grid, number of bus stops and frequency of public buses, which makes this assessment important to ensure feasibility of transition pathways to decarbonise the energy system (Sachs et al., 2019). Fourthly, the policy and modelling insights and conclusion from this work are presented in Sections 4.4 and 4.5 respectively.

4.2 Background and literature review

4.2.1 Spatial settlement and density as a driver of energy demand

As discussed previously, energy demand is not simply driven by economic and population growth, but is a factor of practices, norms, behaviours, and more. Several non-energy policies affect and shape energy demand in the long term (Royston et al., 2021). One of the major underpinning determinants of energy demand is spatial settlement patterns and associated infrastructure. Settlement patterns and infrastructure have significant lock-in effects, and hence there is a need for long-term vision while making investment decisions (Thacker et al., 2019), particularly in the context of the need to rapidly reduce greenhouse gas emissions. Further, infrastructure can act as an enabler or barrier to system transition (Cass et al., 2018). For instance, investment in low carbon infrastructure can induce low carbon preference (Creutzig et al., 2022b).

Spatial planning impacts climate change mitigation efforts and varies by region (Wang et al., 2018; Kennedy et al., 2014). For example, technology uptake and policies to promote sustainable alternatives can have different impacts in urban versus rural settings (Schippl et al., 2020). Further, Lantz et al. (2021) find that energy transition paths are highly correlated to degree of urbanisation. More than half of the world's population lives in urban areas and it is expected that 80% of the population will be urban by 2050 (United Nations Human Settlements Programme (UN-Habitat), 2022). Hence, urban infrastructures and everyday practices makes the role of cities and urban energy transition in climate change significant (Holmes, 2021). Kovács et al. (2022) suggest reorganising transport infrastructure and sparing cities from being epicentres of transport and only allowing city access to vehicles with no/low emissions reduces pollution and make cities greener. Region-specific guidelines for energy transition will allow for setting clear goals while at the same time provide flexibility to tackle regional issues (Van Dijk et al., 2022).

Urbanisation drives energy service demands in complex ways. Tall and compact buildings associated with cities have the greatest heating efficiency while detached dwellings associated with lower density development have the lowest (Rode et al., 2014). Studies have found that urbanisation plays a strong role in driving energy demand in developing countries. Accompanied by increasing incomes, urbanisation drives residential energy demand due to increase in appliances in Asia and Africa (Madlener et al., 2011). Further, urban expansion and morphology is a main driver of space cooling and heating demand (Tewari et al., 2017;

Rode et al., 2014). Salat et al. (2014) show that if present trends in expansion of suburbs in Chinese cities continues, transport energy demand is likely to triple by 2030 and cause infrastructure costs per capita to increase significantly. Schulz et al. (2022) identify public charging infrastructure as a stimulus to diffusion of EVs while Kang et al. (2022) find that residential communities with access to reliable public service facilities have lower EV charging demand. In all these examples, urban expansion policy and access to public infrastructure, both of which are non-energy related, are the main drivers of energy demand. Hence, there is an opportunity to increase the sophistication of energy demand modelling and projections by taking these factors into account.

Increasing the spatial resolution of energy service demand modelling assists regional planning and captures spatial drivers of demand to estimate demand side management potential and represent regional socioeconomic conditions (Eggimann et al., 2019; Tyralis et al., 2017; Verhetsel et al., 2010). The type of growth in cities and towns (dense versus sprawl) will impact decarbonisation efforts and the ability to meet climate goals. EV charging demand per capita is found to be higher in the peripheral areas of Berlin city due to higher car ownership rates and larger cars as compared to inner city (Straub et al., 2021). Chambers et al. (2019) show the importance of estimating heat demand density at the national level for Switzerland to estimate district heating (DH) potential under various scenarios. They conclude that DH networks should be given priority in dense urban areas with sufficient demand density to justify construction and operation of the network. The regional characteristics of energy demand are an important determinant of future technology uptake rates and associated infrastructure needs.

Higher population density increases the feasibility of sustainable energy transition infrastructure such as public transport network, end-use electrification, and district heating network. It is found that energy consumption is a function of population density (Muzayanah et al., 2022). Tamura et al. (2018) conclude that higher population density leads to lower CO_2 emissions and reduces infrastructure cost. The analysis in this study is especially important for developed countries experiencing urban depopulation and expansion in suburban areas simultaneously. Craven et al. (2014) identify low population density, increasing size of houses and urban sprawl to be major challenges associated with developing sustainable transport in Melbourne, whereas, higher population density encourages public transport use in European cities (Buehler et al., 2017). Similarly, Zhu et al. (2017) find that increasing population density is likely to increase commuting by non-motorized modes in urban areas in China. At the global level, access to key infrastructure services such as water, sanitation, electricity and telephone services is higher in urban areas with dense population (Steckel

et al., 2017).

There is a systemic interconnection between social practices and infrastructure (Haberl et al., 2021). An increasing transport mobility is often associated with greater well-being but this can be misleading: greater mobility means greater commuting distance which reduces well-being (Kamble et al., 2021). Large reductions in car travel are needed for sustainable urban development, particularly by reducing the convenience of private car usage (Moriarty, 2022). Demand reduction through mode shifting has significant mitigation potential and enables faster near-term emission reduction (Gaur et al., 2022b; Mastrucci et al., 2020). While policy makers now recognize the importance of sustainable infrastructure, existing infrastructure can hinder this transition (Sovacool, 2016).

4.2.2 Modelling the drivers of Low Energy Demand pathways

Energy demand reduction through efficiency improvement and behaviour change plays an important role in deep mitigation pathways (Riahi et al., 2021). The landmark global Low Energy Demand (LED) study by Grubler et al. (2018) demonstrated the strong potential addressing energy demand has for climate mitigation and limiting temperature rise. The scenario relies on a combination of technological innovation, economic restructuring and behavioural and lifestyle changes to bring about major reductions in demand. However, the scenario has low regional resolution and does not consider socioeconomic trends and technology uptake rates that vary geographically within countries and can have a substantial impact on energy service demands. Barrett et al. (2021) present a detailed LED scenario for the United Kingdom. Their main findings suggest that reducing demand makes increased climate ambition feasible and UK can half its energy demand from current levels by 2050, without compromising quality of life. A LED scenario for Ireland by Gaur et al. (2022b) shows that demand reduction is valuable to meet near-term decarbonisation goals. However, the national LED scenarios account for population density as a mitigation option at an aggregated level. They lack empirical granularity and identify the need for evidence for demand reduction potential as a key requirement for future work.

Energy demand modelling and projections are often driven by assumptions on growth in population and economy, while there are several other factors that impact the level of energy services demanded (Creutzig et al., 2022b). Energy service demands have regional characteristics, that is, the type and level of service depends on the location. Technology uptake rates and infrastructure that drive energy demand in various countries have spatial variability. Capturing this variability while modelling energy service demands will help include regional disparities that could potentially hinder net-zero transition. One of the most important fac-

tors impacting energy service demands and viability of infrastructure is population density. Areas with high population density are associated with high levels of access to energy service demands and social infrastructure. Such geographical inequalities can further aggravate energy perpheralisation (Golubchikov et al., 2020; Yenneti et al., 2016). For instance, households, despite having low incomes, may be forced into car ownership due to lack of adequate public transport services (Robinson et al., 2020). Reducing energy service demands as a mitigation option is gaining importance in energy transition related discussions.

Further, there is a large inequality in energy consumption across income groups, which is impeding SDGs (Oswald et al., 2020). It is being recognised that high levels of service demand may not necessarily imply greater well-being (Creutzig et al., 2022b). Hence, the role of economic growth in contributing to climate change and whether there is decoupling between GDP and CO_2 emissions is increasingly addressed in literature. Wiedenhofer et al. (2020) recommend that studies focus on physical processes of socio-economic development including a thermodynamic understanding of energy drivers.

4.2.3 The role of density on low carbon infrastructure in the Irish context

As discussed previously, where people live is one of the major factors that determines their energy service demands. However, the type of dwelling and location is often driven by various socioeconomic factors such as preferences, economic conditions, type of neighbourhood, access to services, etc., as well as attachment to place. Moreover, the size and location of residential neighbourhood development, which determines settlement density, is driven by land-use policies and regulations (Geshkov et al., 2012). For example, Zhao (2022) shows that land-use restrictions and zoning regulations have great impact on redevelopment of urban areas in which neighbourhoods can be converted from low to high density. Conversely, González-Ochoa (2022) find that the introduction of new construction techniques, that are economically feasible only at certain production volume, led to the development of large scale suburban areas and problem of oversupply of dwellings in a Mexican city.

The settlement pattern drives the provision of infrastructure such as electricity network, water supply, schools, shopping centres, gas grid/district heating network, public transport services, distributed renewable generation and more. In the following subsections, we present a discussion around the essential infrastructure required to enable sustainable development and the role population density plays in ensuring it is feasible. The discussion is centred around the Irish context.

4.2.3.1 Electric grid

One of the major decarbonisation strategies of the Irish Government is electrification of end use sectors such as residential space heating and private car fleet. Given the policy targets, electrification of these sectors will cause an increase in electricity demand, which will require grid reinforcements (transmission and distribution network) and enhanced flexibility. Large scale investments in grid is justified in areas with high population density, as lack of density increases costs for consumers (Nerini et al., 2016; Fell et al., 2020). Electrification of heating demand, analysed using a techno-economic power system optimisation model, in Ireland was found to be favoured in areas with high heat demand (Gaur et al., 2022c). However, Fell et al. (2020) find that charging EVs can be more expensive in high density areas due to congestion in the grid and may need network reinforcement. Network upgrades due to EV charging can be avoided by introducing workplace charging or smart residential charging (Elmallah et al., 2022).

4.2.3.2 Active modes and Public transport infrastructure

Promoting and developing the infrastructure for walking and cycling, and improving public transport services in rural areas are the key emission reduction strategies in the Climate Action Plan (CAP) 2023 (Government of Ireland, 2023). Javaid et al. (2020) systematically review literature on urban transport mode choice and find that infrastructure plays a greater role in mode shift than behavioural changes. Households living in suburbs around Dublin, the capital city of Ireland, experience disproportionate financial burden due to the necessity of car ownership (Rock et al., 2016). Caulfield et al. (2014) find that households living in newer homes around Dublin have longer commute distances and higher car ownership rates. Prioritising 'bus-only' road infrastructure is an important transport planning strategy if public transport is to grow in Ireland (Hynes et al., 2018). However, dispersed settlement pattern makes it difficult to provide public transport infrastructure and further aggravates geographical inequalities. Local policies, that can help control urban expansion and promote the use of active modes for mobility, will be needed to stop urban sprawl (Hernandez-Palacio, 2017).

4.2.3.3 District heating network

District heating (DH) is highly efficient and will play an important role in the transition to net-zero societies, especially in areas with high population density (Ding et al., 2022). In low density areas, individual heat pumps could be a solution to decarbonise the heating sector, however, residential dwellings must have appropriate insulation (thus high retrofit

costs for existing dwellings) for the heat pump to be effective (Pastore et al., 2022; Ding et al., 2022). Ireland has the lowest share of DH compared to other European countries. From heat atlas for Ireland, cost of district heat (€/GJ) decreases with increasing heat demand density (TJ/km^2) (Flensburg, Halmstad and Aalborg Universities, 2019). Hence, dense development is key to utilizing the full DH potential in Ireland.

4.2.4 Ireland's climate commitments and challenges

The analysis presented in this paper focuses on Ireland, which has high per-capita GHG emission: In the residential sector, 1.6 $MtCO_2eq$ per capita in 2018, relative to 1 Mt across the EU 27 as a whole, while transport emissions were 2.5 t per capita, compared to 1.9 in the EU 27 (Government of Ireland, 2021). The energy system accounted for 49.5% of all greenhouse gas emissions in Ireland in 2021, with fossil fuels accounting for 87% of the primary supply in 2021 (SEAI, 2022; Environment Protection Agency, 2021). The transport and residential sectors were responsible for 34% and 27.5% of the energy-related CO_2 emissions respectively in 2021 (SEAI, 2022).

Ireland has committed to increasing climate mitigation efforts by enacting the Climate Action and Low Carbon Development (Amendment) Act 2021, which sets out a process of legally-binding carbon budgets consistent with reducing GHG emissions by 51% by 2030 relative to 2018 and reaching net-zero by 2050 (Government of Ireland, 2021). Sectoral emissions ceilings have been set into law, limiting GHG emissions in the residential sector to 52 $MtCO_2eq$ over the period 2021-2030, which will require emissions in 2030 to be around 40% lower than in 2018 (Government of Ireland, 2022; Government of Ireland, 2023). The sectoral carbon budget ceiling over that time period for transport is 91 Mt, requiring a reduction of around 50% by 2030. The main mitigation measures in the residential sector include: retrofitting 500,000 existing dwellings by 2030 to higher thermal efficiency, installing 400,000 heat pumps in existing dwellings, and supplying up to 2.5 TWh of district heating. The main measures in the transport sector include: reducing car journeys, increasing share and network (infrastructure) of active modes (walking and cycling), one in three private cars to be an electric vehicle (EV), and providing greater access to public transport in rural areas. The measures in the transport sector can be categorised into the 'Avoid-Shift-Improve' (ASI) framework, whereby avoid measures aim to reduce mobility needs through spatial planning.

However, there are several challenges that must be overcome to achieve these targets. Firstly, the transport and residential sectors are carbon-intensive: fossil fuels supply above 90% of final energy in these sectors. 12% of residential sector energy was derived from coal and peat in 2021, and a further 29% from oil for heating (SEAI, 2022).

Secondly, both sectors are also energy-intensive, in part due to the dispersed nature of Ireland's settlement patterns. Detached and one-off houses dominate housing supply[2]. The 2016 Census reports that 26% of all occupied dwellings were one-off houses, and about 40% of dwellings constructed since 2011 were one-off (CSO, 2016). Overall, around 43% of houses are detached, and only 12% are apartments. One-off and detached houses are generally larger than other dwelling types and often built in remote or rural areas (where prices are lower). This is associated with the highly dispersed nature of housing settlement and results in greater material intensity of the built area and higher energy service demands, as discussed in detail in Section 4.3. As of the 2016 Census, more than 35% of the population in Ireland lived in rural areas (compared to 25% in OECD countries (OECD, 2022)). This large proportion of rural population combined with one-off houses has led Ireland to be a highly car-dependent country. Analysis by Carroll et al. (2021) shows that potential spots for forced car ownership in rural Ireland are also affected by low incomes and inaccessibility to public transport, impacting the achievement of Sustainable Development Goals (SDGs).

Ireland is currently facing an under-supply of housing, with slow growth in the housing stock between 2011 and 2016. There was an increase in new dwelling completions between 2016 and 2019, but a subsequent decrease from 2020 onward (CSO, 2016; CSO, 2021). National projections suggest that to keep up with expected population growth, annually about 30,000 new dwellings must be built between now and 2030 (Bergin et al., 2020). This means that the housing stock will grow significantly in the next decade, locking-in infrastructure that will be responsible for emissions for the coming century. At this stage, it is important to have a long-term vision for the development to come, in order to ensure climate change mitigation targets are met while ensuring a just transition.

Energy modelling studies that determine long-term strategies are calling for deeper understanding of energy service demand drivers (Grubler et al., 2018; Barrett et al., 2021; Gaur et al., 2022b; Creutzig et al., 2022a). These models have been critiqued for having a "techno-economic mindset" that ignores larger qualitative and structural drivers of GHG emissions and mitigation options, and therefore prioritise a narrow suite of simplified technological and market-based solutions (Stoddard et al., 2021). Spatial settlement patterns have lock-in effects and are a key determinant of future emissions trajectory (Creutzig et al., 2022b). Population density plays an important role in determining the feasibility of investments in sustainable infrastructure thereby impacting the attainability of climate goals (Buehler et al., 2017; Craven et al., 2014). However, settlement patterns and population density have

[2]A one-off house in Ireland typically refers to a detached house that stands alone, separate from other buildings, with individual sewerage system. It is not part of a larger housing development or a cluster of houses.

not been examined as explanatory factors in modelling studies.

As discussed, understanding the relationship between population density and energy service demand is crucial for developing effective climate policies and making future investment decisions. This paper presents an empirical review of the relationship between settlement density and energy service demands and related infrastructure. The empirical evidence is then used to estimate energy service demand per caita and CO_2 emissions per capita at various population densities. The National Planning framework (NPF) outlines the need for reducing sprawl in Irish cities and towns, and states that about 40% of new housing development should happen close or within existing footprint of built-up area to increase housing and job densities (Government of Ireland, 2018). The review will help demonstrate that dense settlement patterns are essential to reduce energy service demands, providing empirical evidence for and increase granularity of future LED-type scenarios.

It is valuable to study Ireland from this perspective given its high population and housing growth relative to other high income countries. This study can be particularly useful to provide policy insights to developing countries with high population growth, to quantify the benefit of leapfrogging the dispersed settlement patterns that developed countries have followed in the past in seeking to lower final energy demand.

4.3 Analysis and results

4.3.1 Data

The primary data sets utilised for the analysis are derived from the Irish Census of 2006 and 2016 (accessed through the Central Statistics Office's (CSO) database). The detailed data sets for each of the chosen Census years can be found in (CSO, 2007) and (CSO, 2017). The choice of these data sets stems from their comprehensive coverage of demographic and housing information. It's important to note that the Census data is reported at varying spatial resolutions based on availability. We opted for the 2016 Census data as it represents the latest available data set at the time of our analysis. While the 2022 Census has been conducted, the results are not yet available, reinforcing the relevance of our reliance on the 2016 data set for the current study.

The Census details dwelling types, central heating fuel, and construction periods (pertinent to energy consumption) with spatial breakdown. Further, it exclusively covers commuting journeys—such as those to work, college, or school—limiting our analysis to these specific travel patterns.

4.3.2 Exploratory data analysis

One of the important contributions of this work is to understand the status quo with respect to settlement density in the residential and transport sectors and identify the challenges associated with dispersed settlement patterns for future climate mitigation. We perform exploratory data analysis (EDA) on Census data discussed in previous section. EDA refers to the method of exploring data sets to gain insights into the data structure, identify patterns and relationships among variables. It includes statistical analysis and visualisation techniques to summarise key features of the data set. Using this analysis and some of the previous works on energy systems modelling in Ireland (O'Riordan et al., 2021; O'Riordan et al., 2022; Mc Guire et al., 2023), we develop spatial archetypes of energy service demands at various population density levels. This is further used to calculate energy service demand intensity (ESD per capita) and CO_2 emissions intensity (CO_2 per capita).

First, population density is calculated for 2006 and 2016 at the electoral division (ED) level. There are 3440 EDs in Ireland and they are the smallest legally-defined administrative areas. We classify population densities into five groups based on persons per km^2 as follows:

- D1=<30/km^2 : Remote rural area
- D2=30-200/km^2 : Rural/small village
- D3=200-1000/km^2 : Small town area
- D4=1000-3000/km^2 : Town/Urban
- D5=>3000/km^2 : Urban centre

Figure 4.1 shows the percentage of population living in each density group, calculated at the ED level. From the figure, the majority of the population in Ireland lives in low to medium density groups (D1-D3) in both years, and not much difference is seen within the decade, despite high population and housing stock growth, (12.3% and 17% respectively). This implies that the trend of dispersed settlement patterns is very likely to continue in Ireland, if no interventions or regulations are put in place.

In the following two subsections, we establish the relationship between population density and various energy service demands. We calculate correlation coefficients: Pearson coefficient for linear relationships and Spearman's rank coefficient for non-linear relationships.[3] The mathematical correlations do not reflect causation. However, they are useful metrics to gauge energy service demands within areas of varying population density. The correlation

[3]Correlation coefficients measure the strength and direction of the relationship between two variables

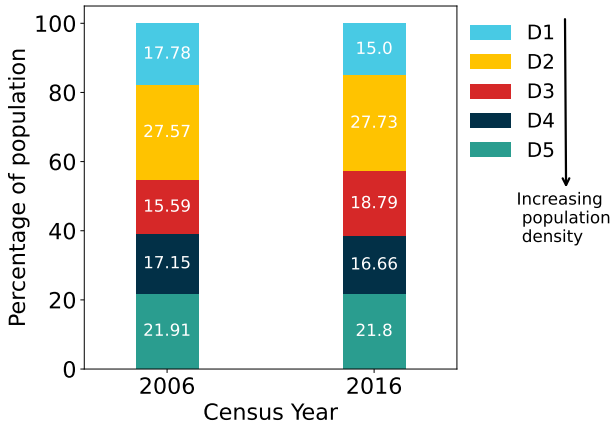


Figure 4.1: Percentage of population living in each group calculated at Electoral Division level

coefficients are important to understand the interrelationship between variables (population density and energy service demands (or their drivers)), and the relationship could be further used as demand-side policy levers while developing decarbonisation scenarios using energy systems models. The aim of this mathematical exercise is also to estimate the consequences of dispersed spatial settlement patterns on energy demand and GHG emissions, and energy service demand reduction potential that can arise from a denser development pattern in the future. These results will be used to develop scenario for future mobility for Ireland, based on different population and housing development growth scenarios, followed by a whole energy systems analysis of the developed scenarios.

4.3.2.1 Residential Buildings

Ireland has a history of dispersed settlement patterns and a significant number of detached dwellings are still being built across the country. Figure 4.2 shows the time series of average size of new dwellings being built by type and the weighted average of all new dwellings constructed between 2011 and 2022. Detached dwellings are significantly larger than attached dwellings and apartments. Larger dwellings require greater built area and higher energy demand. Leahy et al. (2010) identified that Irish households living in detached houses consumed significantly higher electricity than households living in other dwelling types. The weighted average size of new dwellings has been declining, but is still 56% higher than the size of apartments in 2022.

Figure 4.3 shows the share of accommodation in each population density group in 2006 and 2016. At lower population densities, the share of detached dwellings is significantly higher than attached dwellings and apartments. In D1 and D2, the share of detached dwellings is

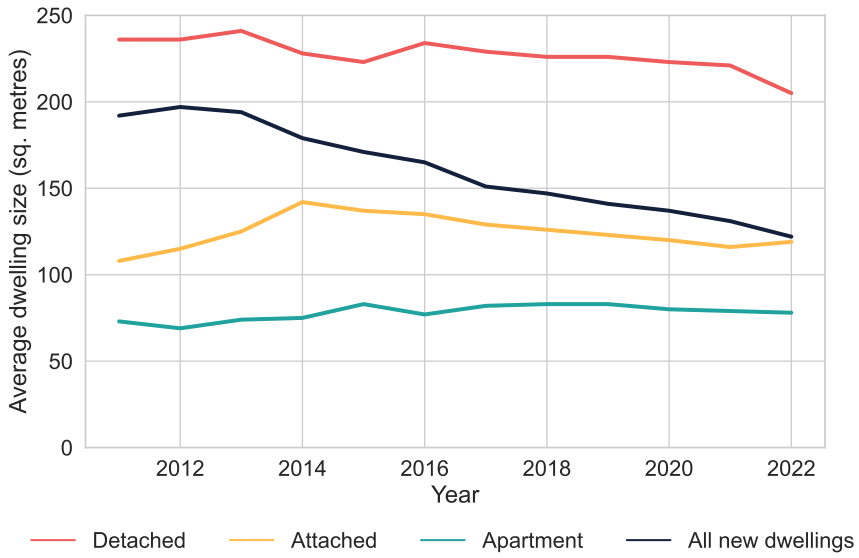


Figure 4.2: Average new dwelling size by type (CSO, 2020a). 'All new dwellings' indicates the weighted average size of all new dwellings constructed in that year

35-37% higher than apartments and 4-5% higher than attached dwellings, while in D3-D5 attached dwellings dominate the mix. As discussed previously, detached houses have, on average, larger floor area than attached dwellings and apartments. In higher population density groups, the share of attached dwellings and apartments is higher, indicating that smaller and compact homes are associated with dense development. Smaller dwellings have lower energy service demands (space heating and lighting), and therefore lower energy and material intensity.

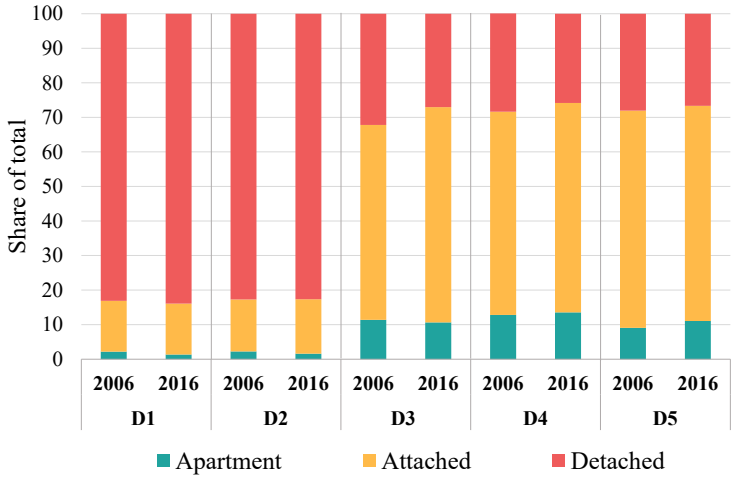
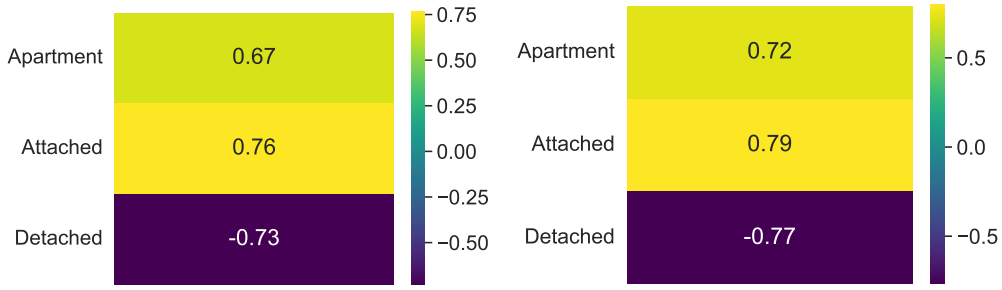


Figure 4.3: Share of type of dwelling in each population density group for 2006 and 2016 Census years

Figure 4.4 shows the Spearman coefficient correlation matrix of population density and dwelling types for 2006 and 2016. There is a strong positive correlation between population density and apartments and attached dwelling types. Further, a strong negative correlation exists between detached dwelling type and population density, implying that detached dwellings are associated with sprawl.



(a) Census 2006 (b) Census 2016

Figure 4.4: Comparison of Spearman correlation matrix for population density and dwelling type calculated at County level

The occupancy of residential dwellings also plays a major role in determining the level of energy service demands. It is reported that households with greater occupancy have lower per capita energy consumption (Kavousian et al., 2013). Figure 4.5 shows the Spearman coefficient of correlation between population density and dwelling type for 2016 Census. As population density increases, occupancy of residential dwellings (for all types) increases.

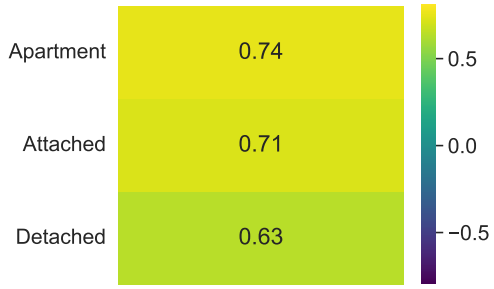


Figure 4.5: Spearman coefficient of correlation between population density and occupancy by dwelling type for 2016

Figure 4.6 shows the share of dwellings by type of central heating system in each population density group. At lower population densities, a large share of dwellings has oil and solid fuels based central heating, whereas at higher densities, natural gas and electricity are more prevalent. In D1, 65% of the dwellings have oil based central heating and 32% have solid fuels as the heating fuel. Similarly in D2, 72% of the dwellings have oil based central heating. Between D3 and D5, share of dwellings with natural gas central heating increases from 26%

to 63%, whereas share of dwellings with oil-based central heating declines from 53% to 19%.

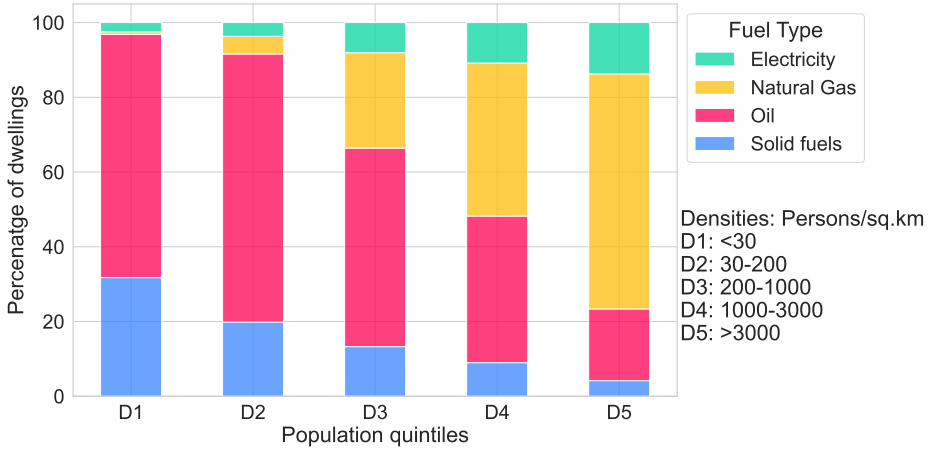


Figure 4.6: Share of dwellings by central heating fuel type in each population density group (CSO, 2017)

The Spearman correlation matrix of population density and heating fuel types is shown in Figure 4.7. Natural gas and electricity are positively correlated with population density, while oil and solid fuels have a negative relationship. Notably, solid fuels, mainly coal and peat (most carbon intensive fuels) are the main heat source in over 30% of dwellings in the group with the lowest density.

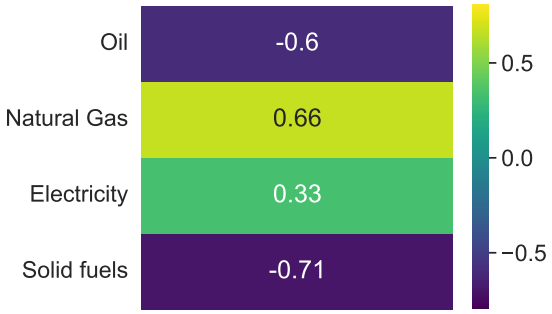


Figure 4.7: Spearman correlation matrix of population density and central heating fuel types in Census 2016

Figure 4.8 shows the percentage of one-off dwellings in each population density group in 2016. About 60% of dwellings in D1 and 35% dwellings in D2 are one-off, which are low density areas. With increasing population density, the share of one-off houses decreases, partly due to declining rural influence in high density areas (D5 represents urban centres, and have no one-off dwellings). Further, Figure 4.9 shows the share of units by type of dwelling for which planning permission was granted in each year from 2001 onward, where multi development

houses refers to two or more houses or a housing estate. A significant number of one-off houses was granted permission between 2011 and 2016, although recently apartments have an increased share (from 23% in 2016 to 61% in 2021). These results imply that in densely populated areas, decarbonising the residential heating sector will be relatively easier, given that alternate options such as district heating and electrification will be feasible.

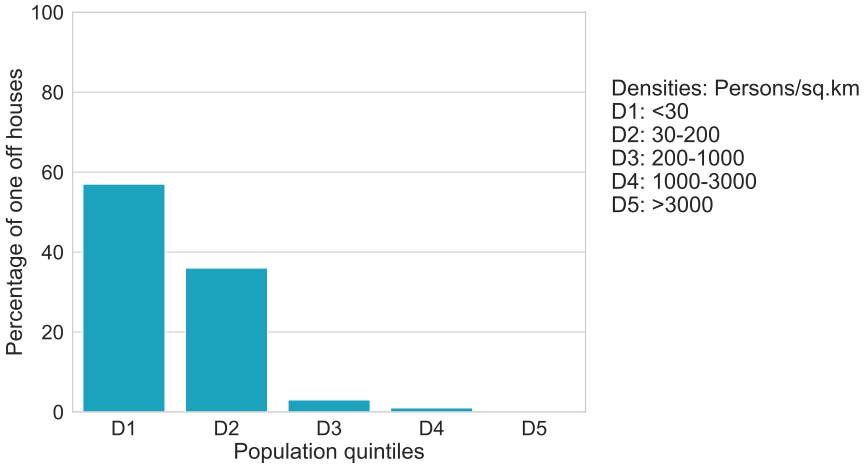


Figure 4.8: Percentage of one-off houses in each population density group (CSO, 2020b)

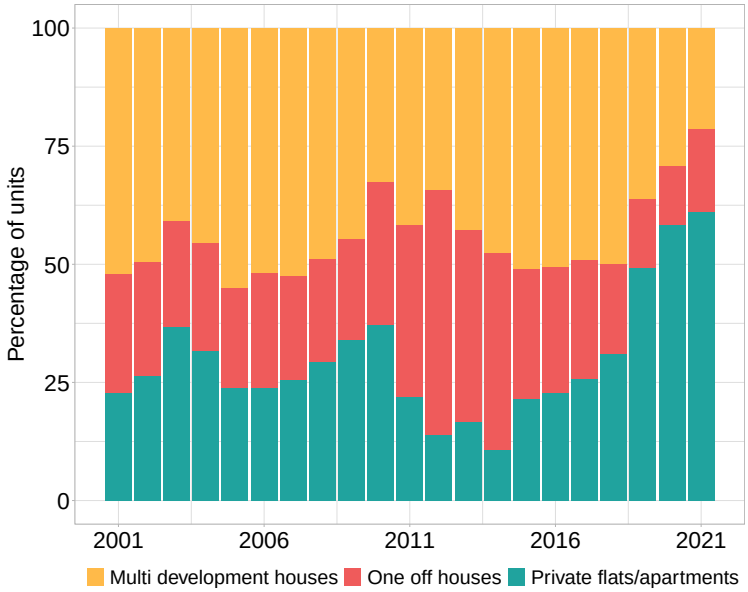


Figure 4.9: Planning permission for all dwelling types between 2001 and 2021

Low density is related to drivers of greater space heating demand and higher carbon intensive fuels. The results show that there is a strong correlation between population density and various residential energy service demands and their drivers. The share of detached houses is higher in low population density groups while the share of attached dwellings increases with

density. A high share of rural one-off houses is found in low density groups. Apartments have a relatively small share in the total housing stock in Ireland, however, the share of new apartments in planning permissions granted in recent years has increased significantly. The type of central heating fuel in residential dwellings varies between population density groups. In low density areas, oil and solid fuels dominate the mix whereas in high density areas natural gas is the main heating fuel. The results show the second order effects of high density: if accompanied with careful spatial planning and infrastructure development, it is associated with lower greenhouse gas emissions.

4.3.2.2 Passenger Transport

Ireland has a high car dependency compared to other European countries (Gaur et al., 2022b). Figure 4.10 shows the percentage of households owning cars and the number of cars in rural and urban areas in 2006 and 2016 Census years. The share of households owning no cars is higher in urban areas and this share decreased in 2016 compared to 2006 in both areas, whereas single car ownership rates are fairly constant across area type and Census years. However, multi-car ownership rates (two and more) are much higher in rural areas, in both Census years, as compared to urban areas. This indicates higher dependency in rural areas, in contrast to the fact that these areas are generally low-income areas (CSO, 2023; CSO, 2019).

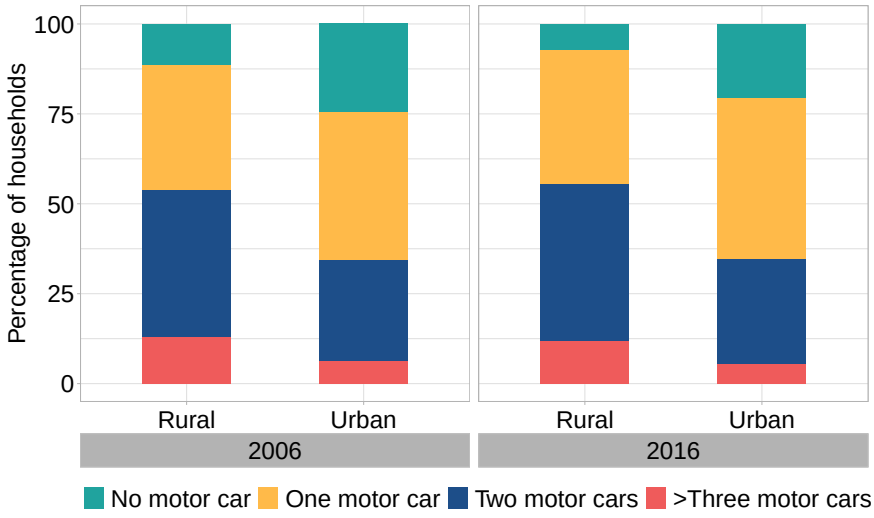
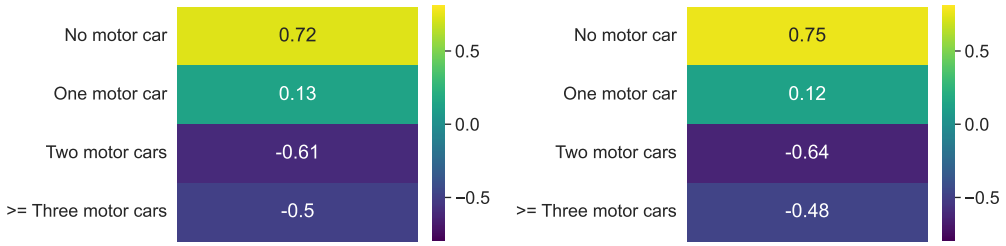


Figure 4.10: Comparison of car ownership rates in urban versus rural areas in 2006 and 2016 Census years

The Pearson coefficient of correlation between population density and car ownership rates is shown in Figure 4.11. Population density and percentage of households owning no cars

are strongly and positively correlated, meaning higher population density is correlated with an increase in share of car-free households. The correlation between population density and single car households is not strong. Further, there is a strong negative correlation between population density and multi-car households: the share of households owning multiple cars increases with decreasing population density. These relationships hold true for both Census years, indicating that "rural sprawl" drives car dependency.



(a) Census 2006 (b) Census 2016

Figure 4.11: Pearson Coefficient of correlation between car ownership and population density calculated at Electoral Division level

Figure 4.12 shows the commuting mode choice according to urban and rural locations in 2006 and 2016. While cars are the dominant mode choice in all cases, it is significantly lower in urban areas (52% in urban areas in 2016, compared with 67% in rural areas). In rural areas, the share of private cars to commute increased by 7% between 2006 and 2016 from 63% to 70% while active modes and public transport share decreased by 1% each. Little change is observed in urban areas in mode choice in the decade.

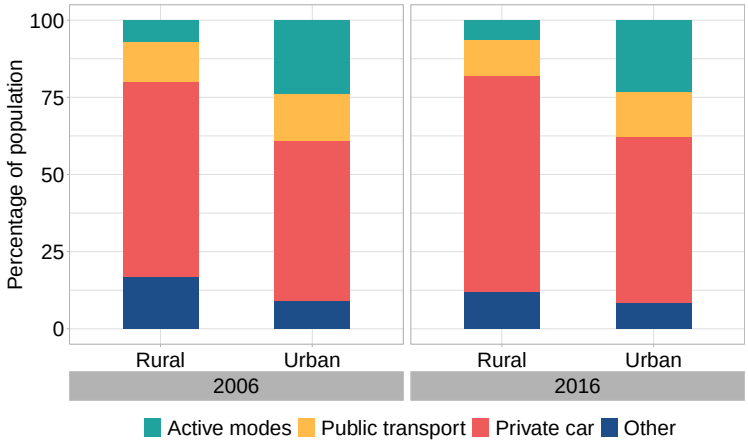
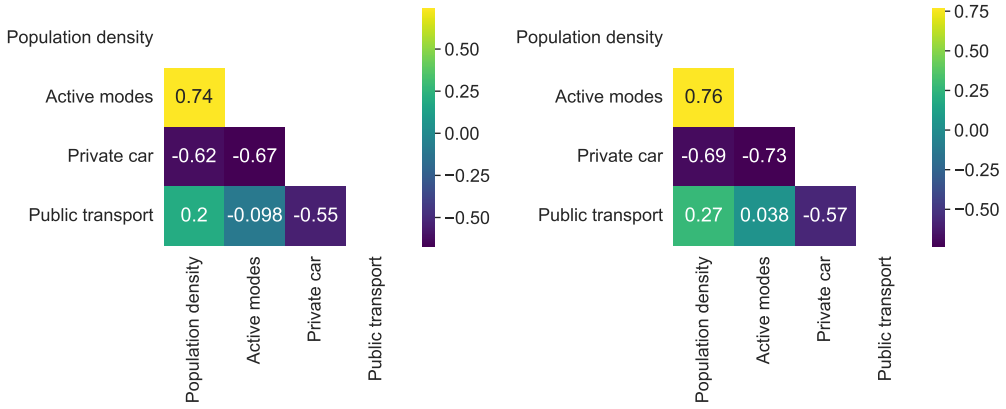


Figure 4.12: Comparison of mode choice in urban versus rural areas for 2006 and 2016 Census years

Figure 4.13 shows the Pearson correlation matrix of population density and mode choice.

There is a strong positive correlation between active modes and population densities, which means that increasing densities decrease travel distances and enable walking/cycling to work/school/college, if appropriate infrastructure is developed. Whereas there is a strong negative correlation between population density and private car usage to commute, indicating decreasing densities promote private car usage. Further, a strong negative correlation exists between private usage and active modes and public transport. Public transport is weakly but positively correlated to population density. These results hold true for both Census years.



(a) Census 2006 (b) Census 2016

Figure 4.13: Comparison of Pearson correlation matrix for population density and mode choice calculated at Electoral Division level

The availability of public transport is a major factor contributing to mode choice and transport energy demand. Figure 4.14 shows the number of public transport (bus, tram, light rail) stops versus population density in 2016. The number of public transport stops increases with increasing population density. Since the relationship between number of stops and population density is non-linear, we estimated the Spearman coefficient of correlation as 0.54. This implies increase in population density is associated with a greater number of public transport stops. The frequency of public transport service also increases with population density, as shown in Figure 4.15 and also indicated by Pearson coefficients in Figure 4.16.

Figure 4.17 shows the distance to public bus stop in each population density group, calculated at the county level. The Spearman coefficient of correlation between distance and population density is -0.7, a strong negative correlation.

The correlation between population density and travel distances to work/school/college is shown in Figure 4.18. There is a weak negative correlation between population density and no travel. We speculate that this is mostly attributed to rural population either working at/from

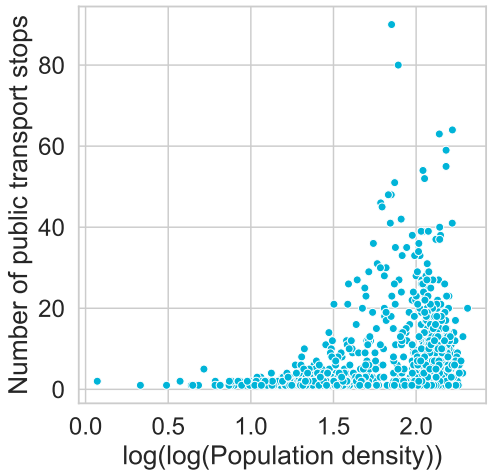


Figure 4.14: Population density versus number of public transport stops calculated at Electoral Division level for 2016 (Geofabrik, 2018)

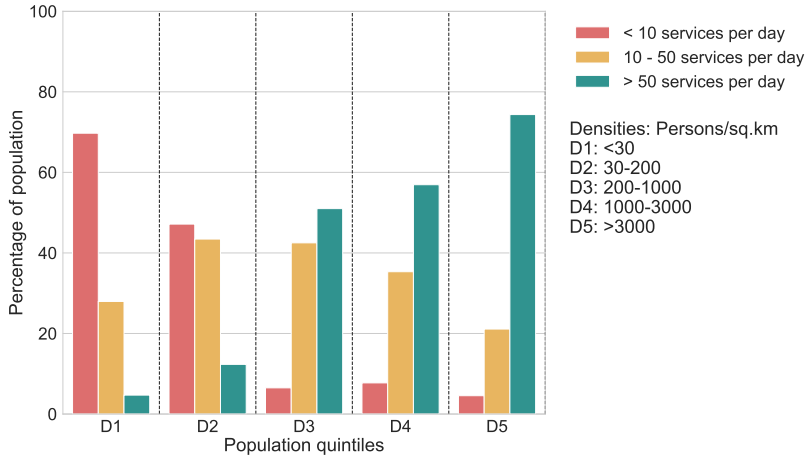


Figure 4.15: Population density versus average frequency of service at nearest public transport stop

home. A positive correlation exists between higher density and short commute distances of 1-4 km. This suggests that areas with higher population density are associated with shorter travel distances for daily activities. In other words, residents in more densely populated areas tend to have workplaces or educational institutions closer to their homes, fostering shorter commutes. However, an increasingly negative correlation is observed between density and increasing commute distances. This implies that, on average, as population density decreases, the distances travelled for work, school, or college tend to increase.

The results of the mathematical exercise show that private car ownership rate and usage is higher in areas with low population density, that also have lower access to frequent public transport infrastructure. The distance to work/college/school is also higher in low population

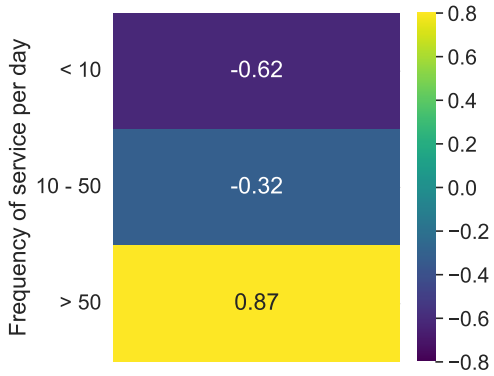


Figure 4.16: Pearson Coefficient of correlation between frequency of bus services and population density

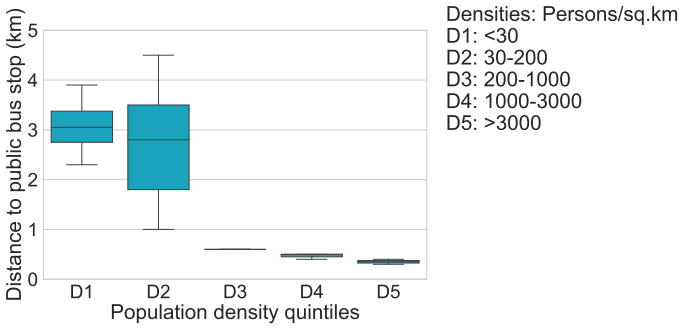
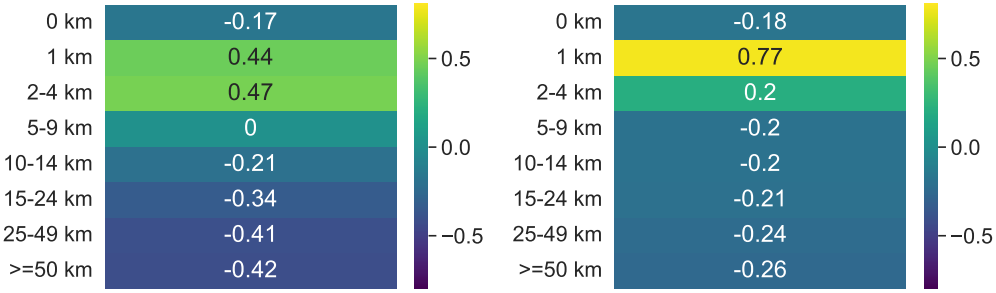


Figure 4.17: Population density versus distance to public bus stop at county level (CSO, 2020)



(a) Census 2006 (b) Census 2016

Figure 4.18: Comparison of Pearson correlation matrix for population density and commute distances calculated at Electoral Division level

density areas, making active transport modes less feasible, and thereby have locked these areas into energy-intensive car-dependency. In areas with high population density, travel distances and car ownership rates are lower and access to public transport infrastructure is better.

