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Improving the Ability of Energy Systems Optimisation Modelling to Inform National Energy Policymaking

Thesis presented by
Vahid Aryanpur B.Eng., M.Eng.

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University College Cork
School of Engineering and Architecture
MaREI Centre, Environmental Research Institute

Supervisors: Professor Brian Ó Gallachóir
Dr. James Glynn
Professor Hannah E. Daly

Head of School: Professor Jorge Oliveira

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Units and Abbreviations

ADF - Augmented Dickey-Fuller

ARIMA - Auto-Regressive Integrated Moving Average

ARDL - Auto-Regressive Distributed Lag

BAU - Business-as-usual

bcm/yr - billion cubic metres per year

BOS - Biofuel Obligation Scheme

BEV - Battery Electric Vehicle

CAP - Climate Action Plan

CCGT - Combined Cycle Gas Turbine

CCS - Carbon Capture and Storage

CGE - Computable General Equilibrium

CNG – Compressed Natural Gas

CO_2 - Carbon Dioxide

CSO - Central Statistics Office

EEA - European Environment Agency

EFOM - The Energy Flow Optimisation Model

ESOM - Energy System Optimisation Model

ETSAP - Energy Technology Systems Analysis Program

EU - European Union

EV - Electric Vehicle

GDP - Gross Domestic Product

GHG - Greenhouse Gas

GIS - Geographic Information System

GJ - Gigajoule

GW - Gigawatt

GWh - Gigawatt Hour

HDV - Heavy-Duty Vehicle

HEV - Hybrid Electric Vehicle

IAEA - International Atomic Energy Agency

ICE - Internal Combustion Engine

IEA - International Energy Agency

IIASA - International Institute for Applied System Analysis

IPCC - Intergovernmental Panel on Climate Change

JCOPA - Joint Comprehensive Plan of Action

kW - Kilowatt

kWh - Kilowatt-hour

LDV - Light-Duty Vehicle

LEAP - Low Emissions Analysis Platform

MARKAL - MARKet ALocation Model

MESSAGE - Model for Energy Supply Systems And their General Environmental impact
MIR - Monetary Incentive Removal
MJ - Megajoule
MOE - Ministry of Energy
MW - Megawatt
MWh - Megawatt Hour
NDC - Nationally Determined Contributions
NG – Natural Gas
NOx - Nitrogen Oxides
NREL - National Renewable Energy Laboratory
NTA - National Transport Authority
OR - Occupancy Rate
OSeMOSYS - Open-Source Energy Modelling System
PHEV - Plug-in Hybrid Electric Vehicle
PJ - Petajoule
pkm - passenger.kilometre
PM - Particulate Matter
POLES - Prospective Outlook on Long-term Energy Systems
PRIMES - Price-Induced Market Equilibrium System
PV - Photovoltaic
ReEDS - Regional Energy Deployment System
REF - Reference
REMIND - Regional Model of Investments and Development
RES - Reference Energy System
SE - Subsidy Elimination
SEAI - Sustainable Energy Authority of Ireland
SR - Subsidy Removal
SSM - State-Space Model
SDGs - Sustainable Development Goals
t.km - tonne.kilometre
TIM - TIMES-Ireland Model
TIMES - The Integrated MARAKL-EFOM System
TWh - Terawatt Hour
UCC - University College Cork
UK - United Kingdom
UN - United Nations
UNFCCC - The United Nations Framework Convention on Climate Change
US - United States
vkm - Vehicle Kilometre
VRES - Variable Renewable Energy Sources
VRT – Vehicle Registration Tax

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.

Vahid Aryanpur

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Executive Summary

Energy Systems Optimisation Models (ESOMs) are extensively used to inform energy and environmental policymaking. They generate valuable insights into the possible pathways that reduce our reliance on fossil fuels and achieve ambitious clean energy transition goals. However, the academic literature identifies a number of priority areas for development with ESOMs to improve their ability to generate useful insights applicable to the energy transition. This thesis explores and delivers key developments in several of these dimensions: spatial resolution, energy-economy linkage, significance of model skill, and heterogeneity of consumers. From a policy perspective, this thesis seeks to improve the model-based analysis in the context of national-level energy sector decarbonisation and thus, mitigation policies are critically investigated. Moreover, the impacts of the mitigation actions on local air pollution levels and promoting energy security are also explored. Accordingly, the main contributions of this thesis are improvements to the state-of-the-art energy modelling methods and applications of the enhanced models to answer key policy questions with convincing evidence. The improvements are demonstrated via two well-established energy systems modelling tools in Ireland and Iran. The thesis concludes with several modelling and policy insights and suggestions on interesting areas for further investigation to strengthen the contribution of ESOMs to ensure improved climate mitigation and energy policies.

The first weakness is the limited spatial and consumer granularity in ESOMs which constrains their ability to analyse region-specific energy transition pathways. This thesis develops a multi-regional representation of the transport sector within the TIMES-Ireland Model (TIM), an ESOM used to develop ambitious mitigation pathways for Ireland's energy system. The multi-regional approach captures region-specific characteristics of transport technologies and infrastructures across 26 counties. It also incorporates the heterogeneity of the impact of air pollution in sub-national regions and estimates the ancillary pollution benefits of the mitigation targets in those regions. The spatially explicit modelling approach also reveals higher economic co-benefits than single region modelling. The single-region method masks the higher damage costs in medium and large cities, thus underestimating total benefits. This thesis also develops a multi-consumer approach, more accurately capturing consumer heterogeneity. Having homogeneous consumers in ESOMs tends to oversimplify purchase decisions, especially for capital-intensive technology adoption. TIM simulates vehicle purchase decisions using hurdle rates. This thesis disaggregates consumers into five groups, ranging from low- to high-income

families, to incorporate a more realistic representation of their behaviour in vehicle purchasing decisions. The results demonstrates that the model with heterogenous consumers offers higher Electric Vehicle (EV) adoption than a single region model calibrated with average national data and identical consumers. Spatially explicit analysis presents valuable insights into regional EVs diffusion and their electricity consumption at a subnational level which are usually challenging to achieve through an aggregated national model.

Secondly, ESOMs often ignore the effects of changes in energy costs on energy service demands, despite their key ability to balance supply and demand. The thesis addresses this by developing a comprehensive representation of the power sector within the MESSAGE model, an ESOM used to explore the impacts of different subsidy reform scenarios in Iran. The thesis develops a soft-linked framework combining MESSAGE with an economic model and analyses both supply and demand sides under harmonised assumptions. The novel soft-linking addresses the structural weakness of ESOMs in capturing the effects of energy price on demand. The hybrid model is used to investigate the impacts of subsidy removal on power demand and the required generation mix. The findings reveal that under an early and steady reform scenario, the system avoids lock-in effect, and thus the development of renewable energy technologies and energy efficiency plans become cost-competitive. By contrast, the late subsidy reform path even with radical removal fails to tackle the lock-in effect’s risk. On the other hand, the long-term energy system transition is deeply uncertain. The hybrid modelling framework in this research is also used to conduct an ex-post analysis exploring the extent to which electricity subsidy reform could have reduced Iran’s energy demand during the last three decades. To minimise the uncertainties, both energy and economic models are calibrated with three decades of historical data. The cost-optimal modelling results are then compared with the real-world transition, revealing a 50% lower cumulative cost in the subsidy removal scenario compared with the real-world transition. This deviation highlights what could have been achieved through the implementation of different policies in the absence of uncertainties, providing valuable insights for informing future policy initiatives. Finally, this hybrid framework is also used to show how synergies and efficiencies from Iran’s energy subsidy reforms and lifting its sanctions could enhance global energy security, with a focus on natural gas. It demonstrates that significant opportunities could be realised through a combination of national energy policy reforms and cross border cooperation in a favourable international environment.

1 Introduction

1.1 Background and motivations

The unequivocal evidence produced by the United Nation's Intergovernmental Panel on Climate Change (IPCC) reaffirm that human activities are the root cause of global warming and the majority of the warming is tied to greenhouse gas (GHG) emissions (IPCC, 2019, 2021). The 2015 Paris Agreement brings all nations together to undertake ambitious efforts to combat global warming and its catastrophic implications. The Agreement set a target of limiting average temperature rise compared with pre-industrial levels to well below two degrees Celsius by the end of the present century, with an aim of limiting temperature rise to 1.5 degrees, and reaching net-zero GHG emissions in the second half of the century (UNFCCC, 2016). In this context, the energy sector plays a key role due to its significant contribution to GHG emissions arising from fossil fuel-based energy systems (Gargiulo and Gallachóir, 2013; Weber *et al.,* 2019). Consequently, exploring mitigation actions is at the heart of energy-related research (Plazas-Niño *et al.*, 2022), and long-term energy planning has turned to focus on deep decarbonisation policies (Oberle and Elsland, 2019).

Nationally Determined Contributions (NDCs) are the cornerstone for implementing the Paris Agreement and achieving the long-term decarbonisation targets (Yeeles, 2018). They reflect the countries' efforts to reduce national emissions based on their capacity and priorities. The Agreement requests each country to outline and communicate their post-2020 climate actions through NDCs. Thus, it is paramount to assess the feasibility of the targets and impacts of policies as well as find optimal mitigation pathways at a national level. Energy modelling can assist decision-makers in determining strategies that ensure deep emissions reduction targets across all sectors (Pye *et al.*, 2020).

Energy Systems Optimisation Models (ESOMs) are a prominent branch of energy planning tools. ESOMs are widely used to inform national level decision-making (Aryanpur *et al.,* 2021). Systematic literature reviews by Pfenninger *et al.* (2014) and Machado *et al.* (2019) reveal that exploring comprehensive decarbonisation pathways is the principal objective of the recent ESOM-based modelling studies. They provide valuable insights into the possible technical configurations that may reduce our reliance on fossil fuels and cut the associated CO_2 emissions (Giannakidis *et al.*, 2015). ESOM findings are highly dependent on the model input and structure (Edenhofer *et al.*, 2006). In addition, energy systems are linked to other key challenges, such as local air pollution and consumer affordability. These challenges together with ambitious decarbonisation goals may increase the complexity of energy system analysis (Savvidis *et al.,* 2019). Thus, using model-based analysis to produce quantitative predictions without considering those challenges could lead to unintended negative consequences and sub-optimal policies (e.g., (Leinert *et al.,* 2013)). To avoid these negative effects and ensure that the policy-making process can actively continue its reliance on modelling, ESOMs should capture the growing complexity of energy systems (Pfenninger *et al.,* 2014). Moreover, they need to be equipped with selective use of features to address new energy challenges while avoiding unnecessary complexities (DeCarolis *et al.,* 2017).

Some previous studies have systematically discussed a number of priorities and technical features that need to be developed to improve the realism associated with model dynamics, particularly in the context of supporting government energy and climate policy. DeCarolis *et al.* (2017) have formalised best practice guidelines based on their collective modelling experience and extensive literature review. Pye *et al.* (2020) have also highlighted the key set of challenges that need to be faced based on conclusions from an expert workshop[1]. Some technical considerations and features arising from these studies are as follows:

- ***Spatial resolution:*** ESOMs often sacrifice spatial granularity for the sake of simplicity or due to a lack of reliable data. A systematic review shows that the aggregated treatment of spatial dynamics for analysing a national energy system with homogeneous sub-regions is often reliable, but spatially resolved models offer crucial added value for heterogeneous regions (Aryanpur *et al.,* 2021). Another review also shows that the evolution of future energy systems is expected to be spatially dependent (Martínez-Gordón *et al.,* 2021). Existing models are typically calibrated with average national data; however, spatially resolved ESOMs can be equipped with a publicly available sub-national dataset.
- ***Significance of model skill:*** Model skill refers to the level of accuracy or reliability of an energy system model in capturing and replicating real-world energy system dynamics. It encompasses the model's ability to predict or simulate energy system behaviour, such as energy demand, supply, and transition pathways, in comparison to historical data or observed outcomes. One weakness of energy system models is that they overlook the significance of model skill by examining the past, and thus, do not consider what could

[1] It was jointly hosted by University College London (UCL) and the UK Energy Research Centre (UKERC) in January 2020. An extensive range of model practitioners and consumers of model results had participated in the workshop (Pye *et al.*, 2020).

have been achieved with different policies in order to inform future policy initiatives. This means that ESOMs may not adequately consider how well they perform in replicating actual historical data or real-world energy system transitions. By assessing the model's skill through examining the past, it can provide valuable insights into the model's accuracy in capturing real-world dynamics (Wen *et al.*, 2023), and how different policies could have influenced the outcomes (Wilson *et al.*, 2021). Moreover, evaluating the model's skill by examining the past can serve as a basis for informing future policy initiatives. It allows for a retrospective analysis of what could have been achieved through the use of various strategies, providing a comprehensive understanding of the potential impacts of alternative pathways. This can help policymakers in making informed decisions and designing more effective energy policies and strategies based on the lessons learned from past experiences.

- ***Energy-economy relationship:*** Decarbonisation of energy systems is likely to increase energy prices (Csereklyei, 2020). A survey of over 400 papers published in the past three decades, utilising different econometric techniques, geographical and temporal scopes, has been conducted by Labandeira (2017). The survey findings reveal that the estimated long-run price elasticity of electricity consumption is moderately elastic. As partial equilibrium models, bottom-up ESOMs are usually better suited to explore technical options and the associated operation and investment costs, rather than interactions between the energy system and sectors of the economy. It is due to the limited ability of model equations to represent the interactions (Hunter *et al.,* 2013). On the other hand, top-down tools are used to determine growth in energy prices and demands (Connolly *et al.,* 2010). In general, bottom-up models cannot individually anticipate how energy prices may change the final demand level (the demands remain unresponsive to price). Incorporation of demand response in energy systems models can be a complex task that presents challenges and difficulties (Morales-España *et al.*, 2022). The hybrid modelling approach is usually applied to cover the macroeconomic impact of energy policies and capture the full economy-wide effects. It combines the economic richness of top-down models with the technological explicitness of bottom-up models (Böhringer and Rutherford, 2008). Some studies have adopted a hybrid approach to capture the interactions between the energy system and the broader economy. This approach has been used to evaluate national energy and climate policies policies (Krook-Riekkola *et al.,* 2017), assess environmental co-benefits (Yang *et al.,* 2021), and analyse the economic impacts of low-carbon energy pathways (Taliotis *et al.,* 2020; Timilsina *et al.,* 2021), and analyse the global-level nexus between energy, carbon, and the environment (Cai *et al.*, 2015). However, the effects of subsidy removal have received limited attention in these studies.

- ***Consumer heterogeneity:*** Although ESOMs accurately capture techno-economic parameters, their vehicle fleet mix predictions may be unreliable due to limited consumer behaviour representation (Ramea *et al.,* 2018) and heterogeneity in consumer demand or choice (DeCarolis *et al.,* 2017). Traditional ESOMs consider homogeneous consumers with rational decisions. This can oversimplify consumer decision making (Patankar *et al.,* 2022) and the complexity of investment decision making behaviour (Worrell *et al.*, 2004). In addition, empirical evidence reveals that technological adoption is often non-rational (Mccollum *et al.,* 2017), and consumer behaviour is gaining increased attention for exploring mitigation pathways (Luh *et al.,* 2022; Süsser *et al.,* 2022). More specifically, when research questions focus on decarbonisation via modern capital-intensive technology adoption, consumer behaviour related to purchase decisions becomes important. For this type of research, incorporating consumer heterogeneity provides a more likely representation of reality and may better inform policy making. A commonly used approach to capture consumer heterogeneity is through segmentation, such as based on driving and settlement patterns (e.g., as driving and settlement pattern discussed in (Mccollum *et al.,* 2017)). The application of discrete choice models (Venturini *et al.,* 2019), disutility costs (DeCarolis *et al.,* 2017), and constant elasticities of substitution (Salvucci *et al.*, 2018) are commonly employed methods. Discrete choice models, such as those used in the global transport model TRAVEL (Girod *et al.*, 2012), are effective for exploring consumer preferences for personal transportation decisions (Horne *et al.*, 2005) and clean fuel vehicles (Ewing and Sarigöllü, 2000), and commonly incorporate non-monetary parameters such as technical risk, model availability, acceptance factors, infrastructure density, and range limitations of immature technologies. Disutility costs account for the aforementioned discomfort costs experienced by different consumers when adopting a specific transport technology (for instance in (Li and Strachan, 2017) and (Bunch *et al.*, 2015)). The constant elasticities of substitution between two input parameters of a utility function measure the consistent percentage change in the relative marginal product of the two parameters in response to a percentage change in the proportion of the parameters (Karplus *et al.,* 2013). Hurdle rates, which are set at a higher level than social discount rates, are introduced to take into account market imperfections that hinder investments (Anandarajah *et al.*, 2009). They consider the risks and obstacles associated with investing in less mature technologies in comparison to fully commercial ones (Mallah and Bansal, 2011; García-Gusano *et al.*, 2016). Evidence from consumer studies reveal diverse discount rates among different households when purchasing durable goods. The evidence also suggests that fuel-efficient equipment has a relatively short amortisation time, resulting in a higher discount rate for vehicles with a longer lifetime, based on capital recovery factor analysis (Schäfer and Jacoby, 2006). Consequently, using income-based disaggregation of households as a proxy to capture consumer behaviour in system-wide modelling has been relatively unexplored. This is particularly evident in the context of car buyers' decisions between purchasing a capital-intensive electric vehicle versus a conventional combustion engine.

In addition to these priorities that aim to improve energy modelling and help inform mitigation policies, ESOMs are used to ensure the security of supply and address Sustainable Development Goals (SDGs) (Aryanpur *et al.,* 2021). Energy security is a critical driver for developing the first generation of energy systems models in the 1970s (Helm, 2002; Lopion *et al.,* 2018), and SDGs emerged as significant research objectives more recently (Bolwig *et al.,* 2019). The UN Member States adopted 17 SDGs in 2015 to ensure peace and prosperity (United Nation, 2015b). Energy production and consumption and their harmful GHG and air pollutions play a central role in many of the SDGs. For instance, SDG 7 aims to achieve affordable and clean energy and SDG 13 supports urgent actions to combat climate change (United Nation, 2015a). Local air pollution is directly mentioned in many SDGs[1]. Accordingly, improving air quality as an important sustainability factor is a vital concern that needs to be addressed in the context of mitigation actions. Mitigation pathways could create economic co-benefits through air quality improvement, which in turn offset or at least compensate for part of the mitigation costs (Gallagher and Holloway, 2020; Karlsson *et al.,* 2020). As a result, capturing co-benefits data into policymaking may synergise mitigation actions. On the other hand, global energy markets have experienced significant volatility during the post-COVID-19 pandemic economic recovery (Tian *et al.,* 2022), and this has been amplified by recent Russia's invasion of Ukraine (Khan, 2022), which has sent gas and oil prices to record high levels. The coincidence of rising demand, constrained supplies, and supply interruptions from the conflict has dramatically triggered energy security concerns. Accordingly, ensuring energy security is another crucial area that may impact mitigation policies.

[1] especially in SDG 3.9 (substantial reduction of health impacts from hazardous substances) and SDG 11.6 (reduction of adverse impacts of cities on people) (Rafaj et al., 2018)

This thesis seeks to address the above priorities and policy considerations in order to improve the model-based analysis of energy systems on a national level. The improvements are shown in separate case studies. From a policy point of view, mitigation actions are critically explored. Two other policy objectives, the impacts of the mitigation policies on local air pollution levels, and promoting energy security, are also explored. Each case study has a different goal and intended audience and thus, an appropriate modelling framework is developed to answer the research question(s) in that case. It is worth noting that, other considerations, such as temporal resolution, are a crucial element of sophisticated modelling. However, they are out of the scope of this thesis. The following sections briefly present the methodology and research framework, research questions, outline of each chapter and the role of collaborations.

1.2 Methodology and research focus

This thesis makes methodological developments to two specific ESOMs and applies them to provide insight that informs energy and environmental policies in Ireland and Iran. The ESOMs incorporate a detailed description of the technical components of an energy system and thus, are categorised as technology-rich, bottom-up optimisation models (Van Beeck, 1999). They can be used to investigate the total system costs and support long-term investment decisions (Lopion *et al.,* 2018). A fundamental advantage of them is the ability to apply optimisation techniques to analyse alternative forms of system configuration using alternative energy sources and technologies, given a set of end-use demands (Bhattacharyya and Timilsina, 2010). They use linear programming techniques to minimise the present cost of energy provision by optimising fuel and technology mix. These models offer feasible multi-decade pathways under an extensive range of user-defined constraints and assumptions such as demand growth, technology innovations, fuel price fluctuations and new policies (Pfenninger *et al.,* 2014). Two well-established ESOMs, TIMES (The Integrated MARKAL[1]-EFOM[2] System) and MESSAGE (Model for Energy Supply Systems And their General Environmental impact), are used to explore decarbonisation pathways in two countries. Further details of methodological contributions are discussed in the following chapters. Both models have been developed over the past four decades:

[1] MARKet ALlocation Model
[2] Energy Flow Optimisation Model

- **TIMES:** It is a model generator for energy–environment systems analysis at various levels of spatial, temporal, and sectoral resolutions (Loulou *et al.,* 2016). It combines the advanced features of the MARKAL models (Fishbone and Abilock, 1981) and the EFOM model (Van der Voort, 1982), as well as various new features developed over time (Loulou *et al.,* 2016). The TIMES model has been developed within the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). It is used for economic analysis of energy policies, and in-depth national, multi-country and global energy and environmental analyses (IEA-ETSAP, 2022).
- **MESSAGE:** The model has been developed at International Institutes for Applied Systems Analysis (IIASA) (Schrattenholzer, 1981). The focus of the primary version was on the supply-side of fossil resources and nuclear energy, and then the mathematical formulation extended to incorporate the full energy system representation (Messner and Strubegger, 1995). IIASA often uses this tool for global energy scenarios and it is a central tool for the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) (Huppmann *et al.,* 2019). Yet, it can be also used for evaluating the energy supply strategies of individual nations. The International Atomic Energy Agency (IAEA) added a user interface to facilitate its application for national analysis in developing countries (IAEA, 2009).

Table 1-1 shows an overview of the research framework and focus. It shows where and how the technical features (spatial resolution, energy-economy linkage, significance of model skill in the absence of uncertainty, and consumer heterogeneity) are addressed across this thesis.

According to Table 1-1, the entire Irish energy system is modeled with TIMES. The model's base year is 2018, and all energy flows, emissions, and energy technology stocks are calibrated to the 2018 energy balance. TIMES-Ireland Model (TIM) spans 32 years. TIM is built with a flexible regional and periodic definitions allowing us to run in multiple modes with multiple configurations of regional resolution and time horizon. The transport sector has a multi-region structure, including 26 counties. It is equipped with region-specific characteristics of transport technologies and infrastructures along with consumer heterogeneity. The end-use demands are exogenously estimated. They are driven by economic and population growth. Different scenarios and sensitivity cases are defined to handle uncertainties. Five groups of consumers (potential car buyers) ranging from low to high income families are defined to capture the consumer heterogeneity. Technology-specific discount rates are then used to capture investment decision-making for each group. The model explores different monetary and non-monetary measures that can contribute to meeting mitigation targets in Ireland. The analysis also examines how higher spatial resolution can change modelling results. While the policy focus is on climate actions, the co-benefits of these actions on local air quality are also assessed.

On the other hand, the electricity supply system of Iran is modelled using the MESSAGE model. Two models with two horizons are developed with MESSAGE. They are single-region model with homogeneous consumers, but two separate economic models are used to estimate final electricity demand under subsidy removal scenarios in each period. In other words, a soft-linked framework combining MESSAGE with an economic model is developed to analyse both supply and demand sides under harmonised assumptions. The linkage deals with the structural weakness of ESOM in capturing the effects of energy price on demand. The whole model investigates the impacts of subsidy removal on power demand and the required generation mix to meet the demand. One modelling framework is used to conduct an ex-post analysis during 1983 to 2017. In this ex-post analysis, both energy-economy models are calibrated with historical statistics to show how real-world transition deviates from cost-optimal scenarios. Consequently, this ex-post modelling exercise can almost remove the parametric uncertainty. Finally, the efficiencies arising from Iran's energy subsidy reforms are assessed during 2017-2050, and the potential impacts on energy security are discussed.

Table 1-1. Research framework and addressing energy modelling priorities in this thesis

Model Focus		TIMES	MESSAGE
Case study		Ireland	Iran
Sectoral focus		Transport	Power
Study horizon		2018 – 2050	1983 – 2017 2017 – 2050
Main policy focus		Mitigation policies Co-benefits of climate policy on air quality	Mitigation policies Energy security
Policy measures		Monetary (purchase grant, tax relief, carbon tax) Non-monetary (biofuel obligation schemes, modal shift, occupancy rate)	Energy subsidy reform (early vs. late actions)
Priorities	Spatial resolution	Multi-region (county level)	Single region (national level)
	Energy-economy linkage	Exogenous demand	Hybrid approach (price-induced demand response)
	Significance of model skill in the absence of uncertainties	Scenarios and sensitivity analysis	Ex-post analysis (actual statistics and historical transition)
	Consumer heterogeneity	Five groups (income level)	Homogeneous consumers

Table 1-2 summarises key methodological contributions across different chapters. The methodology is graphically displayed in each chapter and the last column is connected to the relevant figures.

Table 1-2. Main methodological contribution in each chapter

Case	Chapter	Methodological contribution	Link
Ireland	Chapter 3	Developing TIM with a flexible spatial resolution (nationally and/or locally)	Figure 3-2
	Chapter 3	Capturing consumer behaviour in purchasing more efficient capital-intensive technology	Figure 3-5
	Chapter 4	Quantifying the co-impacts of mitigation actions on air pollution on a county level	Figure 4-1
Iran	Chapter 5	Linking energy-economy models (ex-post analysis)	Figure 5-3
	Chapter 6	Developing a hybrid energy-economy framework (price-induced demand response)	Figure 6-1
	Chapter 7	Linking national and international policies as input for energy system analysis	Figure 7-1

1.3 Policy context

This section introduces the two countries' energy systems and the relevant climate policies that are explored later in this thesis.

- **Ireland**

Fossil-based fuels including oil, natural gas, coal, and peat accounted for 86.7% (11,439 ktoe) of Ireland's total primary energy supply in 2020. Oil and gas accounted for 79.1% of all primary supply. Despite the significant development of renewable energy sources during the last decade, they only accounted for 13.3% of total primary energy in the same year. Ireland's largest energy consumer is the transport sector with 34.3% of total final energy consumption. This was down significantly from 42.2% in 2019, due to the impact of public health measures that limited national and international travel (SEAI, 2021b).

Ireland faces critical challenges in meeting future energy demand with a much lower carbon footprint. It has a high per capita carbon footprint relative to the average European Union (EU). Moreover, in 2021 the government presented a Climate Action Plan (CAP) which set forth sector-by-sector measures to meet a very ambitious target. Ireland’s CAP-21 provides a plan to achieve a 51% reduction in overall GHG emissions by 2030, and a path to reach net-zero emissions by no later than 2050. It includes increasing the renewable electricity share to 70 % by no later than the current decade, for electric vehicles to reach full market share before 2030

(GOV, 2021c). As a result, electrification of the transport sector using renewable energies plays a key role in its decarbonisation pathway.

To meet the ambitious targets, Ireland faces different challenges. First, the agricultural sector is responsible for about one-third of total GHG emissions. This sector is dominated by beef and dairy production and is a large and export-led part of the economy. It is considered more difficult to abate than energy sectors and thus, energy requires a faster mitigation pathway. Second, the energy sector and more specifically transport and heating are heavily dependent on fossil fuels (with about 95% of their total consumption). Third, 86% of renewable electricity generation comes from wind turbines, the relatively isolated nature of the electricity grid and lack of alternative low-carbon electricity sources will make it very challenging to integrate high shares of renewable electricity (Balyk *et al.*, 2022).

To inform increased national climate mitigation ambition and in response to the need for faster mitigation pathway in energy sector, an integrated whole energy system approach is applied in this thesis. The focus is on the transport sector, and especially on decarbonisation through electrification of Light-Duty Vehicles (LDVs). The impact of different monetary (i.e., direct purchase grant, vehicle registration tax relief, and carbon tax) and non-monetary (i.e., modal shift, biofuel obligation, and occupancy rate) policy measures are explored. While the ambitious mitigation targets in Ireland meet its international and EU climate commitments, policymakers are often concerned about the mitigation targets due to associated economic costs. This concern can bias the decision-making process and thus, lead to unintended suboptimal climate policies. As a result, this research integrates co-benefits data into energy systems modelling to show how they can synergise mitigation actions.

- **Iran**

Iran is among the world's largest proven gas and oil reserves holders. British petroleum reports that 17.1% and 9.1% of the total world's gas and oil reserves are located in Iran, respectively (BP, 2021). Currently, more than 98% of the national energy consumption is from fossil fuel energy carriers causing disastrous air pollution. This has also placed the country among the top GHG emitters in the world (Aryanpur *et al.*, 2019).

Besides the abundant fossil fuel resources, Iran possesses a significant potential for renewable electricity generation sources, and the government supports their development (Atabaki *et al.*, 2022). GHG emissions from the power sector accounted for around one-third of Iran's energy sector emissions. Multiple analyses show that the efficiency improvement of fossil-based power units (Ghadaksaz and Saboohi, 2020) and renewable energy sources (Ghorbani *et al.*, 2020) could well cover the Iranian contributions in the energy sector to cut GHG emissions.

On the other hand, substantial energy subsidies are recognised as one of the major reasons that prevent the development of energy efficiency plans and renewable energy technologies. Moreover, energy subsidies encourage inefficient consumption. Compared to the world average and peer countries[1], Iran has high energy intensity (Mohammadi *et al.*, 2022). As a result, an integrated energy-economy modelling framework helps to understand how energy subsidy reforms can impact the electricity demand growth rate, and then, the long-term optimal generation mix to meet the demand.

1.4 Aims and key questions

This thesis aims to improve the robustness of models that inform national energy policymakers in achieving decarbonisation pathways, particularly in the transport and power sectors. To meet this aim, the present research addresses four identified priorities: spatial resolution, energy-economy linkage, importance of model skill in the absence of uncertainties, and heterogeneity of consumers. From policy perspective, in addition to climate change mitigation policies, reducing local air pollutions and energy security are addressed.

In summary, the study aims to answer the following Research Questions (RQ):

- **RQ1:** When, how, and to what extent does higher spatial resolution impact the results of energy systems modelling?
- **RQ2:** How does heterogeneity in potential car buyers with different income level (variations in consumers' ability to pay higher up-front costs) impact the penetration of EVs?
- **RQ3:** How can a hybrid energy-economy modelling method with harmonised assumptions improve energy systems analysis?
- **RQ4:** What potential outcomes could have been realised through the implementation of subsidy reform policies?
- **RQ5:** To what extent can different policy measures support the decarbonisation of LDVs?
- **RQ6:** What are the co-benefits of decarbonisation policies on air pollution levels?

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[1] The annual average growth in energy intensity of Iran has increased by 1.6% during 2000 to 2019. But the average growth in the energy intensity index of Saudi Arabia, Turkey, China, and the world is 0.7%, −1.2%, −3.0%, and −1.6%, respectively (Enerdata, 2021).

- **RQ7:** How synergies and efficiencies from Iran's energy subsidy reform can assist in decarbonising the power sector? What are the potential impacts on energy security?

1.5 Summary of key contributions

This thesis makes a significant contribution to developing new insights through methodological improvements to energy system models by:

- Improving accuracy through higher spatial resolution and incorporating heterogeneity of car buyers
- Extending the scope by capturing price-induced demand response
- Analysing the importance of model skill in the absence of uncertainties by evaluating historical outcomes
- Adding flexibility with a single- and multi-region energy system model that can be run at the national and/or county level
- Informing policymaking by using the developed model to address decarbonisation of the transport and power sectors and quantify co-benefits of mitigation actions.

1.6 Thesis in brief

As earlier mentioned, the main objective of this research is to improve ESOMs for national scale policy making. As shown in Figure 1-1, this objective is divided into various parts: Developing national-scale ESOM and four different improvements. Those improvements are then used to better inform policymaking in Ireland and Iran. The thesis integrates them in a structured manner and is organised into three main parts. Part A conducts a systematic literature review to identify the current state of ESOMs and research gaps, and ultimately to propose the research questions. Part B focuses on the improvements of TIM by adding spatial resolution and consumer heterogeneity and its application for transport decarbonisation. Part C discusses the soft-linked approach to address energy-economy linkages for analysing energy subsidy reform in Iran. Altogether, this structure is used to support decision-making processes. Both parts B and C use ESOMs to explore decarbonisation pathways and improve the accuracy of the models through methodological innovations.

In addition to this introductory (Chapter 1) and a final concluding chapter (Chapter 8), this thesis is presented in six chapters. Figure 1-1 also shows how research questions are answered through this thesis.

- **Part A:** This part has one chapter and presents a comprehensive review of the representation of spatial detail in the existing ESOMs.
    - ***Chapter 2*** is based on a systematic literature review and identifies existing national-scale ESOMs. The review analyses 36 multi-regional ESOMs from 22 countries with varying levels of spatiotemporal resolution, sectoral focus, and planning horizon. The chapter also helps to understand when, how, and to what extent higher spatial resolution impact on the results of energy system analysis.
- **Part B:** It has two chapters and presents the development and application of the TIMES model for the Irish energy system:
    - ***Chapter 3*** describes the development of TIM and comprehensively explains the structure of transport sector. TIM is used to investigate the decarbonisation of the transport sector. Moreover, the impacts of higher spatial resolution and consumer heterogeneity on modelling results are assessed.
    - ***Chapter 4*** applies TIM to analyse the ancillary pollution benefits under a carbon-neutral pathway on a county level in Ireland. The chapter predominately quantifies the co-impacts of decarbonisation pathways on air pollution levels for PM and NOx.

- **Part C:** It has three chapters and discusses the soft-linked process between MESSAGE and an economic model. This multi-model framework is used to quantify energy subsidy reform for the Iranian power sector:
    - ***Chapter 5*** presents an ex-post analysis that examines how subsidy reforms might have avoided inefficient electricity consumption in the absence of uncertainties. The significance of model skill is demonstrated through the analysis of historical data and alternative policy scenarios in this chapter.
    - ***Chapter 6*** also applies a hybrid modelling framework to analyse both supply and demand sides under harmonised assumptions. It improves the understanding of the role of price-induced demand response. A number of scenarios examine the techno-economic and environmental benefits of energy subsidy reforms at different paces.
    - ***Chapter 7*** discusses how synergies and efficiencies from Iran's energy subsidy reforms and lifting its sanctions could impact global energy security, focusing on natural gas.

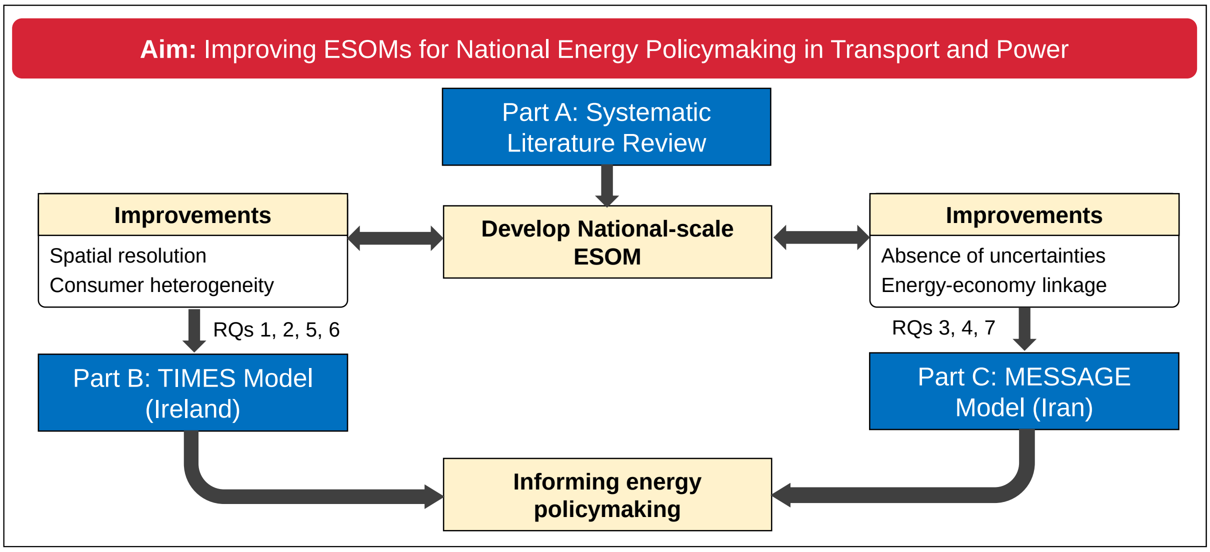

Figure 1-1. Overview of the thesis structure

It is worth noting that despite difference in geographical contexts and different modelling exercises, Parts B and C share similar conceptual frameworks. Both parts of the thesis address weaknesses in ESOMs and use novel approaches to address these issues. In Part B, the thesis develops a multi-regional and multi-consumer approach to capture the heterogeneity of potential car buyers. In Part C, the thesis addresses the weakness of ESOMs in capturing the effects of energy price on demand by developing a soft-linked framework. Furthermore, both parts emphasise the importance of considering uncertainties in ESOMs. Part B addresses the uncertainties through calibration of modelling results with actual data in the first period as well as sensitivity analysis. Part C demonstrates the importance of model skill in examining past performance and evaluating policy impacts, where uncertainties are minimised.

Iran and Ireland share similarities in their policy goals regarding energy due to their commitment to the Paris Agreement. Both countries have ratified the Agreement and are committed to reducing their GHG emissions, increasing energy efficiency, and transitioning to a low-carbon economy. Therefore, their commitment to the Agreement has led to similarities in policy goals between Iran and Ireland, as both countries aim to reduce GHG emissions, increase energy efficiency, and transition to a low-carbon economy. Therefore, this thesis will discuss how the insights gained from two countries can inform the development of energy policies in different contexts.

1.7 Role in collaborations

The large majority of this thesis is my own research work. However, a range of collaborative research plays a significant part in the formation of the chapters. This section clarifies and credits the role of others who have contributed, strengthened, and conducted the thesis. The collaborations gave me an exceptional opportunity to present original modelling approaches. My supervisors Professor Brian Ó Gallachóir and Dr James Glynn advised on all aspects of this work, Professor Hannah E. Daly has advised part B, the introduction, and conclusions of this thesis.

Chapter 2 has been published in a peer-reviewed journal of which I was the lead author. I did the literature study and prepared the draft. My supervisors, Prof. Ó Gallachóir and Dr Glynn, guided the methodology and conceptualisation. My supervisors and other co-authors, Prof. Wenying Chen and Dr. Hancheng Dai, reviewed drafts.

Chapter 3 is based on two published peer-reviewed journal papers. The method section of this chapter provides a comprehensive description of the development of the entire energy sector in Ireland, with my specific responsibility being the transport sector and its interaction with the rest of the model. The first paper, of which I was a co-author, was prepared by Dr. Olexandr Balyk, Prof. Daly, and Dr. Glynn, with contributions from Ankita Gaur, Jason McGuire, and Xiufeng Yue on the demand-side, residential, and power sectors, respectively. The original submission was reviewed and edited by Dr. Olexandr Balyk and Dr. Andrew Smith, and Dr. Balyk also prepared a public repository on GitHub and archived the model (including excel files) on Zenodo. Prof. Daly led an extensive expert review process, involving discussions with internal colleagues and external stakeholders. The other part of this chapter has been published in another peer-reviewed journal paper, for which I was the lead author. In this part, I developed the transport module in TIM, calibrated the model at a county level, and ran the model under different scenarios. Dr. Glynn provided guidance on developing the multi-region model, and Dr. Glynn and Dr. Balyk assisted me in developing and debugging the model. Prof. Daly assessed and validated the results. All the co-authors reviewed drafts of the paper.

Chapter 4 is based on a conference paper presented at the International Energy Workshop. TIM is the basis for this work. As the first author, I did the formal analysis, model development and draft preparation. All my supervisors and Dr Balyk provided guidance and reviewed drafts.

Chapters 5 and 6 have been published in two peer-reviewed journals. I was the lead author in both papers. Prof. Morgan Bazilian assisted me with the conceptualisation of energy subsidy reform in the context of energy system modelling. Dr Siab Mamipour and I further discussed the development of a hybrid energy-economy modelling framework. I conducted the development of the energy model and wrote the draft. Dr Mamipour, Mahsa Ghahremani and

Mahshid Fattahi developed the economic model. Mahsa Ghahremani and Mahshid Fattahi contributed to the result extraction from models, and Dr Mamipour supervised the economic model development and validated its results. Prof. Ó Gallachóir and Dr Glynn assisted with framing the study. All authors reviewed drafts.

Chapter 7 draws on the previous two chapters and a body of research into Iran's domestic energy policies. Professor Ó Gallachóir and Dr Paul Deane provided guidance and reviewed drafts. All authors discussed the results and further developed this part.

1.8 Thesis outputs

JOURNAL PAPERS

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "Decarbonisation of passenger light-duty vehicles using spatially resolved TIMES_Ireland Model", *Applied Energy* (2022), 316, p.119078.

O. Balyk, J. Glynn, **V. Aryanpur**, A. Gaur, J. McGuire, X. Yue, H. Daly. "TIM: Modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1.0)", *Geoscientific Model Development* (2022), 15, 4991-5019.

V. Aryanpur, B. Ó Gallachóir, H. Dai, W. Chen, J. Glynn. "A Review of spatial resolution and regionalisation in national-scale energy systems optimisation models", *Energy Strategy Reviews* (2021), 37, p.100702.

V. Aryanpur, M. Ghahremani, S. Mamipour, M. Fattahi, B. Ó Gallachóir, M.D. Bazilian, J. Glynn. "The Ex-post Analysis of Energy Subsidy Removal through Integrated Energy Systems Modelling", *Renewable & Sustainable Energy Reviews* (2022), 158, p.112077.

V. Aryanpur, M. Fattahi, S. Mamipour, M. Ghahremani, B. Ó Gallachóir, M.D. Bazilian, J. Glynn. How Energy Subsidy Reform Can Drive the Iranian Power Sector towards a Low-carbon Future, *Energy Policy (2022),* 169, p. 113190.

CONFERENCE PAPERS & PRESENTATIONS

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "Co-benefits of air quality and net-zero carbon mitigation pathways: Case of the road transport sector in Ireland", Presented at *40th International Energy Workshop (IEW),* 25 May 2022, Freiburg, Germany.

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "Transition pathway to a carbon-neutral energy system: Implications for passenger light-duty vehicles". Presented at the *14th Integrated Assessment Modelling Consortium (IAMC),* 1 Dec. 2021, Online event.

WORKSHOP & SEMINAR PRESENTATIONS

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "How higher spatial resolution impacts energy systems analysis: Evidence from multi-region TIMES-Ireland model". Presented at the *ETSAP Workshop*, 24 May 2022, Freiburg, Germany.

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "Impacts of monetary incentives and non-monetary policy measures on transport decarbonisation in Ireland". Presented at the *ETSAP Workshop*, 17 Jun. 2021, Online event.

POLICY & TECHNICAL REPORTS

B. Ó Gallachóir, P. Deane, T. MacUidhir, V. O'Riordan, S. McDonagh, **V. Aryanpur**, F. Rogan, 2021 "Emissions Reduction in Transport", Submission to Parliament Committee on Climate Action.

J. Glynn, X. Yue, **V. Aryanpur**, "Vehicle to Grid technology as an enabler of Microgeneration in Ireland", 2021.

POSTERS

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "Developing multi-regional TIMES-Ireland model to support energy policy-making: Impacts of monetary incentives on market uptake of electric vehicles", Presented at *2nd biennial EU Conference on Modelling for Policy support*, Online event, 26 Nov. 2021, Online event.

V. Aryanpur, O. Balyk, H. Daly, B. Ó Gallachóir, J. Glynn. "Impacts of climate policies on transport decarbonisation and implications for energy security", Presented at *International Autumn School* (Climate Policy and Energy System Transformation: New Opportunities and Challenges of the Consideration of Co-Benefits), 14 Sep. 2021, Freiberg, Germany

V. Aryanpur, J. Glynn, O. Balyk, B. Ó Gallachóir, "Analysing the impacts of technology and modal shift in the Irish passenger transport sector", Presented at *MaREI Symposium*, 24 Nov. 2020, Online event.

V. Aryanpur, J. Glynn, O. Balyk, B. Ó Gallachóir, "Developing sustainable scenarios for passenger light-duty vehicles in Ireland", Presented at *30th annual Irish environmental researchers colloquium* (environ2020), 21 Oct. 2020, Online event.

V. Aryanpur, B. Ó Gallachóir, J. Glynn. "Incorporating consumer behaviour from vehicle choice models into energy system optimisation models", Presented at *MaREI Symposium*, 6 Nov. 2019, Limerick, Ireland.

Part A Systematic Review of Energy Systems Optimisation Models

2 Spatial resolution in national-scale ESOMs

Abstracts:

National-scale energy systems optimisation models (ESOMs) have been limited in the past by the lack of sub-national data availability leading to aggregated treatment of spatial dynamics. This chapter first determines how a combination of supply and demand data requirements and socio-economic, environmental and political issues, can challenge the results of a low-spatial resolution model. It also demonstrates the incompleteness of single region ESOMs that do not capture sufficient spatial detail. Specifically, 36 multi-regional ESOMs from 22 countries with varying levels of spatiotemporal resolution, sectoral focus and planning horizon are systematically identified and comprehensively analysed. The review reveals that existing temporally explicit ESOMs with a single sector coverage can permit regional disaggregation up to the first-level administrative divisions within a country (such as state and province) while maintaining computationally tractable. Findings from the literature review also show when, how, and to what extent higher spatial resolution impact on the results of energy system analysis. (1) Finer spatial resolution in ESOMs offers significant added value for regions with heterogeneous renewable potential or across regions with higher variability in energy service demands. However, in homogeneous areas, aggregated single-region modelling is more efficient. (2) Spatially resolved models can significantly change the results of the scenarios with very high shares of variable renewable energies. But it is not straightforward to find a direct relationship between the level of geographic disaggregation and penetration of renewable energies. This trade-off should be explored case-by-case. (3) Total system costs can be under- or over-estimated in various levels of spatial resolutions. Disaggregation of renewable resources leads to lower costs, and disaggregation of transmission grids leads to higher costs.

Keywords: Energy systems optimisation model, Multi-regional, National-scale, Spatial resolution, Spatiotemporal modelling, Variable renewable energy sources

2.1 Introduction

Energy system models are critical tools for supporting energy planning activities and analysing potential future scenarios (Hoffman and Wood, 1976; Mirakyan and De Guio, 2015). They allow policy-makers to explicitly state their views and assumptions, implement policy instruments and explore their impacts on the energy sector and their efficacy in achieving a policy target (Lopion *et al.*, 2018). The demand for a system-wide approach and ensuring security of supply were the critical drivers for developing the first generation of energy system models in the 1970s (Helm, 2002; Lopion *et al.*, 2018). After that period, the economy, market behaviour and technological issues emerged as significant research objectives (Pfenninger *et al.*, 2014) and from 2000, particular attention was paid to the environmental challenges and climate mitigation strategies (Meinshausen *et al.,* 2009; Machado *et al.,* 2019) and more recently, the sustainable development goals (Bolwig *et al.*, 2019). Thus, the optimal diffusion of low carbon technologies, renewable energy sources and the associated demand for flexibility and the implications for GHG emissions reduction became the main focuses of energy system analysis (Lopion *et al.*, 2018). The emergence of national mitigation scenarios as a significant policy analysis topic has resulted from the adoption of the Paris Agreement in 2015 (see, e.g. (Kat *et al.,* 2018; Pan *et al.,* 2018; Shigetomi *et al.*, 2018; Glynn *et al.,* 2019; Horschig *et al.,* 2019; Wei *et al.,* 2019; Lima *et al.*, 2020)). Energy systems optimisation models (ESOMs) are frequently applied to inform national-level decisions, particularly the nationally determined contributions to the Paris Agreement, and to examine the prospects for energy supply and demand (see, e.g. in different countries (Manzoor *et al.*, 2014a; Guemene Dountio *et al.*, 2016; Mirjat *et al.,* 2018; Ozawa *et al.*, 2018; Rečka and Ščasný, 2018; Aryanpur *et al.,* 2019; Hong *et al.*, 2019; Pupo-Roncallo *et al.,* 2019; Kumar *et al.,* 2020; Sharma *et al.,* 2020)). In the absence of sub-national details, these models are still reliable in matching supply and demand (Agnolucci and Mcdowall, 2013) and offer valuable climate and policy insights (Giannakidis *et al.,* 2015); however, they are often criticized for the aggregate treatment of spatial dynamics (Li *et al.*, 2016).

Reviews can be used as a tool for researchers and policy-makers to obtain an overview of the present model landscape and select a proper model structure and design for their specific research question under investigation (Pfenninger *et al.,* 2014). A suite of studies reviewed energy models from different perspectives. Earlier attempts classified and introduced a spectrum of energy system models (see in (Sanstad and Greening, 1998), (Van Beeck, 1999) and (Jebaraj and Iniyan, 2006)). Representation of temporal resolution and integration of renewable energies into energy systems is the focus of numerous reviews (see in (Connolly *et al.,* 2010), (Després *et al.*, 2015), (Collins *et al.,* 2017), (Ringkjøb *et al.,* 2018), (Helistö *et al.,* 2019), (Dagoumas and Koltsaklis, 2019) and (Deng and Lv, 2020)). Some authors also examined the contemporary challenges and new trends in energy system modelling and highlighted some priorities for future energy policy modelling (see in (Lopion *et al.,* 2018), (Pfenninger *et al.,* 2014), (Savvidis *et al.,* 2019) and (Machado *et al.,* 2019)). The capabilities of energy system models for policy-making in developing countries are explored in (Urban *et al.*, 2007) and (Bhattacharyya and Timilsina, 2010). Besides, some researchers reviewed urban energy system models (Keirstead *et al.*, 2012), the interaction between electric vehicles and the power system (Mahmud and Town, 2016), socio-technical energy transition models (Li *et al.,* 2015), integrated energy and transport models (Venturini *et al.,* 2019), open-source ESOMs (Groissböck, 2019), the impacts of climate change in integrated assessment models (Cronin *et al.,* 2018), uncertainty in ESOMs (Yue *et al.,* 2018), planning tools for integrated community energy systems (Mendes *et al.,* 2011), and the application of energy system models for the UK (Hall and Buckley, 2016). Little attention has been paid to spatial resolution in ESOMs, and the impacts of spatial resolution on scenario insights. Camargo and Stoeglehner (2018) reviewed the latest trends in developments of spatiotemporal modelling for distributed energy systems planning in municipalities. Muratori et al. (2020) focused on integrated mobility-energy systems modelling tools. The level of spatiotemporal resolution was used to compare the landscape of this group of models. Martínez-Gordon et al. (2021) identified the main practices to incorporate spatial data in large scale energy system models with a special focus on the North Sea region. However, the previous reviews have not critically assessed regionality and spatial dynamics in national-scale ESOMs. Therefore, they do not apply to the current research questions and challenges of energy systems modelling that are used for national-level decisions. The current work presents a comprehensive overview of existing multi-regional national-scale ESOMs. Then, the models are analysed from four levels of detail: spatial resolution, temporal resolution, planning period and sectoral focus. The aims of this analysis are threefold:

(1) Analyse the potential benefits of regional disaggregation in ESOMs, and show how multi-regional ESOM can capture different dimensions of spatial detail,
(2) Identify the level of spatiotemporal and sectoral details in existing ESOMs and suggest a spatially and temporally explicit modelling framework to support national energy planning studies,
(3) Investigate when, how, and to what extent higher spatial resolution impacts model development, application, and insight generated, especially on optimal development of Variable Renewable Energy Sources (VRES).

The remaining chapter is as follows: Section 2.2 systematically determines the motivations for developing multi-regional ESOMs. Section 2.3 provides the required definitions and review methodology. The spatiotemporal resolution and sectoral coverage of existing multi-regional national ESOMs are reviewed in Section 2.4. This section also shows how various single- and multi-sector models incorporate spatiotemporal details and discusses computational tractability in a high spatiotemporal resolution model. Section 2.5 seeks to provide insights on how the level of spatial resolution influences energy system modelling results. Finally, the conclusion summarizes the significant findings in Section 2.6.

2.2 Motivations for developing multi-regional ESOMs

As shown in Figure 2-1, the motivations for developing multi-regional ESOMs across reviewed studies can be classified into three main categories: (1) Supply-side motivations, (2) Demand-side motivations, and (3) Socio-economic, environmental, and political motivations. They are closely interlinked and affect each other. Although all models are an imitation of the complex real-world (Sterman *et al.*, 2002), the results of an energy system model are meaningfully improved when they combine multiple domains (Li *et al.*, 2015). This chapter defines a complete multi-regional ESOMs as a model that rests at the confluence of the motivations and thus has a rich representation across the three dimensions. On the other hand, a stylised representation captures one aspect of the motivations. The existing multi-regional ESOMs are located on a spectrum between the two extremes as they incorporate a combination of some but not all criteria. The following subsections discuss the dimensions and their interactions.

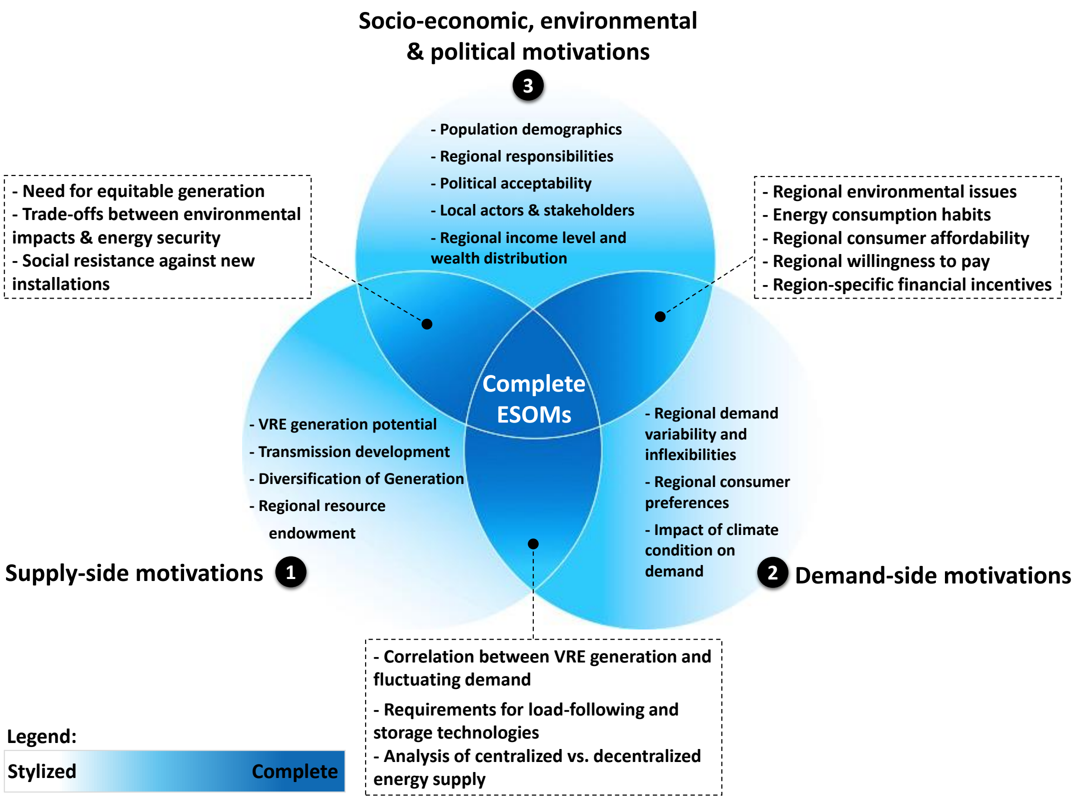

Figure 2-1. Three-dimensional motivations for multi-regional national ESOMs

2.2.1 Supply-side motivation

Single region ESOMs are generally less appropriate for representing real transmission needs than multi-region ones. Moreover, geographical disaggregation in these models is usually not adequately fine to represent the location of VRES, and thus, wind and solar potential are averaged based on large datasets. Of course, although these single region ESOMs provide a practical starting point for large-scale analysis, location-specific investigations are much more reliable (Keles *et al.*, 2017). The existing literature shows multiple supply-side benefits for high-spatial-resolution modelling: detailed meteorological information at solar irradiation and wind speeds can be used to improve the estimation of renewable utilization factors (Egerer, 2016), regional water resource availability and water supply costs may affect the development of upstream processes such as oil and gas extraction, coal mining and washing (Li and Chen, 2019), or even change modelling results in terms of electricity generation from hydropower plants (Victor *et al.*, 2018) and domestic trades of primary energy sources are modelled by the available local capacities for coal, gas and oil transport infrastructures (Vaillancourt *et al.*, 2014; Zhang *et al.*, 2018).

As mentioned, in a single-region-ESOM average data is used for the renewable supply curves. In practice, resource sites with high availability factors and low cost are aggregated with less competitive resources. Averaging the parameters of a poor local resource that does not require a transmission grid with an appropriate remote resource that requires transmission infrastructure may increase the attractiveness of the poor one as it does not require a transmission line. Accordingly, the adoption of attractive resources might not occur in the model that would otherwise be a part of optimal investment in a multi-regional ESOM (Krishnan and Cole, 2016). Furthermore, hydropower provides flexibility to solar and wind generation, which, in turn, enhances their market penetration. This interaction is appropriately represented if sub-national transmission infrastructures exist in the model. The regional approach can also offer an acceptable estimation of adequate transmission development that would be required for ever-growing levels of renewable energy sources. This may unlock untapped renewable sources. Therefore, the results of multi-regional ESOMs provide a balanced expansion of transmission capacities and electricity generation (IRENA, 2017). Representing inter-connectivity between regions also helps to understand the optimal level of centralized versus autonomous and substantially decentralized energy generation schemes (Savvidis *et al.*, 2019). As a result, the potential of diversification in the national generation mix (Odeh and Watts, 2019) and the degree of regional self-sufficiency are explicitly assessed.

2.2.2 Demand-side motivations

One of the typical energy and power planning questions is the location where the capacity should be installed. A multi-regional ESOM may offer capacity expansion close to energy sources or load centres. Regional characteristics are also among the influential factors for distinguishing consumers' attitudes toward alternative end-use technologies. Previous investigations indicate that regional traits such as climate conditions and recharging stations availability may affect heating technology adoption (Li *et al.*, 2018) and alternative fuel vehicles diffusion (Mulholland *et al.*, 2018). Moreover, the incorporation of consumer preferences hinders market penetration of both advanced heating (Aryanpur and Shafiei, 2015) and transport technologies (Mulholland *et al.*, 2018), (Aryanpur and Shafiei, 2015) and (Daly *et al.*, 2015). It indicates that regional preferences might seriously affect the decarbonisation pathway from the demand side.

To simulate the operational flexibility in ESOMs (particularly the capability of load-following operations), hourly and sub-hourly demand profiles are used. In practice, energy supply sectors meet regional demand at each time step. Increased temporal resolution captures more demand variability and inflexibility (Deane *et al.*, 2014). On the other hand, electricity, heating and cooling demand heavily depend on climate conditions and regional patterns of land occupancy and use. These dependencies can be appropriately modelled by integrating a spatial component by means of multiple regions.

2.2.3 Socio-economic, environmental, and political motivations

Region-specific energy modelling allows for representing regional differences in population, socio-demographic differences, economic growth rate, income, wealth, poverty, equity, health and climate policy impacts. For instance, public attitudes towards large-scale adoption of modern energy technologies are heterogeneous and subject to change over a long-term period (Li *et al.*, 2016), (Wang *et al.*, 2020). Recent studies in the UK show that many local communities strongly support wind and solar energy (Parkhill *et al.*, 2013). Nevertheless, substantial objections have been raised against wind turbines installations near local communities (Eltham *et al.*, 2008). On the other hand, affordability issues have a considerable impact on shaping public opinion. Irrespective of investment allocation patterns, consumers finally could bear the extra costs directly through investment or indirectly by additional tax or utility bill payments (Li *et al.*, 2016). Even though consumers are usually willing to pay more for environmentally friendly technology development, their willingness or ability to pay for such technologies depend on wealth distribution, income level and general level of awareness (Kaenzig *et al.,* 2013). These issues differ between socio-demographic groups in urban/rural areas or small/big cities, emphasizing the likely impacts of regional disparities on future national energy transition. It also leaves an uneven distribution of costs and benefits across different regions. A multi-regional ESOM allows for a better understanding as to whether it is justifiable from the social or political point of view for regions to have unequal shares of costs and benefits, as well as the question of whether opportunities exist for co-operation between regions (Li *et al.,* 2016). Another example is introducing region-specific financial incentives to encourage the adoption of advanced technologies (e.g., alternative fuel vehicles and heat pumps). Regional oversight would assist in checking the impacts of policies in other regions. It also helps to explicitly explore regional trade-offs and the development of more efficient policies to improve total benefits, which could unlikely appear in an aggregated national model (Balta-Ozkan *et al.*, 2015).

How should a country cope with the regional features to achieve national emission reduction targets is one of the recurring questions for energy policymakers. Regionally varying efforts and responsibilities could be allocated to each region based on their potentials to improve energy efficiency and meet the national targets (Xu *et al.,* 2019). Moreover, regional actors and stakeholders are crucial elements in the energy transition. Hence, multi-regional modelling can identify where they should take more significant responsibilities to meet the reduction target.

Another motivation emerges from variation in regional resource endowment. Some regions are central players in national energy supply, and the others rest among energy-dependent areas. Consequently, different challenges arise from this diversity for each category. Considering national concerns to meet energy and climate goals, environmental challenges are a vital priority for fossil-fuel producing regions, while non-producing territories must cope with energy security issues. Importing and exporting regions require different administrative capacities and financial resources to manage these worries. The successful management of the national energy system calls into question the different directions of regional energy strategies. Multi-regional ESOMs are appropriate tools to achieve consistent energy policies so that national energy systems can develop sustainably while benefiting sub-national regions (Vaillancourt *et al.,* 2014).

Finally, all investors rationally compete for high-quality sites with strong wind speed and solar radiation intensity. This optimal site goal leads to a higher concentration of new power units at the sites with the best resource potentials. However, some adverse environmental impacts such as loss of biodiversity and disturbances to humans may appear. Therefore, it is unlikely that location choices based solely on investors' preferences end in a regionally optimal allocation from society's perspective. An ideal allocation strategy concurrently includes techno-economic efficiency, social welfare, equity, or distributional considerations (Drechsler *et al.,* 2017). A multi-regional ESOM can address the distributional aspects. In other words, spatial disaggregation also helps energy policy-making with more equitable outcomes (Balta-Ozkan et al., 2015).