4.3.3 Energy demand and carbon emissions intensity

In this section, the above statistical exercise is used to develop spatial archetypes of energy service demands for each population density group. The energy service demand intensity, i.e., the energy service demand per capita, and carbon emissions intensity, CO_2 per capita is calculated for each population density group. The methodology for each sector is described in detail below.

4.3.3.1 Residential space heating

Table 4.1 shows the number of dwellings by type in each population density group in the 2016 Census. The share of central heating fuel by dwelling type for each population density group is summarized in Table 4.2. From the two tables, we calculate the number of dwellings by type and central heating fuel for each population density group. The space heating requirements for each dwelling type are based on the Energy Performance Certificate (EPC) data, which is adjusted for internal temperature to align with the national energy balance. The EPC database contains technological detail, covering half of all dwellings. The EPC internal temperatures are altered to better represent residential space heating in Ireland (Coyne et al., 2021). Once the internal temperature assumptions are applied to different EPC ratings, a weighted average calculation is used to group all existing dwellings (Mc Guire et al., 2023). Then Equation 4.1 is used to calculate the space heating energy consumption for each dwelling type and fuel.

Table 4.1: Number of dwellings in each population density group in 2016 Census

Dwelling type	D1	D2	D3	D4	D5
Apartment	6,228	2,431	543	158,206	36,737
Attached	63,764	23,532	3,185	471,720	195,518
Detached	379,759	123,417	1,381	122,995	81,605

Table 4.2: Summary of central heating fuel share by dwelling type in each population density group (CSO, 2020)

Population density group	Dwelling type	Oil	Natural gas	Electricity	Solid fuel	Other	Total
D1, D2	Apartment	35.6	11.0	36.8	9.5	7.0	100
	Attached	60.7	6.4	4.8	23.7	4.4	100
	Detached	71.3	1.3	2.1	21.0	4.4	100
D3	Apartment	24.6	32.6	30.1	7.3	5.4	100
	Attached	44.4	32.6	4.8	14.9	3.4	100
	Detached	61.9	19.1	2.6	13.0	3.4	100
D4, D5	Apartment	13.6	54.2	23.4	5.0	3.7	100
	Attached	28.1	58.7	4.7	6.1	2.4	100
	Detached	52.4	36.9	3.2	5.0	2.5	100

$$\alpha_{T,F,S} = \beta_{T,F,S} \cdot \overline{(\eta_{T,F,S})} \cdot \delta_{T,F,S} \tag{4.1}$$

In this equation, $\alpha_{T,F,S}$ is the calculated final energy consumption for each of the detached, attached and apartment dwelling archetypes, T, of fuel type, F, and energy service, S. In this paper, we are only concerned with the space heating energy service. The space heating demand is not region specific. Therefore, all population density groups use an average space heating demand per archetype. The results of the space heating demands for each dwelling type and fuel are illustrated in Table 4.3. $\beta_{T,F,S}$ represents the correction factor for each dwelling archetype, fuel, and energy service; this was used to calibrate the space heating consumption with SEAI national energy balance to ensure equilibrium, .i.e, supply equals demand. $\overline{(\eta_{T,F,S})}$ is the average space heating efficiency per dwelling archetype, fuel, and energy service assigned by the EPC assessors. The space heating system efficiency, which converts final energy into useful energy. The last component, $\delta_{T,F,S}$, is the total final energy of the energy service per dwelling archetype and per fuel in the EPC database.

Table 4.3: Dwelling space heating demand, $\alpha_{T,F}$, $(kWh/house/yr)$ for dwelling archetypes and per fuel

Condition	Archetype	Oil	Natural gas	Electricity	Solid fuel	Other
Existing	Apartments	12,633	3,585	1,984	41,184	2,047
	Attached	9,571	6,772	4,707	39,420	7,852
	Detached	15,633	11,565	9,104	67,561	24,227

Table 4.3 shows a large variation in space heating per fuel type, as the low heating system efficiency of solid fuels results in poor EPC ratings with high space heating demand. At the same time, electric heat pumps are associated with good EPC ratings because of their high efficiencies and low dwelling heat loss requirement. Furthermore, the dwelling archetype is also a cause for variation due to floor area. The average floor area of a dwelling is assumed to be 98 m^2, and the average floor area of apartments, attached, and detached dwellings is 80 m^2, 95 m^2, and 118 m^2, respectively (Mc Guire et al., 2023).

Next, we calculate the fuel consumption by dwelling and central heating fuel type for each population density group using the equation below:

$$E_{F,D} = \sum_{T} ND_{T,D} * CHF_{T,F,D} * \alpha_{T,F} \tag{4.2}$$

Where T, F and D denote the type of dwelling, central heating fuel type and population density group respectively. Further, $E_{F,D}$ denotes the energy consumed for space heating by

type of central heating fuel for each population density group in TJ, $ND_{T,F,D}$ denotes the number of dwellings by type for each population density group, $CHF_{T,F,D}$ denotes the share central heating fuel by dwelling type for each population density group and $\alpha_{T,F}$ denotes the space heating demand for each dwelling type and central heating fuel, as calculated in Eq.4.1.

The emission factors for residential space heating fuel are shown in Table 4.4. These emission factors combined with the E_{FD} calculated above are used to calculate CO_2 emissions in each population density group using the equation below:

$$CO_{2D} = E_{F,D} * EF_F \tag{4.3}$$

Where CO_{2D} denotes the carbon dioxide emissions in each population density group and EF_F denotes emission factors from Table 4.4.

Table 4.4: Emission factor for residential space heating fuels (SEAI, 2023)

Fuel	Emission factor (tCO_2/TJ)
Oil	75.6
Natural gas	56.4
Electricity	96.6
Solid fuel	99.2
Other	0.0

From the above two calculations for energy consumption and CO_2 emissions, we then calculate the energy intensity and carbon intensity of residential space heating for each population density group. Table 4.5 shows that with increasing population density, heating demand per capita and CO_2 emissions per capita keep decreasing. There is a 55% decrease in heating demand per capita between D1 and D5, while there is a 62% decrease in carbon emissions per capita between D1 and D5. This indicates that dense settlement reduces the energy intensity and carbon intensity of residential space heating. The heating demand per capita and emissions per capita are marginally higher in D5 as compared to D4 due to higher share of detached dwellings in the former.

Table 4.5: Residential energy service demand and space heating emissions per capita (2016)

Parameter	D1	D2	D3	D4	D5	National average
Heating demand per cap (GJ/cap)	31.23	29.58	19.45	12.84	14.03	19.67
CO_2 emissions (t/cap)	2.67	2.52	1.58	0.94	1.02	1.58

4.3.3.2 Passenger kilometres- journeys to work/school/college

Table 4.6 shows the weighting factor and average distance travelled for particular journey distance category. These assumptions are based on the previous work on the passenger transport sector in Ireland (O'Riordan et al., 2021; O'Riordan et al., 2022). Figure 4.19 shows the share of journeys by distance for each population density group, which is summarized from the exploratory data analysis in the previous section (see Figure 4.18).

Table 4.6: Assumptions for mode share and average distance (O'Riordan et al., 2021)

Distance (km)	Weighting factor				Average Distance (km)
	Active modes	Private car	Public transport	Other	
0	45%	52%	1%	2%	0.0
1	45%	52%	1%	2%	1.2
2 - 4	20%	70%	6%	4%	3.7
5 - 9	8%	78%	10%	4%	7.5
10 - 14	1%	87%	6%	6%	12.5
15 - 24	0%	92%	4%	4%	19.8
25 - 49	0%	95%	1%	4%	35.6
>= 50	0%	97%	1%	2%	96.8

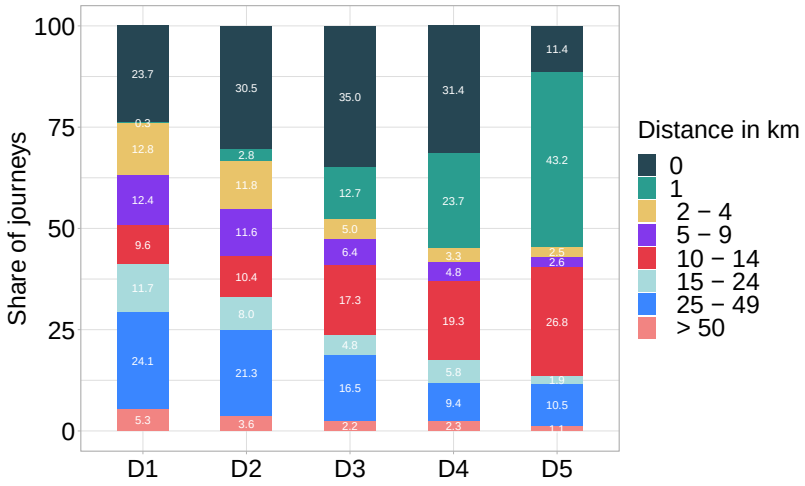


Figure 4.19: Distribution of journeys by distance in each group (2016 Census)

First we calculate passenger kilometres per mode type using the above data for each population density group as below:

$$PKM_{M,D} = JS_D * WF_M * P_D * AD \tag{4.4}$$

Where $PKM_{M,D}$ denotes the passenger kilometres in each population density group D for every mode type M, JS_D denotes the journey share in each population density group (Figure

4.19), WF_M denotes the weighting factor for each mode type (Table 4.6), P_D denotes the population in each density group and AD denotes average distance for each journey distance category (Table 4.6).

The emission factors assumed for each transport mode are shown in Table 4.7 (O'Riordan et al., 2021; O'Riordan et al., 2022). The CO_2 emissions associated with the passenger kilometres in each population density group is calculated using the equation below:

$$CO_{2D} = PKM_{M,D} * EF_M \tag{4.5}$$

Table 4.7: Emission factors

Mode	gCO_2/pkm
Active modes	0.0
Private car	123.0
Public transport	70.0
Other	122.46

The passenger kilometres per capita and CO_2 intensity in each population density group is calculated and summarized in Table 4.8. Both, mobility and emissions are found to decrease with increasing population density. There is about a 50% decrease in mobility requirements between D1 and D5, while the emissions are 52% lower in D5 relative to D1. The emissions per capita are far below the national average of 2.5 t since we only estimate pkm for work/school/college. However, compared to previous works (O'Riordan et al., 2021; O'Riordan et al., 2022), our calculations also underestimate pkm in each density group since the passenger kilometres were estimated based on aggregated commuting counts at electoral division level which is the only publicly available record of travel distance to work/school/college from the 2016 Census (CSO, 2017).

Table 4.8: Passenger kilometres and CO_2 emissions per capita in each population density group (2016)

Parameter	D1	D2	D3	D4	D5	National average
pkm/cap	1865	1527	1199	993	938	1271
CO_2 emissions(t/cap)	0.23	0.18	0.14	0.12	0.11	0.15

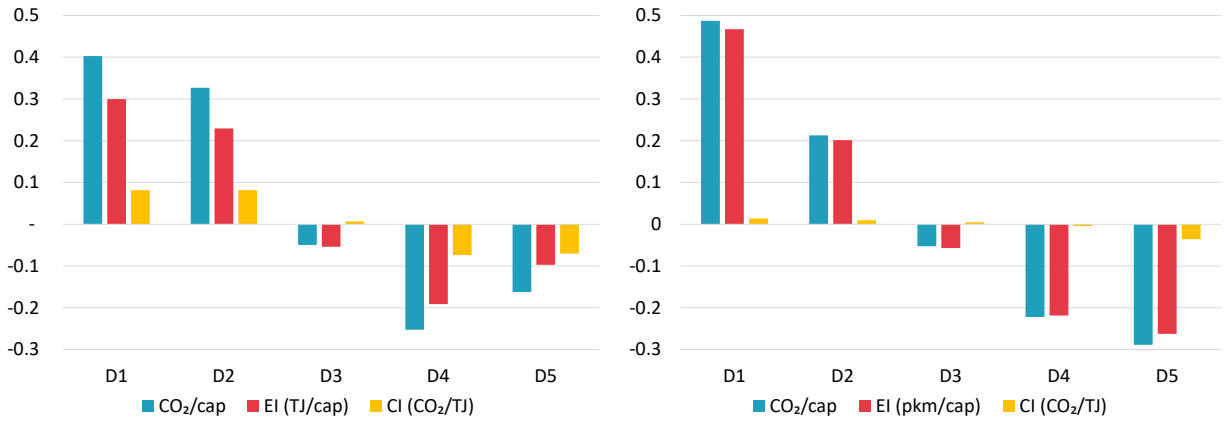
4.3.3.3 Kaya identity

A modified version of the Kaya identity is used to decompose the CO_2 emissions associated with residential space heating and passenger transport for each population density group as

per the equation below:

$$\frac{CO_2}{capita} = \frac{Energy\ service\ demand}{capita} * \frac{CO_2}{Energy\ service\ demand} \tag{4.6}$$

Where $\frac{Energy\ service\ demand}{capita}$ denotes energy intensity (EI) and $\frac{CO_2}{Energy\ service\ demand}$ denotes carbon intensity (CI). Figure 4.20 shows the decomposition of CO_2/cap in terms of EI and CI for the residential space heating and passenger transport sectors (all values relative to total), relative to the national average. In low density groups (D1 and D2), CO_2/cap, EI and CI are higher than national average, indicating the presence of energy and carbon intensive practices in these areas. Conversely, in high density areas (D4 and D5), all the components of the identity are lower than national average, implying high density can reduce EI and CI of energy service demands.



(a) Residential space heating

(b) Passenger transport

Figure 4.20: Kaya identity decomposition of passenger transport emissions for each population density group

4.4 Discussion

4.4.1 Key insights

This paper presents evidence quantifying the role of settlement patterns, in particular density, associated with energy service demands and GHG emissions. This is the first time quantitative evidence has been compiled so that this driver of demand can be parameterised in an energy systems model. The analysis indicates that per-capita transport and residential GHG emissions are 52% and 62% higher respectively for people living in areas with the lowest population density compared with the highest. We provide evidence on how a

dispersed settlement pattern is associated with higher energy service demands and therefore a greater challenge to achieve a net-zero transition. We conduct exploratory data analysis of the Census data for Ireland for 2006 and 2016 and highlight how population density is correlated with various energy service demands.

The results of the exploratory data analysis reveal that majority of the Irish population lives in low-to-medium density areas. This is mainly attributed to the dispersed housing development, wherein a large share of detached houses are still being built across the country. Detached dwellings are generally larger in size as compared to attached dwellings and apartments, which increases their energy service demands (such as demand for space heating and lighting). We find a strong positive correlation between population density and apartments and attached dwelling type, which indicates that such dwelling types increase population density while detached houses lead to sprawl. The type of central heating fuel is highly correlated to the population density of the area, with dwellings in densely populated areas more likely to be either connected to the gas grid or have electric heating while in low density areas, dwellings use oil or solid fuels which are more carbon intensive.

Private car ownership rate is higher in rural areas than in urban areas. Multi-car ownership rate has a strong negative correlation with population density, while no car households are usually present in areas with high density. The correlation matrix of population density and mode choice to commute shows that active modes are strongly and positively correlated with population density while private cars have a strong negative association with density. This implies that people living in dense areas are more likely to commute to work via active modes while private car usage increases with decreasing density. The number of public transport stops and frequency of services is higher in densely populated areas while the distance to nearest bus stop decreases with increasing density. Further, commute distances also decrease with increasing density. These observations imply that density enables sustainable transport infrastructure.

The results from the exploratory data analysis are used to develop spatial archetypes of energy service demand for each population density group. For the residential sector, space heating demand per capita is calculated and based on central heating fuel, carbon emissions are estimated for a single year. Similarly, for the transport sector, passenger kilometres per capita (journeys to work/school/college) is calculated for each population density group and based on the mode share, annual carbon emissions are estimated. The calculations show that energy service demand intensity and carbon emissions intensity both decrease with increasing population density. This implies that dense development can bring about a reduction in energy service demands and emissions.

4.4.2 Policy implications

The dispersed settlement patterns tend to promote higher energy service demands and higher carbon intensity fuel, therefore creates challenges for meeting climate goals. The feasibility of infrastructure development to provide sustainable services, such as public transport and district heating, increases when it is more economically viable. These initiatives not only contribute to carbon reduction but also enhance the overall quality of life by reducing congestion and improving air quality. To date, most public transport infrastructure has been developed in dense urban areas which puts rural areas at the risk of being locked into high carbon intensive practices such as forced car ownership (Carroll et al., 2021). Baobeid et al. (2021) find that the economically disadvantaged rely on low cost or free transport modes but within dispersed settlement pattern these modes seem unviable. This has implications on just transition in rural areas and among low income households, and hence distributional effects of policy must be accounted for while making decisions. This might involve subsidies, community-driven initiatives, or creative solutions to ensure that the economically disadvantaged are not disproportionately burdened by the transition to sustainable practices.

When the cities, town and villages are compact, it is easier to provide alternate solutions. For example, in a densely populated area, heating decarbonisation can be achieved through district heat network development. Similarly, public transport and active mode infrastructure can be developed in areas where more people are likely to use these services. Ek et al. (2021) find that accessibility to cycling and walking infrastructure is likely to increase active mode trips. Further, smaller residential dwellings have greater thermal comfort and with lower energy costs. With the on-going energy crisis, compact growth can reduce energy security related problems by reducing travel distances and space heating requirements. Beyond the environmental benefits, compact urban development has the potential to create more vibrant communities with better access to amenities and services. Recognising this, policies should incentivise compact growth while ensuring that it does not exacerbate existing urban challenges such as housing affordability or inequality.

As discussed, low population density implies greater travel distances which means that electrification of private car fleet will be more challenging, given the current range of affordable EVs does not allow long distance travel and the difficulty of developing a charging infrastructure (Sovacool et al., 2018). Dense settlement patterns will not only encourage environmentally friendly behaviour and lifestyle changes but also make technology and associated infrastructure economically feasible. Policymakers may need to explore a mix of innovative solutions, such as car-sharing programs and last-mile transportation options, to advocate for sustainable practices.

However, we recognize that population density does not ensure uniform concurrent development of essential infrastructure elements such as transportation networks, utilities, schools, and workplaces. Therefore urban/rural planning and climate action must be integrated to get all the benefits of sustainable transition.

4.4.3 Modelling insights

IAMs and energy systems models tend to focus on techno-economic fixes and usually neglect mitigation measures that are not easily quantifiable (Stoddard et al., 2021). Further, the demand side mitigation options are missing in these models or are represented at an aggregated level (Larkin et al., 2018). Since IAMs are integral to informing climate change mitigation policies, it is important to develop methods that allow the inclusion of mitigation measures that may be difficult to quantify, but nevertheless play an important role (Forster et al., 2020).

The quantitative relationship between population density and indicators of energy service demands presented herein is an important step towards adding granularity and improving the empirical base of LED-type scenarios. The energy service demand projections, often driven by population and economic growth, are usually exogenous to energy systems models. The LED-type scenarios that consider energy service demand reduction as a mitigation option generally lack empirical basis. This case study improves the empirical basis of such scenarios by estimating the energy service demand reduction potential arising from dense development. LED-type scenario narratives are heavily reliant on dense settlement patterns to bring about the necessary reduction in energy demand, making this case study important for developing future scenarios.

Settlement patterns also drive technology uptake rates, availability and feasibility of new investments, and access to clean fuels, which are often missing in scenario narratives when modelling mitigation options. Through the quantitative relationships established in this study, the regional disparities that might hinder energy transition can be taken into account as well. For example, the type of heating fuel or mode of transport used by a new household will depend on the dwelling type and its location. Hence, this exercise improves the granularity of scenario narratives and can provide additional modelling insights by considering regional variability of energy service demands. This analysis can help inform the diffusion of low carbon infrastructure such as district heating.

Finally, it also helps in accounting for geographical inequalities that arise due to dispersed settlement patterns. Lack of access to networked infrastructure and alternate fuels can lock

households into carbon and energy intensive practices. The unequal distribution of the benefits of energy transition has implications on just transition and SDGs. This analysis can ensure the inclusion of these concepts within the energy systems modelling framework.

The exploratory data analysis presented in this work has been developed to form a basis for projection of future energy service demands in Ireland. This will allow the development of alternate demand scenarios by considering various population density scenarios and their impact on energy service demands, building upon and expanding previous work by Gaur et al. (2022b). These energy service demand projections will be used in the TIMES-Ireland Model (TIM) as inputs to determine the implications of dense development on the Irish energy systems (Balyk et al., 2022).

4.4.4 Limitations

The empirical results presented herein must be viewed in light of some limitations. In the residential sector, publicly available data is at the county level (urban and rural). The space heating requirement per archetype and central heating fuel is considered to be constant in all population densities due unavailability of spatial data in the EPC database. A more granular analysis of the residential sector would improve the estimations of energy service demand and CO_2 emissions in each population density group.

In the transport sector, we only estimate passenger kilometres for commute and do not account for other journeys such as shopping, leisure and more. The bottom-up approach used here underestimates journeys since rural population working at/from home has longer journeys for other purposes.

It is imperative to acknowledge that our analysis lacks an income dimension, which is an important factor while discussing energy transition. However, the rationale behind excluding income effects across population densities is rooted in our study's emphasis on identifying policy levers that can be actively adjusted. Unlike income distribution, which is not malleable through policy interventions, spatial planning policy represents a tangible lever within the control of policymakers. Future work could use the presented methodology to include income analysis and provide a more comprehensive understanding of the energy transition landscape.

The nuanced relationship between population density and the development of essential infrastructure elements must be carefully considered to avoid oversimplification in IAM scenarios or policy discussions. The empirical correlations established in this study provide a valuable quantitative foundation, but it is crucial to recognise the variability in urban and

infrastructure planning across different contexts.

4.5 Conclusion

Energy systems modelling typically does include spatial drivers of demand, with the future usually represented in the form of aggregated values. However, there is spatial heterogeneity when it comes to uptake of technology, access to services, income, behaviours, and lifestyles. Further, spatial settlement patterns determine the demand for transport, housing, and services. For example, how geographically dispersed people live determines the length of transport trips, the feasibility of walking and cycling, and the effectiveness of public transport provision. Settlement density also influences the size of buildings and the material intensity of the built environment. Given the long lifetime of the built environment, there are significant lock-in effects on spatial development patterns.

We present a case study of Ireland, wherein we perform exploratory data analysis on the Census data and find a negative correlation between population density and energy service demands. This shows that the growth of housing stock in Ireland has led to low density settlement pattern. The Irish housing stock is characterized by large one-off rural dwellings and very small share of apartments, which is very unusual when compared to other developed countries and the EU. Large one-off houses have higher energy service demands, and are often combined with lack of access to the natural gas grid or district heating network or other clean space heating fuels. This has led to a high share of oil and solid fuels in central heating in Ireland. Further, the dispersed settlement pattern has led Ireland to be a car dependent country, especially with multi-car ownership in rural households. Transport energy service demands are higher in sprawling suburban or rural areas due to longer travel distances. Forced car ownership and unavailability of alternative transport modes has put rural Ireland at the risk of being locked-into carbon intensive practices.

The dispersed settlement pattern has implications on just transition and sustainable development goals as well. With lack of access to clean and relatively inexpensive modes of transport, low income households in low population density areas are also at risk of energy poverty.

Hence, concentrated settlement patterns can reduce energy demand, along with various other benefits to the environment and energy system and lower the cost of mitigation. Dense spatial settlement pattern will also make developing sustainable infrastructure more economically feasible, improving access to services and providing cheap alternate solutions to decarbonising the residential and transport sectors. Settlement patterns also impact infrastructure such

as roads, water supply and public transport networks, with higher material and energy intensity in less dense areas. Hence future policies around energy transition must include strategies to reduce energy service demands and allocate investments needed in the enabling infrastructure to bring about these reductions

The analysis in this paper improves the granularity of energy service demand projections for the future. Whether future population growth will continue to be dispersed, following historical patterns, or concentrate in urban areas, will have a very strong determining role in future energy needs. This study provides empirical evidence base for developing energy service demand scenarios based on future settlement patterns in Ireland.

Chapter 5

Implications of heating sector electrification on the Irish power system

Abstract

Electrifying the heating sector, which is energy and carbon intensive, and shifting electricity supply to renewable technologies is one of the main policy options being pursued for decarbonisation of the heating sector. Heat pumps are widely adopted for this purpose. However, the impact of this policy on existing electrical systems, both from the perspectives of supply and demand, is understudied in the literature. This paper examines the system-wide impacts of integrating high quantities of heat pumps, in line with government targets, in Ireland. We provide a broad discussion of the ramifications of heating sector electrification in terms of system costs and expansion planning under renewable energy targets. Results reveal significant changes in generation and increases in associated costs with increasing levels of electrification. On the flip side, the heating sector electrification leads to more efficient utilisation of renewable energy and the transmission network. We also explore alternative policy pathways to minimize impacts on the system. These include determining optimal locations for heat pump integration and a technology-neutral emission reduction target. Optimal distribution of heat pumps has a low impact on system metrics whereas pursuing an emission reduction target makes a large impact on system costs. [1]

Keywords: Decarbonisation, electrification, expansion planning, heat pumps, policy, climate action plan

[1]Published as : Gaur, A., Fitiwi, D.Z., Lynch, M. and Longoria, G., 2022. Implications of heating sector electrification on the Irish power system in view of the Climate Action Plan. Energy Policy, 168, p.113136.

5.1 Introduction

The residential sector accounts for 25% of the energy consumed in Ireland, subsequently responsible for a quarter of the energy related CO_2 emissions. There is about 60% more CO_2 in an Irish household than the average European Union (EU) home, which calls for urgent action to reduce energy consumption and associated GHG emissions within the residential sector (SEAI, 2018). Out of the total energy usage in a typical Irish household, 61% is used for space heating purposes (SEAI, 2018). Currently, gas, oil and solid fuels are the major fuels used for heating Irish homes, whereas electricity and renewable energy have an insignificant share. As a part of the EU decarbonisation strategy, Ireland set a target of meeting 12% of the final heat demand through renewable energy sources by 2020. This target has not been achieved, and decarbonisation of heat therefore remains a key policy priority.

Increasing the share of renewables in the heating sector can be achieved via heat pumps if the electricity sector itself is (at least partially) powered by renewable energy. Other options for renewable heat include the use of biomass boilers or district heating. However, countries with a dispersed settlement pattern, such as Ireland, have limited opportunities to exploit district heating. Biomass based solutions are often faced with feedstock issues. Further, countries that heavily rely on natural gas and crude oil imports should look for increasing renewable electricity and replacing conventional boilers with technologies like heat pumps (Abd Alla et al., 2022). Heat pumps are already in use and if consumer problems are identified, they should be encouraged, especially in regions with limited heat decarbonisation options (Nature Energy Editorial, 2016). These considerations, coupled with a high emphasis on renewable electricity generation, mean that heat pumps have emerged as the de facto option for renewable heat in Ireland, as well as other countries that share similar concerns for district heating and biomass, and lie in the Oceanic climate zone.

The 'European Green Deal' can be used to source funding to incentivize the uptake of heat pumps in residential dwellings. The Deal has singled out building renovations as a key initiative along with adequate funding to implement this. It requires the Member States to increase renewables in the heating and cooling sector by 1.1% every year until 2030, which gives added impetus to the rollout of heat pumps.

Extensive use of heat pumps is one key policy option for decarbonising heat, particularly in countries that have little district heating infrastructure. This is of course predicated on a decarbonised power sector, along with energy efficiency improvements (Nelson et al., 2014; Vaillancourt et al., 2017). Power-to heat options such as heat pumps are a proven technology

with high efficiency, low energy consumption and a potential to reduce GHG emissions (Gaur et al., 2021). However, the associated transformation of the energy system raises operational and planning challenges (Lowes et al., 2020a).

According to the Climate Action Plan 2019, the government of Ireland has set a target of achieving low carbon heat through renewables, biomethane and heat pumps. The detailed plan has a target of installing 600,000 heat pumps by 2030 in Ireland, of which 400,000 are to be in existing homes which will be upgraded to a B2 Building Energy Rating (BER) (NCAP, 2019). Nonetheless, electrifying the heating sector at this scale is bound to challenge the existing electricity system infrastructure. Hence electrification of heat is very likely to have an impact on the power system in terms of costs, capacity expansion and flexibility requirements (Verástegui et al., 2020).

Heat pumps are electrical devices that can be used for space and water heating applications. They are environment friendly and an efficient technology that can replace current fossil-based heating systems in residential, commercial and industrial settings (Gaur et al., 2021). While there are many types of heat pumps available in the market depending on the heat source (air, water, ground), the most suitable and popular in Ireland is the air-source heat pump (ASHP) (Gaur et al., 2021; Bord Gais Energy, 2019). ASHPs convert ambient heat to high grade heat which can then be used for space/water heating. These types of heat pumps have relatively low installation costs but a high coefficient of performance (proxy to efficiency) (Gaur et al., 2021).

A few generation and transmission expansion related studies for Ireland show the consequences of implementing existing policy targets (70% RES-E[2] penetration by 2030) and provide some insights into new recommendations (Fitiwi et al., 2020a; Fitiwi et al., 2020b). However, heat pumps are a new spatially dispersed load that will have an impact on the supply and demand component of the grid. In this context, we move one step further by considering the new electrical heating load along with other policy targets.

Policies can be designed either to increase renewable capacity in the system or to put a cap on CO_2 emissions. A single policy for reducing emissions might not be cost efficient (Fagiani et al., 2014). Fagiani et al. (2014) show that explicitly targeting renewable generation has negative impacts on carbon prices, which could further attract investments in technologies with higher emissions. However combining a renewable policy with a carbon policy could mitigate this impact (Bird et al., 2011). Generally, a renewable policy is more expensive than a technology neutral approach (carbon policy) (Young et al., 2018; Lu et al., 2016).

[2]Renewable Energy sources-Electricity

Lu et al. (2016) also point out that a carbon policy often leads to a more diverse generation portfolio. However, the impact of adding a new spatially diverse electricity load has not yet been quantified.

Heat decarbonisation is a global challenge and there is a need of better evidence with unique insights and greater certainty for policy-makers (Lowes et al., 2020b). Heat pumps are emerging as the main space heating decarbonisation technology. Countries where heat decarbonisation transition has not started or is slow could use more empirical evidence as a motivating factor (Lowes et al., 2020a). A case study of the Italian energy systems shows that heat pumps could play an important role in decarbonisation, however, due to supply demand mismatch it leads to a lower share of renewable generation (Bellocchi et al., 2020). Although cost wise heat pumps are more favourable than other technologies like electric vehicles at current prices (Bellocchi et al., 2020). Zhao et al. (2020) present a bottom-up optimisation framework for feasibility assessment of decarbonisation goals for New York state and conclude that heat pumps would be among the main space heating technologies in the future. Further, replacing gas boilers with heat pumps is an important home decarbonisation strategy in the US as shown by Walker et al. (2022).

Although it has been acknowledged that heat pumps are critical for space heating decarbonisation, limited real-world implementation and lack of reporting have resulted in ineffectiveness of policies (Abbasi et al., 2021). Space heating decarbonisation in residential dwellings is complex as it directly impacts consumers. Hence, empirical evidence is critical to address social factors such as consumer experience, transition disruptions, and fuel poverty (Abbasi et al., 2021). Table 5.1 shows the payback periods of heat pump (HP) systems in various countries. The payback periods differ significantly between countries depending on the weather conditions, type of heat system and applications. Hence, country specific analysis is important to understand economic feasibility.

This paper presents an analysis of the long run power system impacts of electrifying spatially dispersed household heating demand for Ireland under various policy options. The analysis includes the impact on the generation as well as transmission system, using a stochastic optimisation model which is based on linearised AC-power flow. The current policy targets pertaining to renewable energy integration (70%) and heat pump deployment have been considered. The distribution of heat pumps is assumed to be uniform throughout the country (20% and 30% of dwellings electrified at each transmission node).

Next, we explore pathways to reduce costs and the impacts of electrification by taking into account other policy alternatives. In the first instance, the level of heat pump integration in

Table 5.1: Comparison of payback periods of heat pump systems

Sr. no.	Country	HP System	Application	Payback period (years)	Reference
1	Taiwan	Solar+HP	Domestic water heating	3.57- 5.36	(Li et al., 2017)
2	United States	HP	Groundwater treatment facility	6.3-10.9	(Wang et al., 2019a)
3	China	HP	Space heating	8.36	(Dai et al., 2020)
4	Saudi Arabia	HP	Space cooling	10–20	(Alshehri et al., 2019)
5	Sweden	HP+renovation	Space heating	19-23	(Gustafsson et al., 2016)
6	Cyprus	HP+ground heat exchanger	Space heating and cooling	16-21	(Christodoulides et al., 2019)
7	United States	HP+ground heat exchanger	Space heating and cooling	3.2-37.8	(Neves et al., 2021)
8	Croatia	Solar+HP	heating, cooling and DHW	12	(Delač et al., 2022)
9	China	Solar+HP	Water heating	17.3–22.4	(Deng et al., 2016)
10	Australia	Ground Source Heat Pump	Space heating and cooling	20	(Lu et al., 2017)

each region, for a given national target, is an endogenous decision made by the model. In other words, the spatial distribution of heat pumps is optimal depending on the economics and operation of the system. Following this, we analyse the impact of implementing an emission reduction target instead of the RES-E target. The former is a technology-neutral approach that limits the carbon intensity of the power system.

The original contributions of this paper are as follows. First, the power system impacts of shifting heating supply to electricity via Air source heat pumps, for a small isolated system, are quantified. Both investment and operational impacts are considered. Secondly, the spatial distribution of both the supply and demand is considered. Policy makers may benefit from rolling out new technologies such as heat pumps in certain regions in the first instance, exploiting the available resources, reducing costs and gaining information. However, this regional approach may increase public opposition if some regions are seen to benefit from decarbonised heat over other regions. There is thus a trade-off in electrifying the heating sector in the optimal regions versus electrifying across the whole jurisdiction at the same rate. The spatial aspects of this model allow us to provide evidence around this trade off. Finally, we provide evidence on the interaction of various heating and decarbonisation policies, which

informs optimal decarbonisation policy for both the heating and power sectors.

The remainder of the paper is structured as follows. Section 2 outlines the methodology used in this study which includes the model description, data and assumptions along with scenario description. Numerical results are discussed in section 3. Sections 4 and 5 present the discussion and conclusion respectively.

5.2 Methodology

5.2.1 Model Description

To provide quantitative evidence for future policy decisions, we perform a generation and transmission capacity expansion exercise on the Irish grid. For this purpose, we use the Electricity Network and Generation INvEstment (ENGINE) model (Fitiwi et al., 2020a). It is an AC optimal power flow model based on multi-stage stochastic linear programming. The objective function minimizes the overall system cost subject to several techno-economic constraints (physics of the system, climate policy targets, spatial renewable capacity limits, system non-synchronous penetration, etc.). Figure 5.1 shows a summary of the ENGINE model and further details can be found in Appendix A.

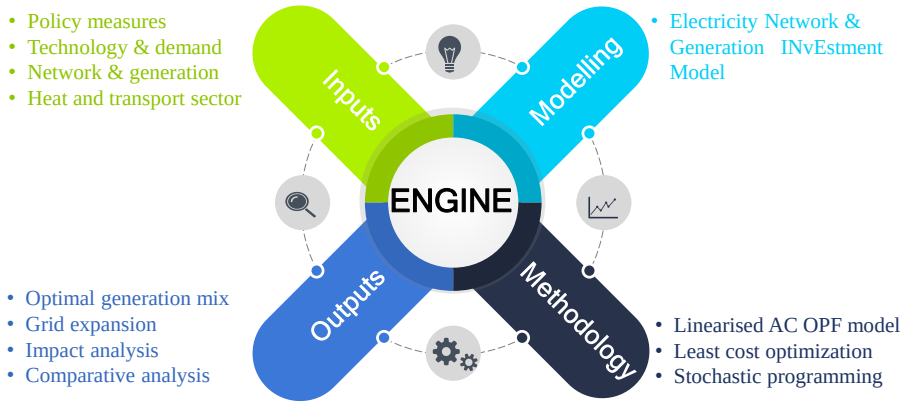


Figure 5.1: Description of the ENGINE model

The ENGINE model accounts for locational aspects such as renewable development constraints, network expansion, voltage issues and load shedding. Such thorough spatial and network details enable the model to simulate closely the physical electricity system at the transmission level. It can also take into account policy measures such as climate policy targets, datacentres, hydrogen storage and e-heating & e-mobility. The ENGINE model can be used to determine the evolution of the electricity infrastructure over the years such as

interconnection points, fossil fuel phase out. This model can also be used to answer various technical and policy related questions such as optimal power generation mix, technology portfolios, flexibility options and more.

In addition to the total generation and transmission costs determined endogenously by the ENGINE model, we also consider the costs of retrofitting residential properties to an energy efficiency standard required to use a heat pump, as well as the installation cost of the heat pumps themselves. We assume a cost of €25,000 for installation and energy retrofit. Given that these costs are policy-driven, we do not include them in the model but add them *ex post* to the total costs as determined by the ENGINE model.

5.2.2 Data and Assumptions

The analysis is carried out on the existing 2017 Irish grid considering the anticipated evolution of the grid through 2030. The considered system consists of 676 nodes and 900 transmission lines (including transformers which are modelled as lines with zero length). This represents a transmission network aggregated at 110 kV or higher for the whole island. Figure 5.2 shows the potential connection nodes for renewable and storage investment.

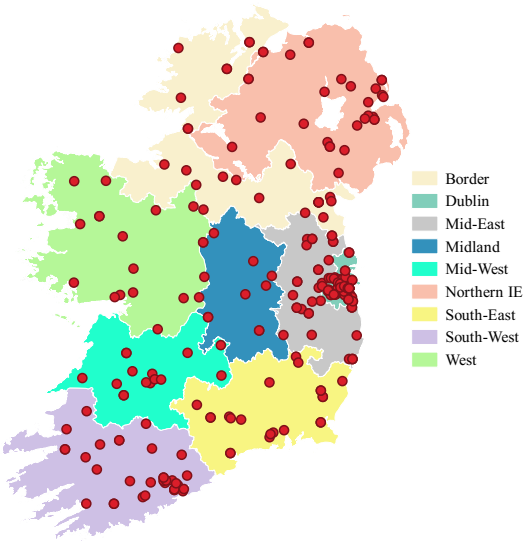


Figure 5.2: Candidate connection nodes of renewable and storage investment

We assume a carbon price of 30 €/ CO_2 for the year 2030. Investments in new thermal power plants and CCS are assumed to be in brownfields. The decision of retiring old power plants is not endogenous but is assumed to be a policy decision. Investment cost assumptions for most generation technologies and transmission infrastructure are as assumed in

(Fitiwi et al., 2020a) while that for onshore wind, offshore wind and solar PV are from (Tsiropoulos et al., 2018). The system non-synchronous penetration (SNSP) limit is set to 75%. We consider two storage technologies in the system to avoid excessive conversion losses: battery energy storage (BES) and thermal energy storage (TES). The BES system is to support the electrical grid and TES supports the heat demand in houses using heat pumps with round trip efficiencies of 90% and 85% respectively. Previous work has shown the benefits of using TES along with heat pumps such as lower grid expansion needs and higher utilisation of renewables (Gaur et al., 2019).

The input data for heat demand consists of two parts: (i) hourly heat demand arising from new builds using heat pumps for domestic heating and (ii) the heat demand from existing houses retrofitted by 2030. Data concerning part (i) is related to the projected growth of demand for e-heating which is provided by EirGrid (EirGrid, 2017). This projection only considers the adoption of heat pumps in new residential dwellings for domestic heating purposes (which includes both space and hot water). Data on existing housing stock (concerning part (ii)) is obtained through a dynamic district information model (DDIM) which simulates heating demand from Irish housing stock (Hoare et al., 2021). This approach allowed the inclusion of household type, occupancy level and impact of retrofitting dwellings on heating demand.

5.2.3 Scenario Description

This section outlines the scenarios that have been analysed in this study and are described below. The scenarios correspond to the current policy targets and pathways to reduce costs and impact on the power system. Table 5.2 outlines the cases discussed in this study.

- Power system impacts of current policy regarding electrification of heat- The impact of heat pumps on the electrical infrastructure considering a RES-E target of 70% in 2030. The level of electrification (20% and 30%) at each node is fixed and uniform throughout the island of Ireland as shown in Equation 5.1. In this equation, $N_HP(i)$ is the number of heat pumps connected to each node i, α $(0 \leq \alpha \leq 1)$ is the fraction of dwellings to be electrified at each node i and $N_Homes(i)$ is the total number of dwellings connected to each node i .

$$N_HP(i) = \alpha * N_Homes(i) \quad \forall\, i \tag{5.1}$$

- Optimal spatial electrification of heating- The level of electrification at each node (α) is an endogenous decision of the ENGINE model for a given national target as shown

in Equation 5.2. The LHS of this equation represents the national target for the total number of heat pumps to be deployed in the country.

$$\sum_{i=1}^{n} N_HP(i) = \sum_{i=1}^{n} \alpha * N_Homes(i) \quad \forall\ i \tag{5.2}$$

- Impact of decarbonisation versus renewable policy- This scenario determines the impact of an emission reduction target against a RES-E target on the deployment of heat pumps. The emission reduction target utilises a technology neutral approach that limits the carbon intensity of the power system.

Table 5.2 describes the various cases analysed in this paper. The level of electrification and type of distribution is varied (no limit implies optimal spatial distribution).

Table 5.2: Description of cases analysed

Cases	Description
Base_RES	Base case with RES target (no retrofits)
20_RES	20% retrofit at each node with RES target
30_RES	30% retrofit at each node with RES target
20_EMI	20% retrofit at each node with emission reduction target
30_EMI	30% retrofit at each node with emission reduction target
20_unlim_RES	20% retrofit overall with RES target and no limit
30_unlim_RES	30% retrofit overall with RES target and no limit
20_unlim_EMI	20% retrofit overall with emission reduction target and no limit
30_unlim_EMI	30% retrofit overall with emission reduction target and no limit

5.3 Results

5.3.1 Power system impacts of current policy regarding electrification of heat

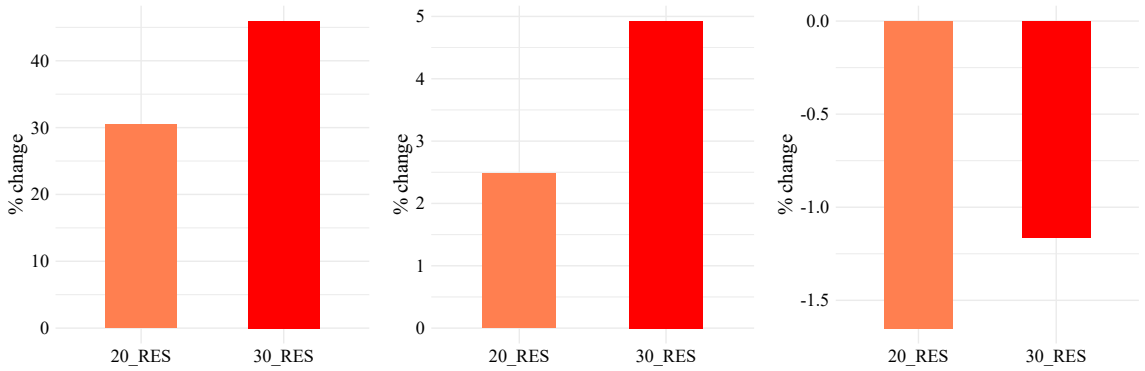
In the first instance, we examine the power system impacts of electrifying heat under the current policy, that of increasing electrification across Ireland. We assume that an equal proportion of electrification takes place at each transmission node. As mentioned above, total costs include the costs associated with heat pumps and retrofits, which account for a significant portion of the increase.

Figure 5.3 shows the percentage change in the total costs, as well as the generation and transmission costs at both levels of electrification with respect to the base case. The total cost increases by 30% in the 20_RES scenario and by 46% in the 30_RES scenario. This

suggests some non-linearity in the relationship between the electrification of heating and the total system costs.

The generation costs increase to supply the additional demand arising due to electrification of the heating sector while the transmission expansion costs decrease slightly The change in generation (2.5-5%) and transmission (1.2-1.7%) costs is small. Further, generation costs make up about 35% of the total costs whereas transmission costs contribute to less than 1% of the total costs. Hence even a small change in generation costs leads to a significant variation in the total costs because generation costs represent a large proportion of total costs. With higher electrification of heating, offshore wind capacity increases while solar PV and the battery storage requirement decreases: in the 20_RES case there is a 148 MW increase in offshore wind but a 135 MW decrease in solar PV and 172 MW in battery storage capacity whereas in the 30_RES case offshore wind capacity increases by 240 MW and solar PV decreases by 51 MW while storage decreases by 113 MW.

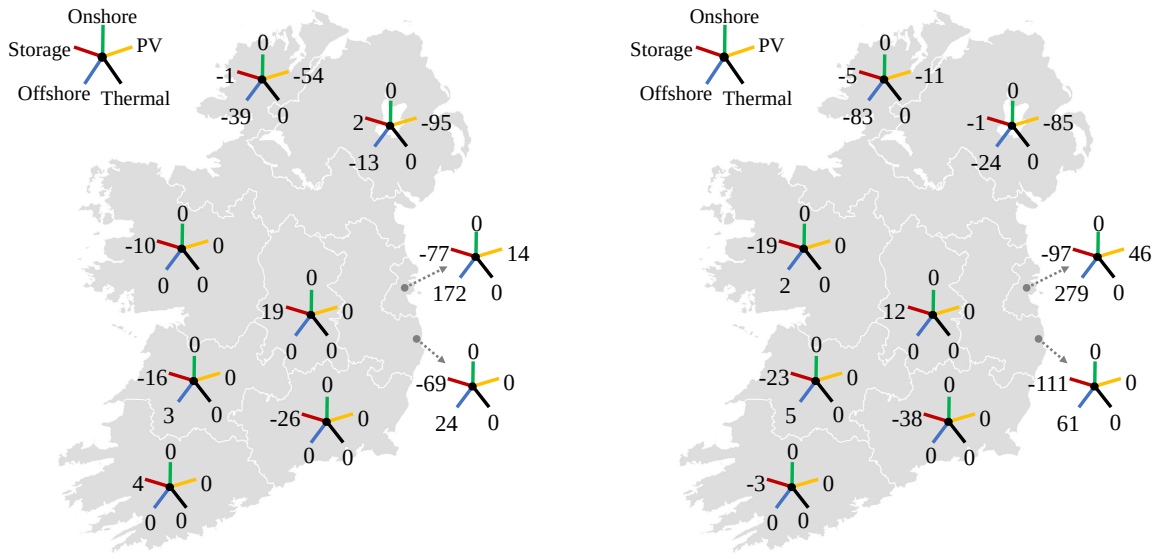
This change in the generation mix is reflected in the regional distribution of the generating capacities. Figure 5.4 shows the change in installed capacity for each generation technology by region, relative to the base scenario of 70% RES-E with no electrification of heating. Battery storage investment decreases across all regions as electrification increases. Offshore wind capacity increases in Dublin, Mid-east, Mid-west and West whereas it decreases in Northern Ireland and the Border region of Ireland as the level of electrification increases. These changes are a result of the number of houses being electrified in each region: RES-E capacity increases in regions that have a greater number of dwellings, and hence a greater increase in electricity demand from electrification of heating. This suggests that the spatial distribution of generation is driven more by demand rather than supply considerations.