2.3 Definitions and review methodology

Spatial extent is the geographic coverage of an individual study (Frew and Jacobson, 2016). It indicates the territorial dimensions at which the study concentrates and shapes the basic structure of an energy system model (Van Beeck, 1999). Geographical coverage is classified into five main categories: global, regional, national, local, and single project (Van Beeck, 1999), (IRENA, 2017). Global energy models usually analyse the universal atmospheric carbon concentration situation (Messner and Schrattenholzer, 2000), worldwide mitigation scenarios and generation mix (Realmonte *et al.,* 2019), (Føyn *et al.,* 2011), climate impacts on international energy supply and demand (Labriet *et al.*, 2015) and technological feasibility to achieve significant emission reduction targets (Akashi and Hanaoka, 2012; Akashi *et al.,* 2012). Regional energy system models analyse energy-related issues on an international region scale (including multi-countries or continental level analysis) such as renewable electricity generation in Sub-Saharan Africa region (Barasa *et al.*, 2018), deep decarbonisation pathways for European countries (Capros *et al.*, 2018; Gaffney *et al.*, 2018; Siskos *et al.*, 2018), and energy security in the Baltic States (IAEA, 2007). The national-level addresses socio-economic activities in a specific country such as ambitious emission reduction commitments in Japan (Fujimori *et al.,* 2019) and Ireland (Glynn *et al.*, 2019), (Yue *et al.*, 2018), fossil-free transport sector for Denmark (Tattini *et al.*, 2018) and power sector development in Iran (Aryanpur and Shafiei, 2015a; Manzoor and Aryanpur, 2017; Atabaki and Aryanpur, 2018), Australia (De Rosa and Castro, 2020) and Egypt (Rady *et al.,* 2018). Regions can be spatial subdivisions within a model framework and can co-exist on entirely different scales (in terms of square kilometres) depending on the reviewed literature. It is also worth noting that the term "region" is used to show two different meanings here: (i) a group of countries such as EU countries and, (ii) sub-national units in a country such as a province, state, or county. The second meaning is the focus of this chapter. A local model reflects sub-national area(s) within a country, such as hydropower generation in British Columbia (Kiani *et al.*, 2013), electrification of the transport sector in New York City (Isik *et al.*, 2021) and modal shift of passenger transport in California (Daly *et al.,* 2015). The project level also refers to a specific site such as techno-economic analysis of a 50 MW grid-tied solar PV at a campus in Ghana (Obeng *et al.,* 2020) and electricity generation from a wind farm in Bouar, in the west of the Central African Republic (Ngbara Touafio *et al.,* 2020).

On the other hand, the spatial resolution indicates the handling of resources, technologies and consumers incorporated in the model. For example, higher resolution deals with site-by-site units, and coarser resolution includes aggregated and uniform development across all sites (Frew and Jacobson, 2016). Geographical resolution decisions are represented by defining single or multiple nodes in an energy system model. The model's objectives should govern the choice of spatial scale and resolution. An international challenge like GHG mitigation differs from a regional issue such as urban air pollution. The former problem requires a global model, while the latter needs a regional or local model. This chapter focuses on multi-regional national-scale energy models. The number of sub-national geographic regions indicates the level of spatial resolution and regional disaggregation. The regions can be defined by official geographic divisions within a country like states and provinces, basic divisions like west and east, climatic conditions such as cold and hot areas, or other planning-relevant zones.

A comprehensive literature survey is conducted to fully capture the diversity of existing multi-regional national-scale energy system analyses. A systematic review was managed by searching the ISI Web of Science database for two main general strings "energy system* model*" and "energy system* optimisation model*" in all fields. The aggregated number of results was 1479 publications. It is worth noting that we have excluded "regional" from the primary keywords as many studies use other words for multi-regional analysis such as "spatial resolution", "spatial disaggregation", "geographical division", "geographical clusters", "sub-division", "sub-national", "provincial", "zone", "states", and "node". Then, the primary search was refined based on three criteria: (1) the document should be a peer-reviewed journal article, (2) the document should be in English, and (3) should be published after 2010. The filtration still leaves a total number of 1024 records. The results were further refined by removing unrelated subject areas such as thermodynamics and atmospheric meteorology sciences. The product of this round was 626 publications. The remaining papers were manually filtered based on a case-by-case review of individual titles and abstracts to exclude those studies that were not within the scope of the current review (such as the works that cover global energy system

(McCollum *et al.*, 2018; Huppmann *et al.*, 2019), highly renewable energy systems and energy trades across multiple countries (Cebulla *et al.*, 2017; Gils *et al.*, 2017; Horsch and Brown, 2017; Scholz *et al.*, 2017; Brown *et al.*, 2018), or heat supply and demand planning (Sperling and Möller, 2012; Delmastro and Gargiulo, 2020) and low-carbon energy communities (Comodi *et al.*, 2019) at the urban or local scale). Furthermore, the bibliographies from the identified papers were followed to ensure that the review covers all relevant publications. The filtration steps retained a set of 76 papers. The case studies with the similar model structure (i.e. the same model, same country and identical sub-national regions) are combined. 36 distinctive multi-regional ESOMs have been identified. This group of models comprises the heart of the current review paper. They mainly used TIMES, MARKAL, ESME, MESSAGE and GENeSYS_MOD for their analyses. Although the remaining studies applied simulation or electricity market models, some valuable findings in terms of multi-regional national-scale energy modelling were obtained from them. These models are: generation expansion planning models in Greece (Koltsaklis and Georgiadis, 2015; Koltsaklis *et al.*, 2015), and in China (Guo *et al.*, 2017; Chen *et al.*, 2019), (Cheng *et al.*, 2015) application of REMix, PowerFlexEU, SCOPE, ELMOD and LIMES in Germany (Ludig *et al.*, 2015; Gils *et al.*, 2019), EXPANSE in Switzerland (Sasse and Trutnevyte, 2019), ESONE and Calliope in the UK (Pfenninger, 2017; Heuberger *et al.*, 2020), US-REGEN (Bistline *et al.*, 2019) ReEDS (Krishnan and Cole, 2016), (Bird *et al.*, 2011; Lantz *et al.*, 2016; Wiser *et al.*, 2016; Cohen and Caron, 2018; Mai *et al.*, 2018; Frazier *et al.*, 2019; Mai, Cole and Reimers, 2019; Reimers *et al.*, 2019) POWER (Frew and Jacobson, 2016) in the US as well as national modelling systems with NEMS (Brown and Baek, 2010; Wilkerson *et al.*, 2013; Weijermars, 2014; Mignone *et al.*, 2017; EIA, 2019) in the US. By virtue of being developed for energy system analysis across multiple countries, some other well-known models are out of the scope of this study (such as the application of multi-regional OSeMOSYS models for investigating the African electricity supply (Taliotis *et al.*, 2016), and energy infrastructure in South American countries (Santos, 2021), or PRIMES for simulating the European energy system and markets on a country-by-country basis (Fragkos *et al.*, 2017)).

2.4 Overview of existing multi-regional ESOMs

As shown in Table 2-1, among thirty-three identified studies, thirteen multi-regional ESOMs have been exclusively focused on the power sector, and five have been applied to the building and residential sector. Some models have been used for multi-sector analysis: ten models have been applied to the entire energy system, and two studies cover power, heating and transport sectors. Of the remaining studies, one deeply investigates hydropower generation, one focuses on biomass supply, and another represents the hydrogen supply system. Some multi-regional studies excluded from Table 2-1, as they explored a sub-region within a country: For example, Jalil-Vega and Hawkes (Jalil-Vega and Hawkes, 2018; Jalil-Vega and Hawkes, 2018) applied Heat Infrastructure and Technology (HIT) model to investigate heat decarbonisation pathways for the local authorities/cities in the UK. Rosenberg et al. (2010) used a MARKAL model to examine the feasibility of hydrogen passenger vehicles in three Norwegian regions. Gaur et al. (2019) developed a multi-regional TIMES model to investigate the role of operational constraints for the long-term power generation scenarios in the Northern region of India, and Jalil-Vega et al. (2020) also developed a spatially-resolved urban energy systems model to analyse decarbonisation pathways in Sao Paulo. Although they are sub-national models, they are still relevant to this review and add some valuable evidence to the analysis.

Table 2-1. List of existing multi-regional national energy system studies

Country	Sub-regions (spatial resolution)	Temporal resolution	Planning horizon	Model Name (Tool)	Spatial details[a]	Sectoral focus	Aim of geographical disaggregation	Source
Austria	79 wind regions and 5 PV regions	12 (4 seasons, 3 daily types)	2005-2050	TIMES	GIS	Power sector	Addressing the role of spatial disaggregation level on electricity generation from VRES	(Simoes *et al.*, 2017)
Brazil	29 electricity regions and 4 international exchange links	192 (24 hourly, 2 daily types, four seasons)	2010-2050	TIMES	IP	Power sector	Assessing transmission bottlenecks in the long-term development of the power sector	(Miranda *et al.*, 2019)
Canada	13 provincial energy systems	12 (4 seasons, 3 daily periods)	2007-2050	TIMES	RES	Energy system	Assessing the penetration of emerging supply-side technologies and alternative energy carriers in a sustainable way to benefit each province	(Vaillancourt *et al.*, 2014)
China	5 regions	Unspecified	2010-2050	TIMES-W	Distribution of energy and water resources	Power sector	Incorporating water resource availability	(Li and Chen, 2019)
China	33 nodes including all first-level administrative divisions	120 (5 typical days, 24 hourly resolution)	2015-2050	Global Energy System Model (GENeSYS-MOD)	RES	Energy system	Representing regional characteristics and disparities to achieve ambitious targets	(Burandt *et al.*, 2019)
China	4 climate regions	Annually	2015-2050	Global Change Assessment Model (GCAM)	MSM	Building sector	Considering spatial heterogeneities in energy consumption habits, economic status and building codes	(Chen *et al.*, 2020)
China	7 power grid regions	Annually	2015-2050	MESSAGE	IP	Power sector	Delivering insights into electricity generation, transmission structure and coal transport considering regional air pollution control policies and resource potentials	(Zhang *et al.*, 2018)
China	5 different climate zones	Unspecified	2010-2050	TIMES	RESD	Building sector	Representing building service demands across diverse climate zones and regional building design standards and energy consumption habit	(Shi *et al.*, 2016)
Denmark	2 regions: East (DKE) and West (DKW)	32 (4 seasons, 2 daily type, 4 hourly)	2010-2050	TIMES [b]	RES	Energy system	Incorporating region-specific transport and residential buildings parameters, electricity trade prices, capacities and availability factors of power grids and intra-regional exchange of electricity	(Balyk *et al.*, 2019) (Salvucci *et al.*, 2018)
Denmark	2 regions: East Denmark and West Denmark	Hourly (ranging from 1 h up to 1409 h per year)	2010-2050	TIMES	GIS	Residential heating	Considering regional air and ground temperatures and spatial constraints	(Petrović and Karlsson, 2016)
Denmark	2 regions (eastern and western)	168 time-steps	2030	Balmorel [c]	RESD	Power, heating and road transport sector	Balancing Electricity and transport supply and demand on a regional basis	(Juul and Meibom, 2011)
Germany	4 basic areas	Annually	2013-2060	TIMES Actors Model (TAM)	RES	Power sector	Capturing geographical distribution of VRES, electricity demand, inter-regional power trades and regional investment decisions	(Tash *et al.*, 2019)
Germany	16 nodes representing one federal state	16 (4 seasons, 4 daily)	2015-2050	GENeSYS-MOD	RES	Energy system	Analysing energy system development on a regional level	(Bartholdsen *et al.*, 2019)
Greece	14 geographical clusters	16 (4 seasons and 4 intra-day blocks)	2011-2050	TIMES	IP and RESD	Power sector	Identifying regional potentials of renewable energy sources with different costs and utilization factors	(Tigas *et al.*, 2015)
India	10 regions	6 (3 seasons and 2 daily fluctuations)	2015-2050	GENeSYS-MOD	RES	Energy system	Reflecting regional characteristics and renewable potential imbalances	(Lawrenz *et al.*, 2018)
Ireland	26 counties [d]	Flexible (from annually to hourly)	2018-2050	TIMES-Ireland Model (TIM)	IP	Energy system	Capturing region-specific characteristics of transport sector	(Balyk *et al.*, 2021)
Italy	6 zones based on bottlenecks of the transmission grids	Hourly	2050	oemof-moea (a bottom-up short-term model)	IP	Electricity, heat and transport	Incorporating transmission constraints between different nodes	(Prina *et al.*, 2020)

Country	Sub-regions (spatial resolution)	Temporal resolution	Planning horizon	Model Name (Tool)	Spatial details[a]	Sectoral focus	Aim of geographical disaggregation	Source
Italy	6 market zones	hourly resolution by soft-linking with PLEXOS	2030	MONET (a TIMES- energy systems model of Italy) and PLEXOS	IP	Power sector	Representing transmission lines data such as max and min flow, overloading ratings and resistance to analyse the security of transmission infrastructure	(Deane *et al.*, 2015)
Japan	9 regions with possible inter-regional power grid connection	504 (3 seasons, 7 representative days, 24 hours)	2010-2030	MRDOM (multi-region dynamic optimisation model)	IP	Power sector	Analysing the natural dynamics of renewable energy sources and real-time cross-regional power flow	(Wang *et al.*, 2016)
Kazakhstan	16 administrative and interconnected regions	Unspecified	2011-2030	TIMES	RESD	Residential sector	Examining regional transition pathways for the residential sector and implications for the supply side energy infrastructure	(Kerimray *et al.*, 2018)
Mexico	9 regions	16 (4 seasons and 4 intraday cuts)	2015-2050	GENeSYS-MOD	RES	Energy system	Incorporating regional demand structure and environmental endowments	(Sarmiento *et al.*, 2019)
Netherland	30 regions	Hourly	2050	Greenfield Renewables Investment Model (GRIM)	Land cover assessment	Power sector	Connecting land cover data and location-specific production profile of VRES with energy system planning	(Wang *et al.*, 2020)
Norway	5 regions based on pricing areas in the Nordic spot market	260 (52 weeks and 5 time-slices per week)	2010-2030	TIMES	RES	Energy system	Exploring inter-regional and cross-countries power trade, regional welfare and economic analysis	(Helgesen *et al.*, 2018)
Norway	7 regions with the exchange of electricity between adjacent regions and neighbouring countries	260 (52 weeks and 5 time-slices per week)	2006-2020	TIMES	IP	Energy system	Analysing the pathways to achieve renewable energy target	(Lind *et al.*, 2013)
Norway	7 regions to calculate hydro-inflow	8 (day & night for each season)	2005-2050	MARKAL	Hydro-inflow at regional level	Hydropower generation	Estimating the impact of climate change on regional hydropower generation	(Seljom *et al.*, 2011)
Portugal	Existing power plants are individually modelled, new options are modelled at municipality level	64 (4 seasons, 2 typical days, 8 hourly)	2016-2050	TIMES	Regional data for VRES	Power sector	Capturing the potential of renewable energy sources at the municipality level	(Amorim *et al.*, 2020)
South Korea	15 sub-regions for different generators	Unspecified	2012-2022	TIMES	IP	Power sector	Demonstrating the electricity sector explicitly and implementing the operation of the renewable portfolio standard policy in details	(Choi *et al.*, 2015)
Sweden and France	21 regions for Sweden and 9 regions for France	Unspecified	2000-2050	TIMES	Regional potential of agricultural and woody biomass sources	Biomass resources and supply	Incorporating site-specific biomass information such as marginal costs, transportation distances, harvest rates and resources accessibility	(Forsell *et al.*, 2013)
Switzerland	15 grid nodes (7 Swiss regions, 7 existing nuclear power plants and 4 neighbouring countries)	288 (4 seasons, 3 typical days, 24 hours)	2015-2050	TIMES	IP	Energy system	Capturing the details of power grid infrastructure to understand better the role of storage technologies and other flexibility options	(Panos, Kober and Wokaun, 2019)
UK	20 zones	8760 (every hour of the year)	2010-2050	highRES+ UKTM [e]	GIS	Power sector	Realizing how water and land-use limitations impact the spatial pattern of installed capacity	(Price *et al.*, 2018)
UK	24 regions (12 on land, 9 offshore, and 3 carbon sequestration sites)	10 (2 seasonal and 5 diurnal)	2010-2050	Energy Systems Modelling Environment (ESME)	RES	Energy system	Exploring regional political feasibility and societal acceptability, geographical resource availability and distribution of future demands, effects on regional actors and infrastructure development	(Li *et al.*, 2016)
UK	2 regions (Scotland and rest of the UK)	Unspecified	2000-2050	UK2R MARKAL	RES	Energy system	Analysing Scotland's decarbonisation pathway and the interactions between Scottish and the UK policy ambition	(Anandarajah and McDowall, 2012) and (Anandarajah, 2014)

Country	Sub-regions (spatial resolution)	Temporal resolution	Planning horizon	Model Name (Tool)	Spatial details[a]	Sectoral focus	Aim of geographical disaggregation	Source
UK	9 urban and 3 rural/semi-rural regions (divided based on population)	Annually	2000-2050	MARKAL	IP	Hydrogen supply system	Allocating optimal resources for hydrogen infrastructure development (production, delivery and use) to cover regional energy service demands	(Balta-Ozkan and Baldwin, 2013)
USA	9 Census Divisions of the US	12 (3 seasons, 4 times of day: day am, day pm, night and peak) [f]	2005-2050	MARKAL[g]	RES	Power sector	Representing resource availability, costs, existing infrastructure, end-use demands and carbon storage capacities in each region	(Victor *et al.*, 2018)
USA	50 US states	Daily temporal resolution for heating and cooling degree days	2005-2095	Global Change Assessment Model (GCAM)	RESD	Commercial and residential buildings	Providing insights from a regional level to better estimate national-level changes and comparing national and aggregated regional values for buildings energy use over time	(Zhou *et al.*, 2014)
USA	32 subregions for power sector and 9 for demand	12 (2 seasons, 6 times of day)	2010-2050	TIMES	IP	Power sector	Capturing geographical relationships and regional heterogeneity that mainly drive the costs of a low-carbon energy transition and addressing carbon policy interactions across regions	(Wright and Kanudia, 2014)

[a] Abbreviations: IP: Infrastructure Planning; RESD: Region-specific Energy Service Demand; GIS: Geographic Information System; MSM: Multi-Scale Modelling; RES: Region-specific Reference Energy System.

[b] Similar model has been developed to analyse the value of residual biomass resources (Venturini *et al.*, 2019), and explore deep decarbonisation pathways for the Danish transport sector (Tattini *et al.*, 2018) and (Hagos and Ahlgren, 2020).

[c] The model has also been employed for analysing the industrial sector (Wiese and Baldini, 2018), health-related externalities (Zvingilaite, 2011) and district heating (Münster *et al.*, 2012) for the case of Denmark. A new version provides flexible handling of the time and space dimensions (Wiese *et al.*, 2018).

[d] Transport sector is divided into 26 sub-regions and other sectors are nationally analysed.

[e] The UKTM explored optimal low carbon transition from 2010 to 2050, but the highRES checked operational decisions for the final year. Moore *et al.* (2018) used a similar framework to analyse electricity generation from offshore wind turbines for Great Britain.

[f] From Lenox *et al.* (2013).

[g] A similar model and number of regions have been used for modelling uncertainties associated with the outcomes of regional regulations (Balash *et al.*, 2013), potential consequences of vehicle automation in the energy system (Brown and Dodder, 2019), and analysing the role of natural gas combined-cycle power plants equipped with carbon capture and storage technologies to achieve a low-carbon future (Babaee and Loughlin, 2018).

2.4.1 Spatiotemporal resolution and planning period

Table 2-1 also reveals that most of the reviewed studies are long-term energy system analyses with a time horizon of 10–90 years. This observation is consistent with the fact that energy system models are often developed to explore optimal transition pathways toward a particular long-term environmental target in various scenarios and to inform policymakers on strategies and means which can be effective over the long run. On the other hand, a few studies ran for a shorter period (less than five years); they characterised underlying aspects of temporal variability instead.

Figure 2-2 presents four levels of detail in the identified models[1]: temporal resolution, spatial scale, planning period and sectoral focus. From a temporal point of view, most of the reviewed models are highly aggregated and have limited time-slices per year in a stylised fashion representing temporal variability. However, this group of models have higher degrees of spatial detail and are appropriate for multi-decade energy system analysis. Adding thousands of time-slices decreases computational tractability in ESOMs. For example, a model with eight planning periods, 8760 hourly time slices per year, 20 sub-national regions, 30 standard generation technologies, and at least two time-dependent constraints (such as storage charging/discharging, upper/lower limit generation in each region) would result in more than 84 million constraints. Reducing the massive size, sparsity and number of non-zeros in this model matrix by even one order of magnitude significantly reduces computational complexity (Pfenninger, 2017). Therefore, some studies performed a detailed temporal data analysis outside of the model to extract significant load variations and renewable dynamics and then used these pre-analysed data in the corresponding models (see, e.g.: MRDM in Japan (Wang *et al.,* 2016) and TIMES in Norway (Helgesen *et al.,* 2018) with 20-year planning horizon). In contrast, MONET in Italy (Deane *et al.,* 2015), REMix in Germany (Gils *et al.,* 2019), and GRIM in the Netherland (Wang *et al.,* 2020) explored the operational feasibility of the power system using an hourly time resolution for a single snapshot year. They show that power system models with hourly temporal resolution can also capture spatial details while keeping their computational tractability. TIMES-DK (Petrović and Karlsson, 2016), TIMES-Ireland Model (TIM) (Balyk *et al.,* 2021), and TIMES-UK (Price *et al.,* 2018) also incorporated spatial details in a high-temporal resolution model. The UK case developed a hybrid framework to

[1] In this figure, the model name is followed by a 2-letter country code based on International Naming Convention (ISO 3166) to have a consistent pattern for naming. As a result, some of these names are different from the original names in the corresponding references. Moreover, some less well-known models or unstated temporal resolutions and limited applications have been omitted from this comparison.

simultaneously examine long-term investment plans and short-term dispatch decisions in a high spatiotemporal resolution. These three models also show the possibility of capturing spatial details in a long-term ESOM with high-temporal resolution while remaining computationally tractable.

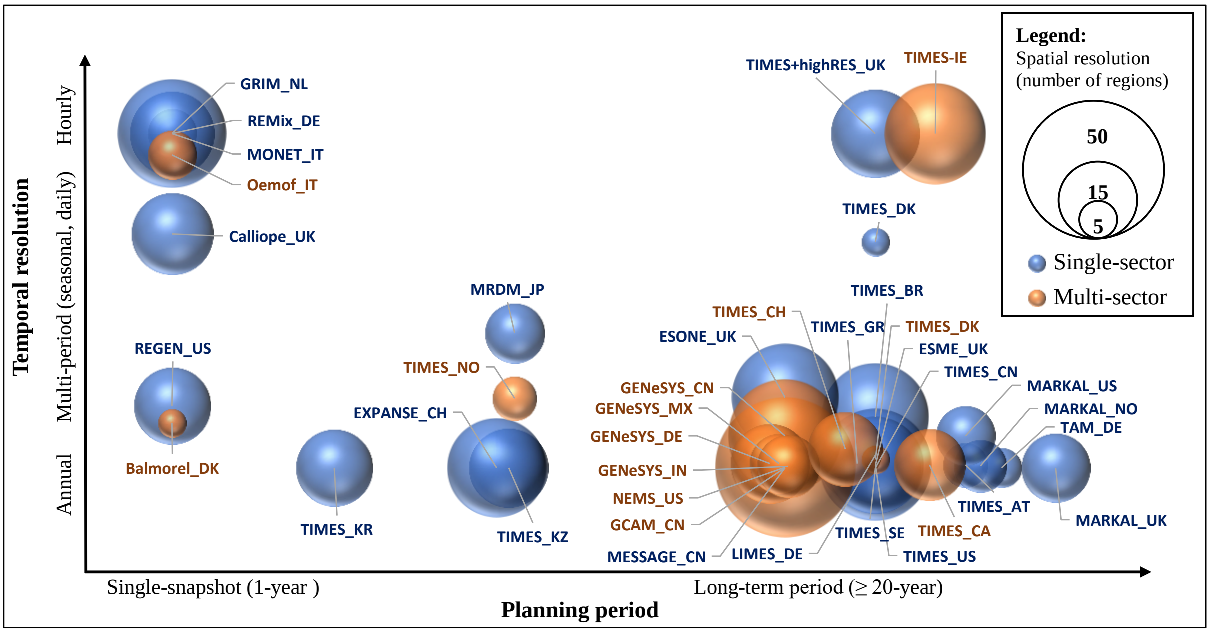

Figure 2-2. Spatiotemporal resolution and planning period of multi-regional energy system models

2.4.2 Incorporation of spatial details in multi-regional ESOMs

Spatial details have been partially considered in most previous studies through infrastructure planning, defining region-specific energy service demands, or using geographic information systems (GIS). A few studies also used a multi-scale modelling approach (see Figure 2-3 for comparison). These partially spatially-resolved models have mainly analysed a single-sector such as power supply in (Simoes *et al.*, 2017) and building sector in (Shi *et al.*, 2016) or focused on technological subsystems such as residential heat pumps in (Petrović and Karlsson, 2016). Multi-regional infrastructure planning is often used to address power sector details. Each region within a country can be characterised according to existing power plants and inter-regional and cross-countries grid connection capacities (see, e.g. , (Obeng *et al.*, 2020), (Koltsaklis *et al.*, 2015), (Guo *et al.*, 2017), (Chen *et al.*, 2019), (Miranda *et al.*, 2019), and (Lind *et al.*, 2013)). Infrastructure planning is sometimes used to model district heating networks (Jalil-Vega and Hawkes, 2018) and pipeline networks for hydrogen delivery (Balta-Ozkan and Baldwin, 2013). The representation of power networks and availability factors of VRES is typically simplified in the existing models. Even though it would be viable to model more grid branches in multi-regional ESOMs, computational burden, and data requirements could act as preventive factors (Ludig *et al.*, 2015). Moreover, availability factors of renewable energy sources are usually quantified on an hourly basis. Due to the limited temporal resolution in most well-known multi-regional ESOMs and to increase computational tractability, these hourly data are aggregated, and an average regional value is used for each time-slice. The averaging process hides some actual variability patterns of renewable sources. Representative days (Nahmmacher *et al.*, 2016) for each region can be employed to reflect the typical fluctuations of these data.

The multi-regional approach can benefit from GIS tools to address different challenges (Biberacher, 2004; Kost *et al.*, 2015; Shafiullah *et al.*, 2016): identification of regional potential, selection of proper locations for new capacities, identification of optimal transmission routes and ideal locations for distribution substations, and determination of location-specific demand patterns (see, e.g. (Wang *et al.*, 2020), (Simoes *et al.*, 2017), (Petrović and Karlsson, 2016)). GIS is also used to reach optimal location and optimal sizes for investment plans and thus, improve the results of typical energy system planning. GIS has a substantial potential for contributing to the necessary geospatial analyses. But, the quality of available weather and land cover information has previously restricted this method. The limitations are higher for larger regions as the reference sites are less representative than for smaller areas (Kost *et al.*, 2015). Moreover, the integration of energy models and GIS encounter numerous challenges (Resch *et al.*, 2014). This linkage requires a range of parameters and datasets and more analyst efforts. It also multiplies the model's complexity. As a result, computational requirements and run-time radically increase, which can discourage the addition of finer spatial resolution. The remarkable growth in computer speeds over time can reduce this concern. To enable computational tractability, some researchers preferred to limit the sectoral coverage (e.g. spatially explicit hydrogen supply in the UK (Balta-Ozkan and Baldwin, 2013), or heat pumps in Denmark (Petrović and Karlsson, 2016)) or reduce the temporal resolution (e.g. limited representative days to model the evolution of power system in the UK (Heuberger *et al.*, 2020)).

Region-specific energy service demands is also used in other studies (see, e.g. (Sasse and Trutnevyte, 2019), (Shi *et al.*, 2016), (Seljom *et al.*, 2011), (Zhou *et al.*, 2014), (Biberacher, 2004)). Energy service demands can be affected by population density, climate, human behaviour, living standards and socio-economic development parameters. Energy service demands within energy models are usually estimated by factors exogenous to the energy models. As implemented in (Helgesen *et al.*, 2018), the demands can be endogenously determined in a hard-link method. It helps to ensure replicability and to avoid human judgment and error within data transfer between models. However, even this unique work needs to further develop through region-specific assessment of energy efficiency improvements in macroeconomic models based on feedback from energy models.

Multi-scale planning procedures have been developed to make a trade-off between national and regional government goals and to determine the role of each region to meet national objectives. In this method, a two or three-stage decision-making process is usually applied, where the first-stage decision corresponds to a national objective such as emission reduction, and the second-stage decision reflects the emission reduction within sub-national regions based on the corresponding regional index such as GDP, population and land areas (see, e.g. (Xu *et al.*, 2019) (Chen *et al.*, 2020)). Some weaknesses are observed for the scope and research methods during multi-scale modelling. One limitation is related to the sectoral coverage in the existing studies. They have focused on a single sector such as the power supply and building sector. On the other hand, inter-regional domestic trades are neglected as energy-related interactions among provinces are not considered (Chen *et al.*, 2020). Moreover, this method usually needs an allocation factor to distribute emission quotas across regions. This factor is determined based on each region's current socio-economic and environmental situation, while it may fluctuate over the planning horizon. A dynamic recursive method is needed to update the allocation factor over time. Similarly, a soft-link between national-scale energy system planning over a long-term period and a detailed regional model was unidirectional in previous studies. A bi-directional method can be used to modify specific parameters and constraints.

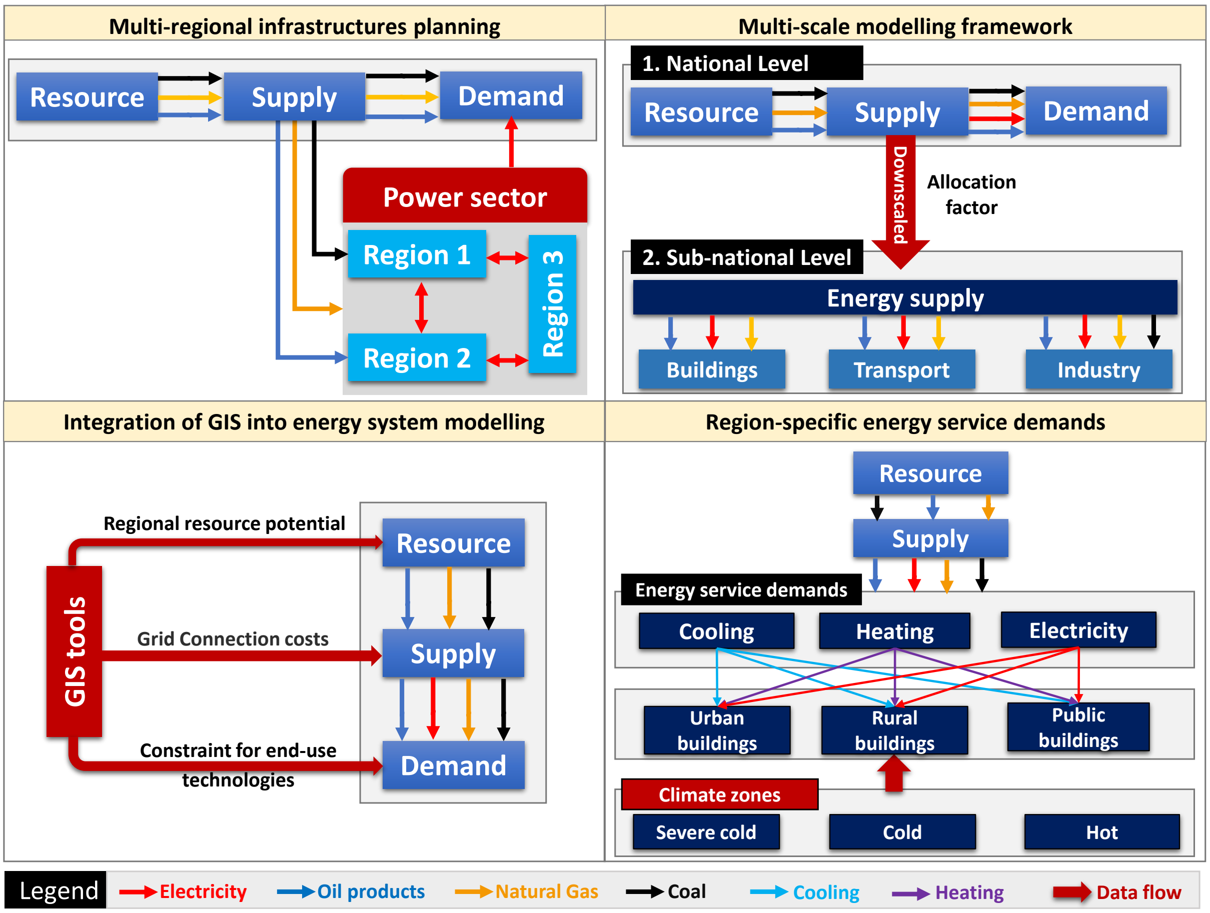

Figure 2-3. Different solutions for multi-regional energy system modelling

In contrast to a significant number of partial attempts, some studies adopted an independent, region-specific Reference Energy System (RES) to reflect spatial detail both for supply and demand-side (e.g. (Victor *et al.*, 2018), (Vaillancourt *et al.*, 2014), (Tash *et. al*, 2019)). Despite a detailed spatial disaggregation, these models have a stylised low-temporal resolution. The insufficient temporal resolution may avoid capturing the entire distribution of load and VRES. Previous efforts (see (Haydt *et al.*, 2011; Ludig *et al.*, 2011; Pina *et al.*, 2011, 2013; Deane *et al.*, 2012; Kannan and Turton, 2013; Poncelet *et al.*, 2016)) revealed that limited temporal resolution leads to an overestimation of both VRES and baseload capacities. At the same time, the value of flexible technologies and storage options cannot be accurately determined.