(a) NPV (b) Generation cost (c) Transmission cost

Figure 5.3: Change in costs with respect to Base_RES

The overall storage capacity (battery and thermal) is higher with higher electrification.



(a) Δ 20_RES

(b) Δ 30_RES

Figure 5.4: Change in regional generation mix (MW) with respect to Base_RES in 2030

Transmission and storage often act as substitutes, where a system with higher storage requires lower transmission investments and vice versa (Fitiwi et al., 2020b). The increased storage and decreased transmission seen in these results confirm this finding but also suggest that the spatial distribution of demand plays a role. Offshore wind is spatially concentrated, while electric heating demand and storage is spatially dispersed, and the increase in dispersed demand is complemented by storage rather than transmission infrastructure.

The percentage change in renewable curtailment is depicted in Figure 5.5. Renewable curtailment decreases with a higher level of electrification. Further, the capacity utilization of wind generation increases by 2% in 20_RES and 4% in 30_RES, compared to Base_RES, thus, heat pumps increase the utilisation of renewable energy in the system. This suggests that electrifying heat allows greater utilisation of available renewable generation, and chimes with the reduction in battery storage investment noted earlier. This observation may also in part explain the non-linearity in the relationship between electrification and costs observed above - higher electrification reduces curtailment, which in turn reduces alternative generation investment requirements.

The change in transmission system losses is shown in figure 5.6. Higher levels of electrification lead to lower losses, implying that heat pumps lead to a more efficient operation of the transmission network. This again may follow from the spatially dispersed nature of the electric demand and tallies with the observation that electrification decreases the requirement for transmission infrastructure and battery storage.

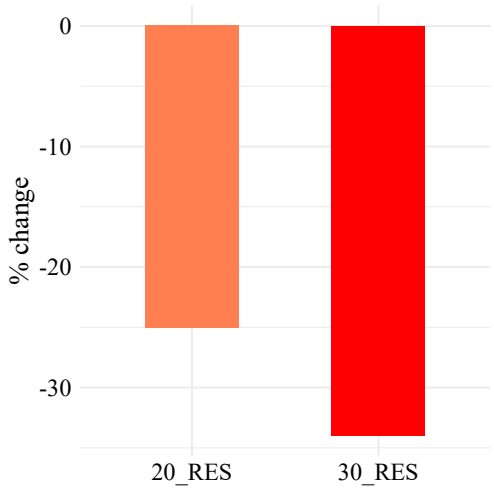


Figure 5.5: Renewable curtailment

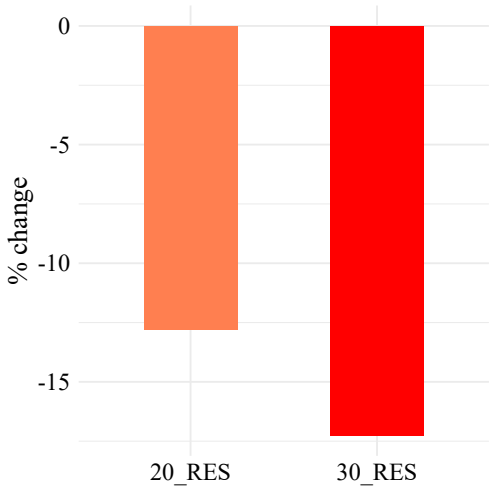


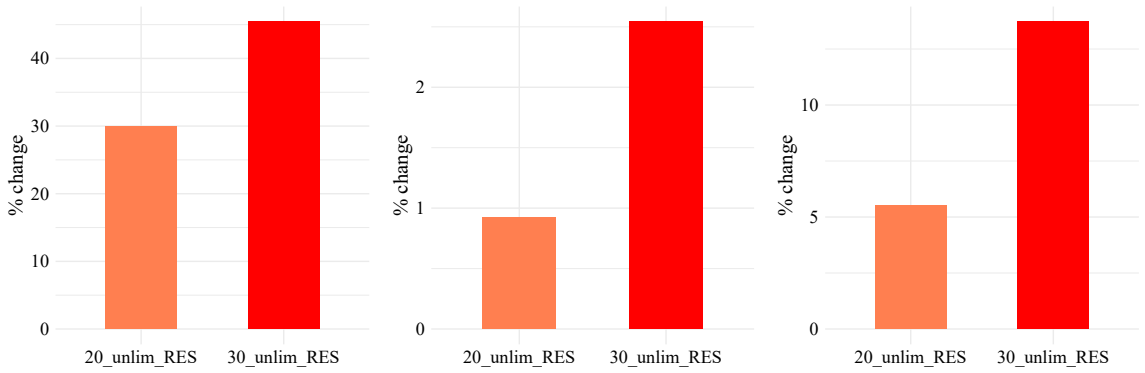
Figure 5.6: System losses

5.3.2 Alternative policy options: Optimal spatial electrification of heating

The analysis above assumes a uniform policy of electrifying heat across a jurisdiction. However, policy makers may wish to consider concentrating the electrification of heat in the regions that can electrify at least cost, due to local variations in supply, demand and infrastructure. In order to examine the impacts of such a policy, we performed two further analyses where the total electrification of the heating network was 20% and 30% respectively, but the level of electrification at each transmission node was determined endogenously by the ENGINE model. This allows us to determine the cost-minimising spatial allocation of electric heating, and the magnitude of any impacts of the same.

Figure 5.7a shows the change in the total costs with respect to the base case when the level of electrification at each node is not fixed. As observed previously, there is a significant increase in the total costs with a higher level of electrification, almost as high as in the case where the electrification of heat is evenly distributed across the system (see Figure 5.3a). However, the change in generation costs under the scenario where heating is electrified in a cost-minimising manner is lower. This implies that much less additional generation capacity is required to supply the increased electricity demand when the demand is strategically located within the power system. Furthermore, only a slight change in the regional distribution of the generating capacities was observed. Transmission costs, on the other hand, have increased as opposed to a scenario where the spatial allocation of electrification is even. When 20% of heating is electrified, any increase in transmission costs relative to a case with no electrification is 5%, and a 14% increase in transmission costs is required when electrifying 30% of heating

demand. However, transmission system investment in Ireland is viewed far less favourably than generation capacity investment (Bertsch et al., 2017), and so policy makers may wish to consider this as a potential extra cost to the electrification of heat (over and above the monetary costs enumerated here).



(a) NPV (b) Generation cost (c) Transmission cost

Figure 5.7: Change in costs with respect to Base_RES

The discrepancy in total costs versus generation and transmission system costs underlines the fact that the primary cost of electrifying the heating sector is the cost of the heat pumps and the retrofits required to raise the energy efficiency of the households. The power system costs of meeting the extra demand are small, at least under the high levels of renewable generation envisaged (70%). The main impact of concentrating electrified heating evenly rather than in the optimal geographic areas, from a spatial perspective, may be in reducing public opposition, given the considerable decrease in transmission system assets required, rather than decreasing power system costs.

Figure 5.8 shows the change in renewable energy curtailment relative to a case with no electrification of heat. Although the curtailment decreases as electrification increases, in line with previous results, the magnitude of the decrease is lower. A similar phenomenon is observed in the system losses depicted in Figure 5.9. This suggests that the uneven spatial distribution of electricity demand for heating leads to less efficient utilisation of both the renewable resources and the transmission network, increasing both curtailment and losses.

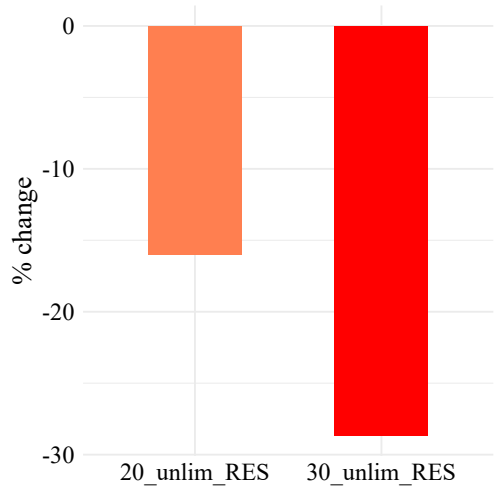


Figure 5.8: Renewable curtailment

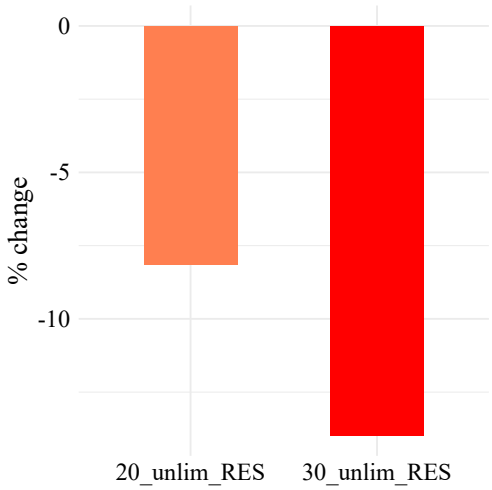


Figure 5.9: System losses

5.3.3 Alternative policy options: Impact of decarbonisation policy versus renewable policy

Finally, we explore the implications of electrification of heating under another alternative policy, that of setting a target for power system carbon emissions rather than a renewable generation penetration target. In this case, we constrain power system emissions to be equal to those observed under the policy target of 70% RES-E penetration, but we do not impose any particular RES-E target and instead allow the emissions target to be achieved in a technology-neutral manner. The results analysed in this section correspond to the percentage change between the RES-E and emission reduction targets.

Figure 5.10 shows the difference in the total costs and RES curtailment between a policy with a RES target and a policy with an emissions reduction target, for each level and type of electrification. The total cost of the system is higher in the RES target scenarios (as shown by the fact that the difference between the two scenarios is negative). This difference in total costs only marginally changes as electrification increases. Furthermore, optimal spatial electrification leads to slightly greater difference in the total system costs across all cases and electrification levels. These results suggest that while the total costs of electrification under a RES-E target are primarily influenced by the costs of heat pumps and the costs of retrofitting, and while optimally locating the electrification can make some difference, these differences are very small when compared to the excess costs of pursuing a specific RES-E policy (as opposed to a least-cost decarbonisation policy).

RES curtailment is higher in the RES target scenarios compared to the emission reduction

scenarios because the renewable capacity is obviously much higher in the RES scenario.

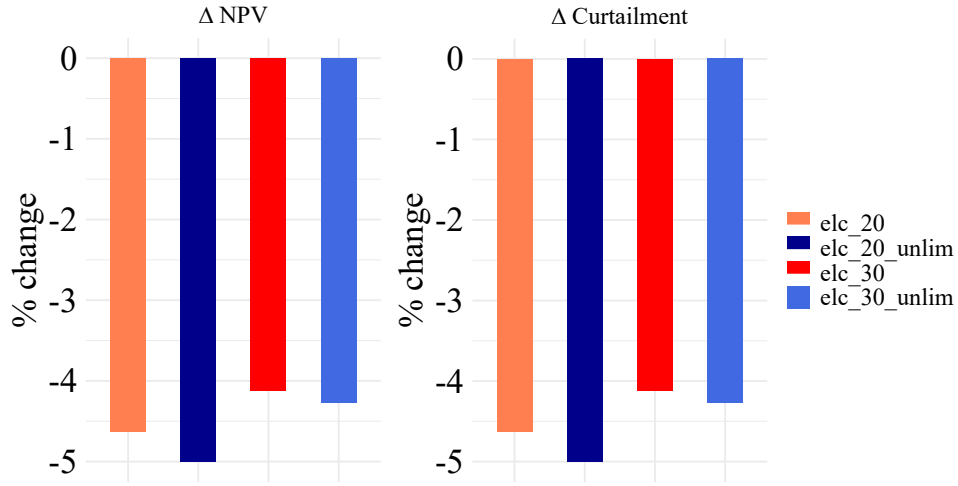


Figure 5.10: Objective function components

The breakdown of relative system wide investment costs is shown in Figure 5.11. The change in costs associated with investment in generation technologies in the case of a carbon reduction target is significantly lower compared to the RES target scenario due to a shift of investment from wind to thermal (Coal and Combined cycle gas turbine (CCGT)) CCS plants, as shown in Figure 5.12. The very low level of emissions intensity targeted, which corresponds to high levels of RES-E, justify investment in CCS technologies. Ireland has spent gas fields that can be repurposed for carbon storage, and it is assumed that this is possible by 2030, which impacts the cost figures used here and by Fitiwi et al. (2020a). Higher cost assumptions around CCS would decrease the optimal level of CCS investment.

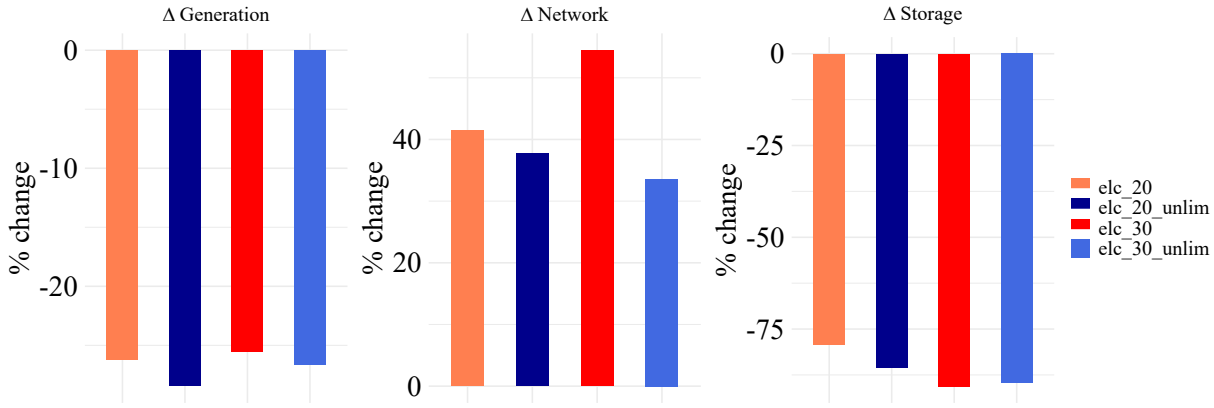


Figure 5.11: Cost components

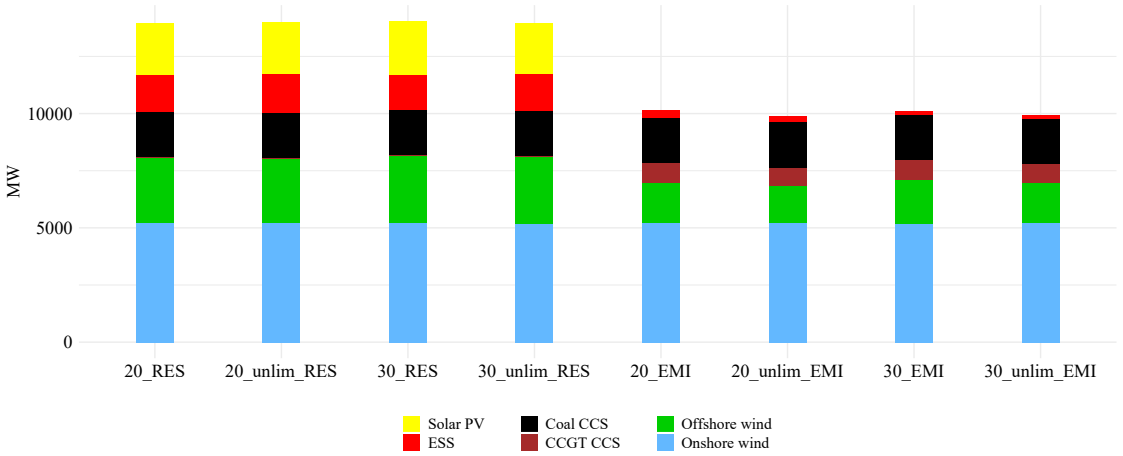


Figure 5.12: Generation mix in 2030

Increasing levels of electrification obviously increase total electricity demand. In the RES-E scenario, this increased demand is matched by an increase in renewable generation capacity and also storage, while the emissions reduction scenario sees the increased demand met by CCGT capacity and some offshore wind.

In the RES target cases, offshore wind capacity increases with the electrification level and in the emission reduction target scenario thermal CCS capacity decreases and offshore wind increases with the electrification level. This suggests that, even in the absence of a specific renewable target, offshore is the optimal marginal investment technology. The overall capacity requirement is higher in the RES target cases since renewable power plants have a lower capacity utilisation factor compared to thermal power plants.

Figure 5.13 shows the change in the transmission expansion capacity between the RES-E target and emission reduction scenarios. Firstly, the transmission capacity requirement is higher in the emissions target cases, and increases with the level of electrification. Secondly, optimally distributing heat pumps requires lower transmission capacity (at a 20% electrification level, the difference is insignificant), because the optimal spatial distribution of heat pumps minimizes transmission expansion. The impact of optimal heat pump placement is sufficiently marked to nullify the impact of variable RES-E, leading to lower transmission requirements in the RES-E cases.

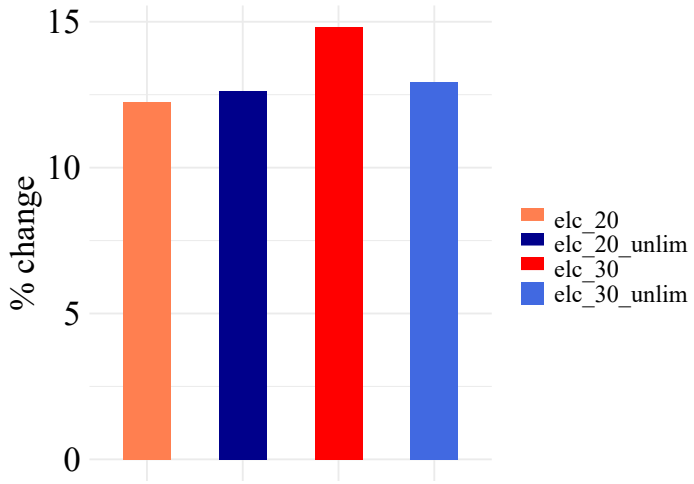


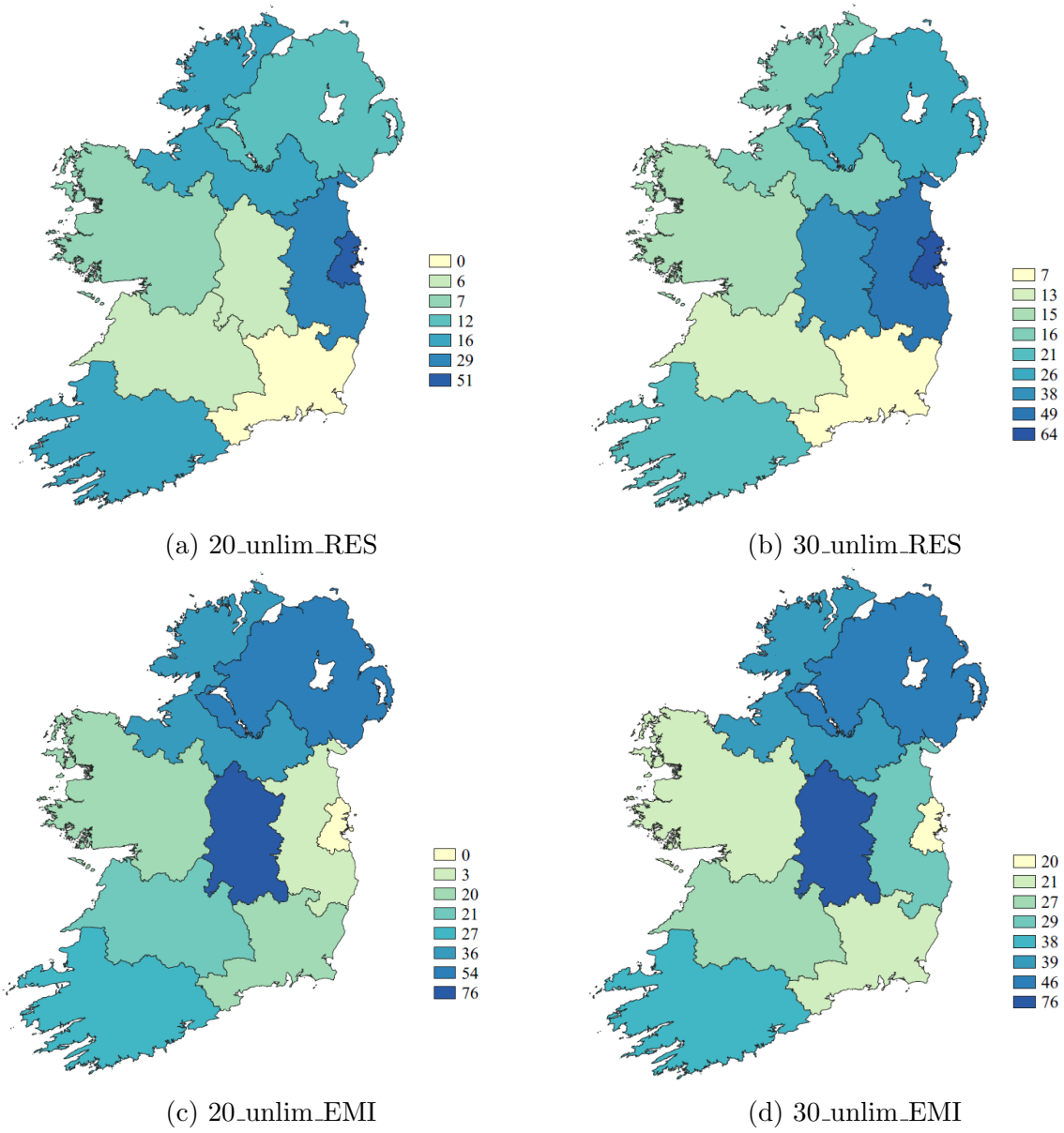
Figure 5.13: Changes in transmission capacity for renewable versus carbon reduction scenario

5.3.4 Spatial comparison of demand and supply under RES-E vs emissions policies

As noted above, under a RES-E policy, altering the regional distribution of heat pumps has little effect on aggregate metrics, and regional differences in investment are driven by demand rather than supply considerations. In order to explore this further, Figure 5.14 shows the optimal percentage of heating that is electrified in each region.

In the RES target scenarios, the highest electrification is in Dublin, which has the highest number of dwellings and so the highest heat demand. After this, electrification is driven by the presence of thermal generators: significant electrification is observed in Mid-west and Northern Ireland followed by the South-west and Midland parts of Ireland. Thus, electrification is driven by minimising transmission investment rather than the presence of renewable generation. As the electrification target increases from 20% to 30%, the midland experiences greater electrification. High electrification levels are seen in areas with high offshore wind and/or thermal generating capacities (see Figure 5.4). Electrification is low in the West and Mid-West, despite these areas having high wind capacity factors and significant land available for onshore wind capacity generation. This suggests that renewable supply considerations do not drive the optimal spatial location of electrification even at high renewable target levels.

In the emission reduction scenario, the highest electrification is in Midlands, followed by Northern Ireland, border region and the South-West of Ireland, with the lowest electrification seen in Dublin. This stark difference in the distribution of heat pumps between the RES



(a) 20_unlim_RES (b) 30_unlim_RES

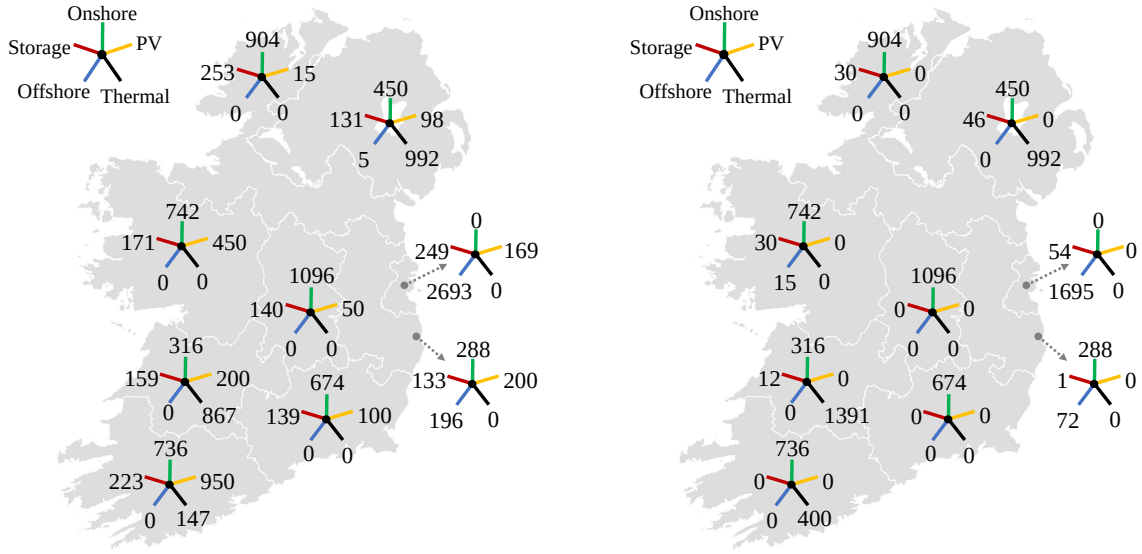
(c) 20_unlim_EMI (d) 30_unlim_EMI

Figure 5.14: Optimal electrification level in every region in 2030

and emission reduction scenario is due to the change in generation mix from onshore wind in the former to thermal and offshore wind in the latter. Higher electrification is therefore observed in geographical areas with significant thermal and wind generation. The distribution of heat pumps is governed by the location of the generating capacity and network constraints. Thus, somewhat surprisingly, supply side considerations feature more heavily in determining optimal spatial electrification under a thermal generation portfolio than renewable generation.

Figure 5.15 shows the regional distribution of the optimal generation capacities in 2030 under

the renewable and climate targets, with 30% electrification. Significant changes are seen in the distribution of offshore wind, storage, solar PV, and thermal generators. Dublin has high offshore wind and solar PV in the RES-E case but has no solar PV and lower offshore wind and storage in the emission target case. Similarly, all other regions witness a reduction in storage capacity in the emission target case compared to the RES-E case. The South-west and Mid-west regions of Ireland have a notable increase in thermal capacity as the electrification level increases, with CCGT capacities increasing in particular.



(a) 30_unlim_RES

(b) 30_unlim_EMI

Figure 5.15: Regional distribution of generation capacity in RES-E and emission target cases in 2030

5.4 Discussion

There are several results that can inform optimal policy for decarbonising both the heating and power sectors. In particular, the quantification of the complex interactions between these policies, and spatial features of the same, are noteworthy, and constitute the main contribution of this paper.

A key result for policy makers is that the spatial distribution of demand drives the optimal power system investments far more than the spatial distribution of supply, particularly renewable supply. Even under a scenario with explicit and high renewable power targets, renewable power capacity has only a small impact on the optimal placement of renewable generation. This result holds whether or not the spatial distribution of electric heating is evenly distributed across the power system or whether the optimal level of electric heating

is installed at each location (subject to a global electrification target). This latter result suggests that the benefits of optimally locating electric heating are minimal. Indeed, the difference in total costs under the two policies is small. Policy makers may thus decide not to target electric heating towards the least cost areas, instead electrifying heat at an even rate across the system.

This result becomes more nuanced under a decarbonisation policy that is technology-neutral, rather than one that commits to specific RES-E targets. Under a RES-E policy, a high level of offshore wind is required. Greater demand for electrification of heating gives rise to an even greater requirement for offshore wind. Thus, under the RES-E policy, it is optimal to concentrate both the increase in demand and renewable supply in Dublin and Northern Ireland, which have high pre-existing levels of demand. Under a technology-neutral climate policy, supply is instead determined on the basis of the available brownfield sites, and the increase in demand from heating is redistributed spatially accordingly. Thus demand drives the spatial distribution of investments under a RES-E policy, with supply playing a stronger role under a technology-neutral policy.

Another key insight for policy makers is the role played by transmission and storage. While transmission makes up a very small proportion of total costs under every scenario, public opposition is often greater for transmission investments than generation investments (Bertsch et al., 2017). Therefore, policy makers may wish to place greater weight on a policy that reduces transmission investment, even if the impact on total costs is small. Given that there is an increase in transmission infrastructure investment under an optimal spatial distribution of heat pumps, there is a potential trade-off for policy makers: the benefits of reducing transmission investment may be worth the political costs of evenly distributing heat pumps across the system. The dynamics of this particular trade-off will likely vary from one system to another.

Power system details that were omitted from the analysis, such as granular spatial details around distribution system upgrades, could impact the results. In particular, large scale installation of heat pumps could trigger new, or exacerbate existing, distribution system constraints. These constraints in turn would lead to an increase in unserved energy and/or require distribution system upgrades, which would increase total costs. This represents yet another exogenous cost of a heat pump installation policy that is not considered here. The effect of this omission is an underestimation of the total costs of heat pump installation, although the magnitude of this effect is unknown.

Heat pump investment in general reduces renewable generation curtailment, and also reduces

transmission system losses, even with a higher investment in transmission. This suggests that heat pumps enable a more efficient utilisation both of renewable generation and of the transmission system. These impacts may aid public acceptance of heat pumps as a policy, which may be of benefit to policy makers given the high cost associated with this technology.

The optimal investment in storage under the various heat pump policies is particularly policy-dependent. Two main patterns emerge. First, storage (battery+thermal) rather than transmission is used to complement renewables, which in turn facilitates the balancing of supply and demand at the local rather than system level. Thus there is significantly more storage investment under a renewable policy versus a technology-neutral policy. Secondly, optimal placement of the heat pumps increases storage investment (5-7%) under a RES-E policy, while it sees an insignificant change in storage investment under a technology neutral policy.

Finally, the main driver of costs modelled here is the cost of the heat pumps themselves, and the energy efficiency retrofits required to render heat pumps feasible as an option for home heating. This remains the case under every policy examined. Thus, this is a high cost way of decarbonising the heating sector, independent of any power system implications, and so policy makers should ensure that alternative pathways to decarbonise and/or renewable heat are considered. In Ireland's case, district heating using waste heat from datacentres has recently come to the fore as one option. Green hydrogen has not received significant policy attention to date, but may have some potential applications (Longoria et al., 2021). In particular, the potential to avoid or delay the significant retrofit cost associated with heat pumps may render green hydrogen a possible alternative policy. Given the path-dependency of the transmission and generation investments required, these alternative polices should be fully considered in advance.

5.5 Conclusion and Policy Implications

This paper examines the power system impacts of electrifying 20% and 30% of Irish heating demand. We utilise a granular spatial model to determine the optimal investment in generation and transmission technologies under various heating and power system policies. We find that the cost of installing heat pumps and the retrofit cost of increasing the insulation of dwellings is by far the most costly aspect of a heat decarbonisation policy that relies primarily on heat pumps, dwarfing power system costs.

Our main results find that spatially distributed demand rather than supply is the primary de-

terminant of power system investments and costs. Generation costs see the highest absolute increase, while transmission costs see the highest relative increase.

Optimally determining the location of heat pumps, rather than evenly locating them across the system, has a negligible impact on total costs, although it does greatly increase transmission investments. Optimally determining decarbonisation of the power system, however, rather than pursuing a renewable generation policy, reduces system costs. Heat pumps themselves give rise to more efficient utilisation of renewable generation and transmission assets.

The results indicate a complex interaction between heat and power system policies. Policy makers should be cognisant of public acceptability and path dependency when determining the optimal decarbonisation policy for both heat and electricity.

Part II: Sustainable development strategies for passenger transport in Global South

Chapter 6

Mobility scenarios for the Global South: Developing an evidence-based framework for a large-scale IAM

Abstract

Integrated Assessment Models (IAMs) play an important role in shaping climate change mitigation policies. However, due to their underlying techno-economic nature and cost-optimization approach, these models typically do not feature direct measures of many socio-cultural, behavioural, and lifestyle phenomena. It is thus difficult to link model representation and scenarios of new transformations, beyond technical change, to empirical evidence—where it exists at all. Further, a detailed analysis of future transport needs for Global South countries is missing and requires greater attention given the expected increase in mobility demand owing to population and economic growth. This work seeks to address both shortcomings by improving the quantification of sustainable mobility scenarios in IAMs for the Global South, with a focus on the South Asian region. We review existing literature to identify quantified causal relationships between passenger mobility and phenomena, and map each phenomenon to exogenous parameters of an IAM, MESSAGEix-Transport. We utilize rich transport data (Indian Census 2011) to develop and calibrate a passenger mobility demand model for the whole of South Asia. Alternate future outcomes for each phenomenon are parameterized from existing literature, prioritizing evidence from Global South cities, countries, and regions. Finally, we develop scenario narratives based on alternate visions of mobility futures consisting of various outcomes for sets of phenomena and establish interactions to produce IAM parametrizations to test our framework. Through these methods, we link detailed transport data to IAM scenarios. The relative richness of the data set allows replacing top-down calculations often encountered in IAM scenarios. Since the developed scenarios are based on evidence and data specifically from South Asia, they better capture

actual potential mitigation in the region. [1]

Keywords: Integrated Assessment Model, passenger mobility, Global South, demand side mitigation, decarbonization scenarios

6.1 Introduction

6.1.1 Motivation

Integrated Assessment Models (IAMs) and Energy Systems Optimisation Model (ESOMs) are integral to informing climate change mitigation policies and exploring different emissions pathways. However, these models have been critiqued for their techno-economic nature and limited representation of demand side mitigation options (Stoddard et al., 2021; Creutzig et al., 2018). In these models, energy systems decarbonisation is often driven by technological change, such as energy end-use electrification via renewables or efficiency improvements (Fragkos et al., 2021). Bottom-up IAMs and ESOMs are developed to explicitly represent efficiency improvements and technology or fuel substitution endogenously, and so are well-suited to study these phenomena. On the other hand, qualitative (societal, cultural, behavioural) and structural (infrastructure and economy) drivers of greenhouse gas (GHG) emissions that are less easily quantifiable are not well represented (Stoddard et al., 2021). In particular, exogenous parameters in these models generally do not include direct measures of many socio-cultural, behavioural, and lifestyle phenomena—even where such quantification are well-established in the literature, and certainly where not (Yeh et al., 2022). Consequently, modellers are limited to tuning the exogenous parameters that *are* captured, using different values across multiple scenarios to capture the assumed impact of such phenomena, even if only distantly related (Berg et al., 2019; Van Soest et al., 2019; Creutzig et al., 2022b).

Further, the modelled scenarios are generally aggregated and lack spatial granularity or resolution below large regions. Technology uptake rates, policies to promote sustainable development and the costs and benefits of energy transition are spatially uneven (Schippl et al., 2020; Golubchikov et al., 2020; Yenneti et al., 2016). Global- and national-level scenarios often do not—or can not—include regional disparities explicitly (Fragkos et al., 2021). This limits the ability to model and analyse regional inequalities in access to energy services and infrastructure, region-specific polices, barriers, costs, etc. in an IAM or ESOM

[1] Working paper: Gaur, A., Javaid, A., Kishimoto, P., and Daly, H., (in preparation). Mobility scenarios for the Global South: Developing an evidence-based framework for a large-scale IAM. In preparation for submission to Transportation Research Part D: Transport and Environment.

framework.

The introduction of new transformations in energy services (novel services, disruptive technology, etc.) in these scenarios is typically not well-connected to empirical evidence. Also, most of the narratives underlying these scenarios assume that a certain phenomenon or causal relationship established in a specific part of the world will have similar impacts across all regions. For instance, the Global North has followed a pattern of increasing private car ownership with rising incomes, and global scenarios such as Grubler et al. (2018) and Kuhnhenn et al. (2020) assume that a similar phenomenon will occur in the Global South as well. Further, the narratives also lack a consideration of the short-run response versus long-run lock-in effects of phenomena or disruptive technologies. For instance, services like app-based ride hailing may improve access to mobility in the short run, while in the long-run lead to increase in congestion and a shift away from non-motorized transport (NMT) and public transport (PT) (Tirachini, 2020).

The transport sector accounted for about 30% of total global final energy consumption in 2019 and is a bottleneck in meeting climate change mitigation targets (IEA, 2023). The electrification of the transport fleet is likely to reduce GHG emissions from this sector. However, the pace and scale of electrification needed to achieve net-zero targets will be difficult to achieve or sustain, given current trends (Gaur et al., 2022b). Even if net-zero targets are met, cumulative emissions from past and ongoing activities can still pose challenges to limiting global temperature rise. Further, the additional electricity demand arising from electrification will challenge the pace of grid decarbonisation (Winkler et al., 2023). Moreover, the growth in car-oriented mobility has negative consequences in the Global North for health, air quality, and community connection (Gaur et al., 2024). Hence, there is a need to consider additional solutions, beyond supply-side and mitigation measures which focus solely on switching technologies or fuels, that can reduce emissions from this sector. In particular, these may include: a shift towards NMT and PT, reducing travel distances, discouraging private car ownership, compact development and more.

Policies and measures to reduce emissions from the transport sector have either proved to be ineffective or progressing at a pace insufficient to meet climate targets. A key contributing factor is the limited depth of exploration in understanding the drivers of demand within this sector (Lamb et al., 2021). Further, as mobility patterns and transport technologies evolve, there is a mutual impact which may invalidate the extrapolation of historical mobility patterns (Daniels et al., 2022). It is therefore important to increase the sophistication of travel demand projections and include the impact of ongoing innovations, policy interventions and feedback effects (Yeh et al., 2022; Daniels et al., 2022; Briand et al., 2023).

While the evidence to support additional demand-focused measures in the transport system is strong, climate mitigation in IAMs and ESOMs is primarily achieved through reduced energy intensity and fuel switches. This indicates a need to improve modelling techniques to include the role of various phenomena that could impact mobility patterns, especially in urban areas (Edelenbosch et al., 2017). There have been some improvements in the representation of consumer behaviour and lifestyle patterns in IAMs and ESOMs, to simulate a broader vision of alternative mobility scenarios (Luh et al., 2022; McCollum et al., 2017). The most common approaches are: representing mobility behaviours endogenously within these models, coupling a behavioural model with an energy systems model and developing exogenous narratives based on several assumptions (Luh et al., 2022; Trutnevyte et al., 2019).

For example, Sluisveld et al. (2016) include measures intended to lower passenger activity (reduced vehicle use and shift to public transport) within the IMAGE IAM and conclude that structural changes in mobility could reduce emissions by 35% by 2050, compared to the 'Baseline'. McCollum et al. (2017) incorporate vehicle purchase decision in a global IAM, MESSAGE-Transport and find that this inclusion leads to significant changes in the portfolio of light duty vehicles and cumulative CO_2 emissions. The default mobility trend in IAMs and ESOMs is typically based on measured causal relationships such as increasing passenger transport activity with rising incomes, while alternate futures in these models are usually represented through scenarios (Trutnevyte et al., 2019). Examples include: 'Low Energy Demand' scenario by Grubler et al. (2018), implementation of the shared socioeconomic pathways (SSPs) by Bauer et al. (2017) and a comprehensive exploration such scenarios is available in the Intergovernmental Panel on Climate Change's (IPCC) Assessment Report 6 (AR6) (Creutzig et al., 2022b; Jaramillo et al., 2022).

The majority of the limitations associated with modelling mobility within IAMs and ESOMs discussed above focus on Global North context, where demand reduction is being recognised as a major decarbonisation strategy (McGarry et al., 2024; Grubler et al., 2018). The Global South, on the other hand, continues to experience higher population and economic growth leading to an expansion of their energy systems. Despite this growth, access to energy services remains disproportionately low in many of these regions. As a result, the relevance of low energy demand scenarios in these countries might seem paradoxical. Since more than 80% of the global population resides in Global South countries, these countries are going to play a pivotal role in shaping the future GHG emissions trajectory and determining the feasibility of achieving the Paris Agreement goals. However, currently the representation of Global South countries in large-scale global IAMs is oversimplified, relying on stylised assumptions that

presume a developmental trajectory similar to that observed in the Global North. Further, Creutzig et al. (2024) highlight the dearth of studies focusing on Global South context that explore how access and service-provision can be improved in these regions at lower emissions. While considerable attention has been directed toward addressing energy access and fuel poverty in households, exemplified by a Sustainable Development Goal (SDG) dedicated to universal household energy access, mobility as a form of energy access is understudied in the literature.

In light of the need to improve the representation of mobility scenarios for Global South regions in large-scale IAMs, the aim of this research is twofold: Firstly, to improve the quantification of sustainable mobility scenarios in IAMs for the Global South to avoid biases arising from reliance on data, literature, and particular phenomena from the Global North. Secondly, to improve the representation of demand-side mitigation options and associated behavioural, lifestyle and socio-cultural phenomena corresponding to the passenger transport sector within an IAM framework, MESSAGEix-Transport. To achieve these aims, we develop a passenger mobility demand model with configurable dimensions to depict the causal relationships between observed phenomena and mobility patterns, as documented in existing literature. In the process, a detailed passenger mobility data set is linked to IAM scenarios.

We take South Asian countries as a case-study to develop and test our modelling framework, at a relatively high spatial resolution. We examine the unique challenges related to passenger mobility that South Asian countries face and elaborate on the significance of this region-specific analysis in 6.1.2. Our overall approach is discussed in 6.1.3. Section 6.2 reviews the existing literature on passenger mobility related phenomena followed by Section 6.3 that describes the methodology developed to represent these phenomena in MESSAGEix-Transport. We present the passenger mobility demand model in Section 6.4. The sustainable mobility scenarios developed for South Asia are discussed in Section 6.5. Finally, the results and, discussion and conclusions are outlined in Sections 6.6 and 6.7 respectively.

6.1.2 Why South Asia?

South Asian countries (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka) account for approximately one-fourth of the global population; about 36.6% live in urban areas. Economic and population growth along with increasing urbanization rates have driven a continuous increase in demand for mobility (passenger and goods) in these countries. These drivers are likely to continue in the region, inevitably leading to increase in demand for mobility and—without intervention—GHG emissions (ITF, 2022). Since

investment in infrastructure has long-term lock-in effects, choices made in the near term will determine energy service demands and therefore climate mitigation options and trajectories in the coming century. At this stage, South Asia *could* leverage green growth policies and technologies to leapfrog the car dependency and emission intensive mobility patterns often observed in the Global North, towards a more sustainable development pathway (Herman, 2021). Currently, there is a lack of coherent data and detailed literature on the passenger transport sector of these countries, which leads to embedded assumptions with global models that the mobility patterns of Global North countries will play out in Global South countries (Herman, 2021).

There are several challenges in achieving sustainable mobility development in South Asia. Firstly, cities are facing rising sprawl with growing population (Kamble et al., 2021; Jain et al., 2019). In most cases, lower income households are forced to live in suburban areas or peripheral settlements, further increasing travel distances (Chaudhry et al., 2023; Hamiduddin, 2023). The longer distances decrease access to employment, healthcare, education, etc., a challenge which is compounded by inability to afford mobility services (IEA, 2021). Secondly, rising income levels and the lack of PT infrastructure have led to increasing vehicle ownership rates (2-wheelers and private cars). This has not only caused a continuous increase in GHG emissions from the transport sector, but has also led to poor air quality and congestion in urban areas (Ellis et al., 2015; Badami et al., 2013). Finally, NMT modes are generally unsafe to use due to lack of supporting infrastructure (IEA, 2021).

Previous studies have tried to address the above challenges in modelling frameworks. By developing a deep decarbonisation scenario for passenger transport for emerging economies (Brazil, India, Indonesia, and South Africa), Briand et al. (2023) find that reaching carbon neutrality would require more than 50% reductions in emissions per passenger distance travelled (PDT). This would require pursuing a wide range of mitigation options including the use of NMT and integrated urban land-use development to curb car use and improve the provision of public transport. Travel demand projection scenarios for India project a 200-540% increase in CO_2 by 2050, highlighting that existing policy targets are likely to be insufficient to reduce, or even stabilise, emissions (Cazzola et al., 2021). Both these studies also emphasize that a lack of data in developing countries limits detailed analysis of mobility patterns. In this study, we aim to address this deficit by developing sustainable mobility scenarios for South Asia by using data and evidence from the region such that the developed scenarios align with actual potential mitigation in the region.

6.1.3 Overview of approach and key contributions

Passenger mobility, encompassing factors like travel distance and mode choice, is influenced by a combination of factors, which we term "phenomena". These phenomena include socioeconomic conditions, behavioural and lifestyle choices, the availability and advancement of infrastructure and technologies, and policy measures. Representing the complex interactions between these phenomena in an IAM is challenging, in part because the phenomena driving demand in such models are aggregated and not distinctly represented.

In this study we develop a framework to effectively represent various passenger mobility related phenomena using exogenous parameters of an IAM as shown in Figure 6.1. We first examine existing literature that explores causal relationships between various phenomena and passenger mobility patterns. Each identified phenomenon is systemically categorised and mapped to exogenous parameters of an IAM, MESSAGEix-Transport. This mapping allows the effects of each phenomenon on passenger mobility patterns to be captured and provides a method for representing these effects using an IAM.

Each phenomenon has the potential to influence multiple parameters of the IAM. To encapsulate all these influences, we individually include each phenomenon with all the parameters it is capable of influencing and parameterize them using empirical evidence from literature, with a priority given to evidence from the Global South. It is possible to define multiple trajectories for each phenomenon to visualise a range of potential mobility futures. In the next step, we utilise rich transport data (Indian Census 2011 and intercity travel) to develop and calibrate our model of passenger mobility demand for the whole of South Asia considering the differences between other countries and India. This step establishes a link between region-specific data to a global IAM.

Finally, we develop four scenarios for passenger mobility based on alternate visions for mobility futures in South Asia. In each scenario, alternate outcomes for multiple phenomena influence the same IAM parameter. Hence we establish interactions among these phenomena to produce IAM parameter data.

In summary, our primary contributions include: Firstly, we conduct a review of mobility-related phenomena, placing an emphasis on literature focusing on South Asia and the Global South. Secondly, we incorporate these phenomena into a novel mobility projection model designed to interface with an IAM. This is an innovative and adaptable framework, that can be applied to other Global South regions and IAMs. And, thirdly, we develop four distinct mobility scenarios using this model, each reflecting alternate visions for mobility based on explicit futures for these phenomena.

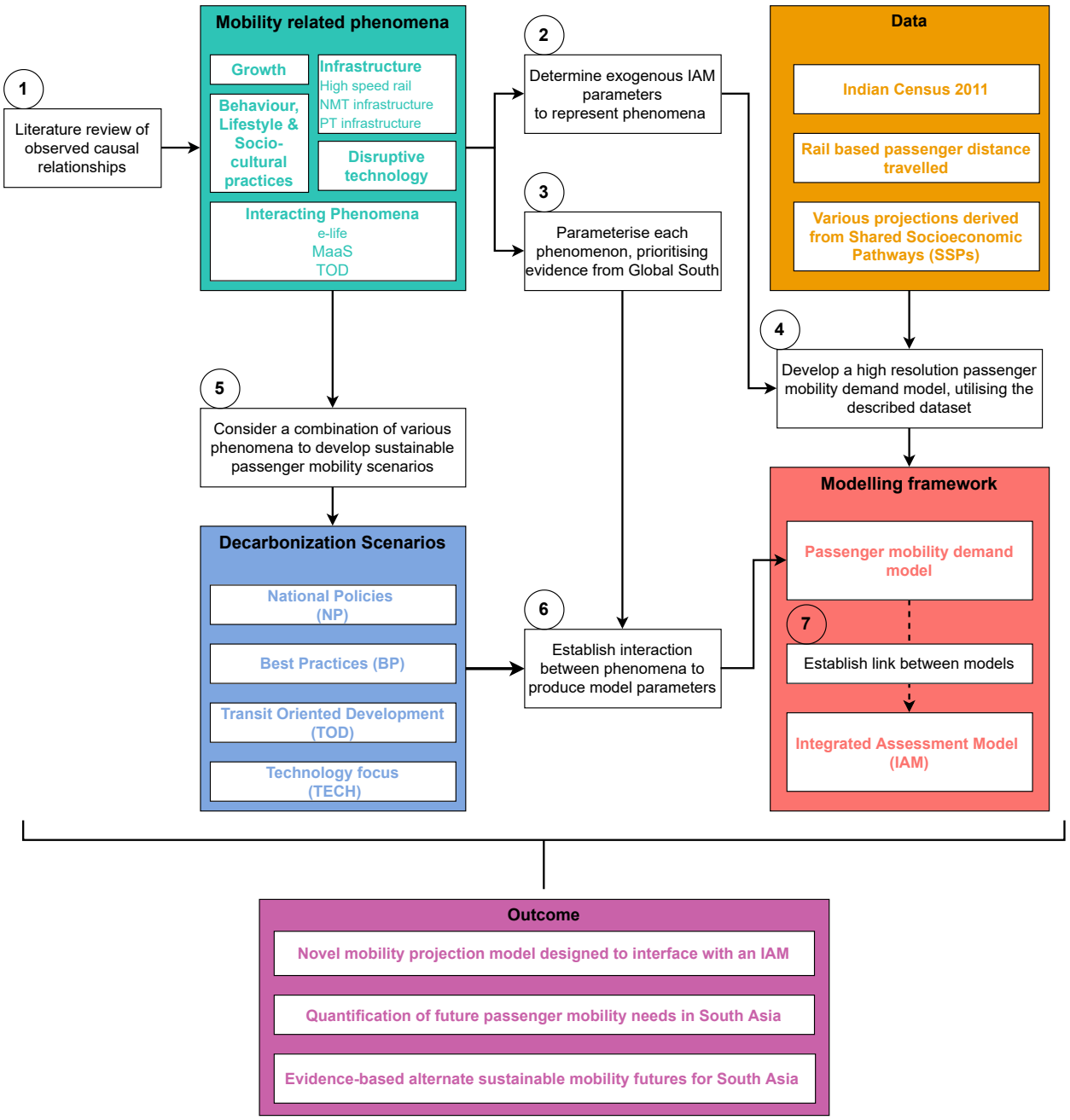


Figure 6.1: Overall workflow of approach describing various steps involved (dotted arrow line indicates future work- Step 7)

6.2 Mobility related phenomena relevant to Global South

This section describes the phenomena captured in the literature review, grouped into several categories that are not mutually exclusive.

6.2.1 Growth and development

The main phenomena that influence growth associated with passenger mobility demand and emissions are population growth, economic growth, and urbanization. As discussed previously, population and economic growth are projected to continue in the Global South until mid century, inevitably leading to the expansion of the transport, energy and economic systems. However, a phenomenon like urbanization has different impacts in the short- versus long-run. In the short-run, urbanization in developing countries leads to increased CO_2 emissions and road transport energy use (Sikder et al., 2022; Poumanyvong et al., 2012). This is due to an increase in income and greater access to technology and services. In the long run, however, higher urban density can reduce mobility demand due to lower travel distances: doubling density could reduce mobility demand by 10-12% in India (Ahmad et al., 2016).

6.2.2 Infrastructure

Infrastructure development, whether public transport or spatial settlement patterns, has significant lock-in effects. The Global South is yet to build a major part of its infrastructure, and hence has a wide range of possibilities to ensure development is sustainable. For example, Vasudevan et al. (2021) find that high quality public transit system development could decrease 2-wheeler ownership in India. Similarly, it is estimated that 35-45% of trips shorter than 5km can be made by NMT modes, which are otherwise made by motorised vehicles (not including cars), when appropriate infrastructure is developed in a large Indian city like Pune (Jain et al., 2010). Further, improving NMT infrastructure is crucial for maintaining the current mode shares of NMT and PT in Indian cities (Tiwari et al., 2016). A case study of two medium-sized Indian cities shows that maximum CO_2 emissions reduction can be achieved when both, NMT and PT infrastructure are developed (Tiwari et al., 2016).

6.2.3 Disruptive technology

Digital technologies can significantly alter mobility patterns, associated transport energy demand, GHG emission trajectories and climate change mitigation options (Noussan et al., 2020; Creutzig et al., 2019). There are many related sub-phenomena, each with distinct and sometimes countervailing impacts. Remote working and online shopping (e-life) can reduce passenger trips, consequently reducing energy consumption and emissions (Zhang et al., 2021a). In contrast, on-demand mobility services like ride hailing are found to increase VDT, have lower occupancy in general and lead to greater traffic congestion in big cities

(Bekka et al., 2020; Henao et al., 2019; Tirachini et al., 2020). Such services have led to a shift away from NMT and PT, and can induce car-based travel (Cazzola et al., 2021; Souza Silva et al., 2018). Ride-sharing can, however, reduce VDT and traffic externatlities like congestion and pollution, and bring environmental benefits (Cai et al., 2019; Chen et al., 2021; Caulfield, 2009). Ride-sharing is expected to decrease CO_2 emissions in the short-term, but substantial rebound mechanisms can be expected in the long-run, through mode switch to cars, and increased travel distances as improved access to mobility service could encourage relocation to suburbs, etc. (Yin et al., 2018).

Autonomous vehicle (AV) have been highlighted for their potential to revolutionise the transport system (Bösch et al., 2018; Millard-Ball, 2019; Meyer et al., 2017). Under some scenarios of deployment, they could increase access to mobility for some (children, elderly, disabled, etc.), reduce private car ownership and increase opportunities to pedestrianise urban centres but on the other hand increase VDT, urban sprawl and a shift away from PT.

6.2.4 Behavioural, lifestyle & socio-cultural practices

Behavioural, lifestyle and socio-cultural practices significantly impact the choices individuals make regarding how they travel. Behavioural changes are specific, short-term travel decisions whereas lifestyle changes are typically broader and more permanent decisions (Van Acker et al., 2016). The evolution of these elements in the future can affect various elements of the transport energy system, urban planning, infrastructure development and emissions.

Environmental awareness can significantly impact travel behaviour (Mandić et al., 2023). For a case study in Delhi, Gupta et al. (2022) find that people with pro-environmental attitudes are likely to use shared mobility and PT for their travel needs, and are willing to reduce private car dependency. Soto et al. (2021) recommend the use of marketing campaigns and financial incentives to encourage people with environmental concerns to shift to sustainable modes.

Socio-cultural norms such as viewing private vehicle ownership as a status symbol are prevalent in Global South countries (Pojani et al., 2018; Chaudhry et al., 2023). While strategies aimed at increasing environmental awareness have been successful in reducing car ownership, the existing evidence primarily pertains to developed countries where such ownership is at or near saturation (Pojani et al., 2018). A shift to low-carbon modes in Global South cities would require addressing safety concerns, enhancing social influence and raising the symbolic profile of PT, along with developing appropriate infrastructure (Javaid et al., 2020; Ashmore et al., 2019). Embracing changes in lifestyle patterns like work-from-home and

online shopping ("Tele-X") can be used to further manage transport demand in large Global South cities (Jamal et al., 2021).

6.2.5 Interacting phenomena

Some transport phenomena are *complex* in that they involve (deliberate or emergent) interaction of multiple types of changes in multiple aspects of the system, giving rise to combined effects.

Mobility as a Service (MaaS) is a novel mobility solution that can provide high accessibility by combining shared mobility services (car-sharing, bike sharing, etc. in combination with PT) and developments in information and communication technologies (ICT) (Kamargianni et al., 2016). The willingness to use MaaS and increase the use of PT was high in a survey conducted by Hasselwander et al. (2022) in Metro Manila, Philippines. However, implementation of MaaS at a large scale in Global South cities would require a different approach than those adopted in developed countries, such as offline access to MaaS platform, integration of intermediate public transport (IPT) modes and more (Hasselwander et al., 2023).

Transit oriented development (TOD) is increasingly becoming a part of sustainable urban development plans at global scale (Knowles et al., 2020; Ibraeva et al., 2020). It combines mixed-use land development and urban design with transport planning (Ibraeva et al., 2020). In Asian cities with well-established metro rail transit (MRT), TOD can reduce vehicle distance travelled (VDT) and traffic congestion, and promote PT and NMT modes (Kumar et al., 2020). Li et al. (2022) further confirm, for a case study in China, that residents in TOD areas are more likely to choose NMT or PT modes. Findings from Nakshi et al. (2021) suggest that mixed land-use policies, shorter distances to bus stops, and higher density are needed in a city like Dhaka to increase public transport accessibility.

6.3 Representing phenomena in an Integrated Assessment Model

This section describes the process of representing each phenomenon within an IAM framework. It is important to emphasise here that our approach does not involve making structural changes to the IAM itself. Instead, we develop a methodology to improve the translation and quantification of passenger mobility related phenomena into exogenous parameters of the IAM.

6.3.1 Integrated Assessment Model

IAMs are valuable tools that provide insights into techno-economic feasibility of climate targets and impact of policy interventions. MESSAGEix-GLOBIOM is one family of such models that consists of a combination of energy, economy, land-use, climate and air-pollution models at the global level (Krey et al., 2020). The representation of the transport sector in the global model is stylised. However, a technology-rich representation of the transport sector is possible and the resultant model is referred to as MESSAGEix-Transport.

6.3.2 Translating phenomena to IAM parameters

Following the comprehensive literature review that explores the causal relationships between each phenomenon and passenger mobility patterns, we now link each phenomenon to the exogenous parameters of MESSAGEix-Transport. This enables effective and distinct representation of each phenomenon in the modelling framework. The exogenous parameters of the IAM tuned in this study are: PDT, mode share, vehicle occupancy, vehicle ownership (private car and two-wheelers), and light duty vehicle (LDV) technology type. PDT in turn is driven by trip rate and trip share by distance category, which are parameters of the estimated demand model presented in the next section. Table 6.1 summarises how each phenomenon can be translated into IAM parameters based on evidence from the literature review above. We parameterize each phenomenon based on a comprehensive literature review. In doing so, we adopt a specific order of precedence: first, evidence from South Asia is prioritised. If this is not available, then evidence from Global South countries outside of South Asia is used. As a last resort, we use evidence from the Global North. This novel strategy is conceived to mitigate the prevalence of wealthy, data-rich, and heavily-studied areas in the literature, by not allowing such over-representation to skew the future outcomes envisioned and modelled for the Global South.

For each specific phenomenon, evidence for both the short-term and long-term effects is compiled. This encompasses a range of values spanning from low to high for each parameter. Table 6.2 shows how each phenomenon is parameterized, prioritising evidence from Global South. The detailed description of the modelling approach for each of these phenomena is outlined in Table B1 in the Appendix B.1.

Notably, phenomena such as AVs and MaaS exhibit novelty even in developed countries, posing challenges in measuring their impacts or observing distinct outcomes in diverse settings. To address this, we have extrapolated outcomes deemed plausible within the South Asian context.

Table 6.1: Representation of phenomenon in MESSAGEix-Transport

Category	**Phenomenon**	**Measurement**	**Parameter(s) in MESSAGEix-Transport**
Growth	Urbanisation	Share of total population	PDT
Disruptive technology	Autonomous vehicle	Mode share	PDT, vehicle ownership, share of PT
	Ride hailing	Share of taxis	PDT, share of PT and NMT, LDV occupancy
	Ride sharing	% of trips	Occupancy of LDVs (taxi)
Infrastructure	High speed rail	Share of rail	Share of rail in intercity travel
	NMT infrastructure		Mode share of NMT
	PT infrastructure		Mode share of PT, occupancy
Behaviour, Lifestyle & Socio-cultural practices	Comfort, reliability, safety		Vehicle ownership and mode shares
	Environmental awareness		Vehicle ownership, Share of LDVs, PT and NMT
	Higher standard of living		LDV ownership and use
Complex	e-life	Trip rate	PDT
	MaaS	Share of various modes	Mode share of LDVs, PT and NMT
	Transit oriented development		PDT (trip share), vehicle ownership, share of PT and NMT

The literature also indicates the contextual nature of a phenomenon like comfort, reliability, and safety. The relationship between infrastructure and individual choices becomes apparent—for example, the development of a robust public transport network fosters a sense of safety and reliability, thereby encouraging its utilization. However, the lack of it may drive individuals towards private vehicle ownership. Another illustrative example involves ride sharing with strangers—which in the Global South context can be perceived as more comfortable than other modes of transport but can also be less preferred, particularly for women (Vanderschuren et al., 2018). Consequently, they may prefer the alternative of ride hailing. However, if the option to travel with other women as co-passengers or a panic button is provided to increase the sense of safety, ride sharing could be widely adopted (Mitropoulos et al., 2021; Meshram et al., 2020). Hence, the outcome of this behavioural response is highly dependent on other phenomena (and their outcome) that are considered in tandem.

Table 6.2: Parameter values for each phenomena

Phenomenon	**Parameter**	**Value**

Table 6.2: **Continued:** Parameter values for each phenomenon

		Short-run	**Long-run**
Urbanisation	PDT	0.4% [1] to 2.3% [2]	0.2% [3] to 1.33% [4]
Autonomous vehicle (AV)	PDT	Dependent on scenario of deployment[33**]	
	Vehicle ownership		
	PT share		
Ride hailing	VDT		83.5% [24**]
	NMT share	-1% [22]	
	PT share	-5.4%[21**] to -17% [20]	-16% [30**]
	Vehicle ownership		-3% [23]
Ride sharing	VDT	-8.21% [18] to -37% [19]	
High speed rail infrastructure	Share of rail in long-distance travel		52.7% [25]
NMT infrastructure	NMT share (trips <5km)		Shift of 35% from 2-wheelers & 45% from bus [31]
PT infrastructure	PT share	Increase in share by 8% [27] to 10.6% [26]	Shift of 45% from 2-wheelers and 11.5% from cars [32]
Comfort, reliability, safety	Vehicle ownership	Context specific- dependent on other phenomena under consideration [34,35]	
	Mode shares		
Environmental awareness	EV sale share	30% [37]	60%
Higher standard of living	LDV ownership		Increase in average ownership by 63% from current level [36]
e-life	Trip rate	-19% [28]	-5% [29**]
MaaS	LDV share	Dependent on scenario of deployment	
	NMT share		
	PT share		
Transit oriented development [‡]	PDT	-0.24% [5] to -0.44% [6]	-20% [7] to -42.5% [8**]
	NMT share	0.3% [9]	17% [10**] to 30% [11]
	PT share	0.1% [12**]	12% [13] to 60% [14**]
	Vehicle ownership	No evidence of reduction in short-run[15]	-10% [16**] to -40% [17**]

[**] Global North [‡] In the short run, TOD is measured as increase in density- values correspond to 1% increase in density [1] Lv et al., 2019 [2] Hao et al., 2014 [3] Wang et al., 2019b
[4] Poumanyvong et al., 2012 [5] Ahmad et al., 2016 [6] Proque et al., 2020 [7] Chen et al., 2017
[8] Stiffler, 2011 [9] Bautista-Hernández, 2021 [10] Zamir et al., 2014 [11] Zhang et al., 2017

[12] Mattson, 2020 [13] Goel et al., 2020b [14] Mees, 2014 [15] Bansal et al., 2018; Tiwari et al., 2016
[16] Dong, 2021 [17] Nasri et al., 2014 [18] Zhu et al., 2022 [19] Chen et al., 2021 [20] Haddad et al., 2019
[21] Ngo et al., 2021 [22] Acheampong et al., 2020 [23] Ward et al., 2019 [24] Henao et al., 2019
[25] Ou et al., 2022 [26] Maluf, 2014 [27] Majid et al., 2018 [28] Kanimozhee et al., 2023
[29] Budnitz et al., 2020 [30] Diao et al., 2021 [31] Jain et al., 2010 [32] Fatima et al., 2014
[33] Moreno et al., 2018 [34] Gupta et al., 2022 [35] Jain et al., 2014 [36] Assuming national average ownership to reach current level of large cities in South Asia (Abdul-Manan et al., 2022) [37] Dixit et al., 2022

6.4 Passenger mobility demand model

This section describes the model constructed to generate IAM parameter data for passenger transport activity, based on the detailed quantities that are directly implicated in the causal relationships from the literature. The estimations of passenger distance travelled and mode shares within the model are underpinned by projections of population growth, the pace and nature of urbanization and GDP per capita. The projections of population growth, pace of urbanization and GDP are derived from the shared socioeconomic pathways (SSPs) (IIASA et al., 2024). Our framework is flexibly designed to incorporate data from any of the five SSPs. However, for the scope of the current study, we use Shared Socioeconomic Pathway 2 (SSP2). SSP2 represents middle-of-the-road development in terms of climate mitigation and adaptation challenges, and the social, economic and technological trends follow historical patterns (Fricko et al., 2017).

The development of future passenger mobility demand trajectories involves various steps. Firstly, we estimate a daily travel passenger mobility demand model, calibrated to the Indian Census 2011 (Section 6.4.1). This model is disaggregated into four area types, eight distance categories and six modes of travel. Secondly, we estimate a long distance or intercity passenger travel demand model at the national level with three modes of travel (Section 6.4.2). The framework is multidimensional, which allows for including detailed assumptions about passenger mobility trends in our future projections. Hence, in the final step, we develop future passenger mobility demand trajectories by tuning various dimensions of our framework (Section 6.4.3). We discuss some of the important outcomes of the passenger mobility demand model in Section 6.6.

The model is developed using open-source data and software (Python). The results and the code used in this version are archived on Zenodo.

6.4.1 Daily travel passenger demand model

We begin with the categorization of population between urban and rural areas. Urban regions in India are further categorized into three groups based on their population size: large cities (>3 million residents), medium cities (between 1 and 3 million), and towns (< 1 million). Comparable classification systems, albeit with distinct population thresholds, are also applied to urban areas in other countries in the South Asian region. The distribution of urban population within area types is outlined in the Appendix B.2.

A daily travel passenger demand model is estimated using data from the Indian Census 2011 (GoI, 2011). This data set includes information regarding commute travel distance ranges, share of each distance range (trip share) and the mode of travel across various regions, distinguishing between urban and rural area within each district and city. Trip rates are included for each area type from (Singh et al., 2008) and adjusted to reflect commute patterns. Commute-related journeys account for about 30% of total passenger trips (Shukla et al., 2015b). Due to lack of comprehensive data for other types of daily passenger trips, it is assumed that comparable travel patterns are exhibited across other trip categories. We calibrate/validate the model by comparing annual PDT per capita for the base year (2011) with values found in literature, finding only marginal differences (Dhar et al., 2015). The detailed model is available in the Appendix B.3.

6.4.2 Long-distance passenger travel demand model

Long-distance or intercity passenger travel demand is calculated at the national level due to lack of availability of spatial data. It is estimated that railways account for about 15% of the total intercity-city travel in India (Dhar et al., 2015). Based on this information, we estimate the total long-distance passenger distance travelled by rail and road (Ministry of Railways, 2020) in the base year. Similarly, in Pakistan, railways account for 10% of total long-distance travel (CAREC, 2021). The long distance PDT is estimated for road and rail (Government of Pakistan, 2019). Similarly, to estimate total long distance PDT in Bangladesh and Sri Lanka, we have assumed that railways account for 12% of total long distance PDT (average of India and Pakistan) (Bangladesh Railway, 2019; Knoema, 2015). The total long distance PDT per capita for Afghanistan, Nepal and Bhutan is assumed to be the average of all other countries (due to lack of data). We have assumed bus accounts for 84% of road based PDT and LDVs for the remaining. Hence, we have the total long distance PDT by mode for the base year as calculated by Equation 6.1. The details of the model are available in the

Appendix B.4.

$$PDT_base_n = \frac{PDT_{rail,n}}{Share_{rail,n}} \tag{6.1}$$

6.4.3 Projecting mobility demand using dimensionality of model

As discussed previously, the passenger mobility demand model developed in this study is based on a multidimensional data set. This allows for the simultaneous adjustment of one or more dimensions, enabling the generation and visualization of detailed and diverse future mobility scenarios. In this section, we discuss the various dimensions of the model being tuned to develop future passenger mobility demand trajectories as summarised by Figure 6.2.

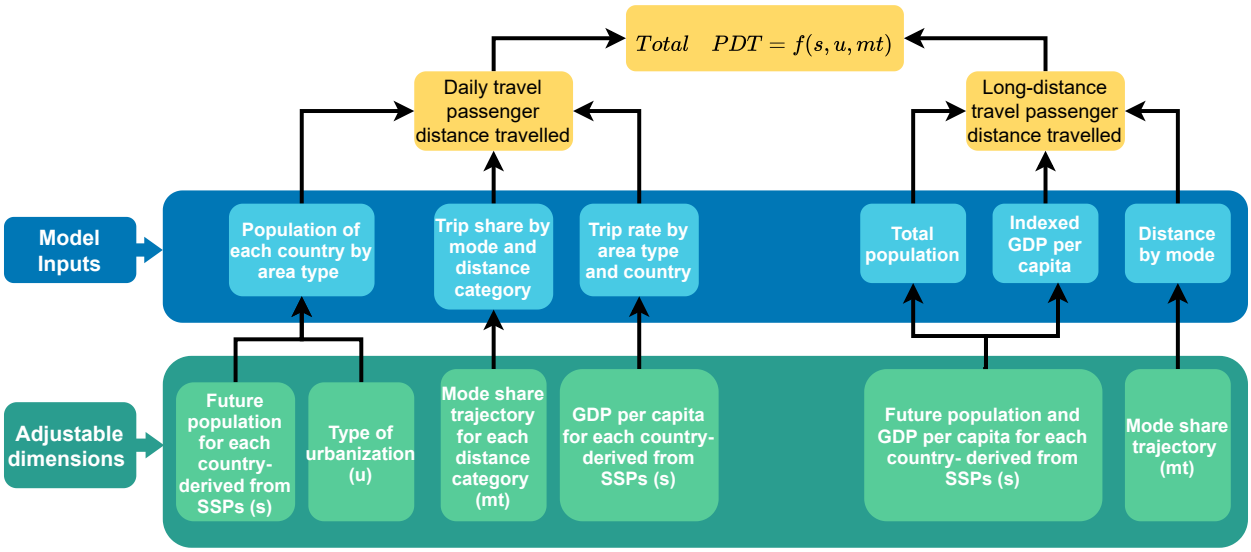


Figure 6.2: Passenger mobility demand model inputs and the adjustable dimensions

The future pace of urbanization is directly derived from the SSP projections. However, determining the nature of urbanization is more complex. The distribution of urban population among large cities, cities, and towns is referred to as the nature or type of urbanization and it plays an important role in shaping mobility patterns. The growth of population in either a city or large city has profound implications, given the differences in settlement patterns and infrastructure provision. Due to lack of comprehensive data in the South Asian region, we have assumed two distinct trajectories for the distribution of urban population that may occur in the future. A more detailed analysis of the impact of the nature of urbanization on mobility patterns is possible, and our modelling framework can accommodate multiple definitions of such trajectories. For the current study, we have defined two trajectories as follows:

- Balanced growth (Trajectory 1): Share of urban population in large cities is assumed to increase by 5% points in 2030 and 2% points in 2050. Conversely, the share in cities and towns is assumed to decrease by 2.5% points each in 2030 and 1% point each in 2050.
- Concentrated growth (Trajectory 2): Share of urban population in large cities is assumed to increase by 10% points in 2030 and 7% points in 2050. Conversely, the share in cities and towns is assumed to decrease by 5% points each in 2030 and 3.5% points each in 2050.

Trip rates in South Asia are significantly lower than those observed in developed countries (Ahern et al., 2013). Hence, we hypothesize that increased affluence within a population positively correlates with higher trip frequency along with increasing trip distances within each trip category. The future trajectories of trip rates are determined by changes in GDP per capita in each country. To project future trip rates, firstly we calculate the percentage change in GDP per capita for three time intervals: from 2011 to 2030, from 2030 to 2050, and from 2050 to 2100. Next, using Equation 6.2 we determine the future trip rates in each time interval, where the TR represents the trip rate, at refers to area type and can take values from the set {large city, city, town and rural}, s denotes the SSP scenario (1-5), the notation y_i represents the year at the beginning of the interval, while y designates the year at the end of the interval, and GDP_cap is the GDP per capita for each country n in the South Asian region. The trip rates are then interpolated to obtain trajectories, as show in Figure 6.3 which is an example of trip rates in each country for SSP2.

$$TR_{at,n,y}(s) = TR_{at,y_i} \times f(GDP_cap_{n,y}(s) - GDP_cap_{n,y_i}(s)) \tag{6.2}$$

Figure 6.4 shows the assumed changes in distance in each distance category. In the base year (2011), we assume a mean value for distance in kilometres in each trip distance category. By 2050, we project a shift towards the upper boundary of the distance interval within each respective category.

The Indian Census data reports mode share for six modes of travel, each distance category and area type. We constructed mode share trajectories for each mode as shown in Figure 6.5. These trajectories depict changes in mode shares relative to the base year of 2011. Further, the mode shares have been adjusted to ensure that these changes do not disrupt the overall level of PDT, which is primarily influenced by trip rates and distances in each trip distance category. For the scope of this study we have used the same mode share changes across all area types and distance categories. However, it is conceivable to define distinct cases

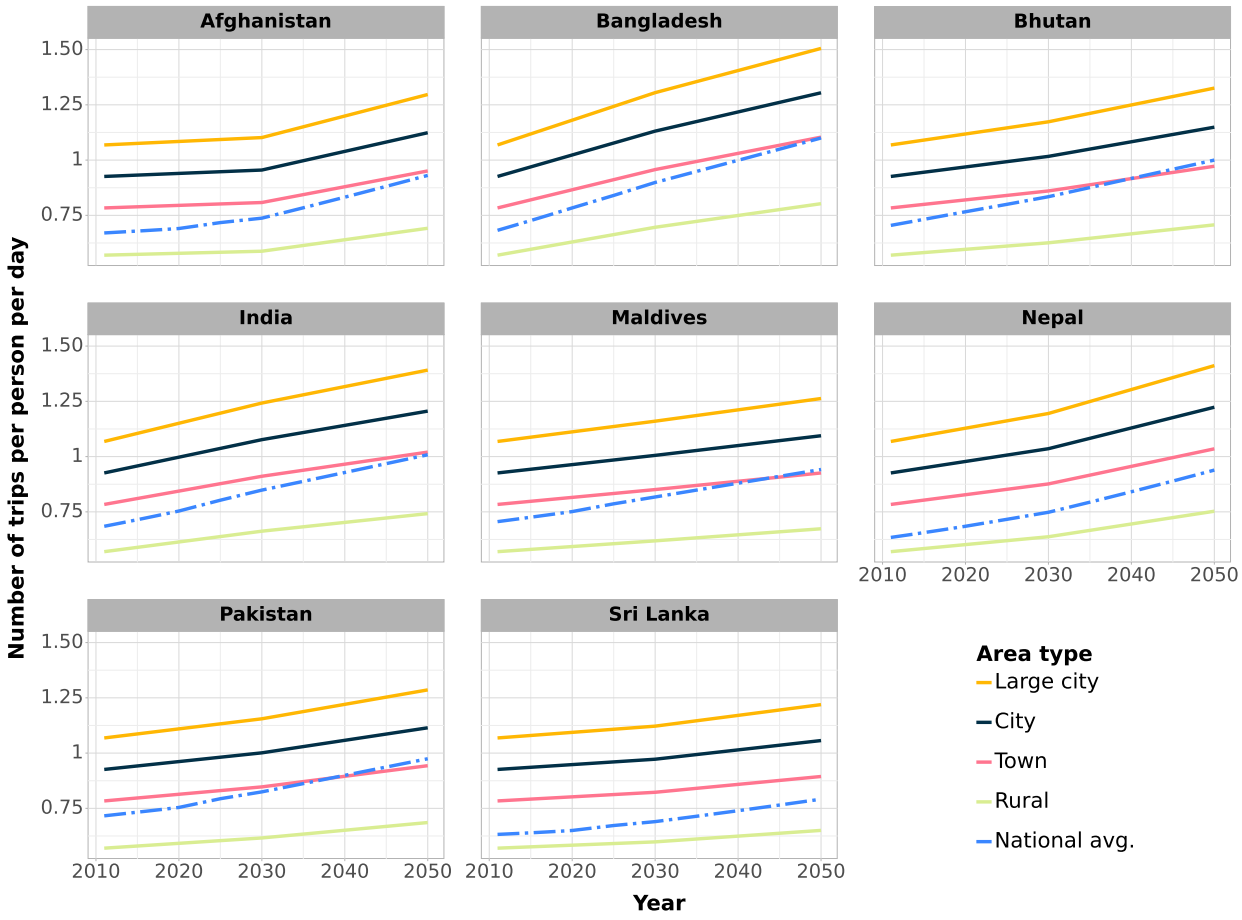


Figure 6.3: Trip rate trajectories in each country (calculated using GDP per capita values from SSP2 projections)

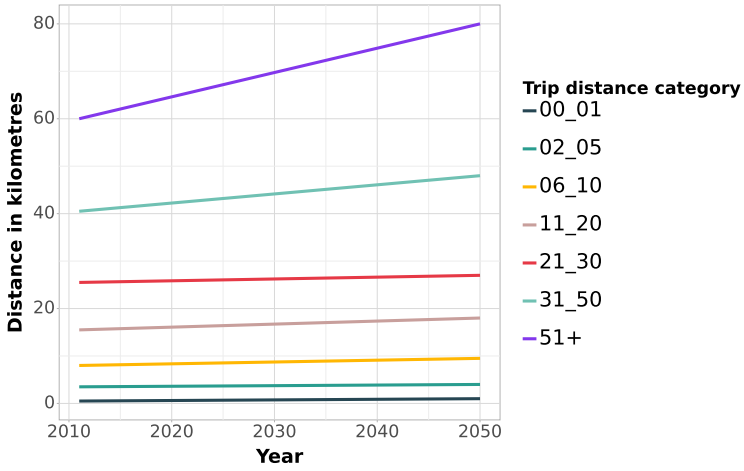
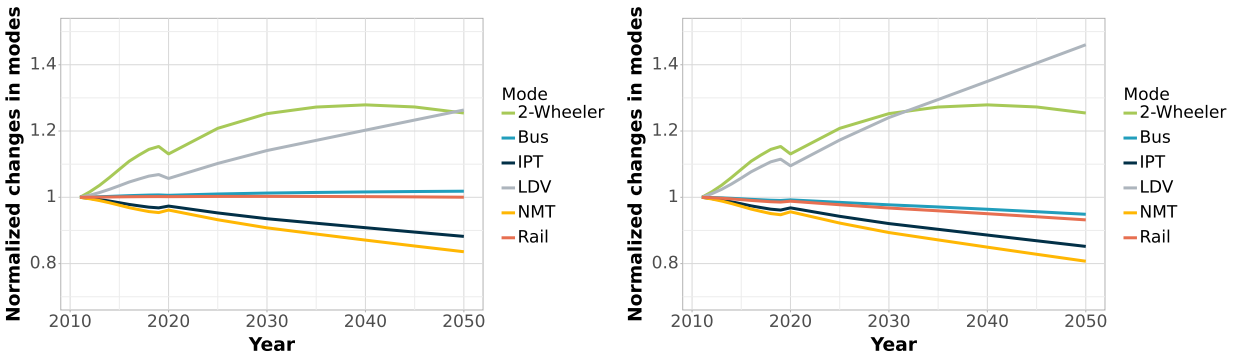


Figure 6.4: Trajectories of distance (in kilometres) in each trip distance category

for each distance category and area type to capture nuances in passenger mobility patterns. The study presents three distinct cases:

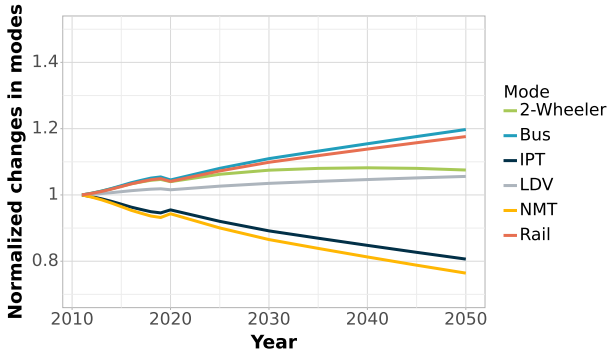
- Business as Usual (BaU): In the Business as Usual (BaU) scenario, we anticipate a shift from NMT to motorized modes (2-wheelers and cars) with increasing GDP per capita. Specifically, the share of 2-wheelers follows an inverted U-curve, with 2-wheelers' growth peaking at a GDP per capita of about $3000- $4000, after which it declines (Law et al., 2015). The growth of cars, on the other hand, follows a monotonically increasing curve with GDP per capita (Nishitateno et al., 2014). In our study, the BaU scenario assumes that the share of NMT decreases as GDP per capita rises, while the share of 2-wheelers increases until reaching $3500 GDP per capita (a consistent value assumed for all countries). The share of cars also increases, albeit at a slower rate than 2-wheelers, and the share of public transport sees a modest increase. Figure 6.5a outlines the normalized changes in modes in the BaU case.
- Car Oriented Future (COF): In the Car-oriented future scenario, we project an accelerated growth of cars compared to the BaU case. Initially, cars are expected to grow slower than 2-wheelers but will overtake the growth of 2-wheelers earlier than in the BaU scenario. The peak of 2-wheelers in this scenario is slightly lower than that considered in BaU. Additionally, public transport is anticipated to experience a modest decrease, while NMT follows the pattern as in the BaU case. This scenario reflects a potential shift towards greater car usage in South Asian countries, highlighting the need for sustainable mobility strategies to mitigate the adverse effects on traffic congestion, air quality, and overall urban livability. Figure 6.5b outlines the normalized changes in modes in the COF case.
- Sustainable Future (SF): In the Sustainable future scenario, we envision a shift towards sustainable modes of transportation, driven by greater investments in public transport infrastructure. This scenario anticipates a significant increase in the share of public transport, with buses and rail growing at a faster rate than in the BaU case. In contrast, the growth of cars and 2-wheelers is lower than in BaU, reflecting a conscious effort to prioritize sustainable modes of transport over private vehicles. Share of NMT goes down faster as compared to BaU and COF. This scenario underscores the importance of sustainable mobility strategies in South Asian countries, highlighting the potential benefits of reducing traffic congestion, improving air quality, and enhancing overall quality of life. Figure 6.5c outlines the normalized changes in modes in the SF case.

Although long-distance travel is estimated on a national scale, we align the definition of mode share trajectories for long distances as well at an aggregate level to ensure consistency



(a) Business as Usual

(b) Car oriented future



(c) Sustainable future

Figure 6.5: Changes in daily travel mode share trajectories for India (SSP2)

with daily travel. In India, the trend indicates a decrease in the share of rail-based travel and an increase in road-based travel with increasing GDP per capita (Shukla et al., 2015a). To reflect this trend, we define a monotonically increasing function of GDP per capita for LDVs and a decreasing function for rail-based travel. Additionally, we observe a modest decrease in the share of bus travel.

The future daily travel PDT is projected as in Equation 6.3, where PDT is the product of trip rate (TR), derived from Equation 6.2, share of trips (TS), which is a function of the mode share trajectory (mt), in each area type for each mode and distance category, an assumed value of typical distance (D) in kilometres for each distance category as in Figure 6.4 and the population (Pop), which is a function of the SSP scenario (s) and trajectory of the type of urbanization (u), in each area type and country. Index at refers to area type and can take values from the set {large city, city, town and rural}, m represents the mode of transport and there are six distinct modes in the model as follows: {car, bus, Intermediate public transport (IPT), 2-wheelers, NMT and rail}, dc denotes trips categorised by distance and there are eight distance categories (in kilometres): {No travel, 0-1, 2-5, 6-10, 11-20, 21-30,

31-50, and 51+}, index n denotes the countries in South Asia and y denotes the year.

$$PDT_{at,dc,m,n,y}(s,u,mt) = Pop_{at,n,y}(s,u) * TS_{at,dc,m,y}(mt) * TR_{at,n,y}(s) * D_{dc} \tag{6.3}$$

The future long distance PDT is a function of GDP per capita in our model. Using the available time series data on rail-based PDT for India, Pakistan, Bangladesh, and Sri Lanka, we estimate a linear equation between GDP per capita and rail based PDT (World Bank, 2023). We use this relationship and Equation 6.4 to project future PDT which is a product of the assumed mode share trajectory (mt) denoted by $Mode$ and $f(GDP_cap_idx_{n,y}(s))$—this is the estimated linear equation between GDP per capita (for each SSP scenario s), indexed to 2011, and the historical long distance travel PDT. We assume that road-based (bus and LDV) long distance PDT follows the same relationship due to lack of data.

$$PDT_{m,n,y}(s,mt) = f(GDP_cap_idx_{n,y}(s)) \times Mode_{m,y}(mt) \tag{6.4}$$

For countries in the region where explicit time series data is lacking, long distance PDT is projected to increase with GDP per capita. Hence, total long distance PDT in these countries is the product of the total PDT in base year PDT_base derived from Equation 6.1, GDP_cap_idx which represents the GDP per capita of each country n in the year y, indexed to 2011 for each SSP scenario s and the assumed mode share trajectory denoted by $Mode$.

$$PDT_{m,n,y}(s,mt) = PDT_base_{n} \times GDP_cap_idx_{n,y}(s) \times Mode_{m,y}(mt) \tag{6.5}$$

Consequently, the cumulative passenger distance travelled becomes a dynamic function of the SSP scenario (s), trajectory of the type of urbanization (u), and the mode share trajectory (mt) as shown in Equation 6.6.

$$Total_PDT = f(s,u,mt) \quad \forall \quad at,dc,m,n,y \tag{6.6}$$

6.5 Sustainable mobility and decarbonisation scenarios

The phenomena discussed in the previous section in tandem with national policies in South Asian countries form the basis for the development of four distinct scenario narratives. The narratives contain a rich description of each phenomenon, underpinned by substantial em-

pirical evidence, primarily from South Asia and the Global South. The central theme of all the narratives is the imperative of ensuring sustainable development of passenger mobility in South Asia. The main focus lies in envisioning pathways that leapfrog traditional private car dependency while at the same time improving access to mobility for all sects of society. Each scenario is discussed below and Table 6.3 outlines the combination of phenomena considered in each scenario.

Table 6.3: Combination of phenomena considered in scenarios

Category	**Variable**	**Scenario**			
		NP [1]	**BP** [2]	**TOD** [3]	**TECH** [4]
Growth	Urbanisation	-	-	✓	-
Disruptive technology	Autonomous mobility	-	-	-	✓
	Ride hailing	-	-	-	✓
	Ride sharing	-	✓	-	✓
Infrastructure *	High speed rail	-	✓	-	-
	NMT related infrastructure	✓	✓	✓	-
	Public transport	✓	✓	✓	-
Behaviour, Lifestyle & Socio-cultural practices	Comfort, reliability, safety	✓	✓	✓	-
	Environmental awareness	✓	-	✓	-
	Higher standard of living	✓	✓	-	-
Complex	e-life or "Tele-X"	-	-	-	✓
	MaaS	-	-	-	✓
	Transit oriented development	-	-	✓	-

* Infrastructure upgrade over BaU
[1] NP- National Policies in South Asia
[2] BP- Best mobility practices in Global South
[3] TOD- Transit Oriented Development
[4] TECH- Technology focus

6.5.1 National Policies in South Asia (NP)

This scenario is founded on the set of phenomena that are named or implicated by the stated national goals, strategies, and/or policies of the countries within South Asia. In most cases, the phenomena are grounded in evidence, driven by dedicated outlines and plans for their implementation. This scenario reflects a case where policy implementation is aligned with targets and goals, resulting in sustainable progress within the passenger mobility sector. In general, the national policies across all countries in the South Asian region recognise the need for effective transport demand management to accommodate the mobility needs for a growing population and improve access to health, education, employment, etc. whilst ensuring the development in the sector is environmentally sustainable. The major passenger transport related policies in each country are as follows:

1. Afghanistan - invest in road network and PT to improve accessibility (Baligh, 2017).
2. Bangladesh - The National Integrated Multimodal Transport Policy (NIMTP) emphasises the need to reduce travel demand through better land management, develop integrated transport network and ensure pedestrian safety. The target in the Revised Strategic Transport Master Plan for Dhaka (RSTP) is to esnure 60% of share of total urban passenger transport demand is met by PT by 2030 (DTCA, 2015).
3. Bhutan - National Transport Policy 2017 recommends integrated land-use and transport planning, greater use of PT, higher road safety for urban transport, and greater inter-city connectivity to improve access (KPMG, 2017).
4. India - The main sustainable transport development related policies are summarised in NMT infrastructure, deployment of electric buses and banning vehicles in urban centres. The Green Urban Transport Scheme aims to reduce pollution by PT in cities (electrification of buses). The National Policy on Transit-Oriented Development aims to increase modal share of PT and NMT through mixed land-use development. The National E-Mobility Programme has set an ambitious target of 6-7 million electric vehicle (EV) and hybrid vehicle sales annually from 2020 onward (incentives for buyers).
5. Maldives - In-Depth Technology Needs Assessment on Transport Sector 2007 outlines the need for public and integrated transport systems, a shift towards EVs and low emissions vehicles, promote public awareness and digitalization of services (Abdulla, 2007).
6. Nepal - Key strategic issues to be addressed outlined in the National Environmentally Sustainable Transport (EST) Strategy for Nepal are: develop integrated transport system, improve NMT infrastructure, and reduce travel demand (Government of Nepal, 2018).
7. Pakistan - The objectives of the National Transport Policy are: integrated transport development, transit oriented development of urban areas, improving public transport system and NMT infrastructure (Planning Commission, 2018).
8. Sri Lanka - The objectives of this Draft National Policy on Transport In Sri Lanka 2009 are to develop public transport system, manage vehicle fleet, promote NMT modes, increase rail passengers, and ensure minimum level of mobility for rural and estate areas (Ministry of Transport, 2009).

6.5.2 Best mobility practices in Global South (BP)

This scenario is a compilation of best mobility practices observed in the Global South. The main premise of this scenario is to apply observed phenomenon from the broader Global South context to the specific context of South Asia. The similarity of socio-economic and demographic conditions in these regions renders the occurrence of such phenomena particularly more plausible than current transformations and/or policy trends taking place in Global North countries (which, again, dominate the literature). The phenomena considered

are based on successful implementation elsewhere. Notably, the development of bus rapid transit (BRT) systems in Latin American and Indian cities has proven to increase the share of PT in urban transport (Maluf, 2014; C40 Cities, 2016). Similarly, high speed rail (HSR) development in China has led to a significant modal shift from aviation to HSR for inter-city travel. Transit oriented development in Beijing resulted in 30% of all trips by NMT (Zhang et al., 2017). Shared mobility is gaining increasing popularity in South Asia.

6.5.3 Transit Oriented Development (TOD)

Amidst the expansion of urban centres in South Asia, both in population and area, this scenario is developed to understand the consequence of compact urban and transit oriented development on passenger mobility within these cities. Central to this scenario is the recognition that as cities are growing, the urban form they take will strongly shape passenger mobility in the coming decades. Embracing compact development could help steer cities away from private motorised transport towards more sustainable solutions. Combined with policy measures and infrastructure for PT and NMT, TOD can reduce travel distances and improve quality of life within urban centres. This scenario also envisages a future where urban expansion is slower compared to current predictions and local economies are regenerated to prevent rural-to-urban migration.

6.5.4 Technology focus (TECH)

This scenario encapsulates transformations in passenger mobility patterns driven by technological innovations and their widespread adoption. Disruptive technologies and electrification of transport fleet are the main drivers of this scenario. The surge of digitalization and practices like work-from-home, online shopping (e-life) further fuel this evolution in passenger mobility. Simultaneously there is heightened environmental awareness, that helps reduce intensity of passenger mobility. This scenario revolves around utilizing technology to leapfrog private vehicle dependency and usage.

6.6 Results

This section outlines the main results of our analysis. Section 6.6.1 presents the modelling outcomes of the passenger mobility demand model. It describes the outcome of the baseline of our study and is hereafter referred to as the 'Base' scenario, which is driven by population, GDP per capita and urbanization for each South Asian country. Section 6.6.2 presents

the outcomes in each sustainable mobility scenario discussed previously. It describes the interactions between various phenomena and other model parameters.

6.6.1 Outcomes of passenger mobility demand model

6.6.1.1 Passenger distance travelled

The total PDT in South Asia are projected to increase by 125-130% between 2011 and 2050, with a compound annual growth rate of about 2%, for s = SSP2 and the two trajectories assumed for u. Figure 6.6 shows the total (daily travel and long distance) PDT per capita (in kilometres) for all countries. The passenger kilometers per capita increases by 118% in Bangladesh, 113% in Nepal and 101% in Sri Lanka between 2011 and 2050. The increase in PDT per capita is above 60% in all other countries in the same time period. The increase in total PDT and PDT per capita highlights the expected expansion of the transport system in South Asia which will heavily determine the GHG emissions trajectory from this sector.