2.4.3 Computational tractability and solution time

Solving highly detailed ESOMs still proves to be demanding even with high-performance computers[1]. Increasing spatial resolution (subdividing models into sub-regions) and temporal

[1] The main specifications of the computers that were used to solve the models in Refs (Panos, 2019; Scholz *et al.*, 2020) are 2 × 24 cores @ 2.7 GHz, 192 GB RAM @ 2666 MHz.

disaggregation exponentially increases computational time and burden in the proposed framework (Panos, 2019). For instance, a comprehensive investigation in (Panos, 2019) shows that an ESOM with 11 sub-regions, 672 time steps and 8 time periods is run in about 8 hours, while a similar model with 22 sub-regions is run in more than 30 hours. As a result, some strategies should be used to run the proposed model. The strategies help modellers to balance between spatial resolution, temporal resolution, computational tractability and acceptable solution time (Sharma *et al.,* 2019). Scholz et al. (Scholz *et al.*, 2020) have systematically assessed the effects of aggregation techniques and parallel computing methods on solution time. A high-resolution ESOM REMix (with 8760 time steps and 488 sub-regions) was used for the benchmark analysis. This reference model explores an energy scenario of the year 2030 in Germany. An optimal solution was obtained after six hours run-time for a spatially aggregated model with 100 regions. The key results show minor deviations within a range of less than 5% compared to the reference model. It is worth mentioning that regionality and time slice resolution are both indices in the equations of an ESOM. In this example, 8760 time slices create much greater computational issues than regional disaggregation, presuming that regional disaggregation is two orders of magnitude smaller (<100 regions). Also, the computational tractability issue is not solely to do with computing power but also memory space within the computer; the larger and sparser the ESOM matrix, the more RAM that is needed.

Another example is annual TIMES-Ireland Model (TIM) that requires less than 1GB of RAM to run. The TIM version with hourly time slices and unit commitment with perfect foresight and 11 periods showed a RAM demand of over 200GB. Regionality is only one dimension of the problem when it comes to computational tractability. It is not the worst issue to solve when it comes to making larger complex models. Finally, further examinations from (Scholz *et al.,* 2020) reveal that parallelisation of linear optimisation problems on a high-performance computer can reduce the runtime by 76%-96%. In a nutshell, these strategies allow energy modellers to explore long-term transition pathways with a high spatiotemporal resolution model.

2.5 Current insights and lessons learned

The significance of spatial resolution for energy system analysis has recently increased, and it is expected to be a crucial part of future energy modelling (Martínez-Gordón *et al.,* 2021). This section aims to analyse when, how, and to what extent higher spatial resolution impacts model development and application.

First, multi-regional ESOMs are usually used to understand better the optimal distribution of power grid infrastructures and heat networks (Lind *et al.,* 2013; Jalil-Vega and Hawkes, 2018; Jalil-Vega and Hawkes, 2018; Miranda *et al.,* 2019; Jalil-Vega *et al.,* 2020), and analyse the diversity of renewable energy shares for each region more reliably (Simoes *et al.,* 2017; Miranda *et al.,* 2019), (Tash *et al.,* 2019). One question that needs to be asked is when regional disaggregation is an essential matter for model development and application. The evidence from TIMES-Austria (Simoes *et al.,* 2017) suggests that when electricity generation is very close to the maximum technical potential of a specific technology or when they are too far from the cost-optimal solution, the results from multi-regional approach might be similar to the single-region one. On the other hand, geographical disaggregation in TIMES-Brazil (Miranda *et al.,* 2019) demonstrates that the generation mix may substantially differ when the number of regions increases, new capacities are only installed where the possibility to deliver generation is high and even may suggest low-quality wind resource sites if there is need for additional local generation. This highlights the point that infrastructure costs should be added to life-cycle costs of a technology to have a realistic comparison with other options. This case also shows finer spatial resolution is more important especially when meteorological conditions vary significantly. The observations from the application of HIT to the UK (Jalil-Vega and Hawkes, 2018) also indicate that higher spatial resolution becomes much more important when there is enough variability of linear heat density across regions. The results for regions with heterogeneous heat density will meaningfully change under finer spatial resolution scenarios. In sum, heterogeneous regions (either in terms of weather-driven variability or higher variability in energy service demands across regions) require more disaggregation while in homogeneous areas, aggregated single-region modelling is more efficient (data and computational complexity reduce).

Second, spatially resolved models are highlighted as one of the key features for modelling scenarios with very high shares of VRES. The need for regional disaggregation can grow with further deployment of decentralised VRE technologies (Martínez-Gordón *et al.,* 2021). Therefore, another interesting research question is how different geographical disaggregation levels effect the optimal development of VRES. The finer spatial granularity in the UK TIMES model encouraged more wind energy (Zeyringer *et al.,* 2015), because the multi-region model could find more locations with higher wind availabilities around the coastal areas in Northern Ireland and Scotland. But the single-region model uses an average resource supply curve which makes wind energy less competitive. A similar effect is observed with the findings from the

ReEDS model for three different spatial resolutions from the US power sector (Krishnan and Cole, 2016). It demonstrates that wind technologies seem less attractive in a higher resolution scenario, and solar PV technologies can become more competitive. In low-resolution scenarios, solar sites with high generation costs (higher cost and lower capacity factor) are averaged with solar sites that have a lower cost. As a result of averaging, the low cost, high performance solar sites are missed while they could be a part of optimal solution in a spatially resolved model. Research using TIMES-Norway (Lind *et al.*, 2013) also states that lower spatial resolution tends to suggest higher development of renewable energy sources as the model cannot capture local resistance and power grid development. It is due to the fact that the low spatial resolution models are blind to grid bottlenecks and ignore congestion (Frysztacki *et al.*, 2021). The observations from other research show that coarser granularity has led to the higher deployment of wind and solar technologies (see in (Short, 2007; Fleischer, 2020)). TIMES-Austria also reveals that wind power is so cost-effective that the model suggested utilizing the whole potential by mid-term. Thus, higher spatial resolution does not translate into different long-term results (Simoes *et al.*, 2017). According to these observations, it is not straightforward to find a direct relationship between geographic disaggregation and renewable capacity deployment. Various complementary mechanisms offer the optimal regional generation mix. It highly depends on the variation of climate data across the country, quality of regional wind and solar resources, their generation profile, the ability to fit with load profile, transmission constraints and distance between generation sites and demand centres. More specifically, short-term operational constraints such as start-up times, ramping constraints and minimum load level can substantially change the longer-term investments c. Therefore, the effects of spatial disaggregation on renewable capacity development should be analysed on a case-by-case basis.

Third, another critical question is how various levels of spatial resolutions can affect overall system costs. The results from multi-regional models of the US power sector indicate opposing trends in different modelling efforts even though they have very similar assumptions (see the details in (Cole *et al.*, 2017) and (Frew and Jacobson, 2016)). The application of POWER model to the US reveals finer resolution (i.e. site-by-site solar and wind deployment) reduces total costs versus the uniform development across all sites (Frew and Jacobson, 2016). Integrated Planning Model (IPM) shows that the lack of regional resolution in renewable-relevant constraints might underestimate the required capacity and total costs. The reduction is associated with higher utilization of more remote but higher-quality wind resources, which prevent the deployment of more capital-intensive technologies. Moreover, these savings can be achieved through avoided transmission losses. The results from US-REGEN also support these findings and show cost savings were achieved through fewer transmission constraints, providing easier accessibility to lower-cost renewable resources. Unlike these trends, ReEDS shows insufficient spatial resolution increases total costs. This trend is driven by the averaging process in which the model cannot see the lowest-cost sites that were selected in the more spatially resolved representation. The application of the PyPSA-Eur model to the European power system discloses that raising the power grid resolution forces the model to generate electricity from local resources with lower capacity factors (Frysztacki *et al.*, 2021). This can significantly increase total system costs. Total system costs in these models vary due to the different treatment for increasing the spatial resolution. It can be concluded that disaggregation of transmission grids leads to higher costs, and disaggregation of renewable resources leads to lower costs. Despite this result, the models with more regions may lead to false precision. For instance, due to the linear nature of these models, even a slight cost difference between the two regions may encourage all new capacity addition in a region with lower cost. Therefore, higher resolutions dictate more accurate regional data to avoid misleading outcomes.

2.6 Conclusions

This chapter comprehensively reviewed regional disaggregation and spatial resolution in national-scale energy systems optimisation models (ESOMs). The review identified 36 distinctive multi-regional national-scale ESOMs from 22 countries. A multi-regional model can have a rich representation across three different dimensions. First, the model incorporates region-specific supply-side details, providing variable renewable energy (VRE) generation potential and their availability, capital-intensive infrastructures, and inter-connectivity between regions. Second, the model covers spatial details on energy service demands and their fluctuations, impact of climate condition and consumer preferences. Third, the model involves regional details on socio-economic, environmental, and political challenges, including spatial population densities and demographics, living standards, local actor behaviour, environmental concerns, social preferences and political dynamics. The review shows that the existing multi-regional ESOMs are located on a spectrum between the two dimensions as they do not capture all dimensions.

The multi-regional modelling approach presents several benefits compared to the single-region one. VRE potentials with higher accuracy are used for each region. This can suggest the cost-optimal locations for renewable and grid development considering the network bottlenecks and the constraints that cannot be clearly captured in single-region models. Although the incorporation of spatial data improves the results of energy systems modelling, it significantly increases the model dimensions and computational complexities. In efforts to maintain computational tractability, previous studies have performed a single sector analysis (mainly power sector), reduced temporal resolution (a stylised fashion represents renewable variability and demand fluctuations), limited the time horizon of the study (1-5 years), or used a soft-link between a single-region ESOM and a high spatiotemporal power system model. However, among the identified spatially resolved models, some of them applied hourly temporal resolution. They show that it is possible to incorporate spatial data, at least up to the first-level administrative divisions such as province or state, in available high temporal resolution models while keeping a reasonable computational requirement. The higher spatial resolution, such as local divisions used in GIS datasets, looks challenging and usually entails prohibitive running times (Martínez-Gordón *et al.*, 2021). Limited data availability, coupled with heterogeneous data formats is another serious challenge for integrating GIS and energy system models. A unified data model and harmonization of the GIS and energy vision are suggested to cope with this issue (Resch *et al.*, 2014). The review also finds that TIMES, ESME, GENeSYS-MOD and MESSAGE have adequate capabilities to move from national level bottom-up energy models to spatially resolved models among different existing tools.

This review demonstrates some valuable indications about the importance of spatial resolution for energy modelling. First, spatial disaggregation does not always offer crucial added value for model development and application. Heterogeneous regions, either in terms of renewable potential and variability or energy service demands, require more disaggregation. However, aggregated single-region modelling is more efficient in homogeneous areas, as data and computational complexity reduce and the results remain almost the same as multi-regional models. Second, it is not easy to find a direct relationship between the level of geographic disaggregation and penetration of renewable energies, and this trade-off should be analysed on a case-by-case basis. Their penetration highly depends on the variation of climate data across the country, quality of regional wind and solar resources, the ability to fit with load profiles, and transmission constraints. Third, total system costs can be under or over estimated in various levels of spatial resolutions. Disaggregation of renewable resources leads to lower costs, and disaggregation of transmission grids leads to higher costs.

Finally, in line with advances in computational capabilities, a more systematic method is required for cost-benefit analysis of increased resolution (Cole *et al.*, 2017). It calls for the development of a complete ESOM with high- spatiotemporal details for a long-term period. This model can comprehensively check resolution trade-offs and find out how more spatial resolution actually makes a difference.

Part B TIMES-Ireland Model

3 Decarbonisation of passenger light-duty vehicles using spatially resolved TIMES-Ireland Model

Abstracts:

Higher spatial resolution is becoming a key component of energy system analysis. Existing multi-regional national scale energy systems optimisation models (ESOMs) facilitate an improved understanding of spatial dynamics. Yet, region-specific characteristics of transport technologies and infrastructures along with consumer heterogeneity have remained under-investigated. The current paper addresses this gap by developing a multi-regional transport sector within the system-wide TIMES-Ireland Model (TIM). The transport sector is divided into 26 sub-regions, and each region is characterised by the existing vehicle fleet, public transport availability, scrappage rate, annual mileage, vehicle fuel economy and the corresponding passenger and freight mobility demand. The consumers (car buyers) are disaggregated based on their income level to incorporate a more realistic representation of their behaviour in vehicle purchasing decisions. While TIM ensures carbon neutrality across the whole energy system by mid-century, this study mainly explores the decarbonisation of passenger Light-Duty Vehicles (LDVs). It shows to what extent different measures (i.e, LDV improvements, monetary incentives, modal shift, biofuel obligation, carbon tax and occupancy rate) can contribute to meeting ambitious mitigation targets by 2030. Spatially resolved analysis as the main novelty of this research presents valuable insights into regional electric vehicles (EVs) diffusion and their electricity consumption. The proposed method can be used to address the uncertainty that arises from consumer heterogeneity in the policymaking process. The findings also suggest keeping financial EV incentives until the mid-2020s to meet the ambitious goals. Finally, decarbonisation without demand-side strategies (i.e., controlling the level of private-car-based mobility) seems to be unachievable.

Keywords: Energy systems optimisation model, TIMES-Ireland Model, Passenger transport sector, Decarbonisation, Electric vehicles, Spatial resolution, consumer groups

3.1 Introduction

3.1.1 Motivation

A record-breaking rate of carbon dioxide (CO_2) emissions in the atmosphere has been observed since the pre-industrial period (Keramidas *et al.,* 2020). Climate scientists warn that this trend in CO_2 emissions drives the world towards catastrophic climate change (Masson-Delmotte *et al.,* 2019). According to the IPCC (Clarke *et al.,* 2014) and the IEA (IEA, 2021), curbing energy-related CO_2 emissions is the key solution to tackle climate change. Therefore, they recommend urgent mitigation actions across all energy sectors in different countries.

Ireland has recently faced several climate issues and is likely to experience more frequent and more intense extreme weather (Government of Ireland, 2019; Murphy *et al.,* 2019; Climate Change Advisory Council, 2020). After the Paris Agreement, which seeks to keep global temperature rise to well below 2°C, the Irish government has taken multiple sustained efforts to combat climate change (Department of Communications and Climate Action and Environment, 2018). More specifically, the government published a Climate Action Plan (CAP) in 2019, setting forth policy measures that would see EU-mandated decarbonisation commitments being achieved (Government of Ireland, 2019). Energy systems analysis across the EU shows that the current decade is critical to achieving carbon-neutrality by mid-century, and delayed actions can jeopardise stabilising Earth's climate (Siskos *et al.,* 2018). The CAP also devises a decarbonisation pathway to 2030, which would be consistent with the adoption of a net-zero target in 2050. To support the climate goals, in 2021, the government established a legally binding Climate Action and Low Carbon Development Bill with clear and more ambitious commitments, including a target of 51% reduction in CO_2 emissions by 2030 relative to the base year 2018 (GOV, 2021c). In line with this Bill and under the supervision of the Irish parliament (Houses of the Oireachtas), the Joint Committee on Environment and Climate Action conducted a sectoral analysis to ensure that the country will meet the very ambitious target of 51% reduction. The Committee has emphasised the 'three legs' approach, i.e., 'avoid-shift-improve' for transport decarbonisation (Houses of the Oireachtas, 2021).

Transport accounts for about one-fifth of Ireland's total emissions (EPA, 2021b). It is the largest energy-consuming sector in Ireland and contributes to 42% of total final energy consumption in 2018. This sector significantly relies on fossil fuels and is responsible for 40% of energy-related CO_2 emissions. Private cars dominate fuel consumption and CO_2 emissions within this sector and account for just under 40% of transport energy use (SEAI, 2020; Houses of the Oireachtas, 2021). Consequently, emissions reduction in the transport sector, particularly in light-duty passenger cars, plays a central role in the CAP and the Low Carbon Bill. These documents have emphasised on different policy measures ranging from the electrification of private vehicles (increase the number to 840,000), and modal shift to environmentally friendly/sustainable modes, to reduce travel need and travel distance, and biofuel obligation schemes (from the current 5% blends to 10% for bioethanol and 12% for biodiesel) (Government of Ireland, 2019).

3.1.2 State of knowledge

Decarbonisation of passenger Light-Duty Vehicles (LDVs) in Ireland have been investigated through simulation method in several previous studies. Smith developed a simple vehicle model to estimate energy consumption in Battery Electric Vehicles (BEVs) (William J Smith, 2010) and Plug-in Hybrid Electric Vehicles (PHEVs) (Smith, 2010) and then used power supply characteristics in Ireland to address the potential benefits of these two technologies in emissions reduction. These two analyses recommended Electric Vehicles (EVs) for short-range and urban travel and highlighted technical issues for inter-city long-range travel. Hennesy and Tol (Hennessy and Tol, 2011) constructed a private car stock model that classified vehicles by engine size, fuel type, and vehicle age. They have shown climate policy measures can remarkably change the fleet's composition over time. Daly and Ó Gallachóir developed a bottom-up car stock model (2011) to calculate private cars' energy consumption and used a top-down econometric model (2012) to forecast travel demand and new car sales across Ireland. They concluded that significant energy and emissions cuts could be made from policy measures providing that the level of car activity is controlled, or low- and zero-carbon alternatives are continually introduced. Mulholland et al. (Mulholland *et al.*, 2018) further developed this car stock model, linking it to a consumer choice model to simulate the adoption of BEVs and PHEVs. The choice model captures both tangible and intangible costs for different consumer groups. The analysis shows that intangible costs such as the model availability of electric vehicles (EVs) and vehicle range may significantly postpone the market uptake of EVs. Leinert *et al.* (2013) linked the car stock model to COPERT, a standard vehicle emissions calculator. This work concluded that the new taxation policy increases diesel car sales, which in turn CO_2 emissions decrease but NO_x emissions increase. O'Riordan *et al.* (2022) developed a mobility model to estimate passenger demand by mode, distance and purpose of travel. Their simulation quantifies the missed targets in active travel during the last decade. Saniul Alam *et al.* (2017) have used a well-to-wheel modelling framework to compare emissions pathways in different scenarios. It highlights EV based policies have been unsuccessful so far, and policymakers need to find further actions to achieve mitigation targets.

Despite the valuable findings of all these studies, there is a need for an integrated approach to explore LDV decarbonisation pathways. This approach addresses synergies and dynamics across the whole energy system, including demand and supply sectors. The current study bridges this gap with the lens of a whole system-wide modelling approach.

Energy Systems Optimisation Models (ESOMs) can inform policymakers in determining optimal policies and least-cost pathways toward low- or zero-carbon energy systems (Nakata, Silva and Rodionov, 2011). National-scale ESOMs have been frequently used for transport mitigation analysis, such as the role of biofuel in Sweden (Börjesson *et al.*, 2014), the role of hydrogen for Norway (Rosenberg *et al.*, 2010) and California (Yang and Ogden, 2013), the potential benefits of synthetic fuel production in Switzerland (Schulz *et al.*, 2007) and the Netherlands (van Vliet *et al.*, 2011), fuel consumption in the US (Yeh *et al.*, 2008), effective options for biofuel productions in Germany (Martinsen *et al.*, 2010) and the UK (Jablonski *et al.*, 2010), and the impact of the carbon tax on decarbonising transport pathways in the US and China (Zhang *et al.*, 2016). This group of studies emphasises the supply-side transformation. Mulholland *et al.* (2017) combined a system optimisation model with the simulation car stock model. The former suggests least-cost technology pathways, and the latter examines the feasibility of the suggested pathways. However, consumer decisions in purchasing new vehicles have been remained unexplored. Other studies have included the demand-side issues to their analyses, such as the cost-effectiveness of EVs in EU countries (Seixas *et al.*, 2015), electrification of the road transport sector in Canada (Bahn *et al.*, 2013) the interaction between long-term climate targets and LDV electrification (Bosetti and Longden, 2013), and modal shift of passenger transport sector as a mitigation option (Daly *et al.*, 2015). In the absence of sub-national details, the national-scale ESOMs can be criticised for the aggregate treatment of spatial dynamics (Li *et al.*, 2016). The significance of spatial resolution for energy system analysis has recently increased, and it is expected to be a key part of future modelling (Martínez-Gordón *et al.*, 2021). A review of spatial details and regionalisation in ESOMs (Aryanpur *et al.*, 2021) shows that the existing multi-regional ESOMs have been often used to better understand the optimal distribution of power grid infrastructures (Miranda *et al.*, 2019) and heat networks (Jalil-Vega and Hawkes, 2018), and analyse the diversity of renewable energy shares for each region more reliably (Simoes *et al.*, 2017). However, Tattini *et al.* (2018) split Denmark into two main regions, each region divided into three sub-regions and then defined four income groups per sub-regions. The higher spatial resolution enables capturing more realistic modal share and public transport accessibility as well as differentiating waiting and walking time for trains across sub-divisions. The consumer groups are used to incorporate intangible costs associated with time value. But this novel approach has been applied in the standalone transportation sector, and thus, without cross-sectoral interactions, it cannot show implications for the whole system.

3.1.3 Contribution to literature

Despite the ability of ESOMs to comprehensively capture techno-economic parameters and reliably match supply and demand, their results for vehicle fleet mix are often questionable due to the limited representation of consumer behaviour (Ramea *et al.,* 2018) and heterogeneity in consumer demand or choice (DeCarolis *et al.,* 2017). A common approach to representing consumer heterogeneity is dividing the consumers into different segments (i.e., driving and settlement pattern in (Mccollum *et al.,* 2017)). Progress has also been made to capture behavioural features and consumers' preferences (Blanco *et al.*, 2019) in ESOMs. Some of the common approaches are using discrete choice models (Venturini *et al.,* 2019), disutility costs (DeCarolis *et al.,* 2017), and constant elasticities of substitution (Salvucci *et al.,* 2018). Another common method is through hurdle rates application (Gao *et al.,* 2017). Hurdle rates are technology-specific discount rates that can simulate the hesitancy to invest in a less mature technology over a fully commercial one. As a result, the disaggregation of households based on their income level can be used as a proxy to capture consumer behaviour. This method has remained under-explored within the system-wide modelling approach. The current chapter develops a multi-region transport sector within an ESOM to incorporate consumer heterogeneity across different regions. TIMES-Ireland Model (TIM) is the basis for this analysis. Region-specific characteristics of technologies and infrastructures are used to build this model. It calculates the cost-optimal fuel and vehicle technology mix to meet future energy service demands across 26 sub-regions in Ireland. Each region is differentiated by the existing vehicle fleet, public transport availability, scrappage rate, annual mileage, vehicle fuel economy and the corresponding passenger and freight mobility demand. The households are disaggregated by their income level to incorporate a more realistic representation of consumers' preferences in vehicle purchasing decisions. Consumers are potential vehicle purchasers.

In sum, the higher spatial resolution in this chapter makes two major contributions. First, the multi-regional approach can capture region-specific characteristics of transport technologies and infrastructures. Second, disaggregation of car buyers enhances the ability to reflect their behaviour and generates more realistic results.

3.1.4 Aims and structure

While the system-wide TIM ensures decarbonisation across the whole energy system by 2050, the main goals of this chapter are to: (1) address to what extent different measures (monetary incentives, modal shift, biofuel obligation, carbon tax and occupancy rate) can reduce CO_2 emissions; (2) explore how the heterogeneity of household income impact on EV adoption and the corresponding power demand; (3) compare the results of a single region ESOM calibrated with average national data versus multi-region ESOM to understand how higher spatial resolution change vehicle fleet composition over the planning period. The comparison will help to know whether national-scale ESOMs need higher spatial resolution or not.

The rest of the chapter is organised as follows: Section 3.2, briefly describes the methodology, modelling approach and model structure of the entire TIM. Section 3.3 comprehensively provides the transport structure and vehicle purchase decision. It provides the main assumptions, data sources and scenario definitions. Next Section provides the results across a reference and multiple alternative scenarios. Then, a sensitivity analysis shows how the main results are affected by variation in the hurdle rates. Finally, the implications for policy design beyond Ireland are discussed. The discussion provides valuable lessons to help inform similar policymaking now being considered or undertaken in other countries. Last section summarises the conclusions and suggest future work.

3.2 Methodology and data

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 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 the sales/stock share target for electric vehicles).

3.2.1 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 (R Loulou *et al.*, 2016; Richard Loulou *et al.*, 2016). 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; https://iea-etsap.org/), a Technology Collaboration Programme (TCP) of the International Energy Agency (IEA), established in 1976. TIMES models can have single or several regions and are typically 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, technoeconomic, 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 that taxes and subsidies can be included to influence the optimisation). It calculates the energy system specification which minimises the 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 the potential salvage values of investments for which the whole lifetime goes beyond the model time horizon.

The user inputs the following to the model generator:

- Reference energy system (RES), which 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 are the quantities of primary energy resources (e.g. wind power) or imported commodities (e.g. oil, gas, and bioenergy) available at specific costs points for differing quality and quantity of energy commodities.
- Technoeconomic parameters of existing and potential future energy technologies are 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, and hydrogen production) and energy demand (e.g. electric vehicles, natural gas boilers, and carbon capture and storage). Technological parameters include the 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.

3.2.2 Model architecture

Figure 3-1 shows a simplified RES in TIM. It describes the structure and energy flows including two major parts, i.e. the 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 and residential) and the corresponding energy service demands (i.e., passenger, freight, and hot water). Energy resources incorporate both domestic fossil-based fuels and renewable resource potential. These fuels are processed and then distributed across the country. End-use technologies consume energy commodities to meet energy service demands. GHG emissions from fossil fuels combustion and process-related emissions in industry are tracked with 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).

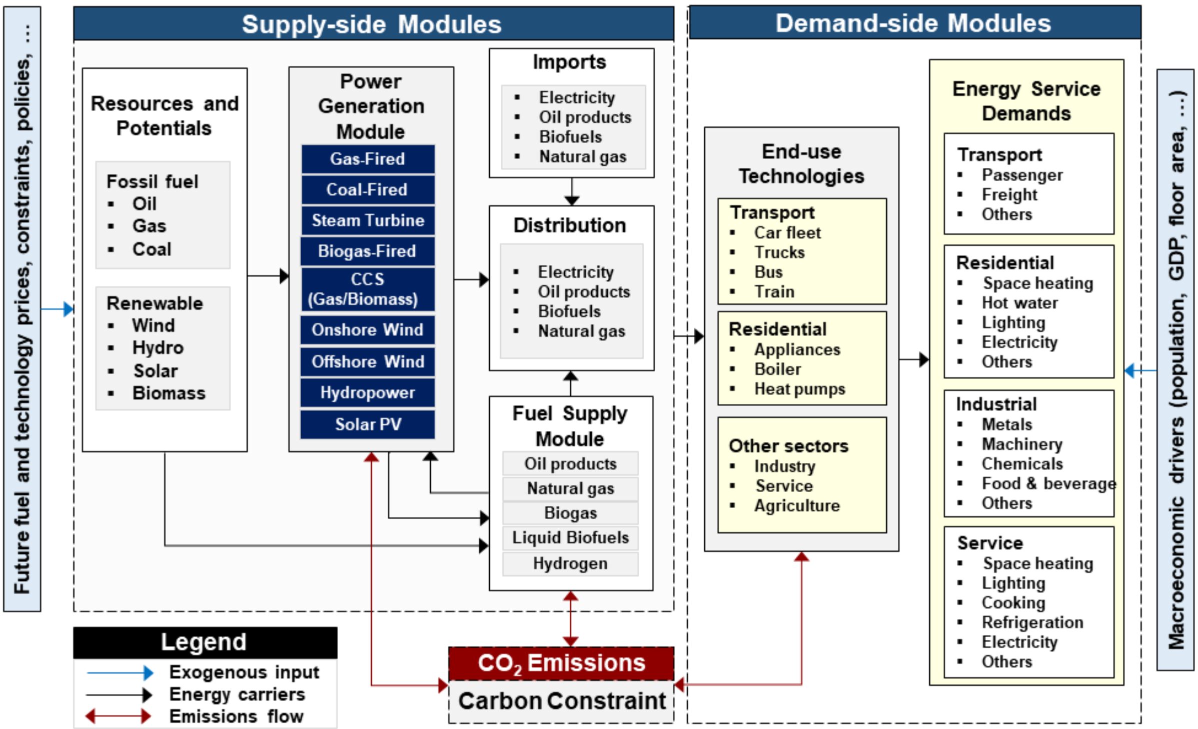

Figure 3-1. Simplified representation of reference energy system in TIM

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 energy systems optimisation modelling (ESOM) scenario with a carbon budget constraint, a higher discount rate would promote later decarbonisation and fewer 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 and Prior, 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.

3.2.3 Time and geography

TIM has been developed with a deep knowledge of the geography of the Irish energy system. A special spatiotemporal 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 time slice, all the way to 26 counties at hourly resolution where supply–demand data are available at that spatiotemporal granularity (electricity, gas, and transport).

High temporal granularity is needed to appropriately model energy futures with high variable renewable energy systems integration, especially in scenarios with high levels of electrification of end-use demands. At the same time, high temporal granularity can be computationally expensive and can significantly increase the time required for model development and testing. In TIM, we address this issue by constraining all time slice model input data to a single file generated with a specific temporal resolution. A time slice tool is used to aggregate raw time series data and create a file in the required format.

High spatial granularity is required to give greater policy clarity on optimal investment needs based on region- and county-specific characteristics to enable the counteraction of 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 levels. Internal file switches, and user shell options, could then be used to apply TIM on either of the levels.

3.2.4 Demands: driver and projections

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.* (2022). See the details of the population and economic projections in (Balyk *et al.*, 2022).

3.2.5 Supply

The supply sector (SUP) in TIM represents the primary and secondary energy commodities and the processes by which those same commodities are imported, exported, domestically produced through mining or capture of renewable energy potentials, and transformed or refined for end-use consumption within the energy system both in the base year (2018) and into the future. The supply sector declares the future available routes for commodity trade for the import and export of energy commodities in terms of the quantity of energy and in terms of import capacity through ports, pipelines, and interconnectors at any given time in the model horizon. For a detailed explanation of energy balance declaration, fuel prices, refineries, fuel potentials, emissions tracking, and trades refer to Balyk *et al.* (2022)

3.2.6 Electricity

Ireland has a high share of variable renewable electricity for a relatively isolated grid, with 32.5 % of electricity generation in 2019 coming from onshore wind energy. Achieving the 2020 electricity from renewable energy sources (RES-E) target has encouraged strong growth in onshore wind, while increasing the non-synchronous penetration of renewables to 70 % by 2030, including offshore wind development, is a key policy objective over the next decade as Ireland moves towards a net-zero carbon electricity system.

3.2.7 Residential sector

The residential stock projections up to 2040 are taken from Bergin and García-Rodríguez (2020) housing demand estimates, which utilise economic growth projections from Bergin *et al.* (2017). The stock is expected to increase by 40% from 2018 levels with a CAGR of 2%. This results in an average of 27,600 new houses per annum between 2021–2040. Beyond 2040, the 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.

3.2.8 Industry

The industrial sector is modelled using a top-down methodology, where energy demand is projected based on an assumed future economic growth. In total, 14 subsectors are represented and are based on SEAI's energy balance. Baseline shares of energy carriers in the final energy consumption by subsector are assumed constant into the future and are based on the 2018 values (SEAI, 2019).