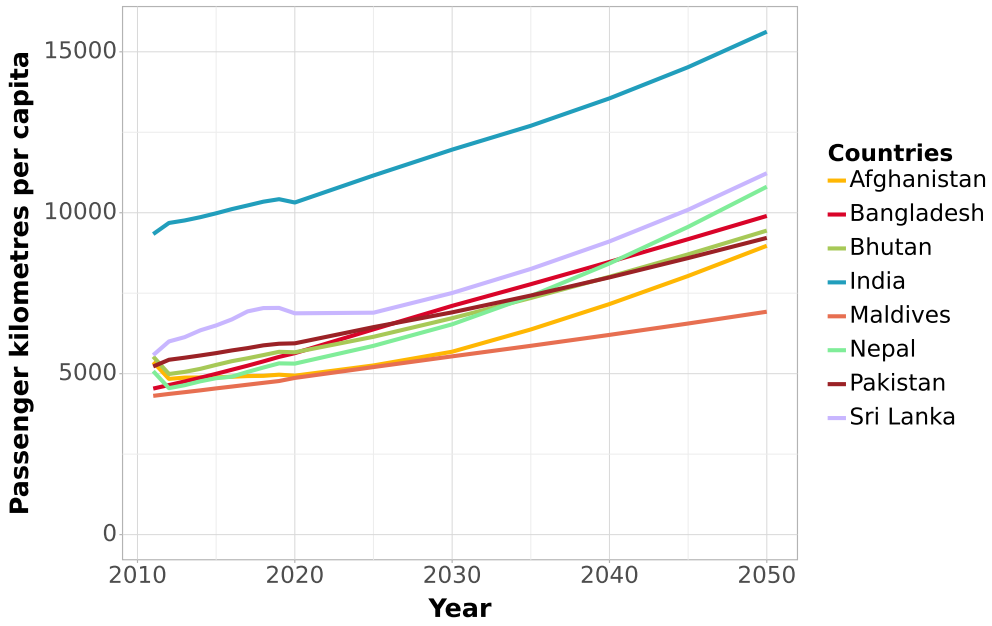


Figure 6.6: Total passenger kilometres per capita in all countries in South Asia for SSP2

Figure 6.7 shows the trends in GDP per capita and total PDT per capita in each country. The growth in mobility demand follows that of GDP, albeit at a lower rate. Bangladesh foresees a six-fold increase in GDP in 2050 relative to 2011, the highest among all countries. However, the PDT only doubles in the same time period, making the ratio of mobility demand and GDP to be the lowest at 34%. Similarly, India anticipates an increase in GDP

by 4.5 times in 2050 and PDT increases by 1.7 times, making the ratio 37%. In Bangladesh and India, while economic growth is anticipated to be robust, growth in mobility demand is anticipated to be comparatively moderate. Conversely, Sri Lanka and Afghanistan anticipate an increase in GDP by a factor of 2.4 and 3 respectively in 2050 relative to 2011. Despite the relatively lower GDP growth rates, the PDT doubles within the same time period. Hence, the ratio of PDT to GDP is 84% for Sri Lanka and 62% for Afghanistan, suggesting a strong correlation between economic growth and mobility demand. Bhutan, Maldives, Nepal and Pakistan anticipate the ratio of PDT to GDP to be between 50-55% in 2050. This indicates a moderate alignment between economic growth and mobility demand in these countries.

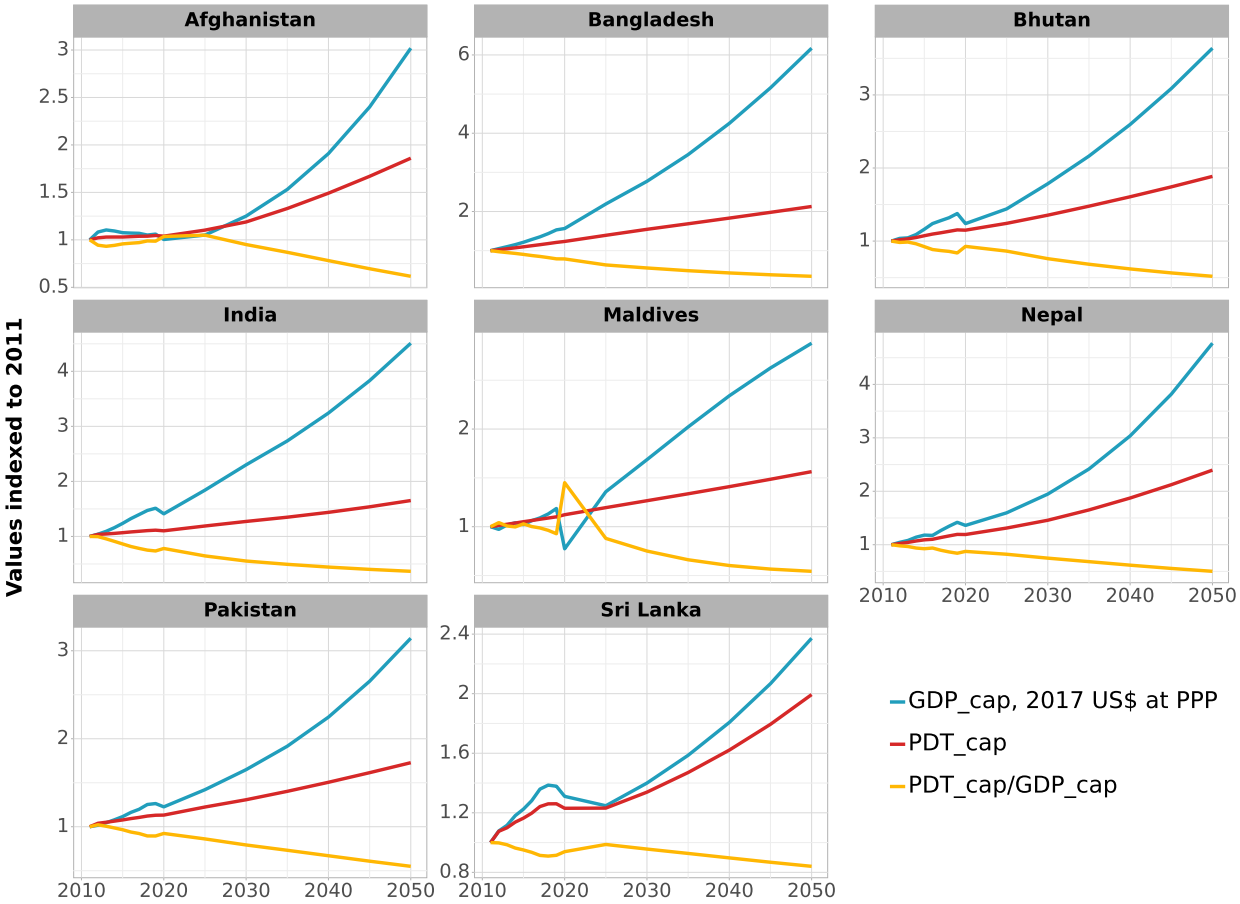


Figure 6.7: Trends in GDP per capita and PDT per capita (values indexed to 2011)

The daily travel passenger kilometres for each country and area type along with long distance travel which is calculated at national level are depicted in Figure 6.8. There is a steady increase in PDT across all countries and area types, and in the long distance travel (no long distance travel by road or rail in Maldives). In India and Sri Lanka, share of long

distance travel is substantial, whereas in other countries, daily travel accounts for most of the passenger mobility. In all countries, except Sri Lanka, most of the growth daily travel in PDT is observed in 'Large city' area type. Large cities have greater passenger mobility per person and the population is assumed to grow in this area type in the future, resulting in a much rapid increase in PDT (See section 6.4.3 for the definition of type of urbanization). PDT in rural areas is mostly constant, except in Pakistan and Afghanistan.

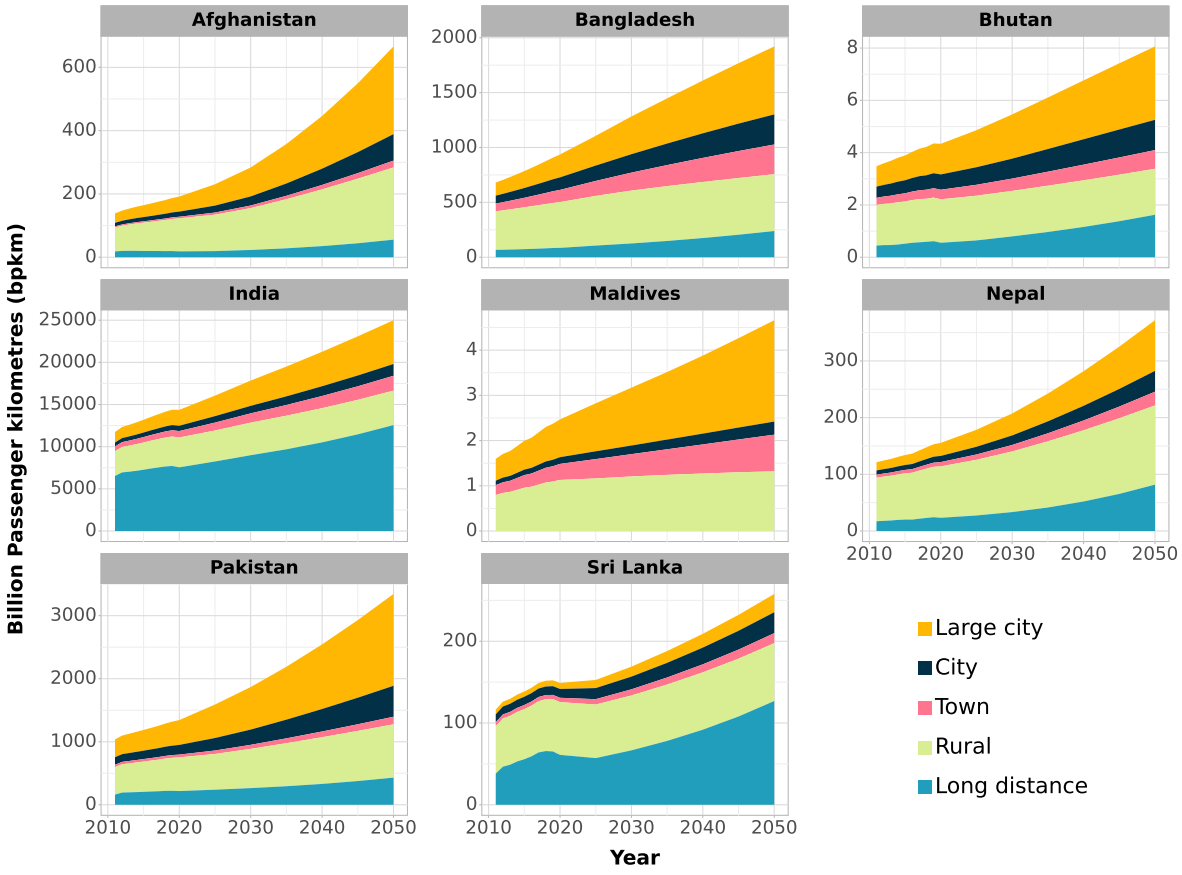


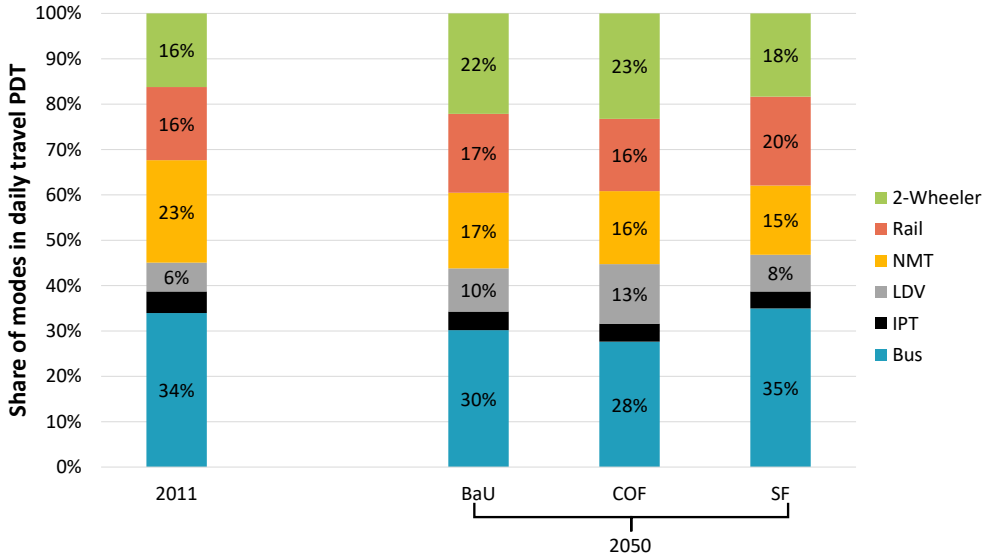
Figure 6.8: Total passenger kilometers disaggregated by area type for SSP2

6.6.1.2 Share of modes in passenger distance travelled

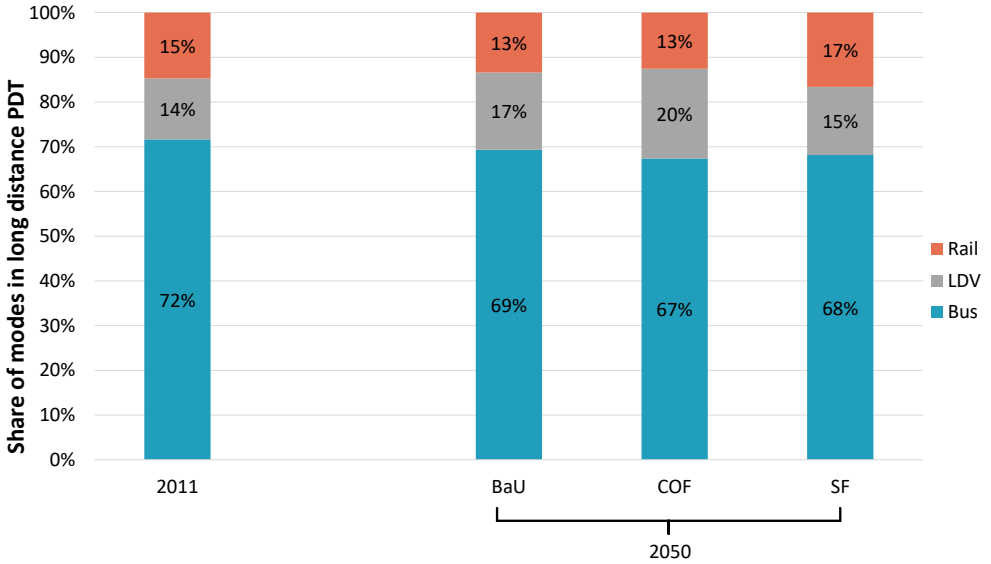
Figure 6.9a shows the resultant share of modes in daily travel PDT in the three distinct mode share trajectories (mt) in 2050. When compared to 2011, there is an increase in the share of private vehicles, LDVs and 2-wheelers in all trajectories, however, the change is modest in SF. The share of NMT declines significantly in all trajectories, by 6-8% points, relative to 2011. The share of rail increases only in SF by 4% points and remains almost the same in the other two trajectories. The share of bus declines in BaU and more significantly

in COF while increases slightly in SF.

The mode shares in long distance travel are shown in Figure 6.9b. In the BaU, share of LDVs increase by 3% points while that of bus and rail decreases by 3% and 2% points respectively. The growth of share of LDVs is much higher in COF relative to other trajectories, while share of rail only increases in SF. Share of bus declines in all trajectories, but still remains the main mode in long distance passenger travel.



(a) Daily travel



(b) Long distance travel

Figure 6.9: Resultant mode shares in all mode share trajectories defined for both travel types (SSP2)

6.6.1.3 Balanced vs concentrated development

The impact of type of urbanization in each country is shown in Figure 6.10. In the concentrated growth trajectory, PDT in large cities is higher, and lower in cities and towns relative to balanced growth, as expected from the definition of the two trajectories (and the higher amount of mobility in large cities). The overall PDT in the urban region of South Asia between 2011-2050 due to concentrated growth is approximately 13% higher than that in balanced growth. The increase in PDT by mode is as follows: bus is higher by 1.8%, rail is higher by 1.4%, LDV and rail are higher by 5% each and NMT is lower by 0.5%.

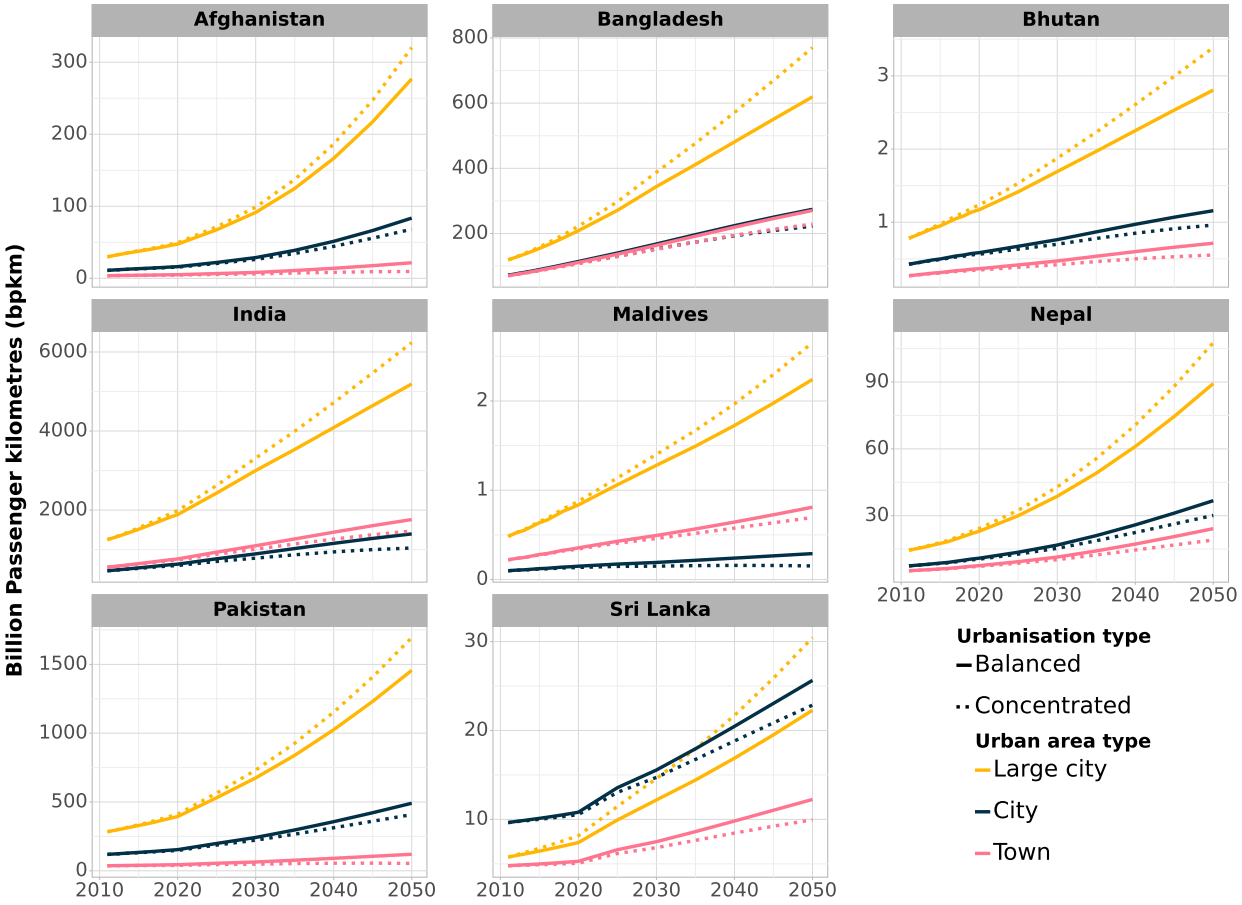


Figure 6.10: Urban PDT in each country for balanced and concentrated types of urbanization

In 2050, PDT in large cities is about 20% higher in the concentrated growth trajectory relative to balanced growth in all countries, except Sri Lanka where the difference is about 37%. Conversely, PDT in cities is about 20% lower in the concentrated trajectory in all countries except Maldives where the difference is greater than 40% and Sri Lanka where the difference is 10%. PDT in town in all countries is also about 20% lower in the concentrated

trajectory except in Afghanistan and Pakistan, where the PDT is lower than 50%.

These outcomes highlight the advantages of developing a high resolution modelling framework, adept at capturing diverse futures and modelling trends in certain contexts. The detailed modelling of distinct passenger mobility patterns across different area types along with the consideration of diverse mode composition of growth in South Asian countries will be helpful in informing and strategizing mitigation efforts for these regions.

6.6.2 Outcomes of phenomena interactions in scenarios

This section describes the results of the quantified effects of different phenomena outcomes passing through the passenger mobility demand model and how these interact with one another, whether constructively or destructively. The results are presented for the entire region in all the scenarios described above and the 'Base' scenario (without any phenomena) for SSP scenario 2 and type of urbanization trajectory 1 (balanced growth). The results discussed herein will serve as inputs to MESSAGEix-Transport in the future.

6.6.2.1 Passenger distance travelled

Figure 6.11 shows the total passenger distance travelled (in kilometres) in all the scenarios by area type and long distance travel. For daily travel, the largest increase in PDT is observed in 'large city' across all scenarios. This is attributed to increase in population combined with higher mobility (PDT per capita) in large cities as compared to other area types. Rural areas foresee the lowest increase, mainly due to lower mobility in this region and decreasing population. The NP and BP scenarios have the highest increase in PDT in all area types relative to Base. Despite penetration of MaaS (modelled as a combination of ride hailing and ride sharing services) which leads to rapid increase in LDV associated PDT from 2030 onward in the TECH scenario, the overall increase in daily travel PDT between 2011-2050 is about 2% lower than in Base. The TOD scenario foresees the lowest growth in daily travel PDT due to shorter travel distances underscoring the influence of transit oriented development in urban areas.

The long distance PDT increases at the same rate in all scenarios, except TECH due to the phenomena e-life (modelled as reduction in long distance travelled and daily travel trip rates).

The increase in PDT since 2011 exhibits notable variations across different urban typologies in each country as shown in Figure 6.12. Across all countries except Maldives, large cities witness the most substantial growth in PDT, while in Maldives, the growth in cities and

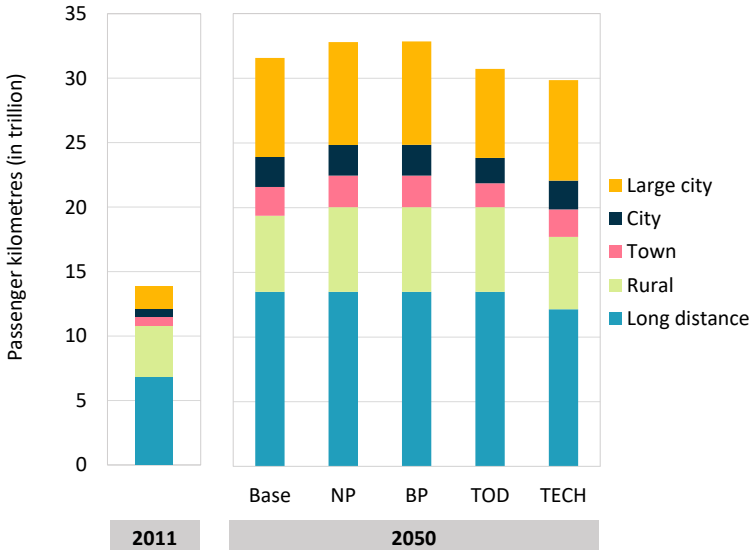


Figure 6.11: Daily travel passenger kilometres by area type and long distance travel at national level in all scenarios in 2011 and 2050

towns is comparable to that in large cities. Afghanistan observes the highest PDT increase across all urban area types and scenarios, with approximately 800% growth in large cities, 600% in cities, 500% in towns, and around 200% in rural areas. Conversely, Bhutan and Sri Lanka anticipate the lowest increase in PDT relative to 2011. Large cities in these countries foresee a growth of about 300%, cities and towns anticipate a growth of about 150%, and rural areas expect a modest increase of around 30%. In Bangladesh, India, Maldives, and Pakistan, PDT is projected to increase by about 400% in large cities and around 300% in cities. Nepal anticipates even higher growth rates, with a projected increase of about 500% in large cities and 300% in cities. Additionally, PDT in towns across these countries is expected to increase by 200-300%, while rural areas foresee a more modest increase ranging from 50% to 100%. Long distance PDT is anticipated to increase between 170-370% in all countries.

There are variations in PDT in 2050 between the scenarios as well. Both Afghanistan and Nepal anticipate a lower PDT in all scenarios relative to Base, specifically in large cities and cities. In contrast, across all other countries, the NP, BP and TECH scenarios anticipate higher PDT than Base in large cities. Similarly, this trend is observed in cities and towns within the NP and BP scenarios. However, in the TECH scenario, PDT levels are projected to be lower in cities and towns compared to the Base scenario. In all the countries, rural areas anticipate a higher PDT in all scenarios, except TECH, relative to Base.

In the NP scenario, the most significant increase in PDT relative to Base is observed in

Maldives, across all area types. Large cities anticipate a 9% higher PDT, cities 10% and towns and rural area anticipate a 14% higher PDT. In Bhutan and Sri Lanka, large cities and cities under the NP scenario are expected to have a PDT 7% higher compared to the Base scenario, while towns and rural areas anticipate increases of 12% and 13%, respectively. For Bangladesh, India, and Pakistan, the NP scenario suggests PDT increases of about 3-4% in large cities, 1-4% in cities, 8-10% in towns, and 11-12% in rural areas compared to the Base scenario.

Conversely, in Afghanistan, PDT in large cities and cities are anticipated to be lower by 1% and 3%, respectively, under the NP scenario. However, towns and rural areas expect increases of 4% and 9%, respectively. Similarly, PDT in large cities and cities in Nepal is anticipated to be lower by 4% and 6% respectively, PDT in towns and rural areas are anticipated to be 1% and 8% higher respectively relative to Base. The BP scenario anticipates comparable trends in PDT to that observed in the NP scenario, with differences of 1-2%.

In the TOD scenario, most notable reduction in PDT relative to Base is observed in Nepal. In Nepal, large cities are expected to have a lower PDT by 18%, while cities and towns anticipate reductions of 24-25%. Similarly, in Afghanistan, PDT is anticipated to decrease by 15% in large cities, and 21-22% in cities and towns. For Bangladesh, India, and Pakistan, PDT reductions relative to the Base scenario are expected to be significant, with decreases of 10-11% in large cities, 14-16% in cities, and 17-19% in towns. Finally, Bhutan, Maldives, and Sri Lanka also anticipate reductions in PDT in the TOD scenario. Large cities expect reductions of 5-7%, while cities and towns anticipate decreases of 8-12% and 12-15%, respectively.

The TECH scenario foresees minor changes in PDT relative to Base. PDT is anticipated to increase by 0-1% in large cities while there it is anticipated to decrease by 3-6% in cities, towns and rural areas. Long distance travel is anticipated to decrease by 10% across all countries in this scenario.

6.6.2.2 Share of modes in passenger distance travelled

Figure 6.13 outlines the mode shares in all the scenarios, considering different mode share trajectories and for both travel types. In the daily travel type, as compared to the Base scenario, NP, BP and TOD foresee a higher share of bus while TECH foresees a reduction. NP, BP and TOD, all consider PT infrastructure development which leads to an increase in the share of bus.

The share of LDVs and 2-wheelers is lower in NP, BP and TOD scenarios relative to Base. The decrease in the share of private vehicles in the NP and BP scenarios (despite the presence

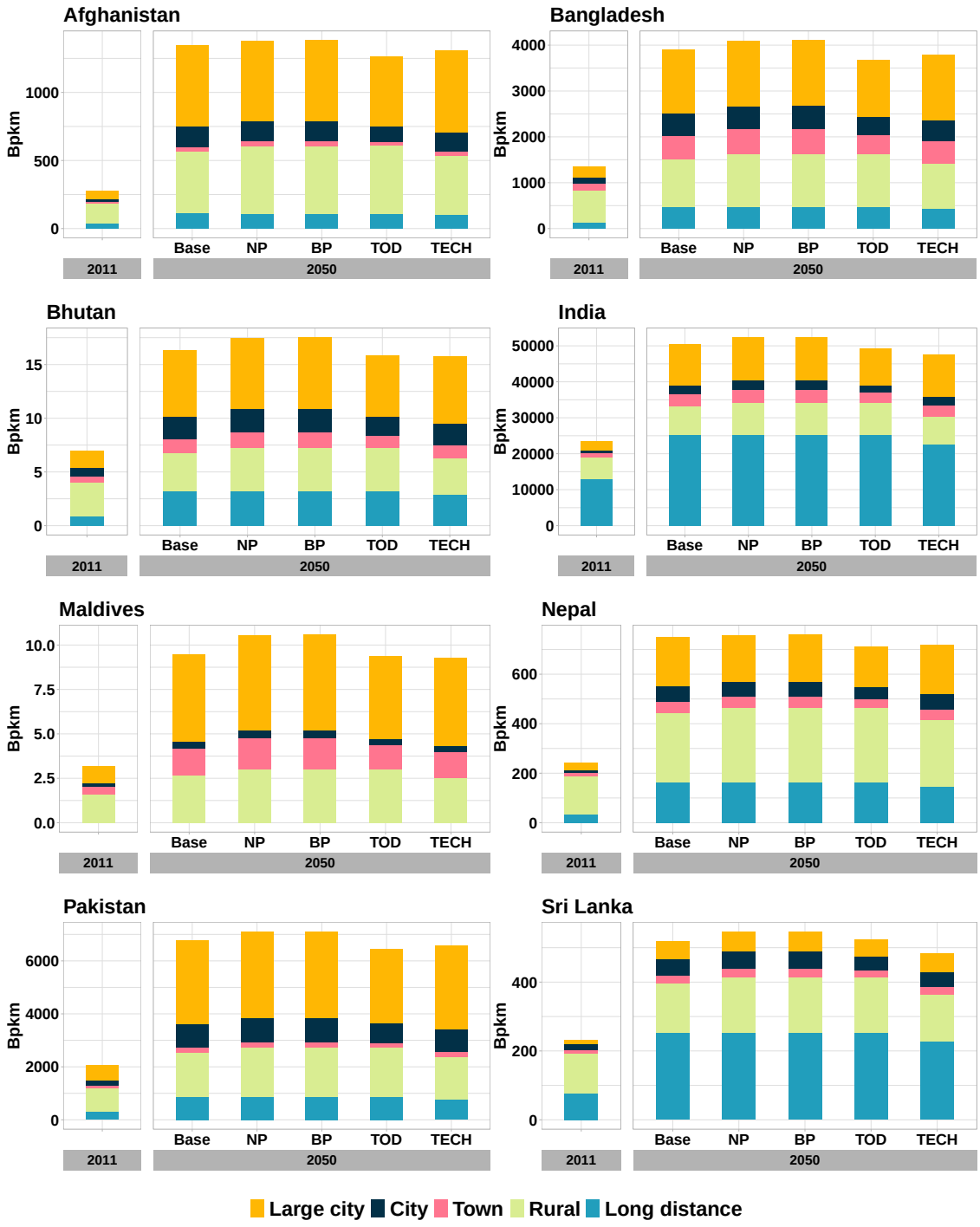


Figure 6.12: Passenger distance travelled in billion passenger kilometres (Bpkm) in every country and scenario

of ride-sharing) can be attributed to the development of PT and NMT infrastructure, which increases the share of PT and NMT (for trips <5 kilometers only) modes while encouraging a long-term shift away from private vehicles. The reduction in TOD is notably greater

due to the interaction of transit oriented development and PT and NMT infrastructure development. Transit oriented development brings about a reduction in total PDT while PT and NMT infrastructure development further reduces share of private vehicles. The TECH scenario anticipates a greater share of LDVs (about 7% points) relative to Base while the share of 2-wheelers is almost the same as in Base.

In the Base scenario, the share of bus in daily travel PDT is 3% points lower in COF and 5% points greater in SF compared to BaU trajectory while the share of LDVs is 3.6% points higher in COF and 1.6% lower in SF. Share of 2-wheelers is about the same in BaU and COF while is 4% points lower in SF relative to BaU. The share of rail is 1.4% points lower in COF and 3% points higher in SF, relative to BaU. In the NP and BP scenario, the relative differences in mode shares echo those observed in the Base scenario for buses and LDVs. However, there are deviations in SF, where the share of 2-wheelers decreases by 2.7% points, and the NMT share decreases by 2.3% points compared to BaU. In the TOD scenario, the relative differences in bus and LDV shares follow similar trajectories as observed in the Base scenario. Notably, the 2-wheeler share decreases by 2.5% points in SF compared to BaU, while the rail share drops by 1% point in COF and increases by 2% points in SF relative to BaU. In the TECH scenario, the bus share decreases by 2.8% points in COF and increases by 4.6% points in SF relative to BaU. LDVs see a substantial 5.6% point increase in COF and a 2.6% point decrease in SF. The 2-wheeler share only experiences a notable change in SF, decreasing by 3.7% points relative to BaU. Additionally, the rail share declines by 2% point in COF and rises by 3% points in SF compared to BaU.

The variation in mode shares in long distance travel across scenarios is determined by the development of high speed rail. since high speed rail development is only considered in the BP scenario, the share of rail almost quadruples relative to the Base scenario, whereas in NP, TOD and TECH scenarios, the share of rail remains the same as in the Base scenario. The share of bus and LDVs is about 40% lower in the BP scenario, relative to Base. Between mode share trajectories, in the Base, NP, TOD and TECH scenarios, share of LDVs is 2.8% points higher in COF relative to BaU and 2% points lower in SF. On the other hand, share of rail is lower by 1% in COF and higher by 3.2% points in SF relative to BaU. In BP scenario these variations are quite small (in the range of -1.5% to 1.5%).

Figure 6.14 shows the comparison of mode shares for daily travel in all countries and across all scenarios. The share of bus decreases in all countries in the Base scenario in 2050 relative to 2011. Notably, the share of bus transportation is projected to decrease in all countries by 2050 in the Base scenario relative to 2011. In Afghanistan and Nepal, this decline is substantial, with an anticipated decrease of 7% and 8% points respectively. Similarly, Bangladesh, India,



(a) Daily travel



(b) Long distance travel

Figure 6.13: Resultant mode shares in all scenarios and mode share trajectories defined for both travel types (SSP2)

and Pakistan are expected to experience a decrease of 3-4% points in bus share, while

Bhutan and Nepal are anticipated to see only a marginal 1% decline. The share of NMT is also anticipated to decline in the Base scenario relative to 2011. Bhutan, Maldives, and Sri Lanka are likely to experience a decrease of 3-5% points in NMT share, while in all other countries, this decline is projected to be steeper at 7-8% points. Conversely, the share of rail is anticipated to increase by 1-3% points in all countries, alongside a rise of 2-4% points in the share of LDVs. The share of 2-wheelers exhibits significant variation among countries. Sri Lanka is expected to see a notable increase of 17% points, followed by Afghanistan with a 13% point rise. In Bangladesh, India, and Pakistan, the increase is projected to range between 5-8% points, while in other countries, it is expected to be more moderate at around 2% points.

In the NP and BP scenarios, the share of bus exhibits a consistent increase of 9-10% points across all countries compared to the Base scenario. Conversely, there is a corresponding decrease in the share of 2-wheelers in these scenarios. Specifically, in Afghanistan and Nepal, the share of 2-wheelers in the NP and BP scenarios is 12% points lower than in the Base scenario. In Bangladesh, Bhutan, and India, this decrease amounts to 9-10% points, while in Sri Lanka, Maldives, and Pakistan, it is around 6-7% points lower. Moreover, the share of NMT experiences a rise of 2-3% points in all countries in the NP and BP scenarios, while the share of LDVs is approximately 1% point lower than in the Base scenario. The share of rail remains relatively constant across all scenarios.

In the TOD scenario, the share of of bus increases by 11-13% points, the share of LDVs is lower by 1-3% points, the share of NMT is higher by 3-4% points, and the share of 2-wheelers is lower by 7-13% in all countries relative to Base. In the TECH scenario, the most notable change is the increase in share of LDVs by 5-8% points in all countries with a comparable reduction in the share of bus relative to Base. All other modes have similar shares to that observed in Base. Comparison of mode share trajectories (BaU, COf and SF) are shown in Appendix B.5.

The scenario outcomes highlight the complex interaction between various factors, including policy interventions, infrastructure development, and technological advancements, which collectively shape the future of mobility. By understanding the nuances captured by this modelling framework, policymakers can make informed decisions to create more sustainable and accessible passenger transport systems for the future.

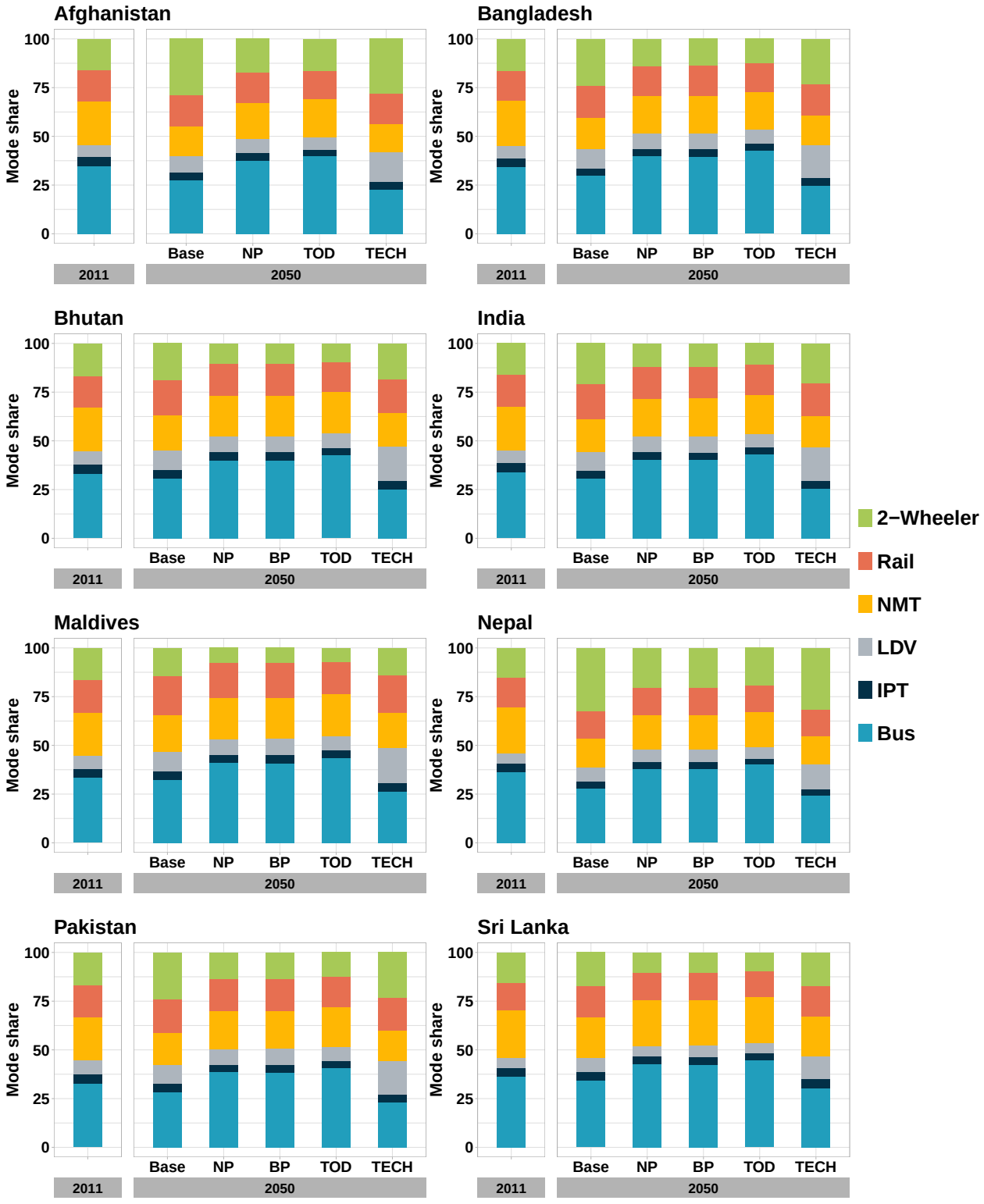


Figure 6.14: Share of modes in daily travel PDT

6.7 Discussion and conclusion

6.7.1 Key insights

The methodological approach adopted in this study is a step towards converting measured data and literature-based evidence into useful IAM inputs. We review existing literature that explores causal relationships between passenger mobility and various phenomena. These relationships are then mapped to exogenous IAM parameters such that the impacts of each phenomenon on transport activity can be effectively represented. The approach also allows including direct measures of "less quantifiable" phenomena like socio-cultural practices, behaviors and lifestyles, that significantly affect passenger mobility patterns, in a large-scale global IAM.

A detailed region-specific passenger transport data set is linked to a global IAM in this study. Thereby, the scenarios developed align with actual mitigation potential in this region. Further, the proposed scenarios are grounded in evidence from the specific region under consideration, South Asia in this case, and other Global South countries. The shared socio-cultural and demographic characteristics in these regions facilitate reasonable extrapolation of the occurrence and impacts of phenomena across them. Since the literature and data collected prioritize evidence from Global South, the methodology adopted can be applied to other Global South regions. This approach helps overcome biases arising from modelling methods and calibrations grounded in evidence from Global North, often encountered in global scenarios.

The high resolution of this framework allows modelling trends within distinct contexts and capturing distributional effects. For example, transit oriented development reduces PDT but this impact can vary between area types, large city versus town. Further, the mode shift due to TOD is not uniform across distance categories (0-1 km versus 11-20 km). Similarly, increase in ride hailing services will lead to greater PDT and share of taxis, with a simultaneous decrease in public transport use. The relative richness of the data set allows including such differential impacts of various phenomena and replacing the typical top-down calculations encountered in IAM scenarios such as in Grubler et al. (2018) and Kuhnhenn et al. (2020).

The demand model outcomes emphasise the anticipated expansion of the passenger mobility system in South Asian countries. It is estimated that the total PDT will more than double in 2050 relative to 2011. Since investment in infrastructure has long-term lock-in effects, choices made in the near-term will determine mobility demand and therefore climate mitigation

options and GHG emissions trajectory in the coming century.

The results indicate that public transport, bus and rail, are likely to be the key modes of transport in South Asia—across all scenarios and growth trajectories. This observation was similarly noted by Dixon et al. (2024) in their analysis of another emerging economy, Kenya. Conversely, the results also indicate a growing share of private vehicles in South Asia, particularly 2-wheelers. The share of private vehicles is above 25% for daily travel even in the most optimistic scenario for sustainable mode share (SF). The increase in private vehicles will further exacerbate passenger mobility associated externalities such as congestion and air pollution. Hence, improving public transport services, its safety and reliability can increase access to mobility for all and help curb forced vehicle ownership, particularly for low income households. This development will also help manage growing mobility demand, especially in urban areas.

The scenario outcomes highlight the effect of interaction between various phenomena and model parameters such as the mode share trajectories. These results show that the combination of PDT and mode shares will lead to different cumulative emissions from the transport sector in each of these scenarios. For example, TECH scenario projects lowest PDT relative to others, however it has the highest share of LDVs, indicating the prevalence of less sustainable development if LDV electrification does not keep pace with PDT growth. Conversely, NP and BP foresee greater increases in PDT compared to the Base scenario. Nonetheless, these scenarios exhibit higher proportions of sustainable modes such as buses and rail.

The scenario results also indicate that TOD will emerge as a pivotal strategy for mitigating and managing transport energy service demand in South Asian countries. Compact development will also enhance the feasibility of networked public infrastructure. However, it is essential to approach these initiatives with caution to avoid exacerbating existing urban challenges, such as overcrowding and the proliferation of informal settlements. Moreover, transport decarbonisation cannot be achieved by designing transport polices in silos but requires holistic and coherent interaction with other sectors such as land-use and urban planning (Danielis et al., 2022; Creutzig et al., 2024).

The results also highlight the regional (country level) differences captured by the modelling framework. As shown by the results discussed in Section 6.6, patterns of economic growth, urbanization rates and the type of urbanization impact the projections of demand for mobility in South Asian countries. These discrepancies underscore the complexity of mitigating emissions within different scenario and regional contexts and offer valuable guidance for policymakers and stakeholders in formulating effective mitigation strategies tailored to the

specific dynamics of each scenario and region.

6.7.2 Limitations

In this study, the national population has been categorized primarily according to area type namely, large city, city, town, and rural areas. We assume that the effects of observed phenomena have a uniform influence across the population group. However, it is imperative to acknowledge the limitation in our approach, as various socioeconomic factors such as income and family size play an important role in shaping individual and community responses to the phenomena considered herein. Furthermore, as the outcomes from the passenger mobility demand model are aggregated, the total PDT loses its various dimensions, and the meaningful differences between scenarios start to disappear. This coupled with the limited resolution of MESSAGEix-Transport, restricts the representation of specific policy measures.

Due to lack of data, we have assumed comparable travel patterns across all trip categories. However, the purpose of trip determines distance and mode of travel, and is impacted by socioeconomic factors and spatial distribution. This assumption oversimplifies some of the complexities of passenger mobility in these regions, potentially making policies less effective. Further, as the primary data set used to calibrate the daily travel demand model is from India, the regional heterogeneity between countries in travel patterns has not been adequately considered. But since India is the largest country (in terms of population and economy), the impact of not accounting for these details on the overall demand for mobility within South Asia is expected to be relatively minimal.

Our analysis lacks a consideration of domestic aviation, whose demand is increasing strongly in South Asian countries. Domestic aviation will play an important role in shaping intercity mobility patterns in these countries. Future work could expand the scenario narratives to include the dynamics of domestic aviation. Similarly, micro-mobility such as e-bikes and scooters are gaining momentum in several countries, and this phenomenon could potentially be important in South Asia in the future. However, since micro-mobility is generally used for first and last mile connection, their share in total PDT under current status of deployment is negligible and is hence not considered in this study.

The literature review and data gathering processes have highlighted the existing data gaps in South Asia and the Global South at large. We also observed considerable variability in the projections of future passenger kilometres for India, ranging from 10-32 trillion for road based travel in 2050 estimated by several other modelling groups (Paladugula et al., 2018;

Gupta et al., 2020) and the projection in this study is about 21 trillion in the 'Base' scenario. This uncertainty in projections underscores the urgent need for measured data to refine the empirical work, ensuring that scenarios and other modelling efforts align with actual regional empiricism.

Although the methodological framework developed in this study can be easily applied to other Global South contexts, its implementation is limited to the IAM under consideration. In instances where IAM parameters deviate, additional efforts maybe required for the application of this framework.

6.7.3 Future work

The future work involves converting the outputs of the described scenarios to the input parameters of MESSAGEix-Transport. This step will establish a connection between the developed framework and the IAM. The future work will also focus on the refinement and expansion of the developed scenario narratives. This enhancement will aim to provide a more comprehensive exploration of the potential outcomes of the interacting phenomena.

An integrated analysis of passenger mobility and freight could provide additional insights into the transport sector. The mobility of people and goods is interdependent, and a holistic understanding would allow for more efficient resource allocation, improved infrastructure planning and better understanding of the overall dynamics in the transport sector.

Additionally, the developed scenario narratives could be aligned with Shared Socioeconomic Pathways (SSPs), providing a more coherent and integrated framework. This will ensure the scenarios developed in this study are consistent with global narratives and projections of future socioeconomic development.

Chapter 7

Conclusions, Insights & Recommendations

7.1 Methodological contributions

The key objective of this thesis is to advance methodologies and techniques for enhancing the representation of demand-side mitigation options in ESOMs and IAMs. The modelling exercises undertaken in this research can be categorized into two overarching themes:

1. Exploration of alternate futures through scenario analysis.
2. Enhancement of scenario quantification methodologies.

In the first theme, this thesis explores the energy systems implications of alternate futures, steering away from conventional assumptions and envisioning pathways divergent from historical trends. Chapter 3 contributes to the sparse literature on LED-type scenarios at the national level. It includes energy service demand reduction and restructuring as mitigation options, and considers region-specific challenges in meeting climate goals. This chapter also highlights the additional (non-energy systems related) benefits of the LED pathway such as improving energy security through lower reliance on energy intensive services, and novel fuels and technologies. Chapter 6 presents novel passenger mobility futures for South Asian countries. By considering regional data, dynamics and policies, these scenarios envision futures where South Asian countries leapfrog traditional private car dependency, often observed in the Global North, towards a more sustainable development pathway.