Energy demand for the industrial sector is projected using GVA per capita for each NACE category and population (Yakut and de Bruin, 2020). Historical energy consumption is obtained from SEAI (2019)'s energy balance. The total energy demand from industry in 2050 is projected to increase by 47% from the 2018 level. Cement demand up to 2025 is projected using the Department of Finance stability programme 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 the 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. Fuel switching is the only mitigation option available for combustion emissions from industry in the model.

3.2.9 Services

The service sector in TIM comprises public and private services. It includes a representation of the following energy services: space heating, space cooling, water heating, cooking, refrigeration, building lighting, and other appliances. Data centres electricity demand and public lighting are also represented.

Future fuel-switching and technology-based efficiency options in the services sector are represented explicitly. However, given a lack of sufficient building-level data to enable a detailed analysis, public and private services are modelled in an aggregated fashion (i.e. the building stock is not divided in categories). This is an area identified as a priority area for future model development. Electricity demand for data centres is obtained from EirGrid's steady evolution scenario. The demand is expected to increase by 6 times in 2030 from 2018 levels. We assume no growth in data centre demand after 2030 since permission requests for new/expanding existing capacities are not available yet. Public lighting units are projected based on the Project Ireland 2040, whereby the five major cities of Ireland, Dublin, Cork, Limerick, Galway, and Waterford are expected to grow by 50 % in 2040. This results in a 12.5 % increase in public lighting units in Ireland by 2040 from 2018 levels with a CAGR of 1 %. Beyond 2040, the units are projected to increase by 1 % per annum until 2050.

3.2.10 Agriculture

The current version of the agriculture sector in TIM comes from the Irish TIMES model and is documented in Chiodi *et al.* (2016). It includes the representation of 12 energy service demands; half of them (dairy cattle, non-dairy cattle, sheep, pigs, poultry, and other animal rearing) belong to the livestock and half (production of pulses, potatoes, sugar beets, barley, oats, and wheat) to the tillage sector. Land availability and water consumption are explicitly represented and accounted for in the sector; however, no specific constraints are set. Future energy service demands in the agriculture sector are left unchanged from the 2018 level. Since the sector is a large and export-led part of the Irish economy, these should be adjusted based on a specific scenario narrative.

Crop-based bioenergy feedstocks are modelled within the agriculture sector. This includes growing of wheat, grass, and rapeseed for biofuel production in the supply sector, as well as the growing of miscanthus, willow, and the availability of forestry residues for biomass. Production of crop-based bioenergy feedstocks is constrained by potentials from SEAI (2015).

3.3 Transport sector structure

As shown in Figure 3-2, transport demand is split into three main categories: passenger, freight, and others. The passenger and freight demands are expressed as activity demands, and others are defined as a final energy demand (PJ). These final energy demands further split into aviation (international and domestic), navigation, fuel tourism, and unspecified, aligned with the energy balance. Fuel tourism refers to cross-border consumers, and a portion of demand is used by unspecified modes.

The inland freight demand is expressed in billion tonne kilometres (Btkm). It comprises two main modes, i.e. goods trucks and trains. The definition of light and heavy goods vehicles varies in different studies. In this model, they are disaggregated by the three unladen weight bands: light-duty trucks (below 5 t), medium-duty trucks (5–10 t), and heavy-duty trucks (over 10 t). Table 3-1 shows freight demand in the base year in million tonne kilometres (Mtkm); the modal shares are assumed constant throughout the modelling horizon. Table 3-2 shows number of different vehicles and the corresponding characteristics in the base year.

Table 3-1 Freight demand in 2018 (Balyk *et al.*, 2022)

Classification	Unladen weight (t)	Demand (Mtkm)	Share (%)
Light-duty trucks	0–5	292	2.5
Medium-duty trucks	5–10	1,140	9.8
Heavy-duty trucks	over 10	10,106	86.9
Train	–	89	0.8
Total freight demand		11,627	100

Table 3-2. Existing vehicles and the corresponding characteristics in the base year (Balyk *et al.*, 2022)

Vehicles	Power train	Stock	Utilisation factor	Occupancy rate	Fuel consumption
		(1000 units)	(1000 km yr−1)	(pass per vehicle)	(MJ per vkm)
Motorcycle	Gasoline ICE	39.85	2.73	1.1	1.7
Cars	Gasoline ICE	946.86	12.82	1.49	2.47
	Diesel ICE	1129.4	20.62	1.49	2.3
	Dual-fuel ICE	0.07	13.44	1.49	2.89
	ICE E85	8.53	13.44	1.49	2.41
	Gasoline HEV	29.8	12.82	1.49	2.05
	Diesel HEV	0.77	20.62	1.49	2.03
	Gasoline PHEV	2.76	12.82	1.49	1.56
	Diesel PHEV	0.03	20.62	1.49	1.58
	BEV	4.53	13.44	1.49	0.85
Taxi	Gasoline ICE	2.5	35.61	1.49	2.63
	Diesel ICE	17.46	39.93	1.49	2.39
	Gasoline HEV	1.35	41.21	1.49	2.03
Bus	Diesel ICE	10.7	36.1	27.25	10.16
Train	Light train (electric)	0.07	55.69	78	24.81
	Heavy train (electric)	0.05	158.48	78	24.81
	Heavy train (diesel)	0.014	73.88	120	76.92

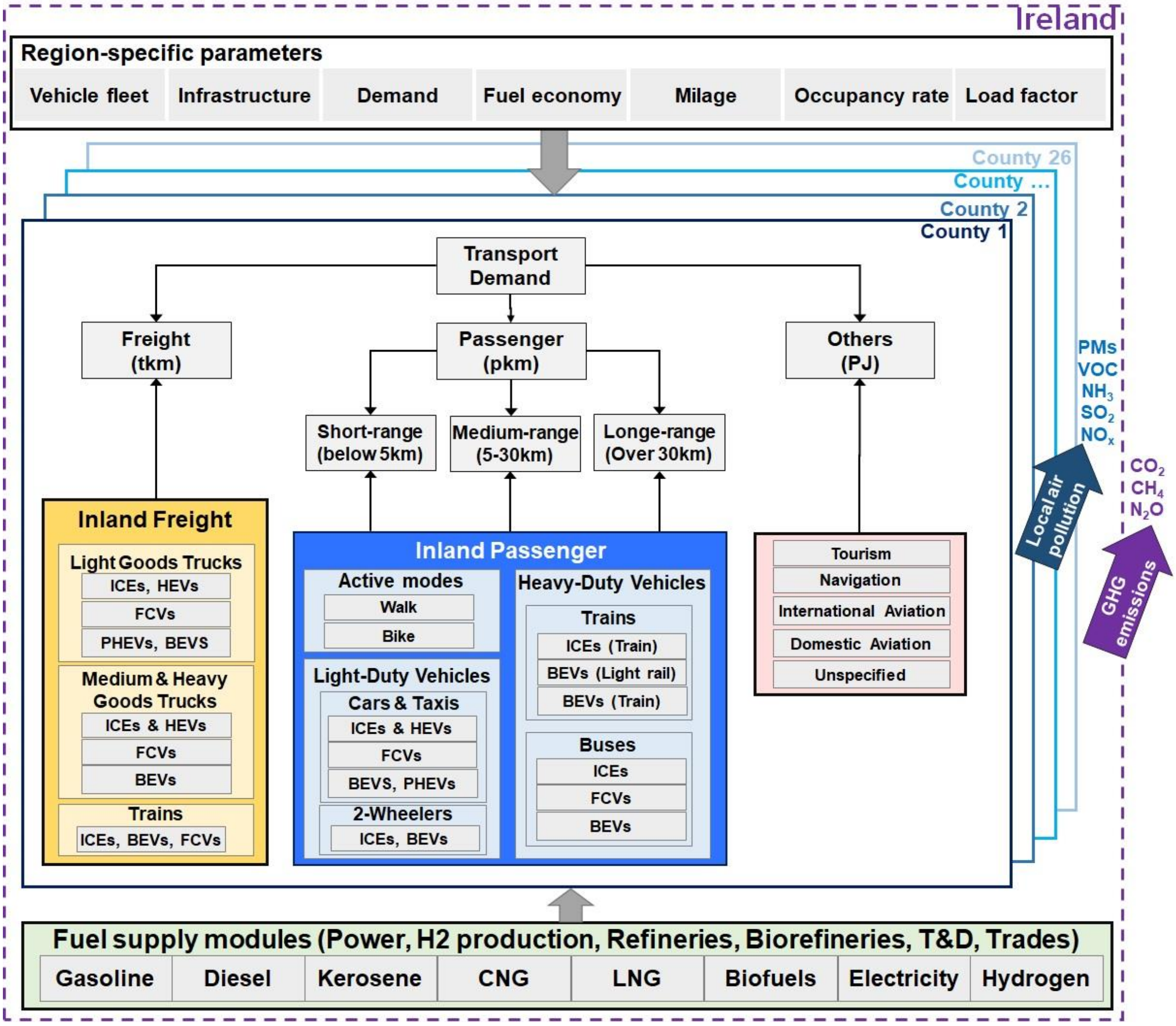

Figure 3-2. Transport structure in TIM

3.3.1 Future transport demand projections

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, i.e. slow growth during low income levels, rapid increase as income levels rise quickly, and finally a saturation period. The Gompertz statistical model has been found to fit the historical relationship between car ownership and income levels best, although other functions have also been used in previous studies (Lian *et al.*, 2018). The basic Gompertz function is shown in:

$$y = \alpha . e{-}\beta . e^{\gamma x} \quad \text{Equation 3-1}$$

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 the CSO.

Projection of future car ownership levels is based on change 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 17,300 yr^{-1}. 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.

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 an average occupancy of 27.5. Large PSV passenger kilometres are expected to increase by 24.2% in 2050, as compared to those 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 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 (Grubb and Mason, 2001; Dantas *et al.*, 2017). 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%.

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 levels 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.

3.3.2 Passenger transport structure in TIMES-Ireland

The transport sector comprehensively describes vehicle technologies, freight and passenger mobility demand on a regional basis. This sector is divided into 26 counties across Ireland. To represent region-specific transport characteristics, some main parameters including vehicle fleet, public transport availability, fuel consumption, annual mileage (activity), and hurdle rate are differentiated on a county level. Transport demand is split into three main categories: passenger, freight, and others. The passenger and freight demands are expressed as activity demands (passenger kilometre and ton kilometre), and others are defined as a final energy demand (PJ). These final energy demands are further split into aviation (international and domestic), navigation, fuel tourism, and unspecified calibrated with Ireland's Energy Balance at SEAI (2019). Fuel tourism refers to cross-border consumers, and a portion of demand is used by "unspecified modes". The passenger transport demands are expressed in billion-passenger kilometres (Bpkm). The total passenger demand is divided into three classes of trip distance range, including short-range (less than 5km), medium-range (5-30km), and long-range (more than 30km). Moreover, four transport modes satisfy travel demands, including 1. public services (bus, train, taxi), 2. private cars, 3. two-wheelers, and 4. active modes (walk and bike). For simplification, non-motorised transport is only used for short-range trips, 2-wheeler are used for short- and medium-range travels, the urban bus is used for short- and medium-range travels, Intercity bus and heavy train are used for long-range trips, and light rail can be only used for the short- and medium-range trips in Dublin County. Demand for each mode can be met with a diverse technology based on cost-optimisation and user constraints. The base year is calibrated according to the actual number of vehicles and the corresponding vehicle activities. Figure 3-3 shows the inland passenger transport structure in TIM. TIM can present local air pollutions on a county basis, but it is out of the scope of this chapter. This study considers those vehicle technologies that have enough potential to enter the market within the time horizon of the analysis. They include five main categories:

(1) Internal Combustion Engines (ICEs) consists of 1- Spark ignition engines fuelled by gasoline, bioethanol, CNG, BioCNG, hydrogen and dual-fuel engines (running either on gasoline or CNG/BioCNG, each one taking 50% of the distance travelled). 2- Compression ignition engines fuelled by diesel and biodiesel.

(2) Hybrid Electric Vehicles (HEVs) are equipped with an ICE and a small electric motor to support the ICE and to recuperate the braking energy.

(3) PHEVs have a similar powertrain to HEVs, but their batteries can be charged from the grid. We assume that 50% of the distance would be driven in the electric mode and it can increase by 80% during the planning horizon.

(4) BEVs solely rely on batteries, and they are charged from the electricity grid.

(5) Fuel Cell Vehicles (FCVs) are equipped with a pressurised hydrogen storage tank and an electrochemical device that generates power to drive a vehicle's electric motor.

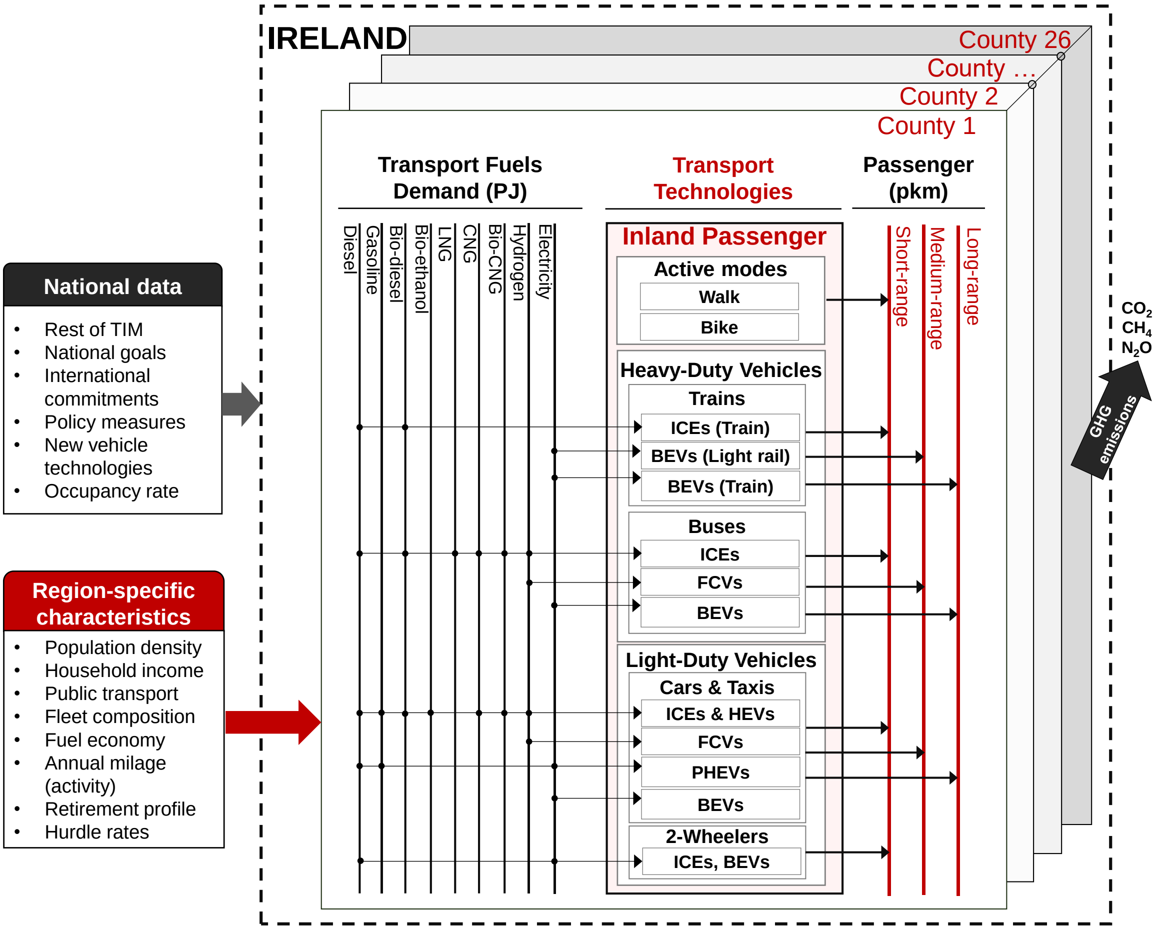

Figure 3-3 Inland passenger transport structure in TIM

Fuel economy and the purchase price of different technologies are shown in Table 3-3. An average occupancy per vehicle is used to estimate passenger transport activity. This average indicates the number of passengers transported in a vehicle. The average vehicle occupancy rate for LDVs, bus, light train and heavy train are 1.49, 27.25, 78, and 120 (Transport Infrastructure Ireland, 2016b; CSO, 2018b), respectively. The purchase price of conventional ICEs is based on the average selling price in the Irish market in December 2018 (Recommended Price Guides, 2018). It is assumed that BEVs will approach purchase price parity with their conventional ICEs counterparts in the early-2030s.

Table 3-3. Average fuel economy and purchase price of LDVs (Mulholland *et al.*, 2017; *Recommended Price Guides*, 2018; Mulholland *et al.*, 2018; Helgeson and Peter, 2020)

Technology (fuel)	Fuel economy (vehicle.kilometre/GJ)		Purchase price (€2018)		
	2018	2050	2018	2030	2050
ICE (Gasoline)	413	413	23,131	23,131	23,131
ICE (E85)	389	418	23,131	23,131	23,131
ICE (Diesel/B20)	573	615	24,888	24,888	24,888
ICE (B100)	556	596	24,888	24,888	24,888
ICE (Dual-fuel)	413	413	24,888	24,888	24,888
ICE (CNG/BioCNG)	413	443	28,079	28,079	28,079
HEV (Gasoline)	556	596	27,077	26,763	25,957
HEV (Diesel)	719	772	29,236	28,878	28,009
PHEV (Gasoline, Electricity)	940	1,081	35,282	32,017	31,543
PHEV (Diesel, Electricity)	1,216	1,398	38,103	34,773	34,262
BEV (Electricity)	1,623	1,886	37,587	26,361	24,888
FCV (Hydrogen)	882	1,012	69,334	35,550	28,267

3.3.2.1 Projection of energy service demands

Energy service demands in end-use sectors are mostly driven by the growth in the demographic (number of households, population) and economic (GDP) trends (see the details in (Balyk *et al.*, 2021)). Future demand follows the historical trend in energy consumption. Road-based passenger transport activity increased by about 56% between 2000 and 2018. The total passenger transport resulted in about 73.7 billion-passenger kilometres (bpkm) in 2018, which is about 15,342 pkm/capita. In this analysis it increases to 17,000 pkm/capita in 2050. The total road freight activity was approximately 11.5 billion ton-kilometre (btkm) in 2018, of which 81% were national journeys. Road-based freight transport increased by 110% between 1995 and 2018, with the current projections, total demand will increase by a factor of 2.18 during the planning period.

3.3.2.2 Modal share

The shares of different modes in total passenger demand are shown in Table 3-4. Each mode has different technologies, and the model simultaneously offers a cost-optimal modal and vehicle shares. For the REF scenario, the shares remain constant during the modelling horizon. According to the National Transport Authority (NTA) (NTA, 2013), multiple plans can increase the walking and cycling modal share in Ireland. For this analysis short-range and medium-range trips through cycling can linearly increase to 14% and 2% in 2050, respectively. The share of walking for short-range travels can also increase to 50% until 2030. The impact of modal shift is assessed in an alternative scenario.

Table 3-4. Total passenger demand and share of transport modes for each class of distance range in the base-year

Modes	Vehicles	Short-range (<5km)	Medium range (5-30 km)	Long-range (>30 km)
Public	Bus	8.3%	13.5%	16.1%
	Light train	0.8%	0.7%	NA.
	Heavy train	NA	NA	8.4%
	Taxi	1.7%	2.2%	1.3%
Private	Light-duty vehicles	51.5%	83.3%	74.2%
2-wheelers	Motorcycle	0.1%	0.3%	NA
Non-motorized (active modes)	Cycle	5.4%	NA	NA
	Walk	32.2%	NA.	NA
Total passenger demand in 2018 (Bpkm)		14.6	31.3	27.1

3.3.2.3 Retirement profile

Vehicle lifetime is usually defined based on an average constant value in ESOMs, and the capacity of specific vehicle type is constant until the end of its lifetime (Tattini and Gargiulo, 2018). However, historic scrappage profiles show that the representation of vehicle's retirement profile based on a constant value in these models is oversimplified. In this chapter, the retirement profile of private cars is distributed over a longer period. This pattern is captured by applying a specific attribute in TIMES as defined in (Tattini and Gargiulo, 2018). The profile is built using the vehicle registration unit in Ireland disaggregated by fuel type, vintage of the vehicles, and county of ownership from 2008 to 2018 (CSO, 2018, 2019). This database was developed in Irish-TIMES to extract a survival profile for private cars (see in (Mulholland *et al.*, 2017)). The retirement profile is updated in the TIM and further disaggregated by each county in Ireland. Figure 3-4 compares the average national retirement profile of the existing cars with the regional profile. It is worth mentioning that a retirement profile similar to that for Diesel ICEs is also used in this analysis for new vehicles. Moreover, importing second-hand cars from other countries has not been modelled.

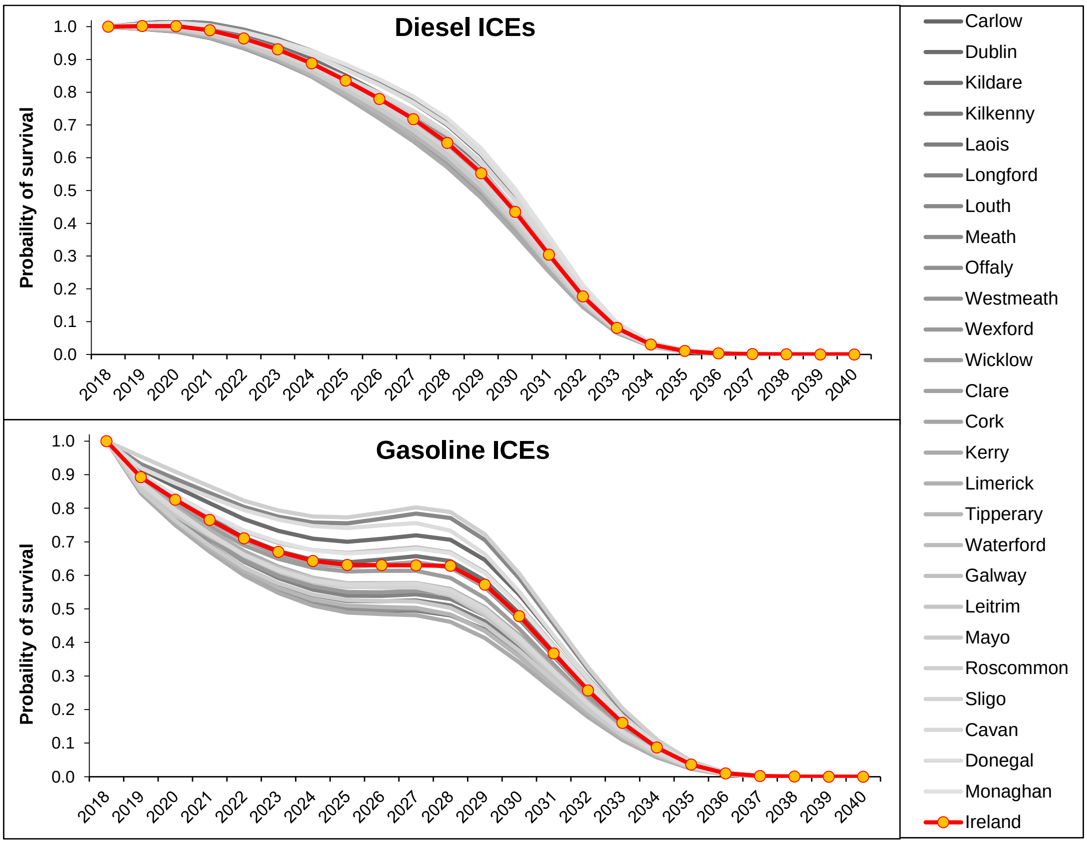

Figure 3-4. Regional and average national retirement profile for the 2018 stock of private cars in Ireland

3.3.2.4 Monetary and non-monetary measures

Different monetary policy measures are analysed in this study: Vehicle Registration Tax (VRT) relief, purchase grant, annual registration tax and carbon tax. VRT is paid by consumers when a new car is registered for the first time in Ireland. The average VRT for private cars is 14% of the original vehicle price displayed by a dealer (Revenue, 2021). All EVs receive VRT relief. This relief is up to €5,000 and €2,500 for BEVs and PHEVs, respectively. The relief is applied until the end of 2021 (SEAI, 2021c). Additionally, the government offers purchase grant of up to €5,000 for EVs purchased in Ireland. As a result, the combination of VRT relief and purchase grant can provide a maximum subsidy of €5,000 for PHEVs and €10,000 for BEVs (GOV, 2021a). Annual motor tax is calculated based on CO_2 emissions, whereby cars with higher emissions pay higher annual tax (GOV, 2021b). The average annual registration tax for ICEs, PHEVs and BEVs are €514, €170, and €120, respectively. Moreover, Ireland applies a carbon tax of €33.5 per ton of carbon emitted from the burning of fossil fuels in 2021 (Department of Finance, 2020). The country is also committed to implement a carbon tax rate of at least €80 per ton by 2030 (Government of Ireland, 2019). In line with the ambitious targets, the government aims to increase the carbon tax up to €100 per ton by 2030. Based on these facts, it is assumed that the carbon tax will increase from €33.5 in 2021 to €100 in 2030.

On the other hand, the government has established a biofuels obligation scheme (BOS) (Government of Ireland, 2019). According to this scheme, the share of biofuel used in the road transport sector will increase to 12% blend penetration rate in diesel (B12), and 10% penetration in petrol by 2030 (E10). The technical limit of the existing diesel engines also allows for a more radical option to achieve biodiesel blend from the B12 to B20. But, having ethanol blend rate above 10% in petrol cars is unlikely without modification. Finally, average occupancy rate of private cars in Ireland is 1.49 ranging from 1.21 for overnight off-peak commuters during weekdays to 1.85 for peak flow weekend trips (Transport Infrastructure Ireland, 2016a). Increasing average vehicle occupancy is another strategy that is analysed in this study.

3.3.2.5 Vehicle purchasing decision and hurdle rates

An economic assessment of investment opportunities within an ESOM needs discounting of payment and income streams to harmonise present and future values. Discount factors are used to convert future outcomes into annualised costs at present value (Steinbach and Staniaszek, 2015). Market penetration of more efficient technologies with higher upfront costs are crucially influenced by the discount rates in ESOMs (Schleich *et al.,* 2016; Andersen *et al.,* 2020). Two types of discount rates are used for energy system analysis: (1) Social discount rates reflect total costs and benefits of energy systems from a social point of view, and (2) Individual discount rates (hurdle rates) are used to model investment decision making revealing the expected return of an investor (Steinbach and Staniaszek, 2015; Schleich *et al.,* 2016). All scenarios are estimated with a social discount rate of 4% in this study. It is in line with the Irish Department of Public Expenditure and Reform suggestion for public infrastructure investments (O'Callaghan and Prior, 2018).

The hurdle rate is a technology-specific discount rate that simulates the individuals' hesitancy to invest in new technology over a fully commercial one. It accounts for the higher investment risk associated with future gains, finance gap, imperfect knowledge, and uncertainty perceived by the consumer (Mallah and Bansal, 2011). An average discount rate that is higher than the social discount rate is usually used for each sector (Capros *et al.,* 2016). However, a number of observations in (Hausman, 1979; Houston, 1983; Dubin, 1992; Harrison *et al.,* 2002; Fujita *et al.,* 2008; Pollitt *et al.,* 2010; Ekins *et al.* 2011; Chunekar *et al.* 2012; Napp *et al.,* 2015) have indicated that the consumer discount rate is highly dependent on household income level, and hence, consumer-specific rates are a more sophisticated method (Venturini *et al.*, 2019). The findings from many surveys on consumers' energy-related decisions in (Train, 1985; Sanstad *et al.*, 1995) confirmed that there is a strong inverse correlation between individual discount rates and household income (the higher the income, the lower the discount rate). This study applies the region-specific hurdle rates to incorporate a more realistic representation of consumers' preferences in vehicle purchasing decisions. These rates are defined based on each region's household median gross income. In other words, regions-specific and consumer-specific hurdle rates are interchangeable in this study.

TIM simulates vehicle purchase decisions across different consumers using region-specific hurdle rates and each region is distinguished with median household income. As illustrated in Figure 3-5, the hurdle rates are estimated in three steps. First, Figure 3-5a shows the findings for the EU and supports the idea that hurdle rates differ by income class. It categorises consumers (i.e. car purchasers) by their income level, and obviously the hurdle rates for low-income groups are much higher than the high- and medium-income percentiles. Then, Figure 3-5b displays the geographical profiles of median household income in Ireland. The median income is €45,256 (CSO, 2018a), and the average national hurdle rate is assumed to be 17% for private cars. This average hurdle rate was taken from (Steinbach and Staniaszek, 2015). This value is quite close to the median consumer discount rate for transport technologies reported from a comprehensive literature study in (Haq and Weiss, 2018). Finally, the regions are divided into three groups, including low-, medium-, and high-income households. As shown in Figure 3-5c, about 50% of regions are medium-income households, and hurdle rates of 17% to 27% are used for this group. These values were also obtained from the ranges of hurdle rates reported in (Train, 1985; Napp *et al.*, 2015; Capros *et al.*, 2016) and references therein. Table 3-5 shows region-specific hurdle rates based on income level in this study.