These alternate futures illuminate the value of challenging ingrained assumption in ESOMs and IAMs, and embracing future outlooks that transcend historical relationships between economic development and energy consumption. This paves the way for informing policy and actualising transformative pathways that align with climate change mitigation and sustainable development aspirations.

In the second theme, the thesis explores current gaps in scenario quantification and discusses methods for addressing these gaps. Chapter 4 explores how an important mitigation lever, population density, can be parameterised in future LED type scenarios for Ireland. Using

open source Census data from 2006 and 2016 for Ireland, this chapter estimates the mathematical relationship between various energy service demands and the dispersal of population. This exercise improves the empirical basis of developing future 'Low Energy Demand' scenarios, that are heavily reliant of compact development. The outcomes of this chapter will be useful in parameterising future LED-type scenarios and provide a method to include spatial settlement patterns as a mitigation lever in ESOMs and IAMs.

Chapter 5 evaluates the impact of residential heating electrification via heat pumps, in line with government targets, on the Irish power system. This chapter extends the ENGINE model to include heat pumps as a new, spatially dispersed load. The key result of this analysis is that the spatially dispersed nature of the Irish housing stock drives the power systems investments and costs rather than the supply constraints of the power system. The chapter also highlights the interactive effect of heat and power system policies, providing evidence for future policymaking processes.

Chapter 6 introduces a novel framework that encompasses various measured concepts pertaining to passenger mobility and transforms them into meaningful IAM parameters. Through this framework, the chapter aims to bridge the gap between empirical evidence and scenarios, thereby facilitating a more nuanced understanding of sustainable mobility transitions. The scenarios developed in this chapter are based on measured data from the specific region under consideration, South Asia in this case, and other Global South countries. The shared socio-cultural and demographic characteristics in these regions facilitate reasonable extrapolation of the occurrence and impacts of phenomena across them.

By integrating empirical evidence with scenario quantification, this thesis improves informed-decision and policy making processes, and the energy transition realism within ESOMs and IAMs. Through research presented in chapters 4 and 6, this thesis develops methodologies for operationalising available data into actionable mitigation levers within an ESOM and IAM frameworks.

The prevalence of large data gaps in Global South regions emerged as a major hindrance to detailed modelling and analysis in this region. However, by highlighting these gaps and raising awareness of their significance, such modelling analyses can prompt and guide data collection initiatives in these regions.

Though the thesis contributes to methods to improve quantification, it is imperative to acknowledge that the purpose of energy transition related scenarios is not empirical exactness but qualitative insights (Krey, 2014).

7.2 Key insights: Answers to research questions

The techno-economic nature of ESOMs and IAMs limits the inclusion of many socio-cultural, behavioural and lifestyle phenomena that have significant potential in reducing GHG emissions, particularly in the residential and transport sectors (Creutzig et al., 2022c). Hence the necessity of including demand-side interventions in mainstream energy systems optimisation models is gaining traction (Creutzig et al., 2022b). Among the demand-side interventions widely discussed in the literature, ESOMs and IAMs are well able to represent efficiency improvements and technology or fuel switches endogenously (Pfenninger et al., 2014). To further enhance the representation of other demand-side mitigation measures in ESOMs and IAMs, several approaches have been considered.

Firstly, integrating demand-side mitigation options directly into the structural framework of IAMs and ESOMs can provide a more comprehensive understanding of their impact. Some examples where behavioural interventions have been included in ESOMs or IAMS are: increasing consumer heterogeneity, introducing a disutility cost or hurdle rates, and incorporating travel behaviour (McCollum et al., 2017; Aryanpur et al., 2022; Daly et al., 2014). However, this approach may introduce complexities and interactions that could potentially lead to misleading results. Secondly, soft-linking a behavioural model with an ESOM or IAM offers a way to incorporate demand-side mitigation measures without fundamentally altering the structure of these models. However, this method can significantly increase computational burdens and resources required to develop and maintain multiple models (Luh et al., 2022; Berg et al., 2019). Further, both the above methods have been used to focus on sectors in isolation in current literature, thereby failing to capture systemic interdependence.

Thirdly, a scenario-based approach has been widely used, where exogenous parameters of ESOMs and IAMs are used to represent demand-side mitigation options. The scenarios have underpinning narratives or storylines which are quantified using assumptions or measured data. Scenarios are coherent and provide a holistic view of system evolution, relatively straightforward to integrate, and can be used across multiple models. Scenarios are widely used by the IPCC to understand the effectiveness of climate change mitigation policies and the uncertainties of future (Riahi et al., 2022).

There is a wide range of scenarios available in the literature containing demand-side mitigation measures. Demand reduction measures provide a buffer against rebound effects, where efficiency improvements lead to increased energy consumption due to lower costs or increased comfort levels (Grubler et al., 2018). Measures such as retrofitting dwellings not only reduce energy and carbon intensity in residential energy service demands but also address energy

poverty. This dual benefit enhances social equity by improving living conditions for vulnerable populations while contributing to emissions reductions as observed by (Coyne et al., 2018). Reducing energy demand bring other benefits such as lower air pollution and other traffic externalities in cities, more comfortable homes and lower energy bills and health benefits by adopting a more active lifestyle. Demand reduction measures play a crucial role in achieving sustainable and resilient energy systems while meeting decarbonisation goals effectively and efficiently.

However, such scenarios in literature are often aggregated and lack underpinning empirical evidence (Grubler et al., 2018; Kuhnhenn et al., 2020; Mastrucci et al., 2023). Further, the focus on the Global South regions has been limited in global IAMs. Through a set of six research questions, this thesis presents a discussion around the importance of exploring alternative pathways that include the role of behavioural patterns, lifestyle changes, societal transitions and policy measures that impact energy service demands. It also develops methodologies to improve the granularity and empirical basis of developing such scenarios in ESOMs and IAMs. Further, it evaluates the impact of residential heating electrification policy on the national power system. Additionally, this thesis provides a comprehensive set of passenger mobility futures for South Asian countries. These scenarios are based on evidence and literature from Global South, with the aim to improve the representation of this region in a global IAM.

RQ1: What is the value of including alternate demand futures in ESOMs and IAMs?

It is being recognised that there is untapped potential on the demand side that can be harnessed to meet climate goals without over relying on supply-side technological options (Creutzig et al., 2016; Creutzig et al., 2018; Grubler et al., 2018; Sethi et al., 2020). Policies focusing on energy demand reduction are likely to increase the probability of limiting the temperature rise to 1.5°C (Méjean et al., 2019). Although low carbon technologies and energy efficiency improvements have been extensively considered in mitigation scenarios, reducing end-use service demands is a relatively new alternate pathway that can limit climate change (Kesicki et al., 2011; Grubler et al., 2018).

Chapter 3 presents an alternate energy service demand future named the Irish Low Energy Demand (ILED) scenario. This scenario includes energy service demand reduction and restructuring, for the whole energy system, as a mitigation option in TIM. This is the first instance of developing such a pathway within a national TIMES model. The research shows that including mitigation options that reduce and restructure energy service demand are more

cost-effective than relying on technological transformations. The ILED scenario broadens the mitigation options available to policymakers. It allows the inclusion of mitigation measures that are cheap thereby reducing the burden of transition on ordinary individuals. By providing details of the scenario development and maintaining an open-source version of the model and outputs, this chapter encourages other national-level modelling teams to include ILED-type scenarios in their analysis.

Chapter 6 presents a new framework that quantifies passenger mobility scenarios for South Asian countries. The representation of such Global South regions is generally oversimplified in global IAMs. Hence, considering evidence and data from the specific region is a step toward improving the representation of these regions in such models. Further, the development of alternate demand scenarios based on various passenger mobility-related phenomena offers valuable guidance to the policymaking processes in these regions. The sustainable mobility scenarios developed in this chapter are primarily driven by green growth that can help leapfrog the traditional private vehicle dependency observed in the Global North while at the same time improve access to mobility.

RQ2: What benefits can demand reduction and restructuring measures, typically overlooked in decarbonisation scenarios, bring for climate change mitigation?

The analysis in Chapter 3 reveals that reducing and restructuring energy service demand can reduce the pace of technology uptake such as offshore wind, EVs and heat pumps to meet a given climate goal. It can also increase the pace of near-term decarbonisation. Reducing energy service demands can alleviate the immediate pressure for rapid adoption of capital-intensive and novel fuels and technologies such as carbon dioxide removal (CDR) technologies and hydrogen. The results reveal that investments needed in the energy system are lower in the ILED pathway by more than 40%. EV uptake rates are up to 90% lower (especially in the near-term) while requirement of novel technology like BECCS is about 23-38% lower in the ILED pathway relative to business-as-usual demand growth pathways. Demand reduction measures can improve energy security, as also highlighted by Bento et al. (2024), in developed countries like Ireland through lower reliance on fossil imports especially under current geopolitical uncertainties. Demand reduction helps meet decarbonisation targets at lower costs since the size of the energy system decreases and the need for expensive infrastructure investments in new energy generation and distribution goes down.

Chapter 3 is national-level study that utilises specific data and policy measures. It allows an in-depth discussion of the potential and feasibility of such LED-type scenarios within the

national context. Such analysis is crucial for policymakers to understand the capacity of demand-side oriented policies to meet climate goals.

RQ3: What is the impact of spatial settlement patterns on energy service demand? How can such drivers of energy service demand be parameterised in an energy systems model?

Spatial settlement patterns and urban forms greatly impact demand for energy services, particularly in the residential and passenger transport sectors. Spatial distribution and density of settlement also determine the viability of networked infrastructure such as district heating and public transport.

The exploratory data analysis undertaken in Chapter 4 showed that population dispersal is highly correlated to energy and carbon intensity of energy service demands in Ireland. The residential and transport GHG emissions are, respectively, 62% and 52% lower for populations living in the highest density regions than in the lowest. The highly dispersed in nature of the Irish stock, with rural one-off housing still being built across the country, has locked households' living in sparsely populated areas into carbon and energy intensive consumption patterns. This dispersion presents a challenge for decarbonisation efforts, given the absence or economic infeasibility of networked infrastructure in sparsely populated regions.

The analysis provides useful insights for developing countries that are undergoing infrastructure expansion. Whether future population settlement will be compact or dispersed will heavily determine networked infrastructure development and mitigation options. Strategic urban planning, coupled with simultaneous infrastructure development, offers a pathway to enhancing access to essential amenities and services while reducing energy poverty and carbon emissions.

The relationships established in this chapter allow future modelling studies to include spatial settlement patterns as a mitigation lever. By developing scenarios of future population growth in varying densities, multiple energy service demand scenarios can be analysed using an ESOM or IAM.

RQ4: What is the impact of electrifying spatially dispersed household heating demand on the Irish power system?

Residential heating electrification is an important heat decarbonisation strategy in countries like Ireland, where the population is dispersed and there is a lack of other options like district heating. One of the main results of the analysis in Chapter 5 is that spatially distributed

demand plays a pivotal role in shaping power investments. Under an ambitious renewable energy target, the investment in heat pumps is higher in regions with higher heating demand such as Dublin rather than in regions with high offshore wind capacity such as the West Coast. The electrification of heating demand leads to a reduction in investments in transmission infrastructure and an increase in storage. Offshore wind is spatially concentrated while the demand and storage is spatially dispersed. This result further confirms that the spatially dispersed nature of demand plays a role in determining power system investments and is complemented by storage rather than transmission infrastructure. Further, the addition of heat pump as a load to the power system reduces renewable curtailment and transmission losses.

RQ5: How can the quantification of sustainable mobility scenarios for the Global South be improved to avoid biases arising from reliance on data, literature, and particular phenomena from the Global North?

Global level IAMs and ESOMs are generally very aggregated, spatially and demographically. Furthermore, it has been noted that these models, and consequently the exogenous scenarios they employ to assess alternative mitigation pathways, often exhibit a bias toward the Global North. This bias arises from an over reliance on data and observations from Global North regions.

To address this gap, Chapter 6 presents a novel framework that quantifies sustainable mobility scenarios for South Asian countries. The development of the framework begins with a literature review of measured causal relationships between passenger mobility and various phenomena such as transit oriented development, urbanisation, ride hailing and infrastructure development. The passenger mobility parameters that these phenomena influence are parameterised from the literature using evidence primarily from Global South. Further, a novel passenger mobility model is developed, calibrated to Indian Census 2011 and other regional data, that is designed to interface with an IAM. The mobility projection model considers various phenomena and their impact to quantify passenger transport scenarios for the region.

Overall, by combining a comprehensive literature review with the development of a region-specific mobility model, the framework offers a novel methodology for improving the quantification of sustainable mobility scenarios while minimising biases originating from data and observed phenomena measured in Global North regions.

RQ6: How can the countries in Global South leapfrog private car dependency towards a more sustainable development of the passenger transport system?

The Global South countries, and especially urban areas, are experiencing a faster population and economic growth relative to the Global North. This has led to continuous expansion of their transport energy systems and GHG emissions. However, stark income inequalities in these nations resulted in an unequal distribution of access to transport energy services. Achieving decarbonisation of this system while ensuring sustainable development requires exploring mitigation options that include a combination of innovative strategies and targeted policies.

The analysis in Chapter 6 reveals that developing a robust public transport system is key in South Asian countries to reduce carbon intensity of the transport system while improving access to mobility, particularly for the disadvantaged. Hence, there is a need to design and implement policies aimed at improving and encouraging the use of public transport services.

The number of private vehicles (2-Wheelers and LDVs) is anticipated to increase substantially in this region which underscores the necessity of electrifying the private fleet. Moreover, to mitigate or minimize the traffic externalities linked with the expansion of private vehicles—such as noise pollution, air pollution, and urban congestion—policy instruments are imperative. These may include measures such as restricting vehicle usage or parking in urban centres, implementing parking or congestion charges, and incentivising practices like carpooling.

As urban peripheries continue to expand in these countries, transit-oriented development will emerge as a pivotal strategy for mitigating and managing transport energy service demand. Compact development will also enhance the feasibility of networked public infrastructure. However, it is essential to approach these initiatives with caution to avoid exacerbating existing urban challenges, such as overcrowding and the proliferation of informal settlements. Moreover, transport decarbonisation cannot be achieved by designing transport policies in silos but requires holistic and coherent interaction with other sectors such as land-use and urban planning (Danielis et al., 2022).

7.3 Policy insights

Achieving the necessary behavior and lifestyle changes to reduce energy and carbon intensity requires more than just individual efforts—it necessitates effective policy design and invest-

ments in supporting infrastructure. Policy designs should involve implementing regulations, incentives, and frameworks that influence individual and collective behavior toward more sustainable practices. For example, policies could include subsidies for renewable technology uptake and incentivise best practices such as car pooling. Similarly, investments in robust public transport infrastructure, district heating networks, and improving energy efficiency of buildings are needed. Beyond individual policies and infrastructure investments, broader systemic changes are needed to address the underlying drivers of GHG emissions. This may involve economic restructuring that promotes sustainable consumption and production patterns, or fostering societal norms such as the 'Flygskam' (a movement in Sweden that discourages flying) that prioritise environmental stewardship. Such systemic changes require coordinated efforts across multiple sectors and levels of governance. And hence, effective policies cannot be designed silos. For example, combining transport policy with urban planning is essential to reduce private vehicle dependency.

Policies aimed at promoting technology uptake, such as subsidies for heat pumps or EVs, must carefully consider the potential for policy failure resulting from income inequality. As discussed in Chapter 5, the dwelling retrofit and heat pump costs are the most substantial component of the policy. Further, since high income households have greater purchasing power and generally better access to information, they are more likely to benefit from policies aimed at technology uptake, thereby exacerbating existing disparities between high- and low-income households. To mitigate the risk of such policy failure, policymakers must design targeted interventions that ensure equitable access to subsidies and incentives for technology uptake. This may involve implementing means-tested subsidy programs that provide greater support to low- and moderate-income households or offering alternative financing options, such as low-interest loans or income-based repayment plans. Policymakers should also consider complementary measures to promote inclusivity and accessibility, such as investing in public infrastructure for EV charging stations or retrofitting social housing units. The analysis in Chapter 4 shows that populations living in dispersed rural areas are at the risk of being locked into carbon intensive practices due to lack of access to cleaner alternatives. Hence, policies must ensure just transition for all and must be carefully designed based on urban/rural context. Additionally, outreach and education campaigns can help raise awareness and empower marginalised populations to take advantage of available incentives and resources. Addressing income disparities and ensuring equitable access to sustainable technologies can create a more inclusive and resilient society while transitioning to a low-carbon future.

Sustainable development policies, especially in Global South regions, should encompass strategies beyond emission reduction and meeting climate goals; they must aim for improving

well-being, promoting equality, and ensuring equitable access to resources and opportunities.

7.3.1 Policy impact

The Irish Low Energy Demand (ILED) scenario which is discussed in Chapter 3 has had a tangible effect on the Irish climate action discourse. It formed a part of recommendations submitted by the Climate Change Advisory Council (CCAC) (Climate Change Advisory Council, 2021). The CCAC is an independent, statutory body providing advice to the Government on national policy relating to climate change. The scenario and its implication were discussed in the Dáil Éireann debate (national parliament of Ireland).

7.4 Recommendations for future work

While the future work emanating from the above research questions has been addressed in the corresponding individual chapters, the following recommendations stem directly or more subtly from these discussions.

- This thesis highlights the essential role of behaviour, lifestyle patterns and societal change in energy transition. Income and its distribution play a critical role in shaping individual behaviors, consumption patterns, vulnerability to climate impacts, policy outcomes, and societal dynamics—all of which are integral to the success of transitions needed to meet climate goals (Luciani, 2020). Since low-to-median-income households have higher impediments to technology uptake and upgrade, energy transition can further exacerbate income inequality (Wang et al., 2024). This income inequality can undermine social cohesion and trust, making it more challenging to garner collective action towards sustainability (Schlesewsky et al., 2018). Furthermore, considering local contextual factors such as access to networked resources is very important in determining policies for equitable transition. It is therefore necessary to assess the role of income and distribution with respect to energy transition policies at regional level.
- Chapter 3, 4 and 6 stress the pivotal role of investments in low-carbon infrastructure in order to reduce carbon intensity of energy service demands. However, for planning and budgeting, and better resource allocation it is necessary to quantify these future investment costs. Quantifying investments can facilitate cost-benefit analysis, risk assessment, and targeted policy development.
- To leverage population density as a mitigation lever for energy demand in Ireland, the

established mathematical relationship between population density and energy service demands, as outlined in Chapter 4, must be integrated into the TIMES-Ireland model (TIM). This involves developing future scenarios of population growth based on how population density might change over time. By using the relationships in this chapter, the energy service demands corresponding to various scenarios of population density can be calculated. These energy service demand will further serve as inputs to TIM. This approach enables policymakers and planners to anticipate and address the implications of population density changes on energy demand, facilitating the development of effective strategies for sustainable energy infrastructure and resource management in Ireland. The methodology can also be used in other ESOMs and IAMs.

- Future work emanating from Chapter 6 involves linking the passenger mobility demand to MESSAGEix-Transport—which is a technology rich representation of the transport sector within the global IAM framework at International Institute for Applied Systems Analysis (IIASA). Upon linking the models, a whole energy systems impact of the sustainable mobility scenarios can be analysed and the cost of meeting each of the scenarios can be computed.

- In future work, it's essential to expand the sustainable mobility scenario narratives outlined in Chapter 6 to encompass multiple potential outcomes of phenomena. Given the contested nature of concepts related to passenger mobility, considering diverse outcomes for each phenomenon is crucial for capturing a comprehensive range of possibilities. However, this can give rise internal inconsistency between phenomena (Tori et al., 2023). To address this challenge, it is imperative to develop storylines in a way that maintains narrative consistency.

- It has been discussed previously that models like TIMES and MESSAGEix have some inherent limitations; while some shortcomings can be effectively addressed within existing frameworks, others may necessitate alternate tools and analytical methods for comprehensive analysis. For example, these modelling tools often overlook elements of system inertia, such as considering the time it takes to obtain planning permissions for or public acceptance of projects like wind farms. Both these elements will determine cumulative emissions trajectory, which is generally not captured by ESOMs and IAMs. It is recommended to include additional insights from other quantitative frameworks.

- It is being recognized that macroeconomic measures of well-being such as GDP might not be able to capture and present the full picture of actual living conditions of ordinary people. Other measured concepts related to energy access such as passenger distance

travelled (PDT) are often used as a proxy for well-being. However, a higher PDT is not necessarily associated with higher well-being; higher PDT indicates greater commuting distances which reduces quality of life and therefore well-being. There is a necessity to redefine "growth" to focus on well-being and develop more comprehensive frameworks to measure this factor.

- Climate change impacts are unequal, with poorer nations having lower resources to tackle such issues. Moreover, energy transition such as EV and heat adoption can exacerbate income inequality in communities. It is therefore important to integrate insights from other disciplines to account for the many dimensions of energy related transition. Interdisciplinary research allows to include more qualitative and very important concepts such as justice and equity of transition. This will ensure that the transition needed to mitigate climate change impacts is fair, equal and creates more resilient societies.

Appendix

A. Supplementary material Chapter 5

A.1 Mathematical formulation of the Electricity Network and Generation INvEstment (ENGINE) model

Nomenclature

Indices and Sets

g/Ω^g	Index/set of all generators
i/Ω^i	Index/set of all nodes
k/Ω^k	Index/set of all lines
s/Ω^s	Index/set of scenarios
w/Ω^w	Index/set of operation states (e.g. hours)
Ω^{el}/Ω^{nl}	Set of existing/new lines
t/Ω^t	Index/set of planning stages

Parameters

COP^{HP}	Coefficient of performance of heat pump
α	Losses in transmission network
ρ_s	Probability of a scenario
π_w	Weight of an operational state (hours)
η_{ch}/η_{dch}	Storage charging/discharging efficiency
η_{stg}	Storage efficiency
$PD^{i,0}_{s,w,t}$	Active load before DR (MW)
$QD^{i,0}_{s,w,t}$	Reactive load before DR (MVAr)
r	Interest rate (%)

Variables

$P_{k,s,w,t}$	Active power flows in a line (MW)
$P^{gen}_{g,i,s,w,t}$	Active power production (MW)

$P^{PNS}_{i,s,w,t}$	Unserved active power (MW)
$PD^{i}_{s,w,t}$	Active power demand with DR (MW)
$PL_{k,s,w,t}, QL_{k,s,w,t}$	Active/reactive losses (MW, MVAr)
$Q_{k,s,w,t}$	Reactive power flows in a line (MVAr)
$Q^{gen}_{g,i,s,w,t}$	Reactive power production (MVAr)
$Q^{PNS}_{i,s,w,t}$	Unserved reactive power (MVAr)
$Q^{rs}_{i,s,w,t}$	Reactive power injected/absorbed at node i by a capacitor/reactor (MVAr)
$QD^{i}_{s,w,t}$	Reactive power demand with DR (MVAr)
$P^{HP,i}_{s,w,t}$	Active power demand by HP
$Q^{HP,i}_{s,w,t}$	Heat supplied directly (MJ)
$Q^{dch,i}_{s,w,t}$	TES discharging variable (MJ)
$Q^{ch,i}_{s,w,t}$	TES charging variable (MJ)
$Q^{unserved,i}_{s,w,t}$	TES discharging variable (MJ)
$TES^{i}_{s,w,t}$	Thermal energy storage level (MJ)

Functions

EC^{gen}_{t}	Expected cost of supplied energy (€)
$EmiC^{gen}_{t}$	Expected emission cost (€)
$InvC^{ntk}_{t}$	Network-related investment cost (€)
$ENSC_{t}$	Expected cost of unserved energy (€)
$MntC^{gen}_{t}$	Maintenance cost of generators (€)
$MntC^{ntk}_{t}$	Network-related maintenance cost (€)
$MntC^{hp}_{t}$	Heat pump's maintenance cost (€)
$OpnC^{hp}_{t}$	Heat pump's operation cost (€)

Objective function

The transmission expansion planning (TEP) problem with integrated heat sector consists of an objective function that minimizes the overall system cost. This is similar to the objective the function given in Fitiwi et al. (2020a), except the additional cost terms added here that are associated with the operation and maintenance of heat pumps. The objective function is described as in (1) and consists of the net present values (NPV) of investment ($TInvC$), maintenance (TMC), operation (TEC), load shedding ($TENSC$), emissions ($TEmiC$) and heat pump operation and maintenance (HPC) with certain relevance factor γ_m; $\forall m \in \{1, 2, ..., 6\}$. Further information on the terms can be found in Fitiwi et al. (2020a).

$$Min \quad TC = \gamma_1 * TInvC + \gamma_2 * TMC + \gamma_3 * TEC + \gamma_4 * TENSC + \gamma_5 * TEmiC + \gamma_6 * HPC \quad (1)$$

where,

$$TInvC = \sum_{t \in \Omega^t} (1+r)^{-t} InvC_t^{ntk} \quad (2)$$

$$TMC = \sum_{t \in \Omega^t} (1+r)^{-t} (MntC_t^{gen} + MntC_t^{ntk}) \quad (3)$$

$$TEC = \sum_{t \in \Omega^t} (1+r)^{-t} EgyC_t^{gen} \quad (4)$$

$$TENSC = \sum_{t \in \Omega^t} (1+r)^{-t} ENSC_t \quad (5)$$

$$TEmiC = \sum_{t \in \Omega^t} (1+r)^{-t} EmiC_t^{gen} \quad (6)$$

$$HPC = \sum_{t \in \Omega^t} (1+r)^{-t} (MntC_t^{hp} + OpnC_t^{hp}) \quad (7)$$

Electrical Network

We use an extended version of the model in Fitiwi et al. (2020a) to represent the physical characteristics of the electrical network. The active power demand balance equation at each node or Kirchhoff's current law is expressed as in (8). This includes part of the electricity demand that goes directly for heating purposes. In this paper, we assume that the reactive power demand balance is not affected by the introduction of HPs, and hence is the same as in Fitiwi et al. (2020a).

$$\sum_{g \in \Omega^g} P_{g,i,s,w,t}^{gen} + P_{i,s,w,t}^{PNS} + \sum_{in,k \in \Omega^k} P_{k,s,w,t} - \sum_{out,k \in \Omega^k} P_{k,s,w,t} = \sum_{in,w \in \Omega^g} \frac{1}{2} PL_{k,s,w,t} + PD_{s,w,t}^{i} + P_{s,w,t}^{HP,i} \quad k \in i; \quad g \in i \quad (8)$$

Others such as network flow constraints, those related to power losses, generator limits, and logical constraints that represent irreversibility of investment decisions are the same as in Fitiwi et al. (2020a). However, the emission reduction potential changes due to the electrification of the heating sector. The RES integration target is imposed as in (9):

$$\sum_{s\in\Omega^s}\rho_s\sum_{w\in\Omega^w}\pi_w\sum_{g\in\Omega^{RES}}\sum_{i\in\Omega^i}P^{gen}_{g,i,s,w,t}\geq p_t*\sum_{s\in\Omega^s}\rho_s\sum_{w\in\Omega^w}\pi_w\sum_{i\in\Omega^i}(PD^i_{s,w,t}+P^{HP,i}_{s,w,t}) \tag{9}$$

Modelling E-Heating The portion of heating needs that is electrified in the whole Island is aggregated to the transmission level. The underlying assumption here is that a certain percentage of the total heat demand is electrified, and supplied through heat pumps integrated with thermal energy storage systems. The first constraint associated with the heating sector is the heat demand balance equation, which is defined in Equations (10)—(12):

$$P^{HP,i}_{s,w,t}(1-\alpha)=(Q_{s,w,t}6HP,i+Q_{s,w,t}6ch,i)/COP^{HP} \tag{10}$$

In (10) it is assumed that a certain percentage (α) of the total heat demand is lost in the form of losses in the heating network.

$$Q^{HP,i}_{s,w,t}+Q^{dch,i}_{s,w,t}=Q^{d,i}_{s,w,t}-Q^{unserved,i}_{s,w,t} \tag{11}$$

$$(Q^{HP,i}_{s,w,t}+Q^{ch,i}_{s,w,t}) \quad \leq \quad C^{HP,i} \tag{12}$$

Equations (13)—(16) represent constraints related to the thermal energy storage system, Equation (13) refers to the thermal energy balance. Equation (14) imposes the storage limits. The levels of charging and discharging variables of the TES cannot exceed preset limits as in (15) and (16), respectively.

$$TES^i_{s,w,t}=\eta_{stg}TES^i_{s,w-1,t}+\eta_{ch}Q^{ch,i}_{s,w,t}-Q^{dch,i}_{s,w,t}/\eta_{dch} \tag{13}$$

$$TES^{i,min}_{s,w,t}\leq TES^i_{s,w,t}\leq TES^{i,max}_{s,w,t} \tag{14}$$

$$0\leq Q^{ch,i}_{s,w,t}\leq Q^{TES,i,max}_{ch} \tag{15}$$

$$0\leq Q^{dch,i}_{s,w,t}\leq Q^{TES,i,max}_{dch} \tag{16}$$

B. Supplementary material Chapter 6

B.1 Detailed description of definition of each phenomenon

Table B1: Modelling approach for each phenomenon in the framework

Phenomenon	**Parameter**	**Description**	
		Short-run	**Long-run**
Urbanisation	PDT	% growth between 2011 and 2030	% growth between 2030 and 2050
Autonomous vehicle	LDV based PDT	% growth between 2011 and 2050	
	PT share	% reduction in bus-based between 2011 and 2050	
Ride hailing	VDT	% growth in taxi-based VDT between 2011 and 2050	
	NMT share	% in NMT-based PDT reduction between 2011 and 2030	% reduction between 2030 and 2050
	PT share	% reduction in bus-based PDT between 2011 and 2030	% reduction between 2030 and 2050
	Vehicle ownership	% reduction between 2011 and 2050	
Ride sharing	VDT	% reduction in taxi-based PDT between 2011 and 2030	% growth in taxi-based PDT between 2011 and 2030 (rebound effect)
High speed rail infrastructure	Share in long distance travel	% growth of rail-based PDT between 2011 and 2050; equivalent reduction in share of road-based travel	
NMT infrastructure	NMT share	% shift in PDT from 2-wheelers and LDVS to NMT between 2011-2050 for trips <5km	
PT infrastructure	PT share	% growth in bus-based PDT between 2011-2030	% growth in bus-based PDT between 2030-2050 due to shift from 2-wheelers and LDVs
Environmental awareness	EV sale share	% growth between 2011-2030	% growth between 2030-2050
Higher standard of living	LDV ownership	% growth between 2011 and 2050	
e-life	Trip rate	% reduction between 2011 and 2030	% reduction between 2030 and 2050
MaaS	-	Combination of ride hailing and ride sharing	
Transit oriented development	PDT	% reduction between 2011 and 2030	% reduction between 2030 and 2050
	NMT share	% growth in NMT-based PDT between 2011 and 2030	% growth in NMT-based PDT between 2030 and 2050

	PT share	% growth in bus-based PDT between 2011 and 2030	% growth in bus-based PDT between 2030 and 2050
	Vehicle ownership	% reduction between 2030 and 2050	

B.2 Share of urban population in each area type for each country in 2011

Table B2: Distribution of population between urban area types in 2011

Country	Large city	City	Town
Afghanistan	57%	31%	12%
Bangladesh	34%	30%	36%
Bhutan	41%	33%	26%
India	43%	23%	34%
Maldives	47%	14%	39%
Nepal	42%	31%	27%
Pakistan	54%	33%	13%
Sri Lanka	20%	50%	30%

B.3 Daily travel model estimated using Indian Census 2011

Table B3: Daily travel demand model

Area type	Trip distance category	Typical distance in km	Trip share	LDV	Bus	NMT	2-Wheeler	Rail	IPT	Not stated
Large city	No travel	0	19%	-	-	-	-	-	-	-
	00_01	0.5	16%	3%	4%	80%	9%	1%	2%	1%
	02_05	3.5	25%	6%	18%	44%	22%	3%	6%	1%
	06_10	8	19%	9%	28%	29%	23%	7%	5%	1%
	11_20	15.5	12%	15%	33%	5%	25%	17%	4%	1%
	21_30	25.5	5%	16%	26%	13%	15%	25%	4%	1%
	31_50	40.5	3%	15%	22%	0%	12%	43%	6%	1%
	51+	60	1%	10%	19%	0%	8%	53%	7%	3%
City	No travel	0	25%	-	-	-	-	-	-	-
	00_01	0.5	15%	2%	2%	78%	14%	1%	2%	1%
	02_05	3.5	29%	4%	11%	51%	29%	1%	5%	1%
	06_10	8	18%	5%	19%	39%	30%	1%	6%	1%
	11_20	15.5	7%	8%	31%	15%	35%	2%	7%	1%
	21_30	25.5	3%	7%	25%	43%	16%	4%	4%	1%
	31_50	40.5	2%	13%	42%	0%	24%	13%	7%	2%

	51+	60	2%	8%	36%	0%	10%	38%	4%	3%
Town	No travel	0	27%	-	-	-	-	-	-	-
	00_01	0.5	20%	1%	2%	81%	14%	1%	1%	1%
	02_05	3.5	28%	3%	7%	58%	26%	1%	5%	1%
	06_10	8	13%	4%	17%	47%	23%	2%	6%	1%
	11_20	15.5	5%	8%	37%	11%	29%	8%	6%	2%
	21_30	25.5	3%	5%	30%	36%	14%	11%	3%	1%
	31_50	40.5	2%	8%	45%	0%	18%	22%	5%	2%
	51+	60	2%	7%	44%	0%	8%	35%	3%	4%
Rural	No travel	0	39%	-	-	-	-	-	-	-
	00_01	0.5	14%	1%	2%	90%	5%	1%	1%	1%
	02_05	3.5	18%	2%	8%	72%	12%	1%	4%	1%
	06_10	8	13%	2%	18%	56%	15%	1%	6%	2%
	11_20	15.5	7%	4%	37%	23%	23%	3%	8%	2%
	21_30	25.5	4%	4%	38%	32%	15%	5%	5%	2%
	31_50	40.5	3%	5%	57%	0%	15%	15%	5%	3%
	51+	60	3%	4%	50%	0%	5%	34%	2%	5%

B.4 Long distance travel estimated in all countries in 2011

Table B4: Long distance travel estimated in billion passenger kilometers

Country	Rail	Bus	LDV
Afghanistan	0.9	14.7	2.8
Bangladesh	8.1	49.6	9.4
Bhutan	-	0.4	0.1
India	978.5	4657.7	887.2
Nepal	-	14.4	2.7
Pakistan	16.1	121.7	23.2
Sri Lanka	4.6	28.2	5.4

B.5 Trends in mode composition of growth in daily travel

Figure B1 outlines the share of modes in daily travel in each country for every mode share trajectory and scenario in 2050 and compared with country level mode share in 2011.

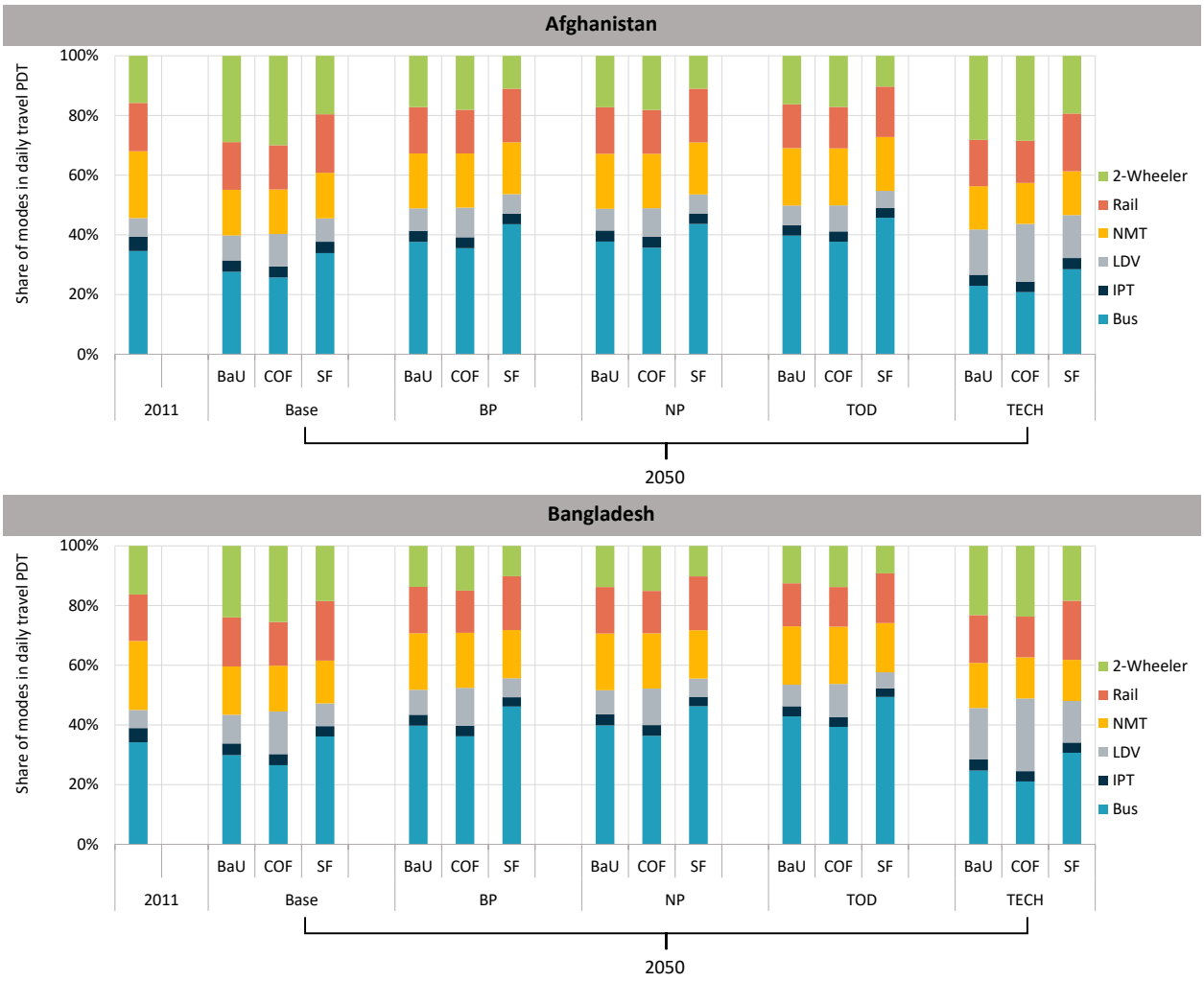


Figure B1: Share of modes in daily travel PDT

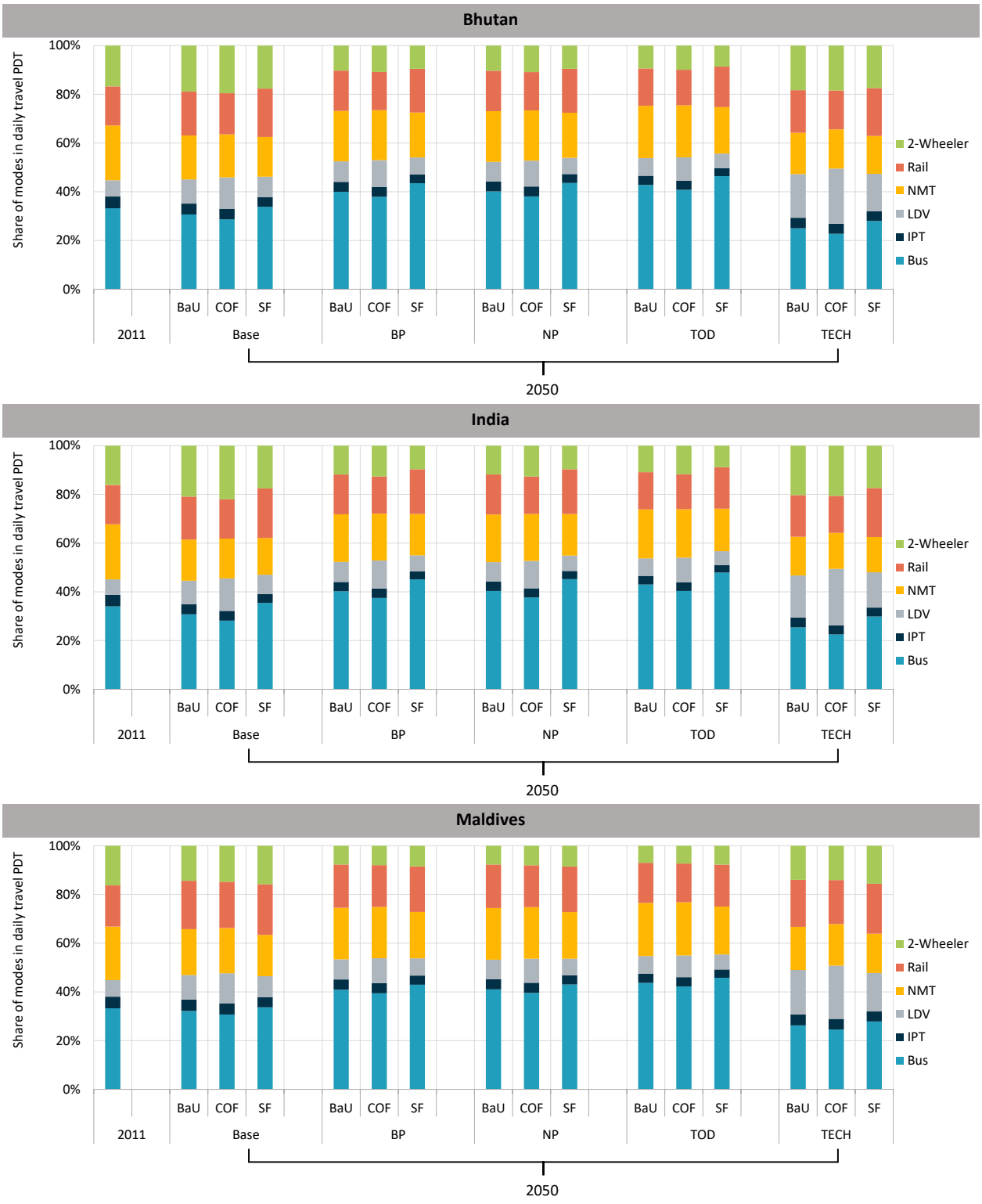


Figure B1: Share of modes in daily travel PDT

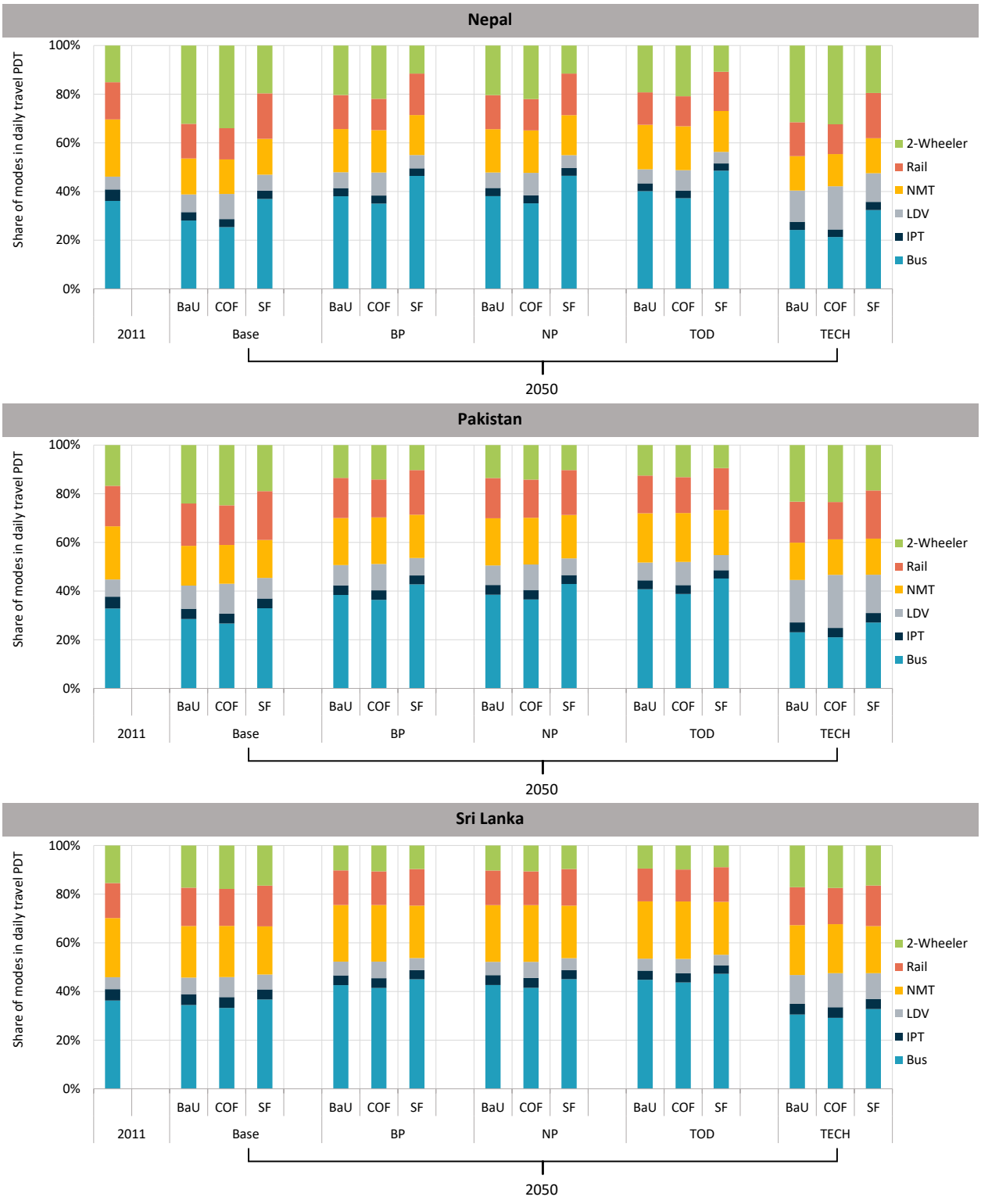


Figure B1: Share of modes in daily travel PDT

Bibliography

Abbagani, V. and B. R. Kadali (2022). "Explore the Factors Contributing to Online Versus Store Shopping in Transportation Perspective: Evidence from India". In: *European Transport* 89.

Abbasi, M. H., B. Abdullah, M. W. Ahmad, A. Rostami, and J. Cullen (2021). "Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology". In: *Sustainable Energy Technologies and Assessments* 48, p. 101630.

Abd Alla, S., V. Bianco, F. Scarpa, and L. A. Tagliafico (2022). "Electrification of the residential heat demand: An analysis of the power market potential to accommodate heat pumps". In: *Thermal Science and Engineering Progress* 27, p. 101173.

Abdul-Manan, A. F., V. Gordillo Zavaleta, A. K. Agarwal, G. Kalghatgi, and A. A. Amer (2022). "Electrifying passenger road transport in India requires near-term electricity grid decarbonisation". In: *Nature Communications* 13.1, p. 2095.