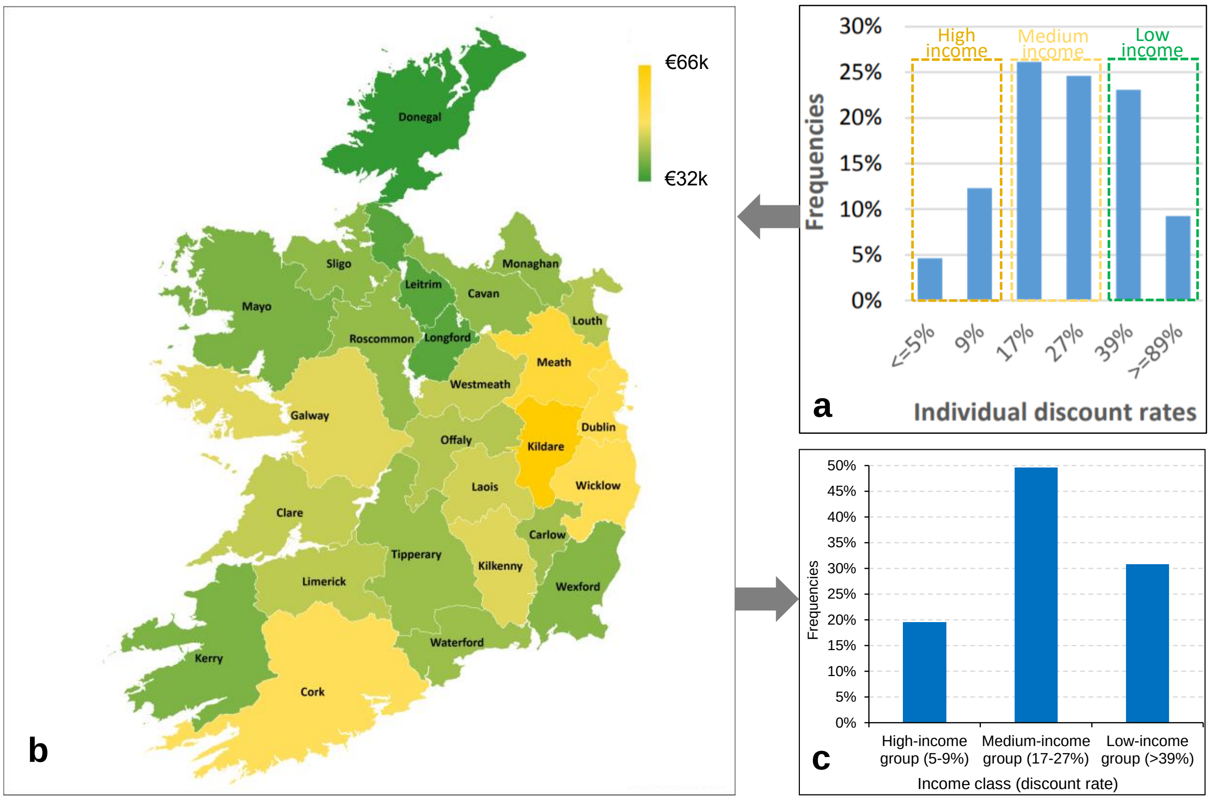

Figure 3-5. Region-specific hurdle rates: (a) Relationship between individual discount rates and income level in EU reference scenario (Capros *et al.*, 2016), (b) Household median gross income per region from (CSO, 2018a), and (c) Values of hurdle rates for individuals in TIM (authors' calculations)

Table 3-5. Hurdle rates in different regions

Region	Hurdle rate	Region	Hurdle rate	Region	Hurdle rate
Ireland	17%	Kildare	5%	Monaghan	39%
Carlow	39%	Kilkenny	27%	Offaly	39%
Cavan	39%	Laois	27%	Roscommon	39%
Clare	27%	Leitrim	39%	Sligo	39%
Cork	17%	Limerick	27%	Tipperary	39%
Donegal	39%	Longford	39%	Waterford	39%
Dublin	17%	Louth	39%	Westmeath	27%
Galway	27%	Mayo	39%	Wexford	39%
Kerry	39%	Meath	9%	Wicklow	17%

3.3.3 Scenario definition

First, the model is run in a REF scenario. Then alternative scenarios investigate how different low-carbon policy measures can impact on transport decarbonisation. While the REF scenario lacks any supportive policies, additional cases explore the potential of other measures in emissions reduction. Modal shift, carbon tax, BOS, occupancy rates and monetary incentives are added to the REF scenario to assess their impacts. However, the REF case can reduce the emissions through adoption of more efficient ICEs and EVs (LDV improvement). Mobility demand level is assumed to follow the same projection across all scenarios (as explained in section 2.2.1). Table 3-6 shows the inclusion of different measures in each case. The assumptions of scenarios and policy measures are as follows:

- **REF Scenario:** There will be no policy measures in this case. Modal shares are fixed across the modelling horizon (see in Table 3-4).
- **Business as usual Scenario (BAU):** It simulates the projected increase in CO_2 emissions by 2030 due to changes in mobility demand activities while the existing vehicle fleet mix is used to calculate the emission level on that year. Therefore, the results of BAU are not from TIM and just and show the continuation of the current trend without any change in technologies and policies.
- **Modal shift:** The share of walking and cycling for short-range travels increases to 49% and 14%, respectively. 1% of medium-range travels is expected to be met by cycling (see the original values in Table 3-4).
- **BOS:** B12 and E10 blend rates are assumed for 2030.
- **RBOS:** Radical option comprises B20 and E10 blend rates for 2030.
- **Carbon tax:** It was introduced in 2010 in Ireland. It is imposed on all fossil fuel consumption except for navigation and international aviation. Carbon tax linearly increases from €33.5 in 2021 to €100 in 2030 and then remains constant.
- **Monetary Incentive Removal (MIR)**: While the REF scenario lacks any monetary incentive, nine MIR cases will keep the incentives in the subsequent years. For example, in MIR2024, incentives are assumed to remain until the end of year 2024 and then removed. In other words, these scenarios show how subsidies can drive EV adoption.
- **Occupancy rate (OR)**: Occupancy rate is a measure of the average number of passengers per car per trip. The overall average occupancy rate of 1.49 represents the national average across all the previous scenarios considered. Seven additional scenarios are defined to assess the impact of higher occupancy rates, with average occupancy rate increases ranging

from 10% to 70% compared to the average national value in the previous scenarios. For example, OR10% indicates an average increase of 10% above the initial value, while OR70% signifies an average increase of 70%. These scenarios provide insights into the effect of different occupancy rates on potential energy consumption and emissions, helping to understand the potential impacts of carpooling behaviour on the energy system.

Table 3-6. The assumptions in the REF scenario and the alternative cases

Scenarios \ Measures	LDV improvements	Carbon tax	BOS	Radical BOS	Active modes	OR 10% to 70%	MIR2021 to MIR2029
REF	✓						
REF+TAX	✓	✓					
REF+BOS	✓		✓				
REF+RBOS	✓			✓			
REF+Modal	✓				✓		
REF+Tax+Modal	✓	✓			✓		
REF+Tax+BOS	✓	✓	✓				
REF+Modal+BOS	✓		✓		✓		
REF+Tax+Modal+RBOS	✓	✓		✓	✓		
REF+OR	✓					✓	
REF+MIR	✓						✓

3.4 Results and discussion

This section first presents aggregated national scale results across different scenarios. Next, it provides spatially explicit distribution of EVs and the corresponding electricity consumption. Moreover, EV adoptions in single- and multi-region TIM are compared. Then, a sensitivity analysis is performed to evaluate the impact of hurdle rate variations on the EV uptake. Finally, the implications for policy design are presented.

3.4.1 Achieving national targets

Figure 3-6 shows the impacts of the measures on emissions reduction from passenger LDVs in the REF scenario. It compares the actual CO_2 emissions in 2018, the projected increase by 2030 due to changes in population and economic growth in the BAU case, emissions reductions due to multiple measures and the target of 51% reduction by 2030 relative to 2018. It is worth mentioning that there is not an explicit target for LDVs for 2030, and it is likely that passenger transport will need to decarbonise more than 51% reduction to make up for the slower progress in other sectors. The results show that the individual measures cannot significantly reduce emissions. Among the single measures, radical BOS has a higher potential in emissions reduction. The combination of the carbon tax, radical BOS and modal shift would result in an 18% cut in CO_2 emissions compared to the actual emissions in the base year, which is still far from the target. In other words, about 2 million ton of CO_2 should be removed through other measures. The results of sensitivity analysis reveal that each 10% increase in average occupancy rate can reduce total emissions by about 0.235 million ton. Therefore, the remaining gap between the actual emission level in the REF+Tax+Modal+RBOS case and the target in 2030 can be balanced by increasing the average occupancy rate by over 80%.

The results also show to what extent each policy measure contributes to emissions reduction in the BAU scenario. The evidence from this analysis suggests that improving strategy, i.e., diffusion of more efficient ICEs and EVs in the REF case would result in a 12% emissions reduction. Shift strategy, including fuel switching to biofuels and modal shift can cut CO_2 emissions up to 14%. The aggregated 26% reduction from these measures indicates the limitations of non-monetary policy measures in reducing tailpipe emissions. Adding carbon tax to the previous measures can reduce emissions by 5%. It is worth noting that carbon tax can potentially cause multiple effects. Because it can induce mobility demand reduction, encourage consumers to adopt more efficient vehicle or low-carbon fuels (Fox *et al.,* 2017; Bhardwaj *et al.,* 2020). In this analysis, a carbon tax could encourage 54k more EVs and increase biofuel consumption by 3.2 PJ in 2030. Energy service demands were exogenously modelled in this work, and thus, the impacts of the carbon tax on mobility demand cannot be assessed. Therefore, improve, shift, and carbon tax can together contribute to 31% of the total reduction. As explained above, the gap can be filled by a radical increase in vehicle occupancy rate. However, avoid strategy (travel demand reduction) is another solution that is out of the scope of this research.

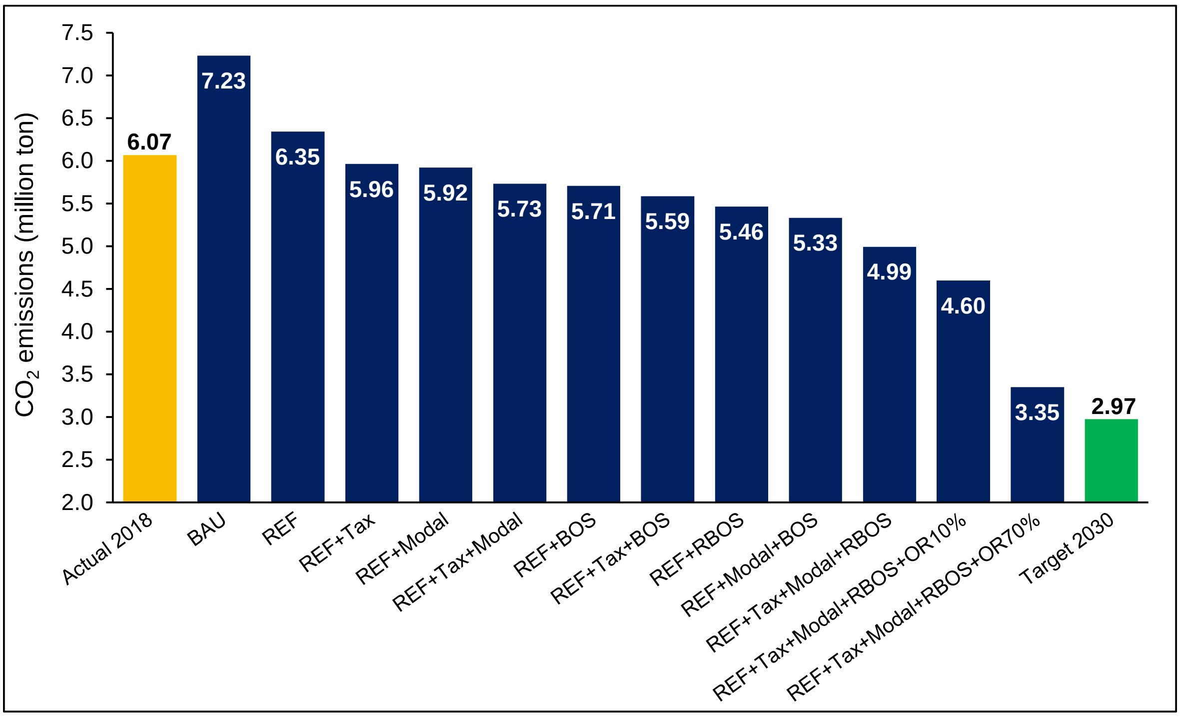

Figure 3-6. CO_2 emissions from passenger LDVs in different scenarios by 2030

Figure 3-7 presents the impact of monetary incentive removal on EV adoption and CO_2 emissions by 2030. In order to achieve the ambitious target of 840k EVs, the model suggests keeping subsidy schemes until 2025. It also suggests that removing the monetary incentives after 2026 can meaningfully increase the market uptake of EVs well above 1 million. Early removal (before the end of 2023) may result in a significant gap between the target and EVs' probable penetration. As expected, in line with the increase in market diffusion of EVs, total emissions from private cars are significantly reduced. However, even a radical uptake of EVs cannot ensure the ambitious reduction target by 2030. A key message from this analysis is that monetary incentives, applied individually, are unlikely to achieve the national decarbonisation targets. This analysis also helps to know how the previous 2 million ton gap can be offset. As illustrated, this gap is filled by emissions savings associated with the adoption of an additional 1.1 million BEVs. These additional measures clearly display the level of ambition in 2030 implied by the Climate Action Bill. It is worth mentioning that power sector results reveal that the generation mix is characterised by a significant share of wind turbines and about 74% of total generation is from renewable energy sources in 2030. The emission intensity of power generation decreases from 334 gCO_2/kWh in 2018 (SEAI, 2020) to 89 gCO_2/kWh in 2030 and reaches to -64 gCO_2/kWh in 2050. Bioenergy power plants combined with carbon capture and storage technologies enable negative emissions in the long-term. The emission intensity values guarantee that even on a well to wheel basis, transport electrification will be an effective decarbonisation policy.

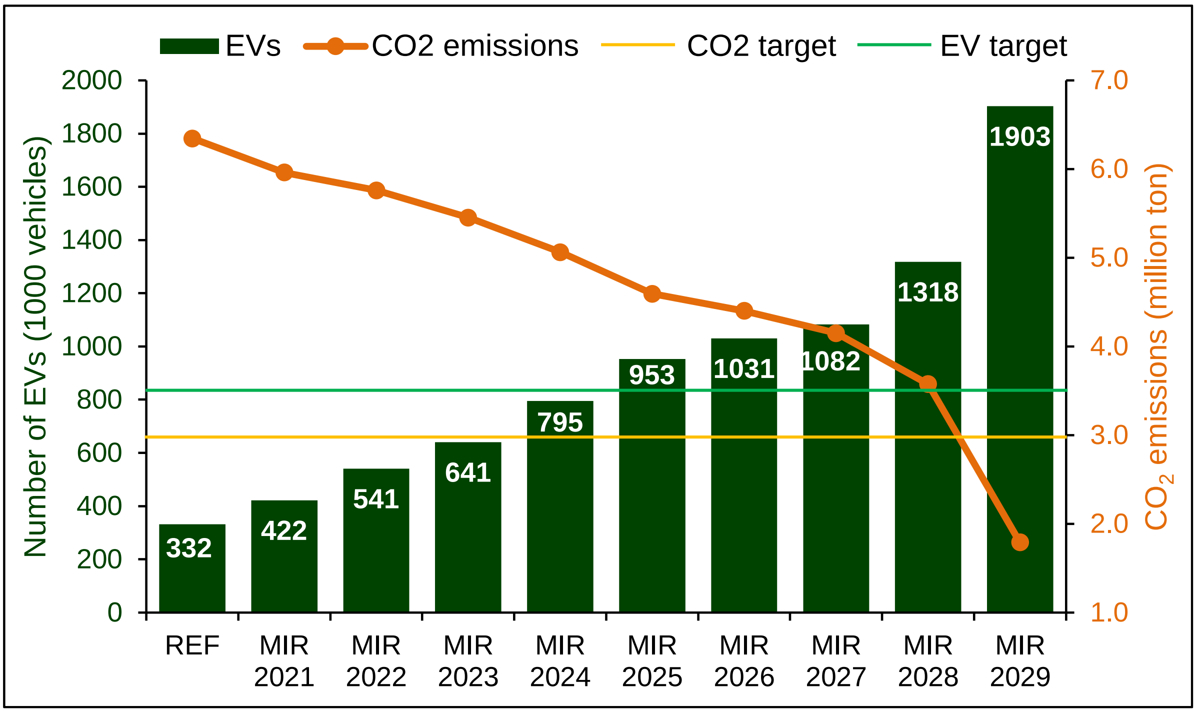

Figure 3-7. EV adoption and CO_2 emissions from LDV stock by 2030, impact of monetary incentives on the REF scenario (e.g., in MIR2025 monetary incentives are kept until the end of year 2025 and then removed from the beginning 2026)

3.4.2 Power generation mix

Figure 3-8 compares the optimal installed capacity of power plants and total generation in the REF and MIR2029 scenarios. These two scenarios are selected to show how minimum and maximum penetration of EVs can impact on the power sector. During 2020-2030, total generation grows at an annual rate of 4.2% and 5.0% in these cases, respectively. Although the model seeks to achieve a 51% emissions reduction in 2030, the generation mix in this year is characterised by a significant share of wind turbines and solar panels, and about 75% of total generation is from renewable energy sources in both scenarios. This shows that the power sector plays a critical role in achieving the decarbonisation target across the whole energy system over the short- to medium-term. In both cases, existing coal and oil power plants are gradually phased out; however, the operation of gas-fired power plants will be attractive mainly due to the lower generation cost, lower emission factor and their power change flexibility in response to the demand fluctuations across different time slices. The higher electricity demand in the MIR2029 scenario is driven by higher EV adoption. To meet the additional demand in

2030, the model suggests 0.5 GW more gas-fired power plants because the adoption of renewable is already saturated in that year. It will be a paradox as the decarbonisation of the transport sector accelerates through the utilisation of more fossil fuel-based power units. It can be said that the government should ensure sufficient carbon-neutral power supply before the vast market penetration of EVs.

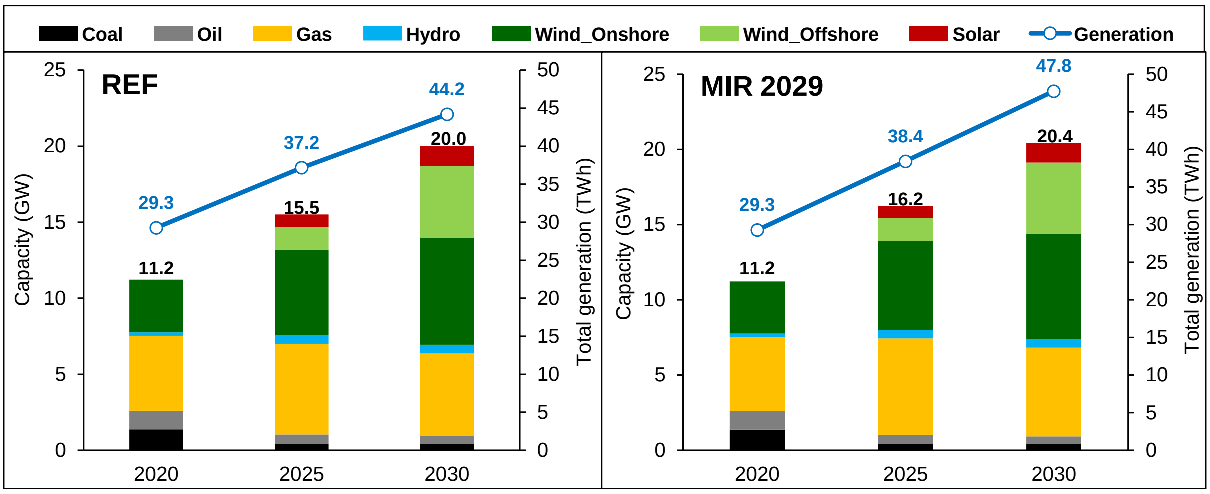

Figure 3-8. Installed capacity of power plants by fuel type and total generation in two scenarios

3.4.3 Spatial uptake of EVs

Figure 3-9 shows spatially explicit distribution of EVs by 2030. The results of the REF case are compared with the MIR2024 scenario. This scenario is selected since the adoption of EVs is close to the target of 840k vehicles in 2030. Therefore, its results can be used to analyse the target's requirements. In both scenarios, the majority of EVs is adopted by the major demand centres in the Eastern counties. Moreover, a higher household income in these counties leads to substantially more EV adoption. However, the number of EVs per capita in Dublin is among the lowest due to the higher population density and higher availability of public transportation. The results also demonstrate that the number of EVs in lower-income regions significantly increases with monetary incentives while the higher-income regions do not experience radical changes. For instance, the number of EVs in Kildare (as the highest income region) moderately increases from 48k to 53k while in Mayo greatly escalates from 6k to 20k. This may call for a more targeted subsidy programme to reduce the burden on low-income regions.

In the REF scenario, 7 out of 26 regions have adopted more than 10k EVs. But keeping monetary incentives until the end of 2024 increases this number to 20 regions, and between 2- to 3-fold increase in EV share of national car stock is observed in most regions. This drives higher electricity demand in the Eastern regions, the South, and the West coast regions of Ireland. On the other hand, the bulk of low-cost wind energy potential has located in the Western Atlantic coastlines (Goodbody *et al.*, 2013; Slednev *et al.*, 2018). As touched upon previously, the electricity generation system becomes increasingly dependent on wind turbines over the next decade. As a result, the Western regions would benefit from the low-cost wind energy sources and additional transmission capacity is needed to transport electricity from high supply to high demand regions. In other words, strengthening inter-regional electricity transmission infrastructure would play a key role in transport electrification in other regions.

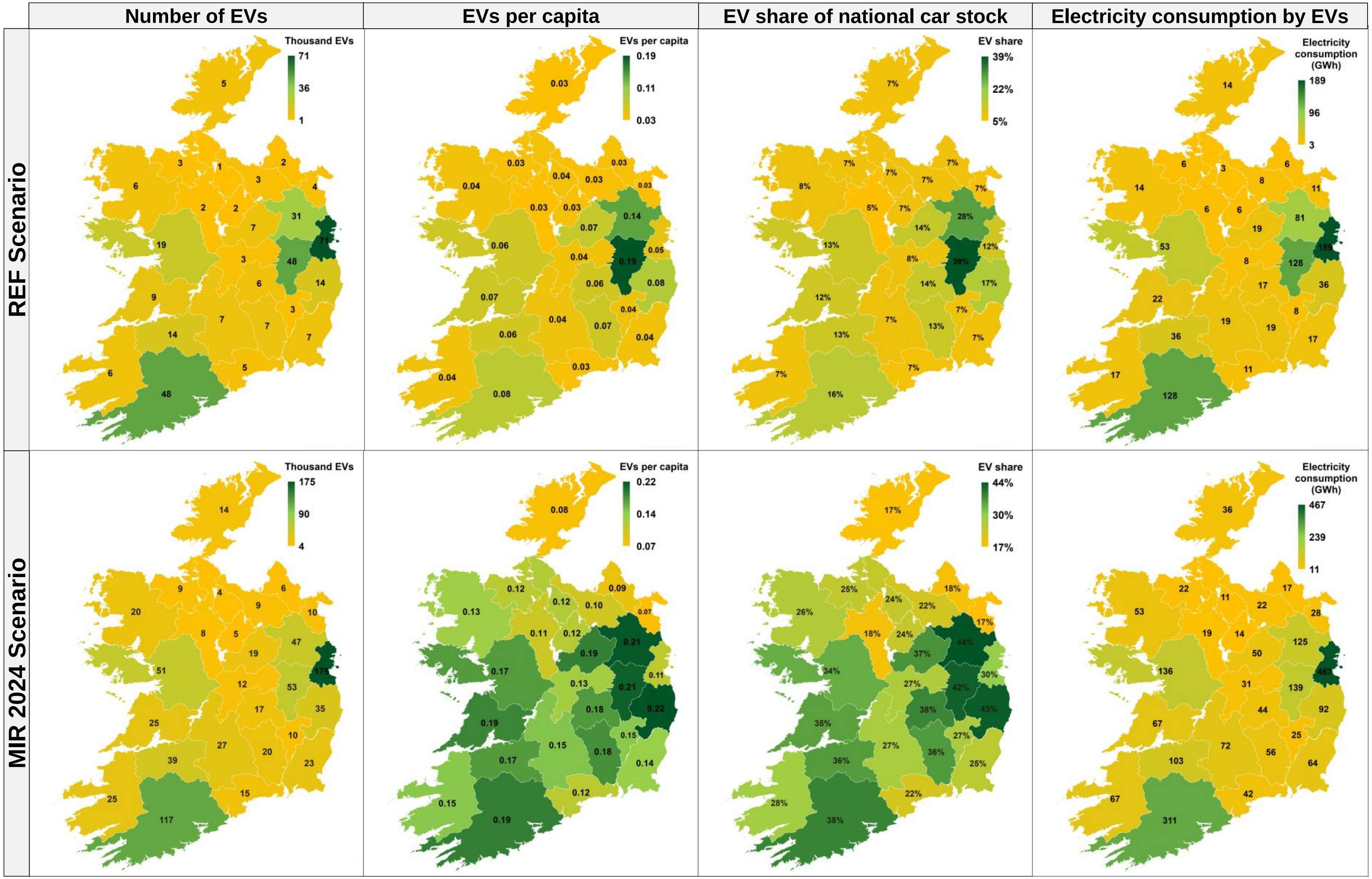

Figure 3-9. Spatially resolved distribution of EVs and the corresponding electricity consumption in the REF and MIR2024 scenarios by 2030

3.4.4 EV adoption in single- and multi-region TIM

Figure 3-10Figure 3-10 shows that the total number of EVs and their electricity consumption in a single-region TIM is lower than in a multi-region one. This difference is mainly driven by the single-region model's averaging process in hurdle rate assumptions. As mentioned, in a single region TIM an average hurdle rate of 17% is used for capturing consumer decisions in purchasing new vehicles. In practice, regions with higher income and lower hurdle rates are aggregated with less income regions. The average hurdle rate can decrease the attractiveness of EV adoption in high-income areas that would otherwise be purchased in the more spatially resolved model. In the spatially explicit analysis, sub-regions with higher income will have hurdle rates of 5%-9% and tend to adopt more EVs with a higher upfront cost. In fact, the averaging process hides the tendency of high-income consumers to purchase EVs. Average retirement profile is another potential source of divergence; however, it has been almost offset in this analysis. It is because the vehicles scrappage in sub-regions with higher population and higher vehicle stock have been distributed on either side of the national average.

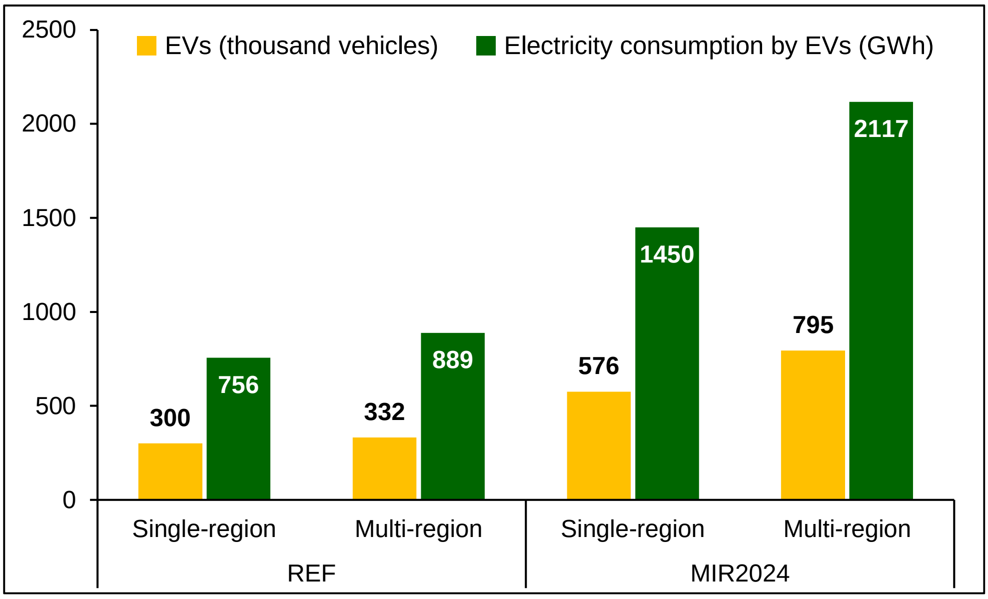

Figure 3-10. Number of EVs, their electricity consumption in single- and multi-region cases by 2030

Higher spatial resolution increases the calculation time and computational burden. The present study used a laptop with 16 GB of RAM and a normal CPU (Intel® Core™ i7-8705G at 3.1 GHz with 4 Cores) to run the scenarios. Table 3-7 summarises model statistics and solution time for single versus multi-region reference cases. Both cases have a similar stylised temporal resolution (40 time slices) and are run for 19 periods until 2050. Other assumptions are the same across the two cases. As indicated, model dimension and solution time under county-level scenarios are almost double compared to the national one. In this analysis, it is important to bear in mind that the spatial resolution has only increased in the transport sector and the other sectors are nationally defined. It is expected that in a complete multi-region case, the increase in model dimension is almost proportional to the number of regions (see some examples in (Panos, 2019; Scholz *et al.*, 2020; Aryanpur *et al.*, 2021)).

Table 3-7. Model dimension and solution time in single- and multi-region model

Statistics	Single-region (national level)	Multi-region (county level)
Number of equations	1,166,014	2,351,860
Number of variables	1,081,415	2,132,977
Non-zero elements	5,943,515	11,332,455
Solution time (min)	4.5	9.1
Iterations	94	169

3.4.5 Sensitivity analysis

This section conducts a sensitivity analysis to assess how the main results are affected by variation in the region-specific hurdle rates. The effect is explored by increasing and decreasing these rates by 5%, 25% and 50%. Figure 3-11 demonstrates the sensitivity of CO_2 emissions and EV adoption for the REF case. As expected, the lower hurdle rate shifts the market to electric cars and vice versa. The reason is that adopting lower/higher hurdle rates makes capital-intensive technologies more/less affordable. The results seem to be insensitive to ±5% variations, but higher variations could significantly influence the EV adoption. The response of EV adoption to hurdle rate variations up to ±25% seems almost symmetric. But, higher variations up to ±50% unequally change the trend between the direction of increase and decrease. A 50% higher hurdle rate could reduce the EV adoption by 41%, while the opposite change in hurdle rate shows 86% more adoption compared to the REF scenario. EV adoption is close to saturation point in high-income regions, and the lower hurdle rate could be ineffective for this group. Instead, this radical change is mainly driven by the adoption of EVs across medium-income households. The initial hurdle rate is 17% in these regions (Dublin, Cork, and Wicklow). A 50% reduction in the sensitivity case could make EVs an affordable option for this group. Moreover, those regions are among the populated counties with higher demand, and thus the adoption intensifies.

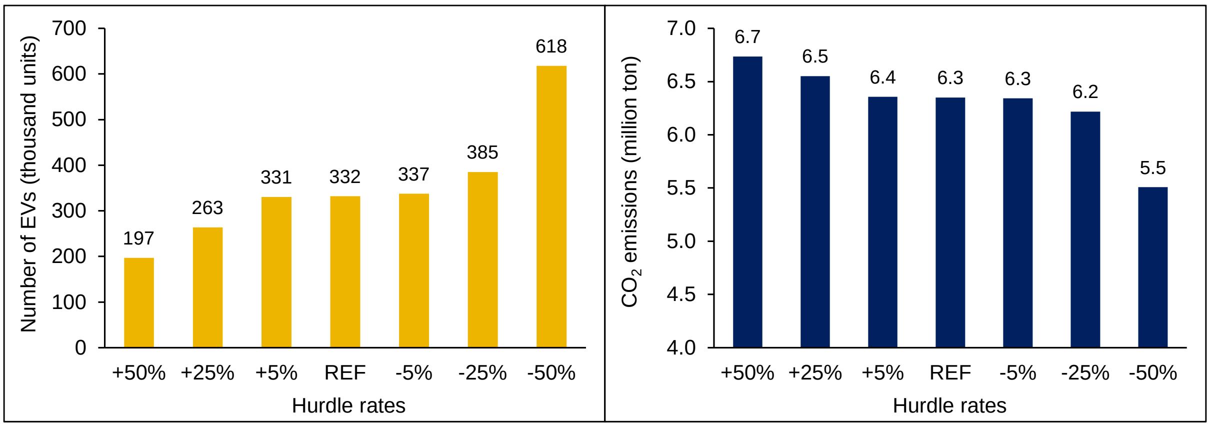

Figure 3-11. Comparison of the total number of EVs and CO_2 emissions for the REF scenario and sensitivity cases in 2030

3.4.6 Implications for policy design

This section discusses the implications of the present research for the policymaking process from three different perspectives:

First, a rational EV buyer ought to compare total costs of ownership (TCO) among commercial vehicle options and then purchase the lowest cost one. However, in practice, all consumers do not have sufficient economic knowledge. They do not necessarily choose their options based on the economic parameters and consider other characteristics such as convenience and aesthetics. On the other hand, there is a heavy reliance on transport electrification to achieve ambitious emissions reduction over the current decade (see the IEA policy database for the planned, announced, and in-force policies across different countries (IEA, 2021d)). Moreover, a growing body of modelling research recommends widespread EV adoption for achieving deep transport decarbonisation. The rationale behind some of those policies and recommendations is the purchase price parity or TCO parity in the different markets such as in the US (Liu *et al.*, 2021), China (Hao *et al.*, 2020), the UK (Santos and Rembalski, 2021), Italy (Danielis *et al.*, 2018), Korea (Moon and Lee, 2019), and New Zealand (Hasan *et al.*, 2021) in the near future. However, the consumer heterogeneity in the present study shows that heavy reliance on price parity as a basis for future projection would overestimate our perception of the actual consumers' tendency to buy an EV. Sensitivity analysis also reveals that consumers' computational weakness in determining cost-optimal options may substantially decelerate the EV growth (see the results for +50% more hurdle rate). Other barriers such as inadequate zero-carbon electricity supply or lack of recharging availability can postpone the achievement of mitigation goals. The former barrier weakens the effect of EVs in reducing CO_2 emissions on a well to wheel basis. The latter decelerates the rate of EV uptake. This example shows how integrated energy system analysis coupled with adequate consumer diversity could improve the policymaking process and help develop better strategies.

Second, the successful penetration of EVs is contingent on being adopted by different consumer groups, the first of which is called early adopters (Lee *et al.*, 2019). In the present study, high-income families play this role because they can afford the higher upfront cost and benefit significantly from the lower discount rate. The anatomy of EV car ownership in a mature market such as Norway (Fevang *et al.*, 2021) also shows that EV owners are more likely to be from higher-income households. It is worth mentioning that, although early adopters lead the population regarding EV adoption (Ramea *et al.*, 2018), they are the minority group and cannot form a substantial share in the whole market. Moreover, this research clearly shows that medium- to low-income households need the incentives to buy an EV to achieve the massive diffusion. However, the government cannot continue the subsidy regimes over a long-term period. Consequently, the subsidies are predominantly in favour of higher-income groups, while one of the original goals of subsidies is to improve equity and social protection systems. The recent analysis of EV subsidy distribution in other countries also shows that the monetary incentives have been mostly allocated to high-income households (Guo and Kontou, 2021; Liu *et al.*, 2022). The current subsidy regime can also impact the distribution of public charging facilities (Li *et al.*, 2022) and hence, further intensify equity concerns. As such, the multi-region TIM developed in this research provides a reference for policymakers to address potential equity issues hidden behind subsidy schemes and reduce regional disparities.

Third, capturing heterogeneity in an integrated energy system model not only improves the ability to generate more realistic results, but the impacts can be investigated across the various sectors of an interconnected energy system (Mccollum *et al.*, 2017). Our findings indicate that low- and medium-income households play a crucial role in achieving widespread EV adoption. Power sector decarbonisation is a prerequisite for transport electrification and meeting the near-term mitigation commitments. However, power sector decarbonisation faces limitations in practice. When the adoption of renewable energy sources saturates, and transport electrification still continues, the cost-optimal analysis may suggest fossil-based power units to meet the additional demand from the widespread EV adoption. It is unlike the mitigation policies. It also highlights the importance of harmonised development of power and transport sectors. Accordingly, the policymakers should ensure adequate carbon-neutral power supply before massive EV market penetration.

3.5 Conclusions

Ireland committed to support the EU's carbon-neutral objective by 2050. The country also has set an ambitious target of a 51% reduction in CO_2 emissions by 2030 relative to 2018. The key questions are how precisely these targets will be achieved at a sectoral level and what the impact of different policy measures will be. The current study approaches this issue focusing on passenger light-duty vehicles, responsible for 16% of energy-related CO_2 emissions in Ireland. To represent region-specific characteristics of transport technologies and infrastructures, this study develops a multi-region transport sector within the TIMES-Ireland Model (TIM). TIM produces optimal energy system pathways consistent with the net-zero emissions pathway by mid-century. Spatially explicit analysis as the main novelty of this research presents valuable insights into regional EVs diffusion and their requirements. The applied method could be used to support similar mitigation policies now being undertaken in other countries. The results reveal that:

(1) Although subsidy schemes do impact on EV adoption rate, they would not individually be an effective policy to reduce emissions. The evidence from this analysis suggests that shift and improve strategies can contribute to about 12% and 14% emissions reduction, respectively. Adding carbon tax may reduce emissions by further 5%. Thus, they together contribute to 31% of total reduction. To meet the decarbonisation target, the country may heavily rely on accelerating EV uptake (i.e., keep monetary incentives until the late-2020s) or increase the average occupancy rate by over 80%. These additional measures demonstrate the level of ambition in 2030 implied by the Climate Action Bill. It can be concluded that without demand-side strategies (i.e., controlling the level of private-car-based mobility), the mitigation goals seem to be unachievable.

(2) To reach the ambitious goals, the evidence from this study suggests that financial EV incentives might be kept until the mid-2020s. Vehicle registration tax relief for BEVs is in place until the end of 2021 (SEAI, 2021a). This early removal policy may substantially delay the targets set for 2030.

(3) The findings present new insights to learn to what extent consumer groups most likely adopt EVs and where in Ireland so that the entire energy sector is steered toward a carbon-neutral at least system costs. The results will finally help policymakers to design more accurate region-specific energy master plans.

(4) Spatially resolved analysis shows that sub-regions with higher income will have higher tendency to adopt more EVs. But a single region model calibrated with average national data will adopt lower EVs in total. In fact, the averaging process in a spatially aggregated model can hide the tendency of high-income households to purchase EVs and may overestimate the EV uptake among low-income families. It can be said that the spatially explicit analysis presents valuable insights into regional EVs diffusion and their electricity consumption at a subnational level which are usually demanding to achieve through an aggregated national model. The results of this study can be used for subnational distribution of recharging stations and the power grid development.

To interpret the results, some caveats need to be noted. Exogenous purchase price assumptions for EVs and their parity with the ICEs are a source of uncertainty. A delay in purchase price parity can decelerate the EV uptake. Moreover, importing second-hand cars will likely change the retirement profile. It would be interesting to explore the efficacy of second-hand car import. Finally, the current study has only examined the historical trend in energy service demand. But different actions can reduce mobility demand (Sperling and Eggert, 2014): lower travel needs (facilities to reduce business travels, telecommunication mobility services, reducing sprawl), shorter travel distances (urban planning), raising the price of travel and transport demand management (dynamic ridesharing). There is, therefore, a definite need for assessing the effects of these different actions on energy service demands and the implications for CO_2 emissions.

This investigation also has some important limitations regarding spatio-temporal resolution and consumer purchase decisions that should be addressed in future studies. The spatial resolution could be extended to other sectors and, more specifically, to the power sector to capture national grid congestion. Future studies deserve more careful analysis that Ireland should invest in remote low-cost wind energy sources and reinforce its power grids or install wind turbines with higher generation costs close to load centres. A complete multi-regional ESOM (Aryanpur *et al.*, 2021) may better explore where should new capacities be installed- close to load centres or energy sources? And when and where is additional inter-regional grid reinforcement necessary? Regarding strong transport electrification, some interesting research agendas are exploring optimal charging/discharging of EV batteries and the impacts of vehicle-to-grid technologies (Heuberger *et al.*, 2020). A high-temporal resolution and detailed operating problems can analyse sector coupling opportunities and challenges. Another improvement is the representation of non-monetary parameters such as range anxiety and charging stations availability that might change individual attitudes toward the adoption of modern technologies.

4 Co-benefits of air quality and net-zero carbon mitigation pathways: Case of the road transport sector in Ireland

Abstracts:

Ireland has a challenging target of net-zero emissions by mid-century. This research focuses on the road transport sector, and the main objective is to estimate the ancillary pollution benefits of the mitigation target. It predominately quantifies the co-impacts of mitigation actions on air pollution levels for PM and NOx. A multi-region Energy Systems Optimisation Model (ESOM) is developed to explore the costs and benefits of climate mitigation strategies. The analysis also examines how higher spatial resolution can change modelling results. The findings demonstrate that the net-zero emission pathway is accompanied by significant reductions in local air pollutants (46% to 93% in populated areas). This reduction can compensate between 2% to 89% of total mitigation investment costs during the study period. Finally, the spatially explicit modelling approach reveals higher economic co-benefits than single-region modelling. The single-region method hides the higher damage costs in medium and large cities, thus underestimating total benefits.

Keywords: Energy systems optimisation model, Road transport, Net zero emissions, Health impact assessment, Local air pollution, PM2.5 and NOx, Co-benefit analysis

4.1 Introduction

The insatiable appetite for burning fossil fuels is the main source of releasing air pollutants in modern societies (Vohra *et al.,* 2021; Reis *et al.,* 2022). These pollutants have been implicated as the major cause of global health risks (Apte *et al.,* 2015) and are responsible for millions of deaths worldwide (Lelieveld *et al.,* 2015; Cohen *et al.,* 2017; Burnett *et al.,* 2018; WHO, 2018). About 350 thousand premature deaths were attributed to chronic exposure to Nitrogen Oxides (NOx) and Particulate Matters (PM10 and PM2.5) in Europe (EEA, 2021). The road transport sector is responsible for 39% of NOx and 11% of PM emissions in Europe (EEA, 2019). Focusing on Ireland, the transport sector accounts for 35% of NOx, 15% of PM2.5 and 7% of PM10 of the total national emissions in 2017 (EPA, 2021c).

Ireland's ambitious Climate Act has set a legally binding path to a 51% reduction in overall GHG emissions by 2030 and net zero society no later than 2050 (Government of Ireland, 2021). While the ambitious mitigation targets meet its international and EU climate commitments, policymakers are often concerned about the mitigation targets due to associated economic costs. This concern can bias the decision-making process and thus, lead to suboptimal climate policies and even goal failures (Karlsson *et al.* 2020). However, mitigation pathways could create economic co-benefits through air quality improvement, which in turn offset (Balbus *et al.,* 2014) or at least compensate for part of the mitigation costs (Kypreos *et al.,* 2018). Moreover, a comprehensive survey (Bain *et al.,* 2015) collected from 24 countries shows that the potential co-benefits of climate mitigation strategies can motivate private, public and financial actions to address climate change. As a result, research should integrate co-benefits data into policymaking to synergise mitigation actions.

According to the 2021 report of the Lancet Countdown (Romanello *et al.,* 2021), there is an unprecedented opportunity to ensure a healthy future for all through reduced health effects and maximised co-benefits of a universal low-carbon transition. There is a growing body of literature using model-based analyses to quantify the mitigation costs and the related health co-benefits on a global scale. Some of them show how energy systems transformation under ambitious decarbonisation targets could avoid premature deaths. West et al. (West *et al.,* 2013) used a global atmospheric model to measure the co-benefits. They showed that slowing climate change would avoid 1.3±0.5 million premature deaths by 2050. Vandyck et al. (Vandyck *et al.,* 2018) simulated global energy supply and demand pathways across different scenarios and reported 0.7-1.5 million for the number of premature deaths in the same year. Incorporating health co-benefits into ambitious China's 2060 carbon neutrality target shows that the neutrality plans could annually avert 0.5-1.2 million premature deaths (Zhang *et al.,* 2021). Some other studies present co-benefits as a percentage of mitigation costs. For instance, comprehensive bottom-up modelling found that air quality co-benefits offset about 75% and 85% of decarbonisation costs at global (Bollen, 2015) and European (Schucht *et al.,* 2015) scales, respectively.

A recent review by Karlsson *et al.* (2020) shows that the co-benefits highly depend on the geographical focus of the analysis. Markandya *et al.* (2018) and Sampedro *et al.* (2020) linked an integrated global change assessment model to an air quality model. They estimated the abatement costs, the local air pollutants concentrations, and the associated morbidity and premature deaths. Then, health impacts are monetised via the value of statistics life. The regional distribution of benefits showed that co-benefits in emerging economies (India and China) would outweigh the costs. An analysis of the climate policy pathways limiting global warming to below 2ºC by 2100 also shows that these two countries would benefit more than other regions (Rauner *et al.,* 2020). These results are in line with the findings from a global energy system model in (Rafaj *et al.,* 2013) and a regional analysis in (Xie *et al.*, 2018). Additionally, some national-scale studies used a similar comparison and revealed that significant co-benefits could also occur in developed countries such as the United States (Ou *et al.*, 2018; Gallagher and Holloway, 2020), Sweden (Krook Riekkola *et al.,* 2011), and Korea (Kim *et al.*, 2020). Other national-scale studies internalised external costs of local air pollutants into the energy modelling to explore technology and fuel mix across the entire energy sector in Italy (Pietrapertosa *et al.,* 2010) and the UK (Lott *et al.,* 2017) and the heat and power sector in Denmark (Zvingilaite, 2011). Although the above studies show that the health co-benefits from climate policies could reach billions of dollars, the benefits depend highly on each country's air quality policies. When health externalities are internalised, cost-optimal net zero emissions pathways will differ for each nation (Scovronick *et al.,* 2019).

One previous study developed a hybrid modelling framework for Ireland to address the climate and air policy challenges (Kelly *et al.,* 2017). First, an Energy Systems Optimisation Model (ESOM) compares a business as usual scenario with a scenario that delivers a 22% reduction in non-emissions trading sectors by 2030. Another model assesses the difference in air pollutant emissions and impact outcomes arising between these scenarios. However, the ambitious Climate Act has been recently ratified in Ireland, and to the best of the author's knowledge, there is no reliable evidence that shows how stringent climate policies can impact the distribution of local air pollution. On the other hand, according to the air quality report, the levels of air pollutants in some of Ireland's monitoring stations were above the World Health Organisation (WHO) guidelines (EPA, 2021a). This report also shows that nitrogen oxide will exceed the EU limit level value in some cities during the post-COVID-19 recovery period. It reveals health inequities across sub-national regions, and thus, within-country inequity remains a significant challenge in moving towards sustainability. The previous single region energy models cannot clearly show the distribution of local air pollutants across different sub-regions and address profound health inequities. National-scale results can be downscaled to estimate regional distribution. But the downscaling process will not have an adequate dynamic to reflect the sectoral and inter-regional interactions (Aryanpur *et al.*, 2021). Policies for alleviating air pollution need to be investigated at the sub-national levels to capture regional disparities (Xing *et al.,* 2018).

This article incorporates regional disparities and the heterogeneity of the impact of air pollution across sub-national regions. A multi-regional ESOM with a county-level resolution is developed to explore the air quality-related health co-benefits that could be realised under net zero commitments. TIMES-Ireland Model (TIM) is the basis for the current analysis. Each region is characterised by passenger transport activity level, existing technologies and infrastructures. It calculates the cost-optimal fuel and vehicle technology mix to meet future energy service demands across 26 sub-regions in Ireland. Finer spatial resolution in this analysis helps to understand the uneven realisation of the health benefits of stringent mitigation actions and provides a basis for socio-economically better policy decisions.

The present research focuses on the transport sector, and the main objective is to estimate the ancillary pollution benefits of climate policy designs. It predominately quantifies the co-impacts of decarbonisation pathways on air pollution levels for PM and NOx. Given that ESOMs play a key role in energy policy assessment in Ireland, a county-level spatial resolution could provide essential insights on the co-impacts of climate and air quality interventions. As such, this article can contribute to previous studies in the following two aspects: (1) Analyse the ancillary pollution benefits under carbon-neutral pathway on a county level in Ireland, (2) Use this case study to show how and to what extent higher spatial resolution impacts energy systems modelling results.

The remaining chapter first provides a description of the TIMES-Ireland model (TIM) and the structure of transport. Next, the main data and scenario assumptions are presented. Then, the results are presented, and finally the conclusion summarises the significant findings.

4.2 Research Methodology

Figure 4-1 depicts the modelling approach in this analysis. As discussed in previous chapter, TIM suggests cost-optimal technology and fuel mix under two main scenarios (i.e., a base case versus a mitigation pathway) for each county. The comparison between the two scenarios generates mitigation costs and the reduction in air pollutant emissions levels. On the other hand, marginal damage values caused by air pollutants across sub-national regions are used to quantify the economic co-benefits. The benefits are calculated based on each pollutants' damage costs and the air pollutant emissions reduction associated with mitigation policies. Finally, the benefits are deducted from estimated mitigation costs to show to what extent health benefits can offset the mitigation costs.

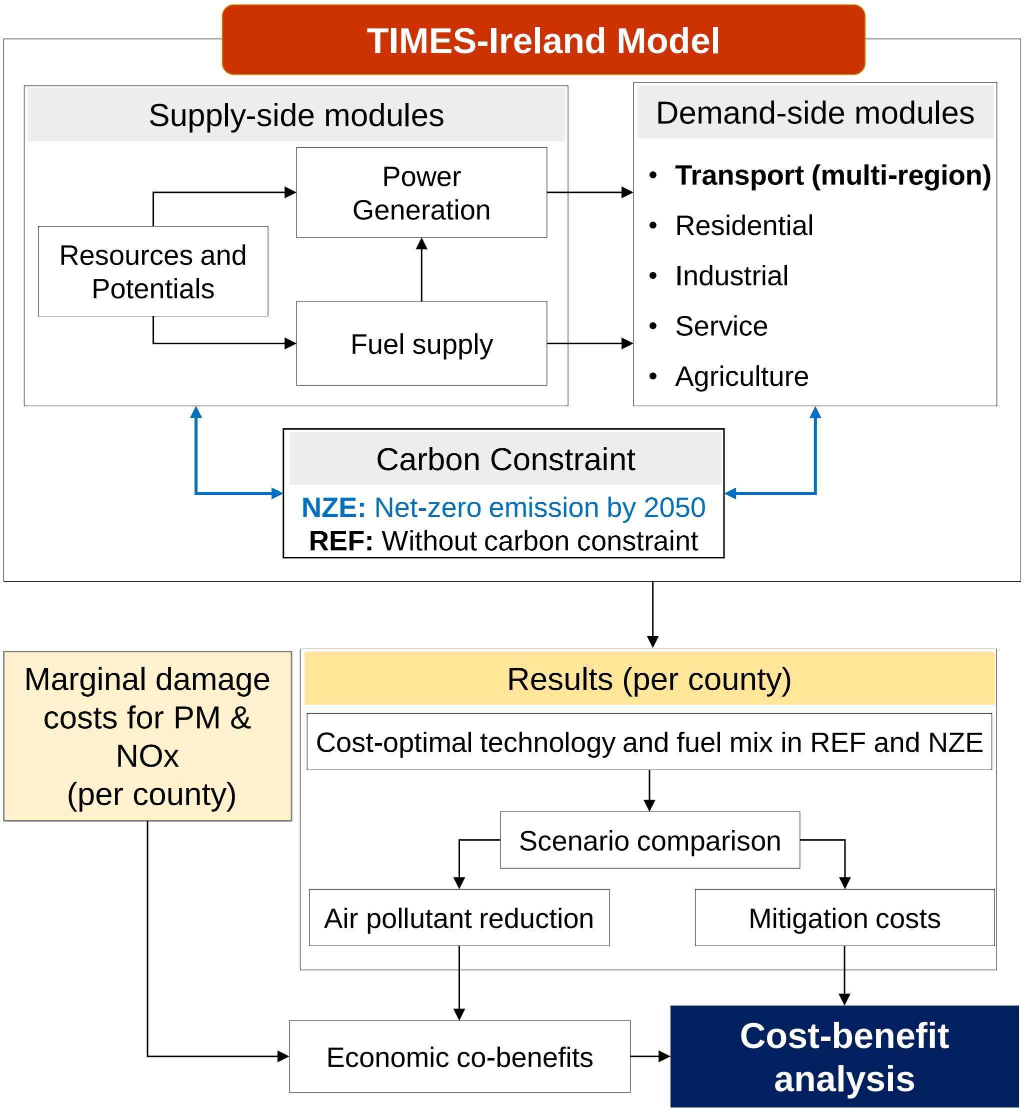

Figure 4-1. The calculation of air pollution and its associated economic costs in the TIM

4.3 Data and scenarios

The base year is 2018, and all energy flows, emissions and energy technology stocks are calibrated using Ireland's energy balance. All costs are in 2018 Euro, and for economic assessments, a social discount rate of 4% has been used. Numerous data from Central Statistics Office (CSO) were used to model actual vehicle activities and the corresponding energy flows and consumption in each county. Therefore, TIM yields for 2018 energy production and consumption are consistent with official statistics for the different counties.

TIM covers Ireland's energy system on a national-scale, while the transport sector is disaggregated into 26 counties with their own specifications. The modelling period is 2018 to 2050, and annual time periods are considered. Each period is further divided into 40 time-slices, including four seasons a year (winter, spring, summer, and fall), two-day types (working/non-working days), and five periods a day (AM off-peak, AM peak, AM-PM intermediate, PM peak, PM off-peak). Energy service demands in end-use sectors are driven mainly by the growth in the demographic (number of households, population) and economic (GDP) trends, and future demand follows the historical trend in energy consumption. The model database consists of more than 300 commodities and more than 2,000 specific technologies. Moreover, more than 150 constraints control the model.

4.3.1 Marginal damage costs

EnvEcon estimated the marginal damage values using a detailed analysis including different steps (EnvEcon, 2015). The spatial distribution of air pollutants and the concentration of pollutants is estimated. Next, the sensitivity and presence of receptors (people and environment) affected by pollutants are measured. Finally, the health impacts (mortality and morbidity) and environmental damage associated with air pollution exposure are assessed. Table 4-1 shows marginal damage costs per tonne per year for different regions in Ireland.

Table 4-1. National and subnational marginal damage costs for air pollutants (€2018 per tonne per annum) (EnvEcon, 2015)

	NOx	PM2.5
Urban Large (Dublin)	10,750	77,625
Urban Medium (pop>15k)	1,800	26,200
Urban Small (pop 10k-15k)	1,600	16,975
Small town (pop<10k)	1,300	11,075
Rural areas	1,050	7,575
National average	1,150	8,625

Note: All values have been rounded to the nearest €25 value.

4.3.2 Scenario definition

A carbon constraint guarantees the mitigation targets across all supply- and demand-side sub-sectors. This constraint is switched off or on in the following scenarios:

- **Reference scenario (REF):** It does not impose emissions reduction targets and is used as a base case to compare a zero-emissions policy scenario.
- **Net-zero emission scenario (NZE):** This scenario aims to meet the government mitigation targets to reduce GHG emissions by 51% by 2030 and net-zero GHGs from the energy system by 2050. Moreover, the scenario represents a particular balance of effort sharing between energy and industry on the one hand and agriculture on the other. It is assumed that 33% reductions are from agriculture by 2030, and 61% reductions are from energy & industry.

4.4 Results

4.4.1 Vehicle fleet and fuel consumption

Figure 4-2 shows the evolution of vehicle stock and fuel mix in each scenario. In the REF case, ICEs dominate the fleet during the planning horizon. The diffusion of BEVs slows down the growth of total fuel use. Diesel and natural gas make up the majority of fuel consumption in this scenario. Freight transport radically shifts toward CNG. BEV would be attractive during the long-term period.

The decarbonisation policy in the NZE scenario firmly shifts the passenger and freight market toward electric and fuel cell vehicles, respectively. Unlike the REF scenario, total fuel consumption will be reduced due to the market uptake of vehicles with higher fuel economy. In both cases, biofuel consumption increases rapidly in the medium term. It is then replaced by electricity and natural gas.

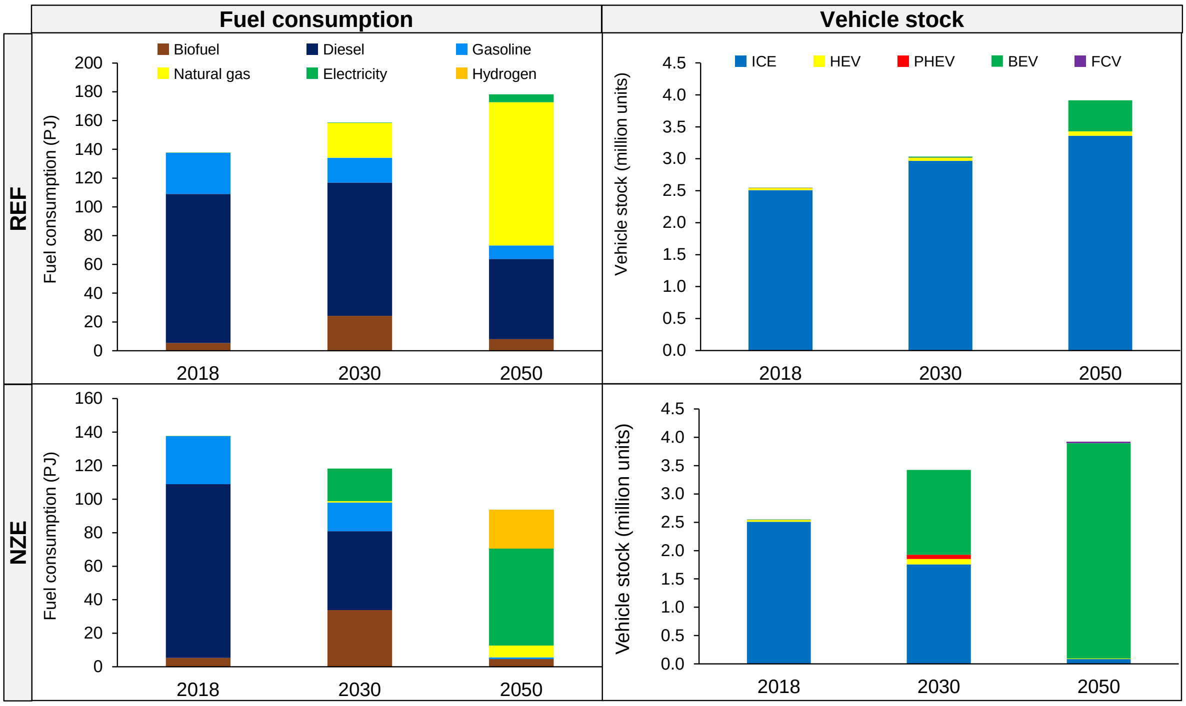

Figure 4-2. Vehicle stock and final energy consumption by the road transport sector

4.4.2 CO_2 emissions pathways

Figure 4-3 compares the CO_2 emissions from the road transport sector in two scenarios. In both cases, a reduction is observed until 2020. It is due to restrictions during the COVID-19 pandemic that caused significant reductions in mobility. Then, the carbon constraint creates a divergence between the two cases. CO_2 emissions remain almost constant during the planning horizon in the REF case. A few reductions over the mid-term are due to the retirement of less efficient existing vehicles and replacing technologies with higher fuel economy. However, it again increases as the fuel economy improvements of ICEs saturate, but the demand growth continues. In the NZE scenario, CO_2 emissions will significantly reduce due to the diffusion of zero emission vehicles. It is worth mentioning that the emissions will not be entirely removed from the road transport sector. Yet, the carbon constraint ensures the carbon-neutrality by developing bio-based power plants coupled with carbon capture and storage technologies. In fact, these technologies deliver net-negative emissions and help the entire system to achieve a net-zero target.

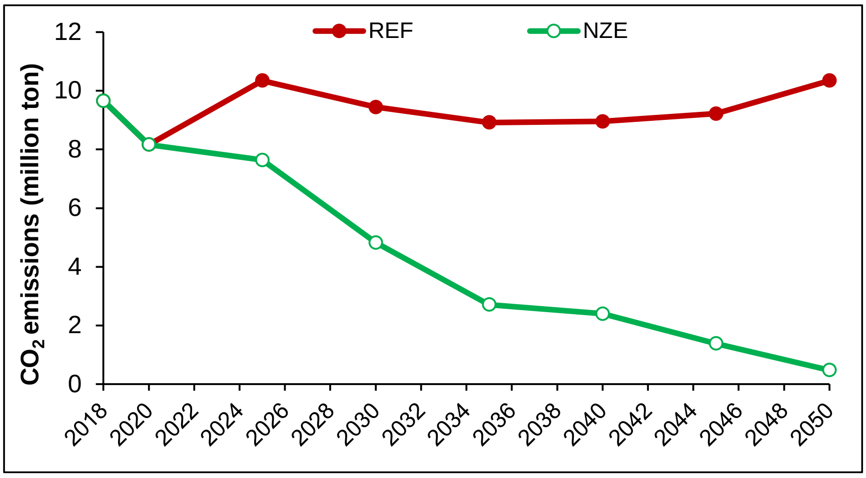

Figure 4-3. CO_2 emissions from road transport sector

4.4.3 NOx and PM emissions

Figure 4.4 shows the spatially resolved distribution of NOx and fine PM in two cases by 2050. Comparing both cases reveals how decarbonisation policies will improve Ireland's air pollution situation. For instance, Dublin, which has the highest population density and annual NOx emissions, is projected to experience an 85% reduction in NOx emissions in the NZE scenario compared to the base year. In other counties, NOx emissions are expected to decrease by 13%-53% in the REF case by 2050, while at least an 88% reduction is observed in the NZE scenario. When comparing the two scenarios in 2050, it is found that 24 out of 26 sub-regions are projected to achieve a reduction of over 90% in NOx emissions.

Dublin's annual fine PM emissions are also expected to decrease from 296 tonnes in the REF scenario to approximately 160 tonnes in the NZE scenario, representing a reduction of about 46%. PM emissions are primarily associated with vehicle activities such as road dust, brake wear, and tire wear, as well as incomplete combustion of fuel, which release tiny particles into the exhaust gases.

It is important to note that PM emissions are influenced by both vehicle activities and fuel consumption, while NOx emissions from conventional vehicles are directly linked to the burning of fossil fuels in the combustion chamber. Therefore, the reduction of NOx emissions is closely tied to fossil fuel consumption, while the adoption of BEVs can partially reduce PM emissions, as vehicle activities such as road dust, brake wear, and tire wear may still occur, albeit at lower levels, even with BEVs. However, NOx emissions can significantly decrease by replacing conventional combustion engines with advanced vehicles.

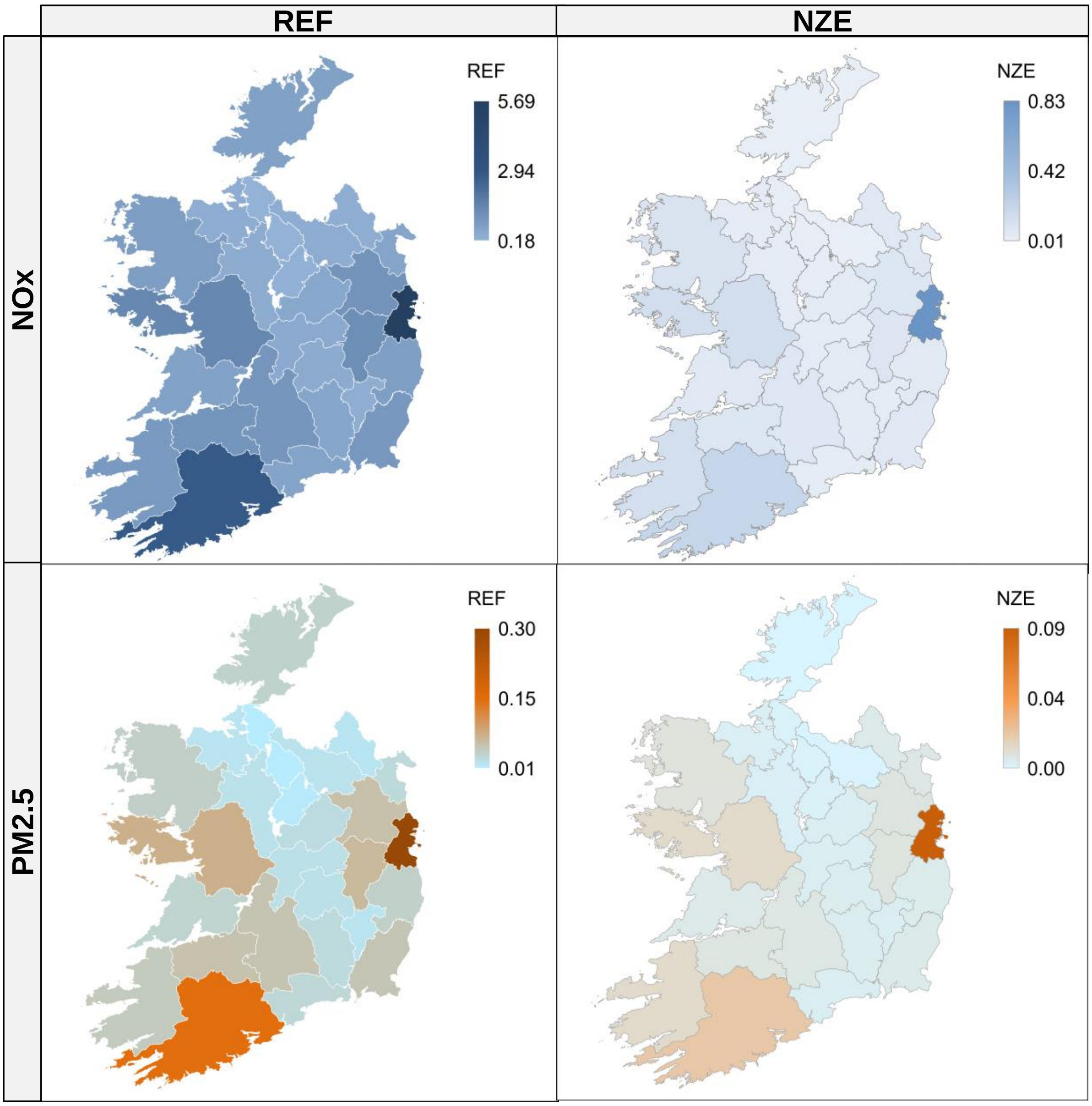

Figure 4-4. NOx and fine PM emissions level across different counties by 2050 (kt)

4.4.4 Cost-benefit analysis

The 5-year cumulative health benefits from air quality improvements and the associated CO_2 mitigation investment costs are shown in Figure 4-5. The total health benefits slowly increase from €11 million during the first period to about €550 million over the last period. The economic benefits from carbon-neutral policies can compensate between 2% to 89% of total mitigation investment costs. The electrification of the transport sector mainly drives this upward trend in co-benefits. In other words, switching from ICEs to BEVs eliminates toxic pollution.