Abdulla, A. A. (2007). *In-Depth Technology Needs Assessment on Transport Sector*.

Acheampong, R. A., A. Siiba, D. K. Okyere, and J. P. Tuffour (2020). "Mobility-on-demand: An empirical study of internet-based ride-hailing adoption factors, travel characteristics and mode substitution effects". In: *Transportation Research Part C: Emerging Technologies* 115, p. 102638.

AECOM (2019). *National Transport Model Update: Travel Demand Forecasting Report*. Tech. rep. Dublin, Ireland: AECOM, p. 185. URL: `https://www.tii.ie/tii-library/strategic-planning/national-transport-model/NTpM-Vol3-Travel-Demand-Forcasting-Report.pdf`.

Agarwal, S., D. Mani, and R. Telang (2023). "The impact of ride-hailing services on congestion: Evidence from indian cities". In: *Manufacturing & Service Operations Management* 25.3, pp. 862–883.

Ahern, A., G. Weyman, M. Redelbach, A. Schulz, L. Akkermans, L. Vannacci, E. Anoyrkati, and A. Van Grinsven (2013). "Analysis of national travel surveys in Europe-OPTIMISM

WP2: Harmonisation of national travel statistics in Europe". In: *Publications Office of the European Union*.

Ahmad, S. and J. A. P. de Oliveira (2016). "Determinants of urban mobility in India: Lessons for promoting sustainable and inclusive urban transportation in developing countries". In: *Transport Policy* 50, pp. 106–114.

Alshehri, F., S. Beck, D. Ingham, L. Ma, and M. Pourkashanian (2019). "Techno-economic analysis of ground and air source heat pumps in hot dry climates". In: *Journal of Building Engineering* 26, p. 100825.

Alvi, S. and U. Khayyam (2020). "Mitigating and adapting to climate change: attitudinal and behavioural challenges in South Asia". In: *International Journal of Climate Change Strategies and Management* 12.4, pp. 477–493.

Anable, J., C. Brand, M. Tran, and N. Eyre (2012). "Modelling transport energy demand: A socio-technical approach". In: *Energy Policy* 41, pp. 125–138.

Andersen, K. S., C. Wiese, S. Petrovic, and R. McKenna (2020). "Exploring the role of households' hurdle rates and demand elasticities in meeting Danish energy-savings target". In: *Energy Policy* 146, p. 111785.

Anderson, K. and J. Jewell (2019). "Debating the bedrock of climate-change mitigation scenarios". In: *Nature* 573.7774, pp. 348–349. DOI: 10.1038/d41586-019-02744-9.

Anderson, K. and G. Peters (2016). "The trouble with negative emissions". In: *Science* 354.6309, pp. 182–183.

Aryanpur, V., O. Balyk, H. Daly, B. Ó. Gallachóir, and J. Glynn (2022). "Decarbonisation of passenger light-duty vehicles using spatially resolved TIMES-Ireland Model". In: *Applied Energy* 316, p. 119078.

Aryanpur, V., B. O'Gallachoir, H. Dai, W. Chen, and J. Glynn (2021). "A review of spatial resolution and regionalisation in national-scale energy systems optimisation models". In: *Energy Strategy Reviews* 37, p. 100702. ISSN: 2211467X. DOI: 10.1016/j.esr.2021.100702. URL: https://linkinghub.elsevier.com/retrieve/pii/S2211467X21000882.

Ashmore, D. P., D. Pojani, R. Thoreau, N. Christie, and N. A. Tyler (2019). "Gauging differences in public transport symbolism across national cultures: implications for policy development and transfer". In: *Journal of Transport Geography* 77, pp. 26–38.

Badami, M. G. and M. Haider (2013). "Urban Policy for Environmental Quality and Well-Being". In: *South Asia 2060: Envisioning Regional Futures*. Ed. by A. Najam and M. Yusuf. Anthem Nineteenth-Century Series. Anthem Press, 160–168.

Baligh, M. (2017). "Afghanistan Transport Sector Master Plan Update (2017—2036)". In: *Asian Development Bank Publisher. Manila. Philippines* 4.

Balyk, O., J. Glynn, V. Aryanpur, A. Gaur, J. McGuire, A. Smith, X. Yue, A. Chiodi, M. Gargiulo, and H. Daly (2021). "TIMES-Ireland Model (v1.0)". In: *Zenodo*. DOI: https://doi.org/10.5281/zenodo.5708681.

Balyk, O., J. Glynn, V. Aryanpur, A. Gaur, J. McGuire, A. Smith, X. Yue, and H. Daly (2022). "TIM: modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1. 0)". In: *Geoscientific Model Development* 15.12, pp. 4991–5019.

Bangladesh Railway (2019). *Information book 2019*. Tech. rep. Bangladesh Railway, Railbhavan, Dhaka. URL: https://railway.portal.gov.bd/sites/default/files/files/railway.portal.gov.bd/page/4ec73cd2_6646_426f_ade5_6c05960865d4/INFORMATION%20BOOK%202019%20(PDF%20Version).pdf.

Bansal, P., K. M. Kockelman, W. Schievelbein, and S. Schauer-West (2018). "Indian vehicle ownership and travel behavior: A case study of Bengaluru, Delhi and Kolkata". In: *Research in Transportation Economics* 71, pp. 2–8.

Baobeid, A., M. Koç, and S. G. Al-Ghamdi (2021). "Walkability and its relationships with health, sustainability, and livability: elements of physical environment and evaluation frameworks". In: *Frontiers in Built Environment* 7, p. 721218.

Barrett, J., S. Pye, S. Betts-Davies, N. Eyre, O. Broad, J. Price, J. Norman, J. Anable, G. Bennett, C. Brand, et al. (2021). "The role of energy demand reduction in achieving net-zero in the UK". In.

Bauer, N., K. Calvin, J. Emmerling, O. Fricko, S. Fujimori, J. Hilaire, J. Eom, V. Krey, E. Kriegler, I. Mouratiadou, et al. (2017). "Shared socio-economic pathways of the energy sector–quantifying the narratives". In: *Global Environmental Change* 42, pp. 316–330.

Bautista-Hernández, D. A. (2021). "Mode choice in commuting and the built environment in México City. Is there a chance for non-motorized travel?" In: *Journal of Transport Geography* 92, p. 103024.

Beach, L. R. (2021). "Scenarios as narratives". In: *Futures & Foresight Science* 3.1.

Bekka, A., N. Louvet, and F. Adoue (2020). "Impact of a ridesourcing service on car ownership and resulting effects on vehicle kilometers travelled in the Paris region". In: *Case Studies on Transport Policy* 8.3, pp. 1010–1018.

Bellocchi, S., M. Manno, M. Noussan, M. G. Prina, and M. Vellini (2020). "Electrification of transport and residential heating sectors in support of renewable penetration: Scenarios for the Italian energy system". In: *Energy* 196, p. 117062.

Bento, N., A. Grubler, B. Boza-Kiss, S. D. Stercke, V. Krey, D. L. McCollum, C. Zimm, and T. Alves (2024). "Leverage demand-side policies for energy security". In: *Science* 383.6686, pp. 946–949. DOI: 10.1126/science.adj6150. URL: https://www.science.org/doi/abs/10.1126/science.adj6150.

Berg, N. J. van den, A. F. Hof, L. Akenji, O. Y. Edelenbosch, M. A. van Sluisveld, V. J. Timmer, and D. P. van Vuuren (2019). "Improved modelling of lifestyle changes in integrated assessment models: cross-disciplinary insights from methodologies and theories". In: *Energy Strategy Reviews* 26, p. 100420.

Berg, N. J. van den, A. F. Hof, K.-I. van der Wijst, L. Akenji, V. Daioglou, O. Y. Edelenbosch, M. A. van Sluisveld, V. J. Timmer, and D. P. van Vuuren (2021). "Decomposition analysis of per capita emissions: a tool for assessing consumption changes and technology changes within scenarios". In: *Environmental Research Communications* 3.1, p. 015004.

Bergin, A., N. Conroy, A. G. Rodriguez, D. Holland, N. McInerney, E. L. Morgenroth, and D. Smith (2017). *COSMO: A new COre Structural MOdel for Ireland*. Tech. rep. ESRI Working Paper.

Bergin, A. and A. García-Rodríguez (2020). *Regional Demographics and Structural Housing Demand At a County Level*. Tech. rep. 111. Dublin, Ireland: The Economic and Social Research Institute, p. 63. URL: https://doi.org/10.26504/rs111.

Berrill, P., F. Nachtigall, A. Javaid, N. Milojevic-Dupont, F. Wagner, and F. Creutzig (2024). "Comparing urban form influences on travel distance, car ownership, and mode choice". In: *Transportation Research Part D: Transport and Environment* 128, p. 104087.

Bertsch, V., M. Hyland, and M. Mahony (2017). "What drives people's opinions of electricity infrastructure? Empirical evidence from Ireland". In: *Energy Policy* 106, pp. 472–497.

Bird, L., C. Chapman, J. Logan, J. Sumner, and W. Short (2011). "Evaluating renewable portfolio standards and carbon cap scenarios in the US electric sector". In: *Energy Policy* 39.5, pp. 2573–2585.

Blanco, H., J. J. G. Vilchez, W. Nijs, C. Thiel, and A. Faaij (2019). "Soft-linking of a behavioral model for transport with energy system cost optimization applied to hydrogen in EU". In: *Renewable and Sustainable Energy Reviews* 115, p. 109349.

Blas, I. de, M. Mediavilla, I. Capellán-Pérez, and C. Duce (2020). "The limits of transport decarbonization under the current growth paradigm". In: *Energy Strategy Reviews* 32, p. 100543.

Bord Gais Energy (2019). *Heat pumps - What they are and why you need one*. URL: `https://www.bordgaisenergy.ie/home/heat-pump-guide`.

Bösch, P. M., F. Ciari, and K. W. Axhausen (2018). "Transport policy optimization with autonomous vehicles". In: *Transportation Research Record* 2672.8, pp. 698–707.

Brand, C., J. Anable, and C. Morton (2019). "Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach". In: *Energy Efficiency* 12.1, pp. 187–207.

Briand, Y., S. Pye, M. d. A. D'Agosto, G. V. Goes, D. Neves Schmitz-Gonçalves, A. Garg, D. Gupta, S. S. Vishwanathan, U. W. Siagian, F. Ahjum, et al. (2023). "Passenger transport decarbonization in emerging economies: policy lessons from modelling long-term deep decarbonization pathways". In: *Climate Policy*, pp. 1–21.

Brockway, P. E., S. Sorrell, G. Semieniuk, M. K. Heun, and V. Court (2021). "Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications". In: *Renewable and Sustainable Energy Reviews*, p. 110781.

Brutschin, E., S. Pianta, M. Tavoni, K. Riahi, V. Bosetti, G. Marangoni, and B. J. van Ruijven (2021). "A multidimensional feasibility evaluation of low-carbon scenarios". In: *Environmental Research Letters* 16.6, p. 064069.

Budnitz, H., E. Tranos, and L. Chapman (2020). "Telecommuting and other trips: an English case study". In: *Journal of Transport Geography* 85, p. 102713.

Buehler, R., J. Pucher, R. Gerike, and T. Götschi (2017). "Reducing car dependence in the heart of Europe: lessons from Germany, Austria, and Switzerland". In: *Transport Reviews* 37.1, pp. 4–28.

Busch-Geertsema, A., M. Lanzendorf, and N. Klinner (2021). "Making public transport irresistible? The introduction of a free public transport ticket for state employees and its effects on mode use". In: *Transport Policy* 106, pp. 249–261.

C40 Cities (2016). "Bus Rapid Transit. Good Practice Guide". In: *Climate Leadership Group*, pp. 1–19.

Cai, H., X. Wang, P. Adriaens, and M. Xu (2019). "Environmental benefits of taxi ride sharing in Beijing". In: *Energy* 174, pp. 503–508.

CAREC (2021). *Railway sector assessment for Pakistan*. URL: https://www.carecprogram.org/uploads/2020-CAREC-Railway-Assessment_PAK_3rd_2021-5-4_WEB.pdf.

Carroll, P., R. Benevenuto, and B. Caulfield (2021). "Identifying hotspots of transport disadvantage and car dependency in rural Ireland". In: *Transport Policy* 101, pp. 46–56.

Cass, N., T. Schwanen, and E. Shove (2018). "Infrastructures, intersections and societal transformations". In: *Technological Forecasting and Social Change* 137, pp. 160–167.

Caulfield, B. (2009). "Estimating the environmental benefits of ride-sharing: A case study of Dublin". In: *Transportation Research Part D: Transport and Environment* 14.7, pp. 527–531.

Caulfield, B. and A. Ahern (2014). "The green fields of Ireland: The legacy of Dublin's housing boom and the impact on commuting". In: *Case Studies on Transport Policy* 2.1, pp. 20–27.

Cayla, J.-M. and N. Maïzi (2015). "Integrating household behavior and heterogeneity into the TIMES-Households model". In: *Applied Energy* 139, pp. 56–67.

Cazzola, P, V Sohu, T Bunsen, M Craglia, and S Kodukula (2021). "Decarbonising India's transport system: charting the way forward". In: *International Transport Forum Policy Papers*.

Chambers, J., K. Narula, M. Sulzer, and M. K. Patel (2019). "Mapping district heating potential under evolving thermal demand scenarios and technologies: A case study for Switzerland". In: *Energy* 176, pp. 682–692. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2019.04.044. URL: https://www.sciencedirect.com/science/article/pii/S0360544219306681.

Chaudhry, A.-G., H. Masoumi, and H.-L. Dienel (2023). "A systematic literature review of mobility attitudes and mode choices: MENA and South Asian cities". In: *Frontiers in Sustainable Cities* 4, p. 1085784.

Chen, F., J. Wu, X. Chen, and J. Wang (2017). "Vehicle kilometers traveled reduction impacts of transit-oriented development: evidence from Shanghai City". In: *Transportation Research Part D: Transport and Environment* 55, pp. 227–245.

Chen, X., H. Zheng, Z. Wang, and X. Chen (2021). "Exploring impacts of on-demand ridesplitting on mobility via real-world ridesourcing data and questionnaires". In: *Transportation* 48, pp. 1541–1561.

Christodoulides, P., L. Aresti, and G. Florides (2019). "Air-conditioning of a typical house in moderate climates with Ground Source Heat Pumps and cost comparison with Air Source Heat Pumps". In: *Applied Thermal Engineering* 158, p. 113772.

Climate Change Advisory Council (2021). *Carbon Budget Technical Report*. URL: https://www.climatecouncil.ie/media/climatechangeadvisorycouncil/Technical%20report%20on%20carbon%20budgets%2025.10.2021.pdf.

Cook, N. and D. Butz (2018). *Mobilities, mobility justice and social justice*. Routledge.

Coyne, B. and E. Denny (2021). "Mind the Energy Performance Gap: testing the accuracy of building Energy Performance Certificates in Ireland". In: *Energy efficiency* 14.6, p. 57. ISSN: 1570-646X. DOI: 10.1007/s12053-021-09960-1.

Coyne, B., S. Lyons, and D. McCoy (2018). "The effects of home energy efficiency upgrades on social housing tenants: evidence from Ireland". In: *Energy Efficiency* 11.8, pp. 2077–2100.

Craven, J., E. Horan, and R. Goulding (2014). "Population growth and infrastructure development in Melbourne". In: *WIT Transactions on Ecology and the Environment* 191, pp. 509–520.

Creutzig, F, J Roy, P Devine-Wright, J Díaz-José, F Geels, A Grubler, N Maïzi, E Masanet, Y Mulugetta, C. Onyige-Ebeniro, et al. (2022a). "Demand, services and social aspects of mitigation". In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 752–943.

Creutzig, F., J. Roy, P. Devine-Wright, J. Díaz-José, F. Geels, A. Grubler, N. Mazi, E. Masanet, Y. Mulugetta, C. Onyige, P. Perkins, A. Sanches-Pereira, and E. Weber (2022b). "Demand, services and social aspects of mitigation". In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M.*

Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. DOI: 10.1017/9781009157926.007.

Creutzig, F., B. Fernandez, H. Haberl, R. Khosla, Y. Mulugetta, and K. C. Seto (2016). "Beyond technology: demand-side solutions for climate change mitigation". In: *Annual Review of Environment and Resources* 41, pp. 173–198.

Creutzig, F., M. Franzen, R. Moeckel, D. Heinrichs, K. Nagel, S. Nieland, and H. Weisz (2019). "Leveraging digitalization for sustainability in urban transport". In: *Global Sustainability* 2, e14.

Creutzig, F., L. Niamir, X. Bai, M. Callaghan, J. Cullen, J. Díaz-José, M. Figueroa, A. Grubler, W. F. Lamb, A. Leip, et al. (2022c). "Demand-side solutions to climate change mitigation consistent with high levels of well-being". In: *Nature Climate Change* 12.1, pp. 36–46.

Creutzig, F., J. Roy, W. F. Lamb, I. M. Azevedo, W. B. De Bruin, H. Dalkmann, O. Y. Edelenbosch, F. W. Geels, A. Grubler, C. Hepburn, et al. (2018). "Towards demand-side solutions for mitigating climate change". In: *Nature Climate Change* 8.4, pp. 260–263.

Creutzig, F., J. Roy, and J. Minx (2024). "Demand-side climate change mitigation: where do we stand and where do we go?" In: *Environmental Research Letters* 19.4, p. 040201.

CSO (2007). *Census 2006 Reports*. Accessed: 03-02-2023. URL: https://www.cso.ie/en/census/census2006reports/.

CSO (2016). *Census of Population 2016 - Profile 1 Housing in Ireland*. URL: https://www.cso.ie/en/releasesandpublications/ep/p-cp1hii/cp1hii/od/.

CSO (2017). *Census 2016 Place of Work, School or College - Census of Anonymised Records (POWSCAR)*. Accessed: 03-11-2022. URL: https://www.cso.ie/en/census/census2016reports/powscar/.

CSO (2017). *Census 2016 Reports*. Accessed: 03-02-2023. URL: https://www.cso.ie/en/census/census2016reports/.

CSO (2017). *Permanent Private Households by Central Heating, Small Areas, Census 2016, Theme 6.5, Ireland, 2016, CSO OSi*. Accessed: 03-11-2022. URL: https://census2016.geohive.ie/datasets/geohive::permanent-private-households-by-central-heating-small-areas-census-2016-theme-6-5-ireland-2016-cso-osi/about.

CSO (2018). *Population and Labour Force Projections 2017 - 2051*. ISSN: 2565-6074.

CSO (2019). *Urban and Rural Life in Ireland, 2019-Income*. Accessed: 03-11-2022.

CSO (2020). *Average Distance of Residential Dwellings to Selected Services and Infrastructure*. Accessed: 03-11-2022. URL: https://data.cso.ie/table/MDS02.

CSO (2020a). *Average New Dwelling Size*. Accessed: 03-11-2022. URL: https://data.cso.ie/table/NDA08.

CSO (2020b). *Percentage of One Off Housing in Rural Areas 2011 to 2016*. Accessed: 03-11-2022. URL: https://data.cso.ie/table/E1065.

CSO (2020). *Private Dwellings in Permanent Housing Units*. Accessed: 03-02-2023. URL: https://data.cso.ie/table/CD435.

CSO (2020). *Projected Population 2016 Based*. URL: https://data.cso.ie/table/PEA22.

CSO (2021a). *Estimates of Household Income*. URL: https://ws.cso.ie/public/api.restful/PxStat.Data.Cube{_}API.ReadDataset/CIA02/CSV/1.0/en.

CSO (2021b). *New Vehicles Licensed for the First Time*. URL: https://data.cso.ie/table/TEM12.

CSO (2021). *Road Traffic Volumes*. URL: https://data.cso.ie/table/THA10.

CSO (2021). *Statistical Yearbook of Ireland 2021: Part 2 Business and Economy*. ISSN: 2009-5341.

CSO (2023). *Estimates of Household Income*. Accessed: 03-11-2022. URL: https://data.cso.ie/table/RAA02.

Cullen, J. M., J. M. Allwood, and E. H. Borgstein (2011). "Reducing energy demand: what are the practical limits?" In: *Environmental Science & Technology* 45.4, pp. 1711–1718.

Dai, B., H. Qi, W. Dou, S. Liu, D. Zhong, H. Yang, V. Nian, and Y. Hao (2020). "Life cycle energy, emissions and cost evaluation of CO2 air source heat pump system to replace traditional heating methods for residential heating in China: System configurations". In: *Energy Conversion and Management* 218, p. 112954.

Daly, H. E., K. Ramea, A. Chiodi, S. Yeh, M. Gargiulo, and B. Ó. Gallachóir (2014). "Incorporating travel behaviour and travel time into TIMES energy system models". In: *Applied Energy* 135, pp. 429–439.

Danielis, R., M. Scorrano, and M. Giansoldati (2022). "Decarbonising transport in Europe: Trends, goals, policies and passenger car scenarios". In: *Research in Transportation Economics* 91, p. 101068.

Daniels, D. and S. Yeh (2022). "Complexities in the energy-transport co-transformation". In: *Progress in Energy* 4.4.

Dantas, T. M., F. L. Cyrino Oliveira, and H. M. Varela Repolho (2017). "Air transportation demand forecast through Bagging Holt Winters methods". In: *Journal of Air Transport Management* 59, pp. 116–123. ISSN: 09696997. DOI: 10.1016/j.jairtraman.2016.12.006. URL: https://linkinghub.elsevier.com/retrieve/pii/S0969699716302265.

Das, D., P. P. Kalbar, and N. R. Velaga (2021). "Framework for comparative evaluation of car-sharing alternatives for urban and suburban regions: case study of Mumbai, India". In: *Journal of Urban Planning and Development* 147.3, p. 05021022.

Dávila, J. D., P Brand, P Jirón, H Vargas Caicedo, F Coupé, J Eliécer Córdoba, M. Mejía G, L Agudelo V, J. Cardona, I Sarmiento O, et al. (2013). *Urban mobility and poverty: Lessons from Medellín and Soacha, Colombia*.

Deane, P., J. Curtis, A. Chiodi, M. Gargiulo, F. Rogan, D. Dineen, J. Glynn, J. FitzGerald, B. Ó Gallachóir, DECLG, UCC, and ESRI (2013). *Technical support on developing low carbon sector roadmaps for Ireland: Low Carbon Energy Roadmap for Ireland*. Tech. rep. 021. Dublin, Ireland: Department of Environment, Community and Local Government, p. 125. URL: https://www.esri.ie/system/files?file=media/file-uploads/2015-07/BKMNEXT292.pdf.

DeCarolis, J., H. Daly, P. Dodds, I. Keppo, F. Li, W. McDowall, S. Pye, N. Strachan, E. Trutnevyte, W. Usher, et al. (2017). "Formalizing best practice for energy system optimization modelling". In: *Applied energy* 194, pp. 184–198.

Delač, B., B. Pavković, M. Grozdek, and L. Bezić (2022). "Cost Optimal Renewable Electricity-Based HVAC System: Application of Air to Water or Water to Water Heat Pump". In: *Energies* 15.5, p. 1658.

Deng, J., Z. Tian, J. Fan, M. Yang, S. Furbo, and Z. Wang (2016). "Simulation and optimization study on a solar space heating system combined with a low temperature ASHP for single family rural residential houses in Beijing". In: *Energy and Buildings* 126, pp. 2–13.

Department of Finance (2020). *Stability Programme Update 2020*. Tech. rep. Dublin, Ireland: Department of Finance, p. 72.

Dhar, S. and P. R. Shukla (2015). "Low carbon scenarios for transport in India: Co-benefits analysis". In: *Energy Policy* 81, pp. 186–198.

Diao, M., H. Kong, and J. Zhao (2021). "Impacts of transportation network companies on urban mobility". In: *Nature Sustainability* 4.6, pp. 494–500.

Ding, T., Y. Sun, C. Huang, C. Mu, Y. Fan, J. Lin, and Y. Qin (2022). "Pathways of clean energy heating electrification programs for reducing carbon emissions in Northwest China". In: *Renewable and Sustainable Energy Reviews* 166, p. 112679.

Dixit, S. K. and A. K. Singh (2022). "Predicting electric vehicle (EV) buyers in India: A machine learning approach". In: *The Review of Socionetwork Strategies* 16.2, pp. 221–238.

Dixon, J., E. C. Pierard, P. Mwanzia, P. Giki, J. Oduor, I. Maranga, D. Kemei, J. Onjala, F. Mwangi, W. Ondanje, et al. (2024). "How can emerging economies meet development and climate goals in the transport-energy system? Modelling co-developed scenarios in Kenya using a socio-technical approach". In: *Energy Strategy Reviews* 53, p. 101396.

Dong, H. (2021). "Evaluating the impacts of transit-oriented developments (TODs) on household transportation expenditures in California". In: *Journal of Transport Geography* 90, p. 102946.

DTCA, J. (2015). "The Project on the Revision and Updating of the Strategic Transport Plan for Dhaka". In: *Dhaka Transport Coordination Authority (DTCA)*.

Duffy, F. N. (2018). "Against the grain: why is timber underutilized in the Irish construction industry, given its environmental properties?" In: *Against the Grain*, p. 1.

Edelenbosch, O. Y., D. McCollum, D. Van Vuuren, C. Bertram, S. Carrara, H. Daly, S. Fujimori, A. Kitous, P Kyle, E. Ó. Broin, et al. (2017). "Decomposing passenger transport futures: Comparing results of global integrated assessment models". In: *Transportation Research Part D: Transport and Environment* 55, pp. 281–293.

Eggimann, S., J. W. Hall, and N. Eyre (2019). "A high-resolution spatio-temporal energy demand simulation to explore the potential of heating demand side management with large-scale heat pump diffusion". In: *Applied Energy* 236, pp. 997–1010. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2018.12.052. URL: https://www.sciencedirect.com/science/article/pii/S0306261918318725.

EirGrid (2017). *Tomorrow's Energy Scenarios 2017*. Tech. rep. Dublin, Ireland: EirGrid, p. 39. URL: http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-Tomorrows-Energy-Scenarios-Report-2017.pdf.

EirGrid (2017). *Tomorrows Energy Scenarios Report 2017*. Tech. rep. URL: http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-Tomorrows-Energy-Scenarios-Report-2017.pdf.

EirGrid (2021). *All-Island Generation Capacity Statement 2021-2030*. Tech. rep. EirGrid, p. 1. URL: https://www.eirgridgroup.com/site-files/library/EirGrid/208281-All-Island-Generation-Capacity-Statement-LR13A.pdf.

Ek, K., L. Wårell, and L. Andersson (2021). "Motives for walking and cycling when commuting–differences in local contexts and attitudes". In: *European Transport Research Review* 13, pp. 1–12.

Electric Ireland (2021). *Energy efficient water heating*. URL: https://www.electricireland.ie/residential/help/efficiency/energy-efficient-water-heating.

Ellis, P. and M. Roberts (2015). *Leveraging urbanization in South Asia: Managing spatial transformation for prosperity and livability*. World Bank Publications.

Elmallah, S., A. M. Brockway, and D. Callaway (2022). "Can distribution grid infrastructure accommodate residential electrification and electric vehicle adoption in Northern California?" In: *Environmental Research: Infrastructure and Sustainability* 2.4, p. 045005.

Emodi, N. V., C. Okereke, F. I. Abam, O. E. Diemuodeke, K. Owebor, and U. A. Nnamani (2022). "Transport sector decarbonisation in the Global South: A systematic literature review". In: *Energy Strategy Reviews* 43, p. 100925.

Environment Protection Agency (2021). *Latest emissions data*. URL: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/latest-emissions-data/#. (accessed: 02.10.2021).

Eom, J., J. Edmonds, V. Krey, N. Johnson, T. Longden, G. Luderer, K. Riahi, and D. P. Van Vuuren (2015). "The impact of near-term climate policy choices on technology and emission transition pathways". In: *Technological Forecasting and Social Change* 90, pp. 73–88.

European Academies Science Advisory Council (2018). *Negative emission technologies: What role in meeting Paris Agreement targets?* Tech. rep. 35. European Academies Science Advi-

sory Council, p. 37. URL: https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf.

Fagiani, R., J. C. Richstein, R. Hakvoort, and L. De Vries (2014). "The dynamic impact of carbon reduction and renewable support policies on the electricity sector". In: *Utilities Policy* 28, pp. 28–41.

Fatima, E. and R. Kumar (2014). "Introduction of public bus transit in Indian cities". In: *International Journal of Sustainable Built Environment* 3.1, pp. 27–34.

Fell, M. J., S. Pye, and I. Hamilton (2020). "Capturing the distributional impacts of long-term low-carbon transitions". In: *Environmental Innovation and Societal Transitions* 35, pp. 346–356.

Fishman, T., N. Heeren, S. Pauliuk, P. Berrill, Q. Tu, P. Wolfram, and E. G. Hertwich (2021). "A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling". In: *Journal of Industrial Ecology* 25.2, pp. 305–320.

Fitiwi, D. Z., M. Lynch, and V. Bertsch (2020a). "Enhanced network effects and stochastic modelling in generation expansion planning: Insights from an insular power system". In: *Socio-Economic Planning Sciences*, p. 100859.

Fitiwi, D. Z., M. Lynch, and V. Bertsch (2020b). "Power system impacts of community acceptance policies for renewable energy deployment under storage cost uncertainty". In: *Renewable Energy* 156, pp. 893–912.

Flensburg, Halmstad and Aalborg Universities (2019). *Irish Heat Atlas*. Accessed: 27-01-2023. URL: https://euf.maps.arcgis.com/apps/webappviewer/index.html?id=101b7da79a7d4e09a92402bd4ce8384c.

Fodstad, M., P. C. del Granado, L. Hellemo, B. R. Knudsen, P. Pisciella, A. Silvast, C. Bordin, S. Schmidt, and J. Straus (2022). "Next frontiers in energy system modelling: A review on challenges and the state of the art". In: *Renewable and Sustainable Energy Reviews* 160, p. 112246.

Forster, J., N. E. Vaughan, C. Gough, I. Lorenzoni, and J. Chilvers (2020). "Mapping feasibilities of greenhouse gas removal: key issues, gaps and opening up assessments". In: *Global Environmental Change* 63, p. 102073.

Fragkos, P. (2020). "Global Energy System Transformations to 1.5° C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets". In: *Energy Technology* 8.9, p. 2000395.

Fragkos, P., H. L. van Soest, R. Schaeffer, L. Reedman, A. C. Köberle, N. Macaluso, S. Evangelopoulou, A. De Vita, F. Sha, C. Qimin, et al. (2021). "Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States". In: *Energy* 216, p. 119385.

Fricko, O., P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Strubegger, H. Valin, M. Amann, et al. (2017). "The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century". In: *Global Environmental Change* 42, pp. 251–267.

Fu, X., J. Cheng, L. Peng, M. Zhou, D. Tong, and D. L. Mauzerall (2024). "Co-benefits of transport demand reductions from compact urban development in Chinese cities". In: *Nature Sustainability*, pp. 1–11.

Gambhir, A. (2019). "Planning a low-carbon energy transition: what can and can't the models tell us?" In: *Joule* 3.8, pp. 1795–1798.

García-Gusano, D., K. Espegren, A. Lind, and M. Kirkengen (2016). *The role of the discount rates in energy systems optimisation models*. DOI: 10.1016/j.rser.2015.12.359.

Gaur, A., O. Balyk, J. Glynn, V. Aryanpur, J. McGuire, A. Smith, X. Yue, A. Chiodi, M. Gargiulo, and H. Daly (2022a). "TIMES-Ireland Model (v1.0.0-s.1)". In: *Zenodo*. DOI: https://doi.org/10.5281/zenodo.6531582.

Gaur, A., O. Balyk, J. Glynn, J. Curtis, and H. Daly (2022b). "Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland". In: *Renewable and Sustainable Energy Transition*, p. 100024. ISSN: 2667095X. DOI: 10.1016/j.rset.2022.100024. URL: https://linkinghub.elsevier.com/retrieve/pii/S2667095X22000083.

Gaur, A., J. McGuire, V. O'Riordan, J. Curtis, and H. Daly (2024). "Dispersed settlement patterns can hinder the net-zero transition: Evidence from Ireland". In: *Energy Strategy Reviews* 51, p. 101296.

Gaur, A. S., D. Z. Fitiwi, and J. Curis (2019). "Implications of Power-to-Heat on Transmission Expansion Needs: A Real Life Case Study". In: *2019 IEEE Milan PowerTech*. IEEE, pp. 1–6.

Gaur, A. S., D. Z. Fitiwi, and J. Curtis (2021). "Heat pumps and our low-carbon future: A comprehensive review". In: *Energy Research & Social Science* 71, p. 101764.

Gaur, A. S., D. Z. Fitiwi, M. Lynch, and G. Longoria (2022c). "Implications of heating sector electrification on the Irish power system in view of the Climate Action Plan". In: *Energy Policy* 168, p. 113136. DOI: https://doi.org/10.1016/j.enpol.2022.113136.

Geels, F. W., T. Schwanen, S. Sorrell, K. Jenkins, and B. K. Sovacool (2018). "Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates". In: *Energy Research & Social Science* 40, pp. 23–35.

Geels, F. W., B. K. Sovacool, T. Schwanen, and S. Sorrell (2017). "The socio-technical dynamics of low-carbon transitions". In: *Joule* 1.3, pp. 463–479.

Geofabrik (2018). *Ireland and Northern Ireland*. Accessed: 03-11-2022. URL: https://download.geofabrik.de/europe/ireland-and-northern-ireland.html.

Geshkov, M. V. and J. S. DeSalvo (2012). "The effect of land-use controls on the spatial size of US urbanized areas". In: *Journal of Regional Science* 52.4, pp. 648–675.

Gi, K., F. Sano, and K. Akimoto (2020). "Bottom-up development of passenger travel demand scenarios in Japan considering heterogeneous actors and reflecting a narrative of future socioeconomic change". In: *Futures* 120, p. 102553.

Gidden, M. J., K. Riahi, S. J. Smith, S. Fujimori, G. Luderer, E. Kriegler, D. P. van Vuuren, M. van den Berg, L. Feng, D. Klein, K. Calvin, J. C. Doelman, S. Frank, O. Fricko, M. Harmsen, T. Hasegawa, P. Havlik, J. Hilaire, R. Hoesly, J. Horing, A. Popp, E. Stehfest, and K. Takahashi (2019). "Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century". In: *Geoscientific Model Development* 12.4, pp. 1443–1475. DOI: 10.5194/gmd-12-1443-2019. URL: https://www.geosci-model-dev.net/12/1443/2019/.

Gill, A. R., K. K. Viswanathan, and S. Hassan (2018). "The Environmental Kuznets Curve (EKC) and the environmental problem of the day". In: *Renewable and Sustainable Energy Reviews* 81, pp. 1636–1642.

Glynn, J., M. Gargiulo, A. Chiodi, P. Deane, F. Rogan, and B. Ó Gallachóir (2019). "Zero carbon energy system pathways for Ireland consistent with the Paris Agreement". In: *Climate Policy* 19.1, pp. 30–42. ISSN: 17527457. DOI: 10.1080/14693062.2018.1464893. URL: https://www.tandfonline.com/doi/full/10.1080/14693062.2018.1464893.

Goel, P. and P. Haldar (2020a). "Shared ride-hailing service in India: an analysis of consumers' intention to adopt". In: *International Journal of Business and Emerging Markets* 12.3, pp. 336–353.

Goel, R. and D. Mohan (2020b). "Investigating the association between population density and travel patterns in Indian cities—An analysis of 2011 census data". In: *Cities* 100, p. 102656.

GoI (2011). *Table B-28: 'Other workers' by distance from residence to place of work and mode of travel to place of work, India - 2011*.

Golubchikov, O. and K. O'Sullivan (2020). "Energy periphery: Uneven development and the precarious geographies of low-carbon transition". In: *Energy and Buildings* 211, p. 109818.

González-Ochoa, D. J. (2022). "Policy-Induced Suburbanization: Mass-Produced Housing and Location Choices in Tijuana, Mexico". In: *Housing Policy Debate*, pp. 1–18.

Government of Ireland (2018). *Project Ireland 2040 - National Planning Framework*. Tech. rep. Department of Housing, Planning and Local Government. URL: https://npf.ie/.

Government of Ireland, (2021). *Climate Action and Low Carbon Development (Amendment) Bill*. URL: https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/.

Government of Ireland (2022). *Sectoral Emissions Ceilings*. Tech. rep. URL: https://www.gov.ie/pdf/?file=https://assets.gov.ie/234926/2ebb2431-d558-4a54-a15c-605817c37b2f.pdf#page=null.

Government of Ireland, (2023). *Climate Action Plan 2023*. Tech. rep. Department of the Environment, Climate and Communications. URL: https://assets.gov.ie/243585/9942d689-2490-4ccf-9dc8-f50166bab0e7.pdf.

Government of Nepal (2018). *National Environmentally Sustainable Transport (EST) Strategy for Nepal*. URL: https://www.uncrd.or.jp/content/documents/2123NESTS-Nepal_140430Meeting_1st-Draft.pdf.

Government of Pakistan (2019). *Pakistan Statsitical Yearbook 2019*. Tech. rep. Pakistan Bureau of Statistics. URL: https://www.pbs.gov.pk/sites/default/files/other/yearbooks/Pakistan_Statistical_yearbook_2019.pdf.

Grant, N., A. Hawkes, T. Napp, and A. Gambhir (2021). "Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways". In: *One Earth* 4.11, pp. 1588–1601.

Grubb, H. and A. Mason (2001). "Long lead-time forecasting of UK air passengers by Holt–Winters methods with damped trend". In: *International Journal of Forecasting* 17.1, pp. 71–82. ISSN: 01692070. DOI: 10.1016/S0169-2070(00)00053-4. URL: https://linkinghub.elsevier.com/retrieve/pii/S0169207000000534.

Grubler, A., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, et al. (2018). "A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies". In: *Nature Energy* 3.6, pp. 515–527.

Gupta, D. and A. Garg (2020). "Sustainable development and carbon neutrality: Integrated assessment of transport transitions in India". In: *Transportation Research Part D: Transport and Environment* 85, p. 102474.

Gupta, S. and K. Sinha (2022). "Assessing the Factors Impacting Transport Usage of Mobility App Users in the National Capital Territory of Delhi, India". In: *Sustainability* 14.21, p. 13768.

Gustafsson, M., M. S. Gustafsson, J. A. Myhren, C. Bales, and S. Holmberg (2016). "Techno-economic analysis of energy renovation measures for a district heated multi-family house". In: *Applied energy* 177, pp. 108–116.

Haberl, H., M. Schmid, W. Haas, D. Wiedenhofer, H. Rau, and V. Winiwarter (2021). "Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism". In: *Ecological Economics* 182, p. 106949.

Haberl, H., D. Wiedenhofer, D. Virág, G. Kalt, B. Plank, P. Brockway, T. Fishman, D. Hausknost, F. Krausmann, B. Leon-Gruchalski, et al. (2020). "A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights". In: *Environmental Research Letters* 15.6, p. 065003.

Haddad, E. A., R. S. Vieira, M. S. Jacob, A. W. Guerrini, E. Germani, F. Barreto, M. L. Bucalem, and P. L. Sayon (2019). "A socioeconomic analysis of ride-hailing emergence and expansion in São Paulo, Brazil". In: *Transportation Research Interdisciplinary Perspectives* 1, p. 100016.

Hamiduddin, I. (2023). "Why the car is not always king in Global South cities: Evidence from Ulaanbaatar". In: *Urban Planning* 8.3, pp. 14–26.

Hammond, G. P. (2014). "Editorial: Progress in energy demand reduction – from here to 2050". In: *Proceedings of the Institution of Civil Engineers - Energy* 167.3, pp. 89–104. DOI: 10.1680/ener.167.3.89. URL: https://doi.org/10.1680/ener.167.3.89.

Hanna, R. and R. Gross (2021). "How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners". In: *Energy Policy* 149, p. 111984.

Hao, H., Y. Geng, H. Wang, and M. Ouyang (2014). "Regional disparity of urban passenger transport associated GHG (greenhouse gas) emissions in China: a review". In: *Energy* 68, pp. 783–793.

Hardt, L, P Brockway, P Taylor, J Barrett, R Gross, and P Heptonstall (2019). *Modelling demand-side energy policies for climate change mitigation in the UK: a rapid evidence assessment.*

Hasnath, S. A. (2013). "Urban Futures, Urban Challenges". In: *South Asia 2060: Envisioning Regional Futures*. Ed. by A. Najam and M. Yusuf. Anthem Nineteenth-Century Series. Anthem Press, 169–176.

Hasselwander, M. and J. F. Bigotte (2023). "Mobility as a Service (MaaS) in the Global South: research findings, gaps, and directions". In: *European Transport Research Review* 15.1, pp. 1–16.

Hasselwander, M., J. F. Bigotte, A. P. Antunes, and R. G. Sigua (2022). "Towards sustainable transport in developing countries: Preliminary findings on the demand for mobility-as-a-service (MaaS) in metro Manila". In: *Transportation Research Part A: Policy and Practice* 155, pp. 501–518.

Henao, A. and W. E. Marshall (2019). "The impact of ride-hailing on vehicle miles traveled". In: *Transportation* 46.6, pp. 2173–2194.

Henke, H., M. Dekker, F. Lombardi, R. Pietzcker, P. Fragkos, B. Zakeri, R. Rodrigues, J. Sitarz, J. Emmerling, A. Fattahi, et al. (2023). "Comparing energy system optimization models and integrated assessment models: Relevance for energy policy advice". In: *Open Research Europe* 3.

Herman, K. S. (2021). "Green growth and innovation in the Global South: a systematic literature review". In: *Innovation and Development*, pp. 1–27.

Hernandez-Palacio, F. (2017). "A transition to a denser and more sustainable city: Factors and actors in Trondheim, Norway". In: *Environmental Innovation and Societal Transitions* 22, pp. 50–62.

Hickel, J. (2019). "Degrowth: a theory of radical abundance". In: *Real-world Economics Review* 87.19, pp. 54–68.

Hickel, J. and G. Kallis (2020). "Is green growth possible?" In: *New Political Economy* 25.4, pp. 469–486.

Hilaire, J., J. C. Minx, M. W. Callaghan, J. Edmonds, G. Luderer, G. F. Nemet, J. Rogelj, and M. del Mar Zamora (2019). "Negative emissions and international climate goals—learning from and about mitigation scenarios". In: *Climatic Change* 157.2, pp. 189–219.

Hoare, C., R. Aghamolaei, M. Lynch, A. Gaur, and J. O'Donnell (2021). "A Linked Data Approach to Multi-Scale Energy Modelling". In: *Working paper*.

Holmes, T. (2021). "Roles, responsibilities and capacities: Theorizing space, social practice, and the relational constitution of energy demand in and beyond Manchester". In: *Energy Research & Social Science* 82, p. 102293.

Holz, C., L. S. Siegel, E. Johnston, A. P. Jones, and J. Sterman (2018). "Ratcheting ambition to limit warming to 1.5 C–trade-offs between emission reductions and carbon dioxide removal". In: *Environmental Research Letters* 13.6, p. 064028.

Hynes, M., O. Bolbocean, M. McNally, M. Conroy, D. Bednarczuk, F. Hyland, E. Coyne, and C. Marie (2018). ""Howya gettin'on?" Investigating Public Transport Satisfaction Levels in Galway, Ireland". In: *Urban Science* 2.4, p. 102.

Ibraeva, A., G. H. de Almeida Correia, C. Silva, and A. P. Antunes (2020). "Transit-oriented development: A review of research achievements and challenges". In: *Transportation Research Part A: Policy and Practice* 132, pp. 110–130.

IEA (2021). *India Energy Outlook 2021*. OECD Publishing.

IEA (2021). *Net Zero by 2050 A Roadmap for the Global Energy Sector*. Tech. rep. URL: https://www.iea.org/reports/net-zero-by-2050.

IEA (2023). *Energy Statistics Data Browser*. URL: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser.

IEA-ETSAP (2020). *etsap-TIMES/TIMES_model: Latest TIMES Version*. DOI: 10.5281/zenodo.3865460. URL: https://doi.org/10.5281/zenodo.3865460.

IIASA and contributing modeling teams (2024). *SSP Scenario Explorer (SSP 3.0, Release January 2024)*. URL: https://data.ece.iiasa.ac.at/ssp/#/about.

International Energy Agency (2020). *World Energy Outlook 2020*, p. 464. DOI: https://doi.org/https://doi.org/10.1787/557a761b-en. URL: https://www.oecd-ilibrary.org/content/publication/557a761b-en.

ITF (2022). "ITF South and Southwest Asia transport outlook". In: *International Transport Forum Policy Papers* 104.

Jain, A (2013). "Sustainable urban mobility in southern Asia". In: *unpublished regional study prepared for the Global Report on Human Settlements*.

Jain, G. V. and S. A. Sharma (2019). "Spatio-temporal analysis of urban growth in selected small, medium and large Indian cities". In: *Geocarto International* 34.8, pp. 887–908.

Jain, H., G. Tiwari, and M. Zuidgeest (2010). "Evaluating bicyclists comfort and safety perception". In: *12th World Conference on Transport Research, WCTR 2010*. WCTR Society, pp. 1–19.

Jain, S., P. Aggarwal, P. Kumar, S. Singhal, and P. Sharma (2014). "Identifying public preferences using multi-criteria decision making for assessing the shift of urban commuters from private to public transport: A case study of Delhi". In: *Transportation Research Part F: Traffic Psychology and Behaviour* 24, pp. 60–70.

Jamal, M. T. and N. A. Khan (2021). "Adoption of telecommuting and its impact on traffic congestion, energy consumption and emission levels in India". In: *Interdisciplinary Environmental Review* 21.3-4, pp. 249–268.

Jaramillo, P, S. K Ribeiro, P Newman, S Dhar, O. Diemuodeke, T Kajino, D. Lee, S. Nugroho, X Ou, A Hammer Strømman, and J Whitehead (2022). "Transport". In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]*. DOI: 10.1017/9781009157926.012.

Javaid, A., F. Creutzig, and S. Bamberg (2020). "Determinants of low-carbon transport mode adoption: systematic review of reviews". In: *Environmental Research Letters* 15.10, p. 103002.

Javid, M. A., T. Mehmood, H. M. Asif, A. U. Vaince, and M. Raza (2017). "Travelers' attitudes toward carpooling in Lahore: motives and constraints". In: *Journal of Modern Transportation* 25, pp. 268–278.

Johnson, E., S. Betts-Davies, and J. Barrett (2023). "Comparative analysis of UK net-zero scenarios: The role of energy demand reduction". In: *Energy Policy* 179, p. 113620.

Ju, Y., M. Sugiyama, E. Kato, Y. Matsuo, K. Oshiro, and D. S. Herran (2021). "Industrial decarbonization under Japan's national mitigation scenarios: a multi-model analysis". In: *Sustainability Science* 16.2, pp. 411–427.

Kainuma, M, T Masui, K Oshiro, and R Zhang (2017). "Pathways to deep decarbonization of the passenger transport sector in Japan". In: *Institute for Sustainable Development and International Relations (IDDRI), Paris*.

Kamargianni, M., W. Li, M. Matyas, and A. Schäfer (2016). "A critical review of new mobility services for urban transport". In: *Transportation Research Procedia* 14, pp. 3294–3303.

Kamble, T. and S. Bahadure (2021). "Investigating application of compact urban form in central Indian cities". In: *Land Use Policy* 109, p. 105694.

Kang, J., H. Kong, Z. Lin, and A. Dang (2022). "Mapping the dynamics of electric vehicle charging demand within Beijing's spatial structure". In: *Sustainable Cities and Society* 76, p. 103507. ISSN: 2210-6707. DOI: https://doi.org/10.1016/j.scs.2021.103507. URL: https://www.sciencedirect.com/science/article/pii/S2210670721007733.

Kanimozhee, S and S. Srikanth (2023). "Modeling of COVID-19's impact on employee's travel behavior". In: *Innovative Infrastructure Solutions* 8.7, p. 198.

Kant, P., P. K. Machavarapu, and H. Gajjar (2023). "Assessment of drivers and barriers in the adoption of Mobility as a Service (MaaS): a case study of Noida, India". In: *Urban, Planning and Transport Research* 11.1, p. 2247044.

Kavousian, A., R. Rajagopal, and M. Fischer (2013). "Determinants of residential electricity consumption: Using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior". In: *Energy* 55, pp. 184–194.

Kennedy, C., N Ibrahim, and D Hoornweg (2014). "Low-carbon infrastructure strategies for cities". In: *Nature Climate Change* 4.5, pp. 343–346.

Keppo, I., I. Butnar, N. Bauer, M. Caspani, O. Edelenbosch, J. Emmerling, P. Fragkos, C. Guivarch, M. Harmsen, J. Lefevre, et al. (2021). "Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models". In: *Environmental Research Letters* 16.5, p. 053006.

Kermeli, K., W. H. Graus, and E. Worrell (2014). "Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector". In: *Energy Efficiency* 7.6, pp. 987–1011.

Kesicki, F. and G. Anandarajah (2011). "The role of energy-service demand reduction in global climate change mitigation: Combining energy modelling and decomposition analysis". In: *Energy Policy* 39.11, pp. 7224–7233.

Kikstra, J. S., A. Mastrucci, J. Min, K. Riahi, and N. D. Rao (2021). "Decent living gaps and energy needs around the world". In: *Environmental Research Letters* 16.9, p. 095006.

Knoema (2015). *Sri Lanka - Number of passengers carried by railways*.

Knowles, R. D., F. Ferbrache, and A. Nikitas (2020). "Transport's historical, contemporary and future role in shaping urban development: Re-evaluating transit oriented development". In: *Cities* 99, p. 102607.

Köhler, J., F. De Haan, G. Holtz, K. Kubeczko, E. A. Moallemi, G. Papachristos, and E. Chappin (2018). "Modelling sustainability transitions: an assessment of approaches and challenges". In.

Kovács, K. D. and I. Haidu (2022). "Tracing out the effect of transportation infrastructure on NO_2 concentration levels with Kernel Density Estimation by investigating successive COVID-19-induced lockdowns". In: *Environmental Pollution* 309, p. 119719. DOI: https://doi.org/10.1016/j.envpol.2022.119719.

KPMG (2017). *National Transport Policy 2017 POLICY PROTOCOL REPORT*. URL: https://www.moic.gov.bt/media/files/Draft-Final-PPR.pdf.

Krey, V, P Havlik, P. N Kishimoto, O Fricko, J Zilliacus, M Gidden, M Strubegger, G Kartasasmita, T Ermolieva, N Forsell, M Gusti, N Johnson, J Kikstra, G Kindermann, P Kolp, F Lovat, D. L McCollum, J Min, S Pachauri, P. S. C, S Rao, J Rogelj, G Ünlü, H Valin, P Wagner, B Zakeri, M Obersteiner, and K Riahi (2020). *MESSAGEix-GLOBIOM Documentation*

– *2020 release*. Tech. rep. International Institute for Applied Systems Analysis (IIASA). DOI: 10.22022/iacc/03-2021.17115. URL: https://pure.iiasa.ac.at/id/eprint/17115.

Krey, V. (2014). "Global energy-climate scenarios and models: a review". In: *Wiley Interdisciplinary Reviews: Energy and Environment* 3.4, pp. 363–383.

Kuhnhenn, K., L. F. C. da Costa, E. Mahnke, L. Schneider, and S. Lange (2020). *A societal transformation scenario for staying below 1.5° C*. Tech. rep. Schriften zu Wirtschaft und Soziales.

Kumar, P. P., C. R. Sekhar, and M. Parida (2020). "Identification of neighborhood typology for potential transit-oriented development". In: *Transportation Research Part D: Transport and Environment* 78, p. 102186.

Lamb, W. F., T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J. G. Olivier, D. Wiedenhofer, G. Mattioli, A. Al Khourdajie, J. House, et al. (2021). "A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018". In: *Environmental Research Letters* 16.7, p. 073005.

Lantz, T. L., G. Ioppolo, T. Yigitcanlar, and R. Arbolino (2021). "Understanding the correlation between energy transition and urbanization". In: *Environmental Innovation and Societal Transitions* 40, pp. 73–86.

Larkin, A., J. Kuriakose, M. Sharmina, and K. Anderson (2018). "What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations". In: *Climate policy* 18.6, pp. 690–714.

Law, T. H., H. Hamid, and C. N. Goh (2015). "The motorcycle to passenger car ownership ratio and economic growth: A cross-country analysis". In: *Journal of Transport Geography* 46, pp. 122–128.

Le Quéré, C., J. I. Korsbakken, C. Wilson, J. Tosun, R. Andrew, R. J. Andres, J. G. Canadell, A. Jordan, G. P. Peters, and D. P. van Vuuren (2019). "Drivers of declining CO 2 emissions in 18 developed economies". In: *Nature Climate Change* 9.3, pp. 213–217.

Leahy, E. and S. Lyons (2010). "Energy use and appliance ownership in Ireland". In: *Energy Policy* 38.8, pp. 4265–4279.

Lee, H., K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. Thorne, C. Trisos, J. Romero, P. Aldunce, and A. C. Ruane (2024). "CLIMATE CHANGE 2023 synthesis report summary for policymakers". In: *CLIMATE CHANGE 2023 Synthesis Report: Summary for Policymakers*.

Levesque, A., R. C. Pietzcker, and G. Luderer (2019). "Halving energy demand from buildings: The impact of low consumption practices". In: *Technological Forecasting and Social Change* 146, pp. 253–266.

Li, F. G. (2017). "Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions". In: *Energy Strategy Reviews* 15, pp. 57–71.

Li, X., Q. Xiao, Y. Zhu, and Y. Yang (2022). "Influence of TOD modes on passenger travel behavior in urban rail transit systems". In: *Urban Rail Transit* 8.3-4, pp. 175–183.

Li, Y.-H. and W.-C. Kao (2017). "Performance analysis and economic assessment of solar thermal and heat pump combisystems for subtropical and tropical region". In: *Solar Energy* 153, pp. 301–316.

Lian, L., W. Tian, H. Xu, and M. Zheng (2018). "Modeling and forecasting passenger car ownership based on symbolic regression". In: *Sustainability (Switzerland)* 10.7, p. 2275. ISSN: 20711050. DOI: 10.3390/su10072275. URL: http://www.mdpi.com/2071-1050/10/7/2275.

Liu, J.-Y., S. Fujimori, K. Takahashi, T. Hasegawa, W. Wu, Y. Geng, J. Takakura, and T. Masui (2020). "The importance of socioeconomic conditions in mitigating climate change impacts and achieving Sustainable Development Goals". In: *Environmental Research Letters* 16.1, p. 014010.

Lo Piano, S., M. J. Lőrincz, A. Puy, S. Pye, A. Saltelli, S. T. Smith, and J. van der Sluijs (2023). "Unpacking the modeling process for energy policy making". In: *Risk Analysis*.

Longoria, G., M. Lynch, and J. Curtis (2021). "Green hydrogen for heating and its impact on the power system". In: *International Journal of Hydrogen Energy*.

Loulou, R., G. Goldstein, A. Kanudia, A. Lettila, and U. Remme (2016a). *Documentation for the TIMES Model Part I: TIMES Concepts and Theory*.

Loulou, R., A. Lehtila, A. Kanudia, U. Remme, and G. Goldstein (2016b). *Documentation for the TIMES Model Part II: Reference Manual*.

Lowes, R., J. Rosenow, M. Qadrdan, and J. Wu (2020a). "Hot stuff: Research and policy principles for heat decarbonisation through smart electrification". In: *Energy Research & Social Science* 70, p. 101735.

Lowes, R. and B. Woodman (2020b). "Disruptive and uncertain: Policy makers' perceptions on UK heat decarbonisation". In: *Energy policy* 142, p. 111494.

Lu, L., P. V. Preckel, D. Gotham, and A. L. Liu (2016). "An assessment of alternative carbon mitigation policies for achieving the emissions reduction of the Clean Power Plan: Case study for the state of Indiana". In: *Energy Policy* 96, pp. 661–672.

Lu, Q., G. A. Narsilio, G. R. Aditya, and I. W. Johnston (2017). "Economic analysis of vertical ground source heat pump systems in Melbourne". In: *Energy* 125, pp. 107–117.

Luciani, G. (2020). "The impacts of the energy transition on growth and income distribution". In: *The geopolitics of the global energy transition*, pp. 305–318.

Luh, S., R. Kannan, T. J. Schmidt, and T. Kober (2022). "Behavior matters: A systematic review of representing consumer mobility choices in energy models". In: *Energy Research & Social Science* 90, p. 102596.

Lv, T. and X. Wu (2019). "Using panel data to evaluate the factors affecting transport energy consumption in China's three regions". In: *International Journal of Environmental Research and Public Health* 16.4, p. 555.

Machavarapu, P. K. and S. Ram (2022). "Infrastructure evaluation, role of public bike sharing systems–Global and Indian context". In: *Case Studies on Transport Policy* 10.3, pp. 1841–1854.

Madlener, R. and Y. Sunak (2011). "Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management?" In: *Sustainable Cities and Society* 1.1, pp. 45–53. ISSN: 2210-6707. DOI: https://doi.org/10.1016/j.scs.2010.08.006. URL: https://www.sciencedirect.com/science/article/pii/S2210670710000077.

Majid, H., A. Malik, and K. Vyborny (2018). "Infrastructure investments and public transport use: Evidence from Lahore, Pakistan". In: *International Growth Center*.

Maluf, A. (2014). "Development of Sao Paulo Integrated Bus Rapid Network : 2002-2013". In: May, pp. 47–57.

Mandić, A., S. K. Walia, and S. M. Rasoolimanesh (2023). "Gen Z and the flight shame movement: examining the intersection of emotions, biospheric values, and environmental travel behaviour in an Eastern society". In: *Journal of Sustainable Tourism*, pp. 1–23.

Mansoor, U., M. T. Kashifi, F. R. Safi, and S. M. Rahman (2022). "A review of factors and benefits of non-motorized transport: a way forward for developing countries". In: *Environment, Development and Sustainability* 24.2, pp. 1560–1582.

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W Moufouma-Okia, C Péan, R Pidcock, et al. (2018). "Global warming of 1.5 C". In: *An IPCC Special Report on the impacts of global warming of* 1, pp. 1–9.

Mastrucci, A., J. Min, A. Usubiaga-Liaño, and N. D. Rao (2020). "A framework for modelling consumption-based energy demand and emission pathways". In: *Environmental Science & Technology* 54.3, pp. 1799–1807.

Mastrucci, A., L. Niamir, B. Boza-Kiss, N. Bento, D. Wiedenhofer, J. Streeck, S. Pachauri, C. Wilson, S. Chatterjee, F. Creutzig, et al. (2023). "Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs". In: *Annual Review of Environment and Resources* 48, pp. 761–792.

Mattson, J. (2020). "Relationships between density, transit, and household expenditures in small urban areas". In: *Transportation Research Interdisciplinary Perspectives* 8, p. 100260.

Mbah, M. F., A. Shingruf, and P. Molthan-Hill (2022). "Policies and practices of climate change education in South Asia: towards a support framework for an impactful climate change adaptation". In: *Climate Action* 1.1, pp. 1–18.

Mc Guire, J., F. Rogan, O. Balyk, T. Mac Uidhir, A. Gaur, and H. Daly (2023). "Developing decarbonisation pathways in changing TIMES for Irish homes". In: *Energy Strategy Reviews* 47, p. 101086. ISSN: 2211-467X. DOI: https://doi.org/10.1016/j.esr.2023.101086.

McCollum, D. L., A. Gambhir, J. Rogelj, and C. Wilson (2020). "Energy modellers should explore extremes more systematically in scenarios". In: *Nature Energy* 5.2, pp. 104–107.

McCollum, D. L., C. Wilson, M. Bevione, S. Carrara, O. Y. Edelenbosch, J. Emmerling, C. Guivarch, P. Karkatsoulis, I. Keppo, V. Krey, et al. (2018). "Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles". In: *Nature Energy* 3.8, pp. 664–673.

McCollum, D. L., C. Wilson, H. Pettifor, K. Ramea, V. Krey, K. Riahi, C. Bertram, Z. Lin, O. Y. Edelenbosch, and S. Fujisawa (2017). "Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices". In: *Transportation Research Part D: Transport and Environment* 55, pp. 322–342.

McGarry, C., J. Dixon, J. Flower, W. Bukhsh, C. Brand, K. Bell, and S. Galloway (2024). "Electrified heat and transport: Energy demand futures, their impacts on power networks and what it means for system flexibility". In: *Applied Energy* 360, p. 122836.

Mees, P. (2014). "TOD and multi-modal public transport". In: *Planning Practice & Research* 29.5, pp. 461–470.

Méjean, A., C. Guivarch, J. Lefèvre, and M. Hamdi-Cherif (2019). "The transition in energy demand sectors to limit global warming to 1.5 C". In: *Energy Efficiency* 12.2, pp. 441–462.

Meshram, A., P. Choudhary, and N. R. Velaga (2020). "Assessing and modelling perceived safety and comfort of women during ridesharing". In: *Transportation Research Procedia* 48, pp. 2852–2869.

Meyer, J., H. Becker, P. M. Bösch, and K. W. Axhausen (2017). "Autonomous vehicles: The next jump in accessibilities?" In: *Research in Transportation Economics* 62, pp. 80–91.

Millard-Ball, A. (2019). "The autonomous vehicle parking problem". In: *Transport Policy* 75, pp. 99–108.

Millward-Hopkins, J., J. K. Steinberger, N. D. Rao, and Y. Oswald (2020). "Providing decent living with minimum energy: A global scenario". In: *Global Environmental Change* 65, p. 102168.

Ministry of Housing and Urban Affairs (2015). "National transit oriented development (TOD) policy". In: *New Delhi: Government of India*.

Ministry of Railways (2020). *Annual report and accounts 2019-20*. URL: https://indianrailways.gov.in/railwayboard/uploads/directorate/stat_econ/Annual-Reports-2019-2020/Indian-Railways-Annual%20-Report-Accounts%20-2019-20-English.pdf.

Ministry of Transport (2009). *Draft National Policy on Transport In Sri Lanka*. URL: https://www.transport.gov.lk/web/images/downloads/tp.pdf.

Mitropoulos, L., A. Kortsari, and G. Ayfantopoulou (2021). "A systematic literature review of ride-sharing platforms, user factors and barriers". In: *European Transport Research Review* 13, pp. 1–22.

Moreno, A. T., A. Michalski, C. Llorca, and R. Moeckel (2018). "Shared autonomous vehicles effect on vehicle-km traveled and average trip duration". In: *Journal of Advanced Transportation* 2018.

Moriarty, P. (2022). "Making urban travel sustainable: Travel reductions are needed". In: *Cleaner Production Letters*, p. 100010.

Muzayanah, I. F. U., H. H. Lean, D. Hartono, K. D. Indraswari, and R. Partama (2022). "Population density and energy consumption: A study in Indonesian provinces". In: *Heliyon* 8.9, e10634.

Nadeem, M., M. Matsuyuki, and S. Tanaka (2023). "Impact of bus rapid transit in shaping transit-oriented development: evidence from Lahore, Pakistan". In: *Journal of Asian Architecture and Building Engineering*, pp. 1–14.

Nakshi, P. and A. K. Debnath (2021). "Impact of built environment on mode choice to major destinations in Dhaka". In: *Transportation Research Record* 2675.4, pp. 281–296.

Napp, T., S. Few, A Sood, D Bernie, A Hawkes, and A. Gambhir (2019). "The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets". In: *Applied Energy* 238, pp. 351–367.

Nasri, A. and L. Zhang (2014). "The analysis of transit-oriented development (TOD) in Washington, DC and Baltimore metropolitan areas". In: *Transport Policy* 32, pp. 172–179.

Nature Energy Editorial (2016). "The heat is on". In: *Nature Energy* 1.12. DOI: 10.1038/nenergy.2016.193.

Nayak, S. and D. Pandit (2021). "Potential of telecommuting for different employees in the Indian context beyond COVID-19 lockdown". In: *Transport Policy* 111, pp. 98–110.

NCAP (2019). *CLIMATE ACTION PLAN 2019*. en. Tech. rep. Government of Ireland. URL: https://www.dccae.gov.ie/en-ie/climate-action/topics/climate-action-plan/Pages/climate-action.aspx (visited on 02/28/2019).

Nelson, J., A. Mileva, J. Johnston, D. Kammen, M. Wei, and J. Greenblatt (2014). *Scenarios for Deep Carbon Emission Reductions from Electricity by 2050 in Western North America using the Switch Electric Power Sector Planning Model: California's Carbon Challenge Phase II, Volume II*. Tech. rep. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Nerini, F. F., O. Broad, D. Mentis, M. Welsch, M. Bazilian, and M. Howells (2016). "A cost comparison of technology approaches for improving access to electricity services". In: *Energy* 95, pp. 255–265.

Neves, R., H. Cho, and J. Zhang (2021). "State of the nation: customizing energy and finances for geothermal technology in the United States residential sector". In: *Renewable and Sustainable Energy Reviews* 137, p. 110463.

Ngo, N. S., T. Götschi, and B. Y. Clark (2021). "The effects of ride-hailing services on bus ridership in a medium-sized urban area using micro-level data: Evidence from the Lane Transit District". In: *Transport Policy* 105, pp. 44–53.

Niet, T., N. Arianpoo, K. Kuling, and A. S. Wright (2022). "Increasing the reliability of energy system scenarios with integrated modelling: a review". In: *Environmental Research Letters* 17.4, p. 043006.

Nishitateno, S. and P. J. Burke (2014). "The motorcycle Kuznets curve". In: *Journal of Transport Geography* 36, pp. 116–123.

Noussan, M. and S. Tagliapietra (2020). "The effect of digitalization in the energy consumption of passenger transport: An analysis of future scenarios for Europe". In: *Journal of Cleaner Production* 258, p. 120926.

Ó Gallachóir, B., P. Deane, J. Glynn, and F. Rogan (2020). *The Role of Energy Technology in Climate Mitigation in Ireland: Irish TIMES Phase 3*. Tech. rep. Dublin, Ireland: Environmental Protection Agency, p. 42. URL: https://www.epa.ie/publications/research/climate-change/Research{_}Report{_}326.pdf.

O'Callaghan, D. and S. Prior (2018). *Staff Paper 2018 Central Technical Appraisal Parameters Discount Rate, Time Horizon, Shadow Price of Public Funds and Shadow Price of Labour*. Tech. rep. Department of Public Expenditure and Reform, p. 70. URL: https://igees.gov.ie/wp-content/uploads/2019/07/Parameters-Paper-Final-Version.pdf.

OECD (2013). *What have we learned from attempts to introduce green-growth policies?* OECD Publishing.

OECD (2018). *Economic Outlook No 103 - July 2018 - Long-term baseline projections*. URL: https://stats.oecd.org/Index.aspx?DataSetCode=EO103_LTB.

— (2021). *Freight transport (indicator)*. DOI: 10.1787/708eda32-en.

OECD (2022). *National population distribution*. Accessed on 12 December 2022. DOI: 10.1787/7314f74f-en.

OECD (2022). *Passenger transport (indicator)*. DOI: 10.1787/463da4d1-en.

O'Riordan, V., F. Rogan, B. Ó. Gallachóir, T. Mac Uidhir, and H. Daly (2022). "How and why we travel–Mobility demand and emissions from passenger transport". In: *Transportation Research Part D: Transport and Environment* 104, p. 103195.

Oshiro, K., S. Fujimori, Y. Ochi, and T. Ehara (2021). "Enabling energy system transition toward decarbonization in Japan through energy service demand reduction". In: *Energy* 227, p. 120464.

Oswald, Y., A. Owen, and J. K. Steinberger (2020). "Large inequality in international and intranational energy footprints between income groups and across consumption categories". In: *Nature Energy* 5.3, pp. 231–239.

Ou, X., Z. Yuan, Y. Wang, and L. Ren (2022). "The Development of High-Speed Rail in China". In: URL: `https://transition-china.org/wp-content/uploads/2022/06/20220621_HSR-Study-English-Final.pdf`.

O'Riordan, V, F Rogan, B. Gallachóir, and H. Daly (2021). *Irish Passenger Transport Emissions and Mobility (IPTEM) Model V 2.8*.

Paladugula, A. L., N. Kholod, V. Chaturvedi, P. P. Ghosh, S. Pal, L. Clarke, M. Evans, P. Kyle, P. N. Koti, K. Parikh, et al. (2018). "A multi-model assessment of energy and emissions for India's transportation sector through 2050". In: *Energy Policy* 116, pp. 10–18.

Palmer, J., N. Terry, and P. Pope (2012). "How much energy could be saved by making small changes to everyday household behaviours". In: *A report for Department of Energy and Climate Change*.

Pastore, L. M., G. L. Basso, L. Cristiani, and L. de Santoli (2022). "Rising targets to 55% GHG emissions reduction–The smart energy systems approach for improving the Italian energy strategy". In: *Energy* 259, p. 125049.

Petrović, S., A. Colangelo, O. Balyk, C. Delmastro, M. Gargiulo, M. B. Simonsen, and K. Karlsson (2020). "The role of data centres in the future Danish energy system". In: *Energy* 194, p. 116928.

Pfenninger, S., A. Hawkes, and J. Keirstead (2014). "Energy systems modeling for twenty-first century energy challenges". In: *Renewable and Sustainable Energy Reviews* 33, pp. 74–86.

Plaga, L. S., M. Lynch, J. Curtis, and V. Bertsch (2024). "How public acceptance affects power system development—A cross-country analysis for wind power". In: *Applied Energy* 359, p. 122745.

Planning Commission (2018). *National Transport Policy of Pakistan*.

Pojani, D. and D. Stead (2018). "Policy design for sustainable urban transport in the global south". In: *Policy Design and Practice* 1.2, pp. 90–102.

Poumanyvong, P., S. Kaneko, and S. Dhakal (2012). "Impacts of urbanization on national transport and road energy use: Evidence from low, middle and high income countries". In: *Energy Policy* 46, pp. 268–277.

Proque, A. L., G. F. dos Santos, A. A. B. Junior, and W. D. Larson (2020). "Effects of land use and transportation policies on the spatial distribution of urban energy consumption in Brazil". In: *Energy Economics* 90, p. 104864.

Pye, S. and H. Daly (2015). "Modelling sustainable urban travel in a whole systems energy model". In: *Applied Energy* 159, pp. 97–107.

Pye, S., F. Li, J. Price, and B. Fais (2017). "Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era". In: *Nature Energy* 2.3, pp. 1–7.

Pye, S., O Broad, C. Bataille, P Brockway, H. Daly, R Freeman, A Gambhir, O Geden, F Rogan, S Sanghvi, et al. (2020). "Modelling net-zero emissions energy systems requires a change in approach". In: *Climate Policy*, pp. 1–10.

Rahman, M. H., S. N. Sadeek, A. Ahmed, S. M. Rifaat, and M. Abrar (2021). "Effect of socio-economic and demographic factors on ride-sourcing services in Dhaka City, Bangladesh". In: *Transportation Research Interdisciplinary Perspectives* 12, p. 100492.

Raj, P., E. Bhaduri, R. Moeckel, and A. K. Goswami (2023). "Analyzing User Behavior in Selection of Ride-Hailing Services for Urban Travel in Developing Countries". In: *Transportation in Developing Economies* 9.1, p. 1.

Rasmussen, L. B. (2008). "The narrative aspect of scenario building-How story telling may give people a memory of the future". In: *Cognition, Communication and Interaction: Transdisciplinary Perspectives on Interactive Technology*, pp. 174–194.

Realmonte, G., L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A. C. Köberle, and M. Tavoni (2019). "An inter-model assessment of the role of direct air capture in deep mitigation pathways". In: *Nature Communications* 10.1, pp. 1–12.

Rehman, F. U., M. M. Islam, Q. Miao, and A. S. M. Metwally (2023). "Does transport infrastructure make South Asian economies growth more inclusive? An application of a new

transportation infrastructure index". In: *Research in Transportation Business & Management* 49, p. 101013.

Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G. Peters, A. Rao, S. Robertson, A. Sebbit, J. Steinberger, M. Tavoni, and D. van Vuuren (2022). "Mitigation pathways compatible with long-term goals". In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley. Cambridge, UK and New York, NY, USA: Cambridge University Press. DOI: 10.1017/9781009157926.005.

Riahi, K., C. Bertram, D. Huppmann, J. Rogelj, V. Bosetti, A.-M. Cabardos, A. Deppermann, L. Drouet, S. Frank, O. Fricko, et al. (2021). "Cost and attainability of meeting stringent climate targets without overshoot". In: *Nature Climate Change* 11.12, pp. 1063–1069.

Riahi, K., E. Kriegler, N. Johnson, C. Bertram, M. Den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, et al. (2015). "Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals". In: *Technological Forecasting and Social Change* 90, pp. 8–23.

Riahi, K., D. P. Van Vuuren, E. Kriegler, J. Edmonds, B. C. O'neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, et al. (2017). "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview". In: *Global Environmental Change* 42, pp. 153–168. DOI: 10.1016/j.gloenvcha.2016.05.009.

Rinkinen, J., E. Shove, and M. Smits (2021). "Conceptualising urban density, energy demand and social practice". In: *Buildings and Cities*. DOI: 10.5334/bc.72.

Robinson, C. and G. Mattioli (2020). "Double energy vulnerability: Spatial intersections of domestic and transport energy poverty in England". In: *Energy Research & Social Science* 70, p. 101699.

Rock, S., A. Ahern, and B. Caulfield (2016). "The economic boom, bust and transport inequity in suburban Dublin, Ireland". In: *Research in Transportation Economics* 57, pp. 32–43.

Rode, P., C. Keim, G. Robazza, P. Viejo, and J. Schofield (2014). "Cities and Energy: Urban Morphology and Residential Heat-Energy Demand". In: *Environment and Planning B: Planning and Design* 41.1, pp. 138–162. DOI: 10.1068/b39065. URL: https://doi.org/10.1068/b39065.

Rogelj, J., A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, et al. (2018). "Scenarios towards limiting global mean temperature increase below 1.5 °C". In: *Nature Climate Change* 8.4, pp. 325–332. DOI: 10.1038/s41558-018-0091-3.

Royston, S. and J. Selby (2021). "How non-energy policies shape demand for energy". In: *Research Handbook on Energy and Society*. Edward Elgar Publishing.

Sachs, J., D. Moya, S. Giarola, and A. Hawkes (2019). "Clustered spatially and temporally resolved global heat and cooling energy demand in the residential sector". In: *Applied Energy* 250, pp. 48–62.

Sahakian, M., D. Fuchs, S. Lorek, and A. Di Giulio (2021). "Advancing the concept of consumption corridors and exploring its implications". In: *Sustainability: Science, Practice and Policy* 17.1, pp. 305–315.

Salat, S. and L. Bourdic (2014). "Spatial growth and urban densities in China - trends and impacts on economic and energy efficiency". In: *International Journal of Sustainable Building Technology and Urban Development* 5.2, pp. 100–108. DOI: 10.1080/2093761X.2014.908813. URL: https://doi.org/10.1080/2093761X.2014.908813.

Saxena, A. and V. Gupta (2023). "Carpooling: Who is closest to adopting it? An investigation into the potential car-poolers among private vehicle users: A case of a developing country, India". In: *Transport Policy* 135, pp. 11–20.

Schippl, J. and B. Truffer (2020). "Directionality of transitions in space: Diverging trajectories of electric mobility and autonomous driving in urban and rural settlement structures". In: *Environmental Innovation and Societal Transitions* 37, pp. 345–360.

Schlesewsky, L. and S. Winter (2018). "Inequalities in energy transition: the case of network charges in Germany". In: *International Journal of Energy Economics and Policy* 8.6, pp. 102–113.

Schulz, F. and J. Rode (2022). "Public charging infrastructure and electric vehicles in Norway". In: *Energy Policy* 160, p. 112660.

SEAI (2018). *Energy in the Residential Sector*. Tech. rep. Sustaianble Energy Authority of Ireland, p. 1. URL: https://www.seai.ie/publications/Energy-in-the-Residential-Sector-2018-Final.pdf.

SEAI (2019). *Ireland's Energy Balance 2018*. Tech. rep. Sustaianble Energy Authority of Ireland, p. 1. URL: https://www.seai.ie/publications/2018-National-Energy-Balance-Final.pdf.

SEAI (2021). *Save Energy at Home*. URL: https://www.seai.ie/home-energy/take-climate-action/save-energy-at-home/.

SEAI (2022). *National Energy Balance*. Tech. rep. Sustaianble Energy Authority of Ireland, p. 1. URL: https://www.seai.ie/data-and-insights/seai-statistics/key-publications/national-energy-balance/.

SEAI (2023). *Conversion factors*. URL: https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/.

Semieniuk, G., L. Taylor, A. Rezai, and D. K. Foley (2021). "Plausible energy demand patterns in a growing global economy with climate policy". In: *Nature Climate Change* 11.4, pp. 313–318.

Sethi, M., W. Lamb, J. Minx, and F. Creutzig (2020). "Climate change mitigation in cities: a systematic scoping of case studies". In: *Environmental Research Letters* 15.9, p. 093008.

Shah, S. A. H. and K. Hisashi (2022). "Analyzing travelers' attitude towards ride-hailing services in developing countries: Case of Lahore, Pakistan". In: *IATSS Research* 46.2, pp. 223–235.

Sharmina, M., O. Edelenbosch, C Wilson, R Freeman, D. Gernaat, P. Gilbert, A. Larkin, E. Littleton, M. Traut, D. Van Vuuren, et al. (2021). "Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2 C". In: *Climate Policy* 21.4, pp. 455–474.

Shukla, P, M. Pathak, S. Mittal, and S. Dhar (2015a). "Scenarios and roadmap for intercity transport in India: The role of high speed rail". In: *UNEP: Delhi, India*.

Shukla, P., S. Dhar, M. Pathak, D. Mahadevia, and A. Gargaa. (2015b). "Pathways to deep decarbonization in India". In: *SDSN - IDDRI*. October, pp. 1–58. ISSN: 1608-3105. URL: papers2://publication/uuid/E7622E05-580D-4FEC-9AB7-DFE70AA5D572.

Shukla, P., R. S. J. Skea, A. A. Khourdajie, R. van Diemen, D. McCollum, S. S. M. Pathak, P. Vyas, R. Fradera, M. Belkacemi, G. L. A. Hasija, S. Luz, and e. J. Malley (2022). " Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change ". In: *Cambridge University Press, Cambridge, UK and New York, NY, USA*. DOI: 10.1017/9781009157926.

Sikder, M., C. Wang, X. Yao, X. Huai, L. Wu, F. KwameYeboah, J. Wood, Y. Zhao, and X. Dou (2022). "The integrated impact of GDP growth, industrialization, energy use, and urbanization on CO2 emissions in developing countries: evidence from the panel ARDL approach". In: *Science of the Total Environment* 837, p. 155795.

Singh, V. S., V. Puvvada, L. PC, and J. Pradeep (2008). *Study on traffic and transportation policies in urban areas in India*.

Sluisveld, M. A. van, S. H. Martínez, V. Daioglou, and D. P. van Vuuren (2016). "Exploring the implications of lifestyle change in 2 C mitigation scenarios using the IMAGE integrated assessment model". In: *Technological Forecasting and Social Change* 102, pp. 309–319.

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie, E. Kriegler, et al. (2016). "Biophysical and economic limits to negative CO 2 emissions". In: *Nature Climate Change* 6.1, pp. 42–50.

Solano-Rodríguez, B., A. Pizarro-Alonso, K. Vaillancourt, and C. Martin-del Campo (2018). "Mexico's transition to a net-zero emissions energy system: Near term implications of long term stringent climate targets". In: *Limiting Global Warming to Well Below 2° C: Energy System Modelling and Policy Development*. Springer, pp. 315–331.

Soto, J. J., V. Cantillo, and J. Arellana (2021). "Market segmentation for incentivising sustainable transport policies". In: *Transportation Research Part D: Transport and Environment* 99, p. 103013.

Souza Silva, L. A. de, M. O. de Andrade, and M. L. A. Maia (2018). "How does the ride-hailing systems demand affect individual transport regulation?" In: *Research in Transportation Economics* 69, pp. 600–606.

Sovacool, B. K. (2016). "How long will it take? Conceptualizing the temporal dynamics of energy transitions". In: *Energy Research & Social Science* 13, pp. 202–215.

Sovacool, B. K., L. Noel, J. Kester, and G. Z. de Rubens (2018). "Reviewing Nordic transport challenges and climate policy priorities: Expert perceptions of decarbonisation in Denmark, Finland, Iceland, Norway, Sweden". In: *Energy* 165, pp. 532–542.

Steckel, J. C., N. D. Rao, and M. Jakob (2017). "Access to infrastructure services: Global trends and drivers". In: *Utilities Policy* 45, pp. 109–117.

Stiffler, N. L. (2011). "The effect of transit-oriented development on vehicle miles traveled: A comparison of a TOD versus a non-tOD neighborhood in Carlsbad, CA". In.

Stoddard, I., K. Anderson, S. Capstick, W. Carton, J. Depledge, K. Facer, C. Gough, F. Hache, C. Hoolohan, M. Hultman, et al. (2021). "Three decades of climate mitigation: why haven't we bent the global emissions curve?" In: *Annual Review of Environment and Resources* 46, pp. 653–689.

Straub, F., S. Streppel, and D. Göhlich (2021). "Methodology for Estimating the Spatial and Temporal Power Demand of Private Electric Vehicles for an Entire Urban Region Using Open Data". In: *Energies* 14.8. ISSN: 1996-1073. DOI: 10.3390/en14082081. URL: https://www.mdpi.com/1996-1073/14/8/2081.

Süsser, D., N. Martin, V. Stavrakas, H. Gaschnig, L. Talens-Peiró, A. Flamos, C. Madrid-López, and J. Lilliestam (2022). "Why energy models should integrate social and environmental factors: Assessing user needs, omission impacts, and real-word accuracy in the European Union". In: *Energy research & social science* 92, p. 102775.

Sustainable Energy Authority of Ireland (2020). *Energy-related CO2 Emissions in Ireland 2005-2018*. Tech. rep., p. 40.

Tamura, S., S. Iwamoto, and T. Tanaka (2018). "The impact of spatial population distribution patterns on CO_2 emissions and infrastructure costs in a small Japanese town". In: *Sustainable cities and society* 40, pp. 513–523.

Tattini, J., M. Gargiulo, and K. Karlsson (2018a). "Reaching carbon neutral transport sector in Denmark–Evidence from the incorporation of modal shift into the TIMES energy system modeling framework". In: *Energy Policy* 113, pp. 571–583.

Tattini, J., K. Ramea, M. Gargiulo, C. Yang, E. Mulholland, S. Yeh, and K. Karlsson (2018b). "Improving the representation of modal choice into bottom-up optimization energy system models–The MoCho-TIMES model". In: *Applied energy* 212, pp. 265–282.

Tewari, M., F. Salamanca, A. Martilli, L. Treinish, and A. Mahalov (2017). "Impacts of projected urban expansion and global warming on cooling energy demand over a semiarid region". In: *Atmospheric Science Letters* 18.11, pp. 419–426.

Thacker, S., D. Adshead, M. Fay, S. Hallegatte, M. Harvey, H. Meller, N. O'Regan, J. Rozenberg, G. Watkins, and J. W. Hall (2019). "Infrastructure for sustainable development". In: *Nature Sustainability* 2.4, pp. 324–331.

Tirachini, A. (2020). "Ride-hailing, travel behaviour and sustainable mobility: an international review". In: *Transportation* 47.4, pp. 2011–2047.

Tirachini, A. and A. Gomez-Lobo (2020). "Does ride-hailing increase or decrease vehicle kilometers traveled (VKT)? A simulation approach for Santiago de Chile". In: *International Journal of Sustainable Transportation* 14.3, pp. 187–204.

Tiwari, G., D. Jain, and K. R. Rao (2016). "Impact of public transport and non-motorized transport infrastructure on travel mode shares, energy, emissions and safety: Case of Indian cities". In: *Transportation Research Part D: Transport and Environment* 44, pp. 277–291.

Tori, S., G. Te Boveldt, I. Keseru, and C. Macharis (2023). "Brussels mobility in 2050: participatory mixed-method scenario building to explore alternative futures". In: *Transportation Research Interdisciplinary Perspectives* 22, p. 100919.

Trentmann, F. and A. Carlsson-Hyslop (2018). "The evolution of energy demand in Britain: politics, daily life, and public housing, 1920s–1970s". In: *The Historical Journal* 61.3, pp. 807–839.

Trutnevyte, E., L. F. Hirt, N. Bauer, A. Cherp, A. Hawkes, O. Y. Edelenbosch, S. Pedde, and D. P. van Vuuren (2019). "Societal transformations in models for energy and climate policy: the ambitious next step". In: *One Earth* 1.4, pp. 423–433.

Tsiropoulos, I, D Tarvydas, and A Zucker (2018). "Cost development of low carbon energy technologies: Scenario-based cost trajectories to 2050, 2017 edition". In: KJ-NA-29034-EN-N (online),KJ-NA-29034-EN-C (print). ISSN: 1831-9424 (online),1018-5593 (print). DOI: 10.2760/490059(online),10.2760/23266(print). URL: https://publications.jrc.ec.europa.eu/repository/handle/JRC109894.

Tyralis, H., N. Mamassis, and Y. N. Photis (2017). "Spatial analysis of the electrical energy demand in Greece". In: *Energy Policy* 102, pp. 340–352.

UNDP (2022). *Urban population (% of total population) — Data*. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS.

UNFCC (2016). *The Paris Agreement.* Accessed: 03-11-2022. URL: https://unfccc.int/process-and-meetings/the-paris-agreement.

United Nations Human Settlements Programme (UN-Habitat) (2022). *World Cities Report 2022: Envisaging the Future of Cities*. Accessed: 05-05-2023. URL: https://unhabitat.org/wcr/.

Vaillancourt, K., O. Bahn, E. Frenette, and O. Sigvaldason (June 2017). "Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework". In: *Applied Energy* 195, pp. 774–785. ISSN: 03062619. DOI: 10.1016/j.apenergy.2017.03.104.

Van Acker, V., P. Goodwin, and F. Witlox (2016). "Key research themes on travel behavior, lifestyle, and sustainable urban mobility". In: *International Journal of Sustainable Transportation* 10.1, pp. 25–32.

Van Dijk, J., A. J. Wieczorek, and A. Ligtvoet (2022). "Regional capacity to govern the energy transition: The case of two Dutch energy regions". In: *Environmental Innovation and Societal Transitions* 44, pp. 92–109.

Van Soest, H. L., D. P. Van Vuuren, J. Hilaire, J. C. Minx, M. J. Harmsen, V. Krey, A. Popp, K. Riahi, and G. Luderer (2019). "Analysing interactions among sustainable development goals with integrated assessment models". In: *Global Transitions* 1, pp. 210–225.

Van Vuuren, D. P., E. Stehfest, D. E. Gernaat, M. Van Den Berg, D. L. Bijl, H. S. De Boer, V. Daioglou, J. C. Doelman, O. Y. Edelenbosch, M. Harmsen, et al. (2018). "Alternative pathways to the 1.5 C target reduce the need for negative emission technologies". In: *Nature Climate Change* 8.5, pp. 391–397.

Vanderschuren, M. and J. Baufeldt (2018). "Ride-sharing: A potential means to increase the quality and availability of motorised trips while discouraging private motor ownership in developing cities?" In: *Research in Transportation Economics* 69, pp. 607–614.

Vasudevan, V., R. Agarwala, and S. Dash (2021). "Is vehicle ownership in urban india influenced by the availability of high quality dedicated public transit systems?" In: *IATSS research* 45.3, pp. 286–292.

Ven, D.-J. Van de, M. González-Eguino, and I. Arto (2018). "The potential of behavioural change for climate change mitigation: a case study for the European Union". In: *Mitigation and adaptation strategies for global change* 23, pp. 853–886.

Venturini, G., J. Tattini, E. Mulholland, and B. Ó. Gallachóir (2019). "Improvements in the representation of behavior in integrated energy and transport models". In: *International Journal of Sustainable Transportation* 13.4, pp. 294–313.

Verástegui, F., Á. Lorca, M. Negrete-Pincetic, and D. Olivares (2020). "Firewood heat electrification impacts in the Chilean power system". In: *Energy Policy* 144, p. 111702.

Verhetsel, A. and T. Vanelslander (2010). "What location policy can bring to sustainable commuting: an empirical study in Brussels and Flanders, Belgium". In: *Journal of Transport Geography* 18.6, pp. 691–701.

Vogt-Schilb, A., S. Hallegatte, and C. De Gouvello (2015). "Marginal abatement cost curves and the quality of emission reductions: a case study on Brazil". In: *Climate Policy* 15.6, pp. 703–723.

Wadud, Z. (2020). "The effects of e-ridehailing on motorcycle ownership in an emerging-country megacity". In: *Transportation Research Part A: Policy and Practice* 137, pp. 301–312.

Wadud, Z. and J. Namala (2022). "The effects of ridesourcing services on vehicle ownership in large Indian cities". In: *Transportation Research Interdisciplinary Perspectives* 15, p. 100631.

Walker, G. (2014). "The dynamics of energy demand: Change, rhythm and synchronicity". In: *Energy Research & Social Science* 1, pp. 49–55.

Walker, I. S., B. D. Less, and N. Casquero-Modrego (2022). "Carbon and energy cost impacts of electrification of space heating with heat pumps in the US". In: *Energy and Buildings* 259, p. 111910.

Wang, Q., Z. Yang, and R. Li (2024). "Bridging energy transition and income inequality: The moderating effect of institutional transparency". In: *Sustainable Development*.

Wang, S.-H., S.-L. Huang, and P.-J. Huang (2018). "Can spatial planning really mitigate carbon dioxide emissions in urban areas? A case study in Taipei, Taiwan". In: *Landscape and Urban Planning* 169, pp. 22–36.

Wang, X., J.-J. Zhu, and P. R. Anderson (2019a). "Heat pump system assessment for a groundwater-source municipal drinking water utility". In: *Environmental Progress & Sustainable Energy* 38.3, e13047.

Wang, Z., Z. Ahmed, B. Zhang, and B. Wang (2019b). "The nexus between urbanization, road infrastructure, and transport energy demand: empirical evidence from Pakistan". In: *Environmental Science and Pollution Research* 26, pp. 34884–34895.

Ward, J. W., J. J. Michalek, I. L. Azevedo, C. Samaras, and P. Ferreira (2019). "Effects of on-demand ridesourcing on vehicle ownership, fuel consumption, vehicle miles traveled, and

emissions per capita in US States". In: *Transportation Research Part C: Emerging Technologies* 108, pp. 289–301.

Wiedenhofer, D., D. Virág, G. Kalt, B. Plank, J. Streeck, M. Pichler, A. Mayer, F. Krausmann, P. Brockway, A. Schaffartzik, et al. (2020). "A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping". In: *Environmental research letters* 15.6, p. 063002.

Wilson, C., L. Kerr, F. Sprei, E. Vrain, and M. Wilson (2020). "Potential Climate Benefits of Digital Consumer Innovations". In: *Annual Review of Environment and Resources* 45, pp. 113–144.

Winkler, L., D. Pearce, J. Nelson, and O. Babacan (2023). "The effect of sustainable mobility transition policies on cumulative urban transport emissions and energy demand". In: *Nature Communications* 14.1, p. 2357.

World Bank (2023). *Railways, passengers carried (million passenger-km) — Data*. (Accessed on 12/03/2023). URL: https://data.worldbank.org/indicator/IS.RRS.PASG.KM.

Yakut, A. M. and K. de Bruin (2020). *Technical documentation of I3E model, Version 3*. Tech. rep. Dublin, Ireland: Economic and Social Research Institute. DOI: 10.26504/sustat91. URL: https://www.esri.ie/publications/technical-documentation-of-i3e-model-version-3.

Yeh, S., J. Gil, P. Kyle, P. Kishimoto, P. Cazzola, M. Craglia, O. Edelenbosch, P. Fragkos, L. Fulton, Y. Liao, et al. (2022). "Improving future travel demand projections: a pathway with an open science interdisciplinary approach". In: *Progress in Energy* 4.4, p. 043002.

Yenneti, K., R. Day, and O. Golubchikov (2016). "Spatial justice and the land politics of renewables: Dispossessing vulnerable communities through solar energy mega-projects". In: *Geoforum* 76, pp. 90–99.

Yin, B., L. Liu, N. Coulombel, and V. Viguié (2018). "Appraising the environmental benefits of ride-sharing: The Paris region case study". In: *Journal of Cleaner Production* 177, pp. 888–898.

Young, D. and J. Bistline (2018). "The costs and value of renewable portfolio standards in meeting decarbonization goals". In: *Energy Economics* 73, pp. 337–351.

Zamir, K. R., A. Nasri, B. Baghaei, S. Mahapatra, and L. Zhang (2014). "Effects of transit-oriented development on trip generation, distribution, and mode share in Washington, DC, and Baltimore, Maryland". In: *Transportation Research Record* 2413.1, pp. 45–53.

Zhang, M. and P. Zhao (2017). "The impact of land-use mix on residents' travel energy consumption: New evidence from Beijing". In: *Transportation Research Part D: Transport and Environment* 57, pp. 224–236.

Zhang, R. and J. Zhang (2021a). "Long-term pathways to deep decarbonization of the transport sector in the post-COVID world". In: *Transport Policy* 110, pp. 28–36.

Zhang, R., J. Zhang, Y. Long, W. Wu, J. Liu, and Y. Jiang (2021b). "Long-term implications of electric vehicle penetration in urban decarbonization scenarios: An integrated land use–transport–energy model". In: *Sustainable Cities and Society* 68, p. 102800.

Zhao, N. and F. You (2020). "Can renewable generation, energy storage and energy efficient technologies enable carbon neutral energy transition?" In: *Applied Energy* 279, p. 115889.

Zhao, W. (2022). "The long-run effects of minimum lot size zoning on housing redevelopment". In: *Journal of Housing Economics* 55, p. 101806.

Zhu, P. and H. Mo (2022). "The potential of ride-pooling in VKT reduction and its environmental implications". In: *Transportation Research Part D: Transport and Environment* 103, p. 103155.

Zhu, Z., Z. Li, Y. Liu, H. Chen, and J. Zeng (2017). "The impact of urban characteristics and residents' income on commuting in China". In: *Transportation Research Part D: Transport and Environment* 57, pp. 474–483.