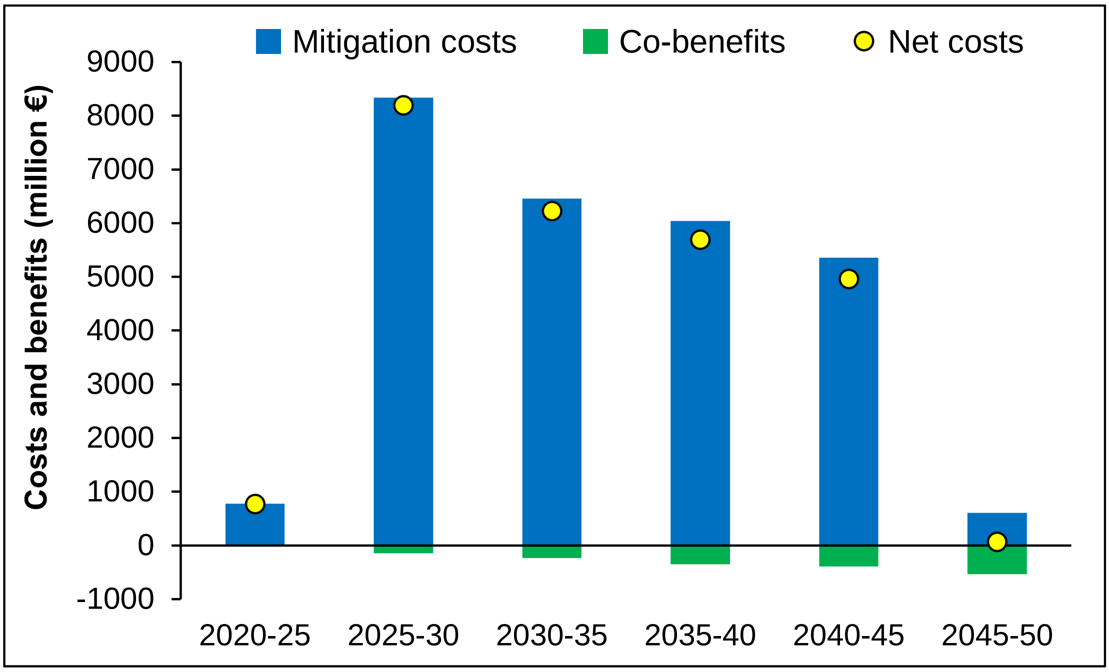

Figure 4-5. Health co-benefits of carbon-neutral policy from the road transport sector

4.4.5 The impact of spatial resolution

The spatial resolution of TIM is flexible and can be run in two modes: single-region (whole Ireland) and multi-region (26 sub-regions). Table 4-2 shows that cumulative economic co-benefits of mitigation actions in the multi-region case study is €1 billion more than the single-region one. This difference is mainly driven by the average marginal damage costs reflected in Table 4-1. In a single-region modelling approach, the sub-national damage costs in populated regions are aggregated with rural and small towns. Since most transport activities are in large cities, the higher spatial resolution captures the region-specific damage costs. But, the single-region method hides the higher damage costs in medium and large cities and thus, underestimates total benefits

Table 4-2. Cumulative benefits in single- and multi-region model (Billion €)

	Single-region	Multi-region
Cumulative economic co-benefits	1.8	2.8

4.5 Conclusions

Ireland has a challenging target of net-zero emissions no later than 2050. The target is challenging due to the associated mitigation costs. This research focuses on the road transport sector, and the main objective is to estimate the ancillary pollution benefits of deep decarbonisation pathways. This investigation predominately quantifies the co-impacts of mitigation actions on air pollution levels for PM and NOx. A multi-region Energy Systems Optimisation Model (ESOM) is developed to explore the costs and benefits of mitigation actions. It also shows how and to what extent higher spatial resolution impacts modelling results. The main findings of the analysis are as follows:

Deep cuts in CO_2 emissions from road passenger transport highly depend on the market penetration of electric vehicles from the short- to the long-term. Fuel cell vehicles play a key role in the decarbonisation of freight mobility. It highlights the importance of investment for developing sufficient infrastructure to support timely adoption.

The result shows that the net-zero emission pathway is accompanied by significant reductions in local air pollutants (46% to 93% in populated areas). Therefore, mitigation policies improve ambient air quality. Sub-national NOx emissions in 2050 will experience at least 88% reduction across sub-regions compared to the base year.

The average economic co-benefits of the mitigation pathway is estimated to be €55 million per annum. Health co-benefits can compensate between 2% to 89% of total mitigation investment costs during the study period. However, the stringency of carbon neutrality is so demanding that the cost of climate policies is above benefits.

Spatially resolved modelling approach shows higher economic co-benefits. It is due to the fact that the higher spatial resolution captures the region-specific damage costs. But, the single-region method hides the higher damage costs in medium and large cities and thus, underestimates total benefits.

It is worth noting that the current study has only examined the road transport sector and dealt with limited air pollutants. Therefore, a part of the potential benefits was assessed in this study.

Further research needs to investigate the co-benefits related to air quality under mitigation policies that were not covered here (especially residential and power sectors). Moreover, the marginal damage costs were estimated based on the spatial distribution of emissions at the county level. It would be interesting to refine the approach with a finer resolution for detailed impact assessment and compare the outcomes with the current work. Finally, pollutant exposure varies on a temporal basis, and further trials should assess variation in air pollutants level and exposure on a spatio-temporal scale.

Part C MESSAGE model: Developing a hybrid modelling framework

5 Ex-post analysis of energy subsidy removal through integrated energy systems modelling

Abstracts:

Energy subsidies can incentivise the overconsumption of energy resources and contribute to other economic or social distortions. In this chapter, an *ex-post* analysis is presented that explores the extent to which electricity subsidy reform could have reduced Iran's energy demand during the period 1984-2017. It also quantifies the techno-economic and environmental benefits that could have been achieved through such reforms. A time-varying econometric model is linked to an energy systems optimisation model. The former estimates electricity demand under different subsidy removal scenarios, and the latter identifies the cost-optimal generation mix to meet the demand. The results of cost-optimal transition pathways under subsidy removal scenarios are compared with the real-world energy system development during the study horizon. The comparison reveals that the subsidy reform could have reduced the total cumulative electricity consumption by 22%. Renewable share in power generation could have increased from 5% to 15%. Moreover, the reform combined with a cost-optimal generation pathway would have saved \$69 billion and avoided 944 million tons of CO_2 emissions. The analysis also shows that every five-year delay in subsidy removal causes about 100 million tons of additional CO_2 emissions. Finally, the analysis presents lessons learnt for future energy modelling.

Keywords: Energy subsidy reform**;** Energy systems optimisation model; Power sector; Ex-post analysis; Renewable energy sources; CO_2 emissions

5.1 Introduction

5.1.1 Background and motivations

Energy subsidies have been implemented in many countries to improve equity and social protection systems (Verme, 2017; Verme and Araar, 2017), enhance the security of energy supply and economic development (IEA, 2011), support domestic production and associated employment, and control inflation (Bazilian and Onyeji, 2012). However, they can also have negative implications by stimulating inefficient energy consumption, which, *inter alia*, reduces the incentive to invest in energy-efficient and renewable energy technologies (Fattouh and El-Katiri, 2013; IMF, 2013; Verme, 2017; Moerenhout, 2020). Additionally, energy subsidies can promote smuggling to neighbouring countries where energy prices are higher (IMF, 2013; Ghoddusi *et al.*, 2018).

Figure 5-1 presents the top ten countries which pay the most subsidies in their energy sector - showing Iran as the most extensive energy subsidy provider globally (IEA, 2017). The Iranian government has paid around $86 billion for energy subsidies in 2019 alone, and its power sector, with about 60% of total payment, has become the highest element of global energy subsidy flow. The substantial subsidy has caused considerable techno-economic challenges and environmental damage.

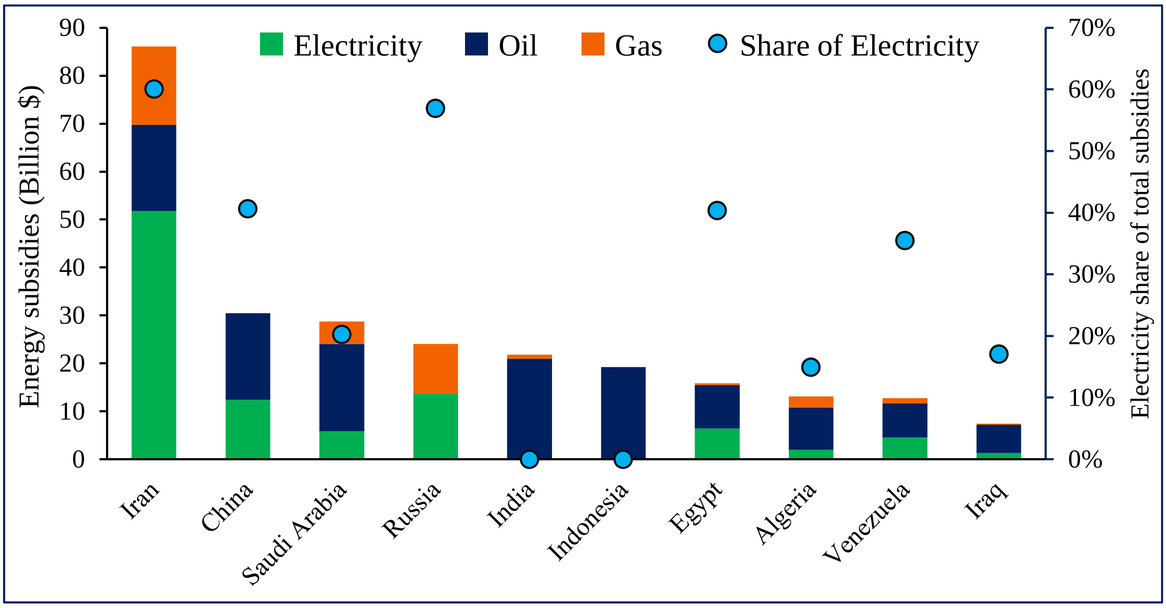

Figure 5-1. Ten countries with the highest energy subsidies in 2019 (IEA, 2017).

A review of Iran's power sector development during 1984-2017 shows that electricity production's average annual growth rate has been about 7% (*TAVANIR*, 2015). As shown in Figure 5-2, liquid fossil fuels have met more than half of power plant needs, but over time, they have been gradually replaced by natural gas so that the share of natural gas reached about 86% in 2017. Although replacing liquids with natural gas is an effective policy in controlling CO_2 emissions, satisfying the ever-increasing electricity demand has released over 170 million tons of carbon dioxide in 2017 (*TAVANIR*, 2015; MOE, 2017). Emissions reduction from the power sector in Iran has been highlighted in several previous studies (see, e.g. in (Shafiei *et al.*, 2009a; Manzoor *et al.*, 2014b; Aryanpur and Shafiei, 2015a; Manzoor and Aryanpur, 2017; Atabaki and Aryanpur, 2018; Aryanpur *et al.*, 2019)). The evidence shows that the analysis of removing energy subsidies in Iran is a crucial case study.

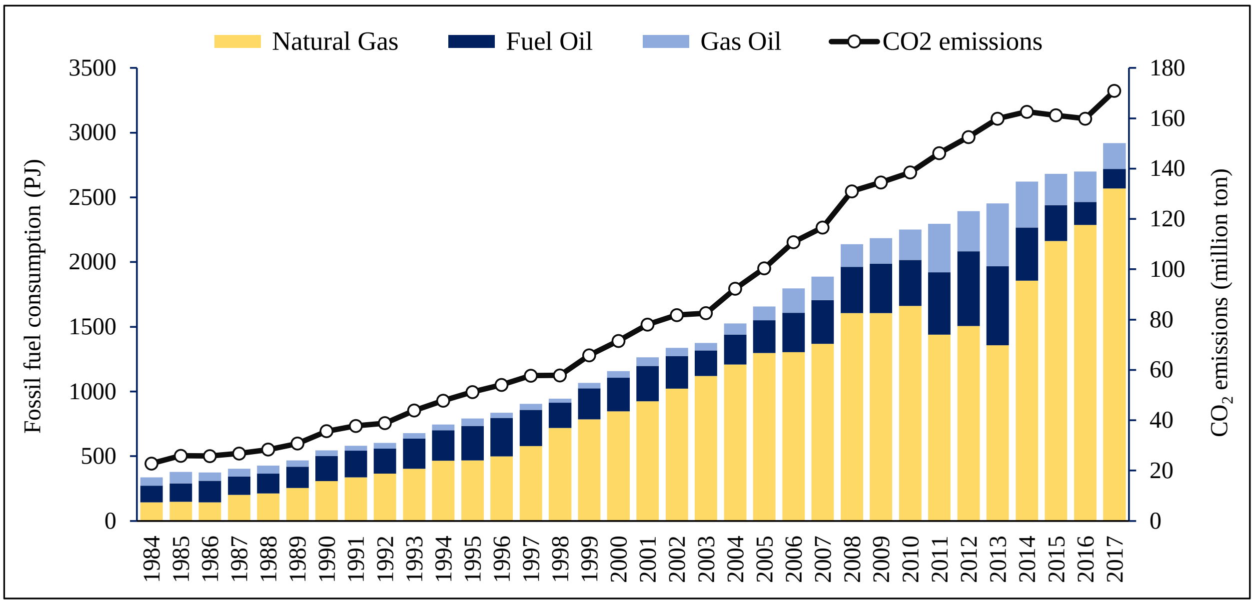

Figure 5-2. Historical fuel consumption and carbon dioxide emissions in Iran's power sector (TAVANIR, 2015; MOE, 2017) (IPCC emission factors (2006) used for calculating the total emissions).

5.1.2 State of research

Many researchers have studied the diverse aspects of subsidy reforms in different countries. Uri and Boyd (1997) and Lin and Jiang (2011) used a computable general equilibrium (CGE) model to analyse subsidy removal in Mexico and China, respectively. These studies show that rising prices reduce energy consumption, decrease harmful environmental effects, and ultimately increase government revenues. Hope and Singh (1995) examined the impact of increasing energy prices in six developing countries. They concluded that energy subsidy reform does not harm socio-economic indicators in the medium- to long-term period. Yet, energy-intensive industries are usually vulnerable to energy price fluctuations. Another work in Mexico (Division and Presidency, 2004) indicated that electricity subsidy removal would decrease households' welfare, mostly low-income families. Analysis of energy subsidies at the G-20 summit in 2009 shows that eliminating fossil fuel subsidies can accelerate economic growth in developing countries (IEA, 2011). Liu and Li (2011) used a price-gap approach to calculate the scale of energy subsidies in China and then used a CGE model to analyse the impacts of energy subsidy reforms in different scenarios. To avoid adverse effects on socio-economic indicators, they suggested a gradual cut in coal and oil subsidies. Li and Sun (2018) found that eliminating fossil fuel subsidies in China could effectively mitigate CO_2 emissions because the subsidies would impede the development of renewable energies. The effects of removing fossil fuel subsidies on emissions reduction and fiscal balance have also been investigated in different countries (Schwanitz *et al.*, 2014; Mundaca, 2017; Chepeliev and Mensbrugghe, 2020).

Some earlier works highlighted the link between energy subsidy reform and economic welfare: Shafie-Pour and Farsiabi (2007), Khalili and Barkhordari (2012), and Farajzadeh and Bakhshoodeh (2015) indicated that subsidy reform can be a basis for redistribution of revenues among low-income families and would enhance overall welfare in the long-term. Breton and Mirzapour (2016) found that the reform may lead to inflationary expectations and emphasised that an appropriate reform should not remove all subsidies. Moshiri (2015) explored energy demand elasticities for rural and urban households and concluded that energy subsidy removal alone could not reduce energy consumption.

Several attempts have focused on the potential impacts of energy subsidy reform on specific industries in Iran. Barkhordar et al. (2018) examined the relationship between efficiency improvement in energy-intensive industries and the energy subsidy reforms. They disclosed that subsidy removal, while non-price barriers such as financial and regulatory ones persist, reduces the adoption of energy efficiency measures. Ansari and Seifi (2012) showed how subsidy removal could encourage more efficient Iranian iron and steel industry technologies. This study indicated that energy-saving plans might reduce natural gas consumption by 33% over a long-term period. Shahverdi et al. (2014) assessed the impact of energy subsidy reform on small-scale fuel cell power plants and spread the results to other distributed generators.

A number of authors have explored the development of power generation technologies using bottom-up Energy Systems Optimisation models (ESOMs) in Iran. Shafiei et al. (2009a, 2009b) linked an optimal R&D resource allocation model to an ESOM to assess the wind turbine, solar PV, and fuel cell diffusion. Aryanpur et al. (2015a; 2019), Atabkai and Aryanpur (2018) investigated the transition to renewable-based, more efficient generation mix across different scenarios. Shakouri and Aliakbarisani (2016) incorporated sustainability costs in determining the optimum strategy for long-term power planning. Ghorbani et al. (2020) assessed the ambitious 100% renewable electricity generation and potential solutions for water scarcity. Ghadaksaz and Saboohi (2020) analysed the transparency challenge of Intended Nationally determined Contributions (INDCs) and emphasised the efficiency improvements of fossil fuel power plants.

Generation technologies have been carefully investigated in all these studies, but energy service demands have exogenously modelled. While the potential implications of energy subsidy removal are well documented for industrial and household sectors, research in the power sector mainly showed how subsidy reforms disincentivise wasteful electricity consumption. As a result, there is a lack of an integrated approach that shows how subsidy reforms could change the demand and impact the required electricity generation. Moreover, the literature is mostly limited to the long-term implications of the reforms. Therefore, the accuracy and reliability of models cannot be easily validated as the future is inherently uncertain (Peace and Weyant, 2008). Model skill encompasses the accuracy and reliability of an energy system model in replicating real-world energy dynamics, including energy demand, supply, and transition pathways, as compared to observed outcomes. One weakness of energy systems modelling is that they often overlook the significance of model skill by neglecting to examine historical data and considering alternative policy scenarios, which could provide valuable insights for future policy initiatives. This implies that energy system models may not adequately assess their performance in replicating historical data or real-world energy transitions.

5.1.3 Contribution of this chapter

This chapter closes the identified research gap and aims to highlight the significance of model skill, particularly in the absence of uncertainties, to analyse past performance. An *ex-post* modelling exercise in this study helps to deal with the uncertainty surrounding the future energy transition. With this approach, the parametric uncertainty can be nearly removed (specifically around fuel cost, fuel availability and technology costs), as historical data are used as input for the model. This research also develops an integrated modelling framework and analyses energy subsidy reforms with an ESOM. It seeks to address three main questions: (1) To what degree might subsidy reforms in the power sector have avoided inefficient electricity consumption from 1984 to 2017? (2) How could subsidy removal have changed the generation mix over that period? (3) What is the maximum potential deviation in techno-economic and environmental benefits that could have been achieved by implementing subsidy reforms in the power sector? In fact, this study quantifies the maximum saving potential that could have not been achieved in the real-world transition.

By evaluating the model's skill through examining the past, valuable insights can be gained into the model's accuracy in capturing real-world dynamics and how different policies may have influenced outcomes. Additionally, assessing the model's skill by examining the past serves as a foundation for informing future policy initiatives. It enables a retrospective analysis of what could have been achieved with alternative strategies, providing a comprehensive understanding of the potential impacts of different pathways. This ex-post analysis can assist policymakers in designing more effective energy policies based on lessons learned from past experiences.

The structure of the remaining chapter is organised as follows: first, the soft-link process between economic and ESOM is discussed. Then, the data sources and scenarios are presented. Next, the insights from the multi-model assessment and analysis of the impacts of delay in subsidy reform are presented. Finally, the implications for future energy modelling, limitations of this study, and suggestions for further research are discussed.

5.2 Methodology: Linking SSM with MESSAGE model

A State-Space Model (SSM) is applied to estimate electricity demand under different subsidy removal scenarios. SSM is a powerful method to capture dynamic behaviour and time-varying characteristics of the consumers (Nagbe *et al.,* 2018; Alptekin *et al.,* 2019). Then, the estimated electricity demand is used as an input for an ESOM which is called MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts). It offers the cost-optimal generation mix to meet the forecasted demand during the planning horizon. Four alternative cases are defined to examine the effects of delays in energy subsidy removal. Then, the results of cost-optimal pathways are compared to the actual historical trend to calculate techno-economic and environmental benefits that would have been achieved through appropriate subsidy removal plans. Figure 5-3 presents the linkage between the SSM and an ESOM.

Accurate and reliable models that can forecast electricity demand are critical to support the decision-making process (Zhang and Hong, 2019) and achieve sustainable energy systems (Al-Musaylh *et al.,* 2018; AL-Musaylh *et al.,* 2018, 2019). One of the most well-known forecasting methods is based on statistical models. They are devoted to looking for the power loads' recurrent relationships among previous time periods (Zhang *et al.*, 2020). The SSM as a statistical model emerged in the 1960s in the region of control engineering, and this model has recently become a continuously important instrument for research in finance and economics (James D Hamilton, 1994). One of the main characteristics of the SSMs is that the electricity demand is estimated more reliable by using the time-varying parameter (TVP) approach based on the Kalman filter. The TVP approach not only considers unobserved variables such as economic activity, the regulation of prices, and structural changes but allows to show price and income elasticity over time (Tong and Yang, 2011; Arisoy and Ozturk, 2014). The main purpose of this study is to investigate the energy subsidy reform over time, and the SSM is a very suitable model to capture the dynamic and time-varying impacts of these price regulations on energy consumption. The SSM consists of an observation (measurement) equation and a transition equation. The dependent variable is described as a time-varying linear function of independent variables in the observation equation. The observation equation for dependent variable (y) and a single independent variable (x) is as equation 1.

$$y_t = \alpha_t + \beta_t x_t + u_t \ , \ \ u_t \sim N(0, \sigma_u^2) \ , \ t = 1, \cdots, T \tag{1}$$

Where α_t and β_t are the time varying intercept and coefficient on x_t, respectively. The transition equation represents how the time-varying parameter change over time, and it is assumed to follow random walk transition (Eq. 2).

$$\alpha_t = \alpha_{t-1} + \ \varepsilon_t \ , \ \varepsilon_t \sim N(0, \sigma_\varepsilon^2) \tag{2a}$$

$$\beta_t = \beta_{t-1} + \ \vartheta_t \ , \ \vartheta_t \sim N\left(0, \sigma_\vartheta^2\right) \tag{2b}$$

The state vector (α_t and β_t) is a first-order autoregressive process that describes the dynamics of the unobserved state variables (for more details on SSM, see (Harvey, 1990; Hamilton, 1994)). The unobserved component in electricity demand may include consumer consumption preferences, availability of substitutions, change in technology and policy, and regional climate condition (Wang and Mogi, 2017).

Before estimating Eqs. (1) and (2), the possibility of existing parameter instability should be checked by the Hansen test (Hansen, 2002). The null hypothesis of the Hansen test presents parameter stability, and if the null hypothesis is rejected, the Kalman filter is the most appropriate method to estimate time-varying coefficients of electricity demand.

There are various determinants for electricity consumption, but the real price and income variables have been considered to estimate energy demand in the existing literature (e.g. Arisoy and Ozturk (2014); Nakajima and Hamori (2010); Dilaver and Hunt (2011); Masike and Vermeulen (2022)). Thus, the electricity demand generally is the function of the real price and income, as shown in Eq. (3).

$$Ln(EC_t) = \beta_{0t} + \beta_{1t}\, Ln(GDP_t) + \ \beta_{2t}\, Ln(P_t) + \varepsilon_t \tag{3}$$

$$\beta_{st} = \ \Phi\beta_{st-1} + \ e_t, \mathrm{s} = 0, 1, 2 \tag{4}$$

Where EC is electricity consumption, GDP is the real gross domestic product (income), and P is the real electricity price. Moreover, β_1 and β_2 represent the income and price elasticity of electricity, respectively. Eq. (4) is a transition equation about β_{st} which explains the state variable and follows a random walk process. ε_t and e_t have a normal distribution and are independent of each other (Ma *et al.,* 2011). According to the theory of consumer behaviour, the point price elasticity of demand changes with price changes (Nicholson, 2005). In subsidy reform scenarios, electricity price increases from the year of subsidy reform. As a result, it is necessary to calculate the price elasticity associated with the new price level. After estimating equations 3 and 4 for the reference case, the price elasticity of demand is considered as a function of electricity price. Next, the price elasticity of demand is endogenously obtained by the price level. In the other scenarios, along with the changes in electricity prices, the corresponding price elasticity is obtained, and finally, the electricity consumption is estimated based on the ceteris paribus assumption.

MESSAGE is utilised for the comprehensive assessment of the electricity supply in this study. It is a bottom-up ESOM that minimises the total discounted system costs during the study period (Schrattenholzer, 1981). The International Institute for Applied System Analysis (IIASA) developed this model in the late 1970s. Besides, to facilitate its application, a user interface was added by the International Atomic Energy Agency (IAEA) (Hainoun *et al.,* 2010). It has been frequently used for analysing international climate policies and addressing global energy challenges (see, e.g., in (Messner and Schrattenholzer, 2000; Klaassen and Riahi, 2007; McCollum *et al.,* 2013; Leibowicz *et al.*, 2016)), and developing low-carbon transitions and the corresponding investment portfolio in different countries (see, e.g., in (Liu *et al.*, 2009; AlFarra and Abu-Hijleh, 2012; Manzoor *et al.,* 2014b; Aryanpur and Shafiei, 2015a; Nogueira De Oliveira *et al.,* 2016; Pang *et al.,* 2019)). The main core of MESSAGE is a Reference Energy System (RES) that demonstrates all the possible energy chains from resources to end-use technologies (Messner and Schrattenholzer, 2000; Rogner and Riahi, 2013). It clearly describes energy forms and technologies in all levels of energy chains (John, 2015). Resources cover all fossil fuels, nuclear and renewable potentials, and the conversion consists of power plants. Power trades are defined at the transmission level, and demand involves different consumers.

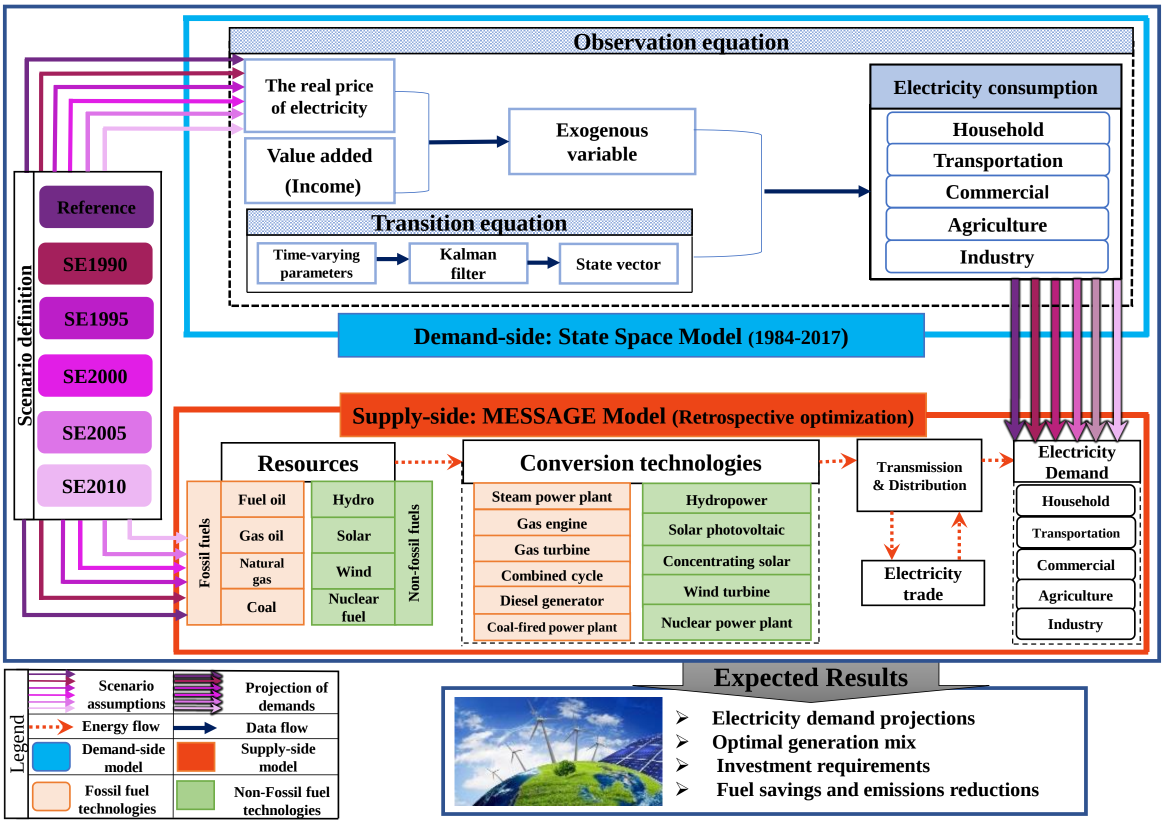

Figure 5-3. The linkage between state-space and energy systems models.

5.3 Data and scenario description

5.3.1 Data

The study is an ex-post analysis. The data are fed into the models for the period 1984 to 2017. According to the country's financial needs and resources, the annual discount rate is assumed to be 10% (Plan and Budget Organization of Iran, 2012). Previous studies also show that for the economic assessment of power sector projects in Iran, this level of discount rate is appropriate (Shafiei *et al.*, 2009a; Aryanpur and Shafiei, 2015a; Aryanpur *et al.*, 2019). The assumptions across demand- and supply-side models are as follows:

5.3.1.1 Required data for SSM

The annual electricity demand is estimated using the SSM for the period 1984 to 2017. Table 5-1Table 5-1 provides the data used for SSM. Electricity consumption in Iran has increased by an average of about 7% per year, while the average real GDP growth was about 3% during the same period. Significant energy subsidy payments combined with chronic inflation in the Iranian economy have led to a continuous decline in real electricity prices. As shown in Figure 6-2, there is a substantial differential between the average electricity price and the average supply cost. Specifically, the selling price is estimated to be only 22% of the supply cost, highlighting a notable disparity between the two. The real price of electricity has decreased by an average of about 8.8% annually. Figure 5-4a shows that the income per capita in Iran increases by 1.2% per year, while the electricity consumption per capita grows by more than 5% per year. According to the demand theory, there is an inverse relationship between the demand for a commodity and its price. When the real price decreases, the consumers' sensitivity to price changes dwindles. Figure 5-4Figure 5-4b shows when the real electricity price declines, it is expected that price sensitivity also decreases, and electricity consumers may react less to changes in its price. Figure 5-4c illustrates the direct relationship between income (GDP) and electricity demand. It reveals that electricity is a normal commodity, and as income increases, electricity consumption rises. Regarding the substitution and income effects, which are in the same direction for a normal commodity, when the real price of electricity falls, both the income and substitute effects lead to higher electricity consumption. Consequently, electricity consumption has increased more than ten times during the study period.

Table 5-1. Data descriptive statistics during the study period (MOE, 2017; CBI, 2021; The World Bank, 2021)

Variable		Unit	Mean	Min	Max	Std. Dev.	AAGR*
Electricity Consumption	total	TWh	112.9	28.2	255.0	69.1	6.9
	per capita	MWh	1.6	0.6	3.1	0.8	5.1
Real GDP (Constant 2010)	total	Billion $	350.0	193.1	560.6	111.0	3.0
	per capita	Thousand $	5.3	3.7	6.9	0.9	1.2
Real Electricity Price (Constant 2010)	total	Cent/kWh	6.6	0.6	26.0	6.7	-8.8

* Average Annual Growth Rate.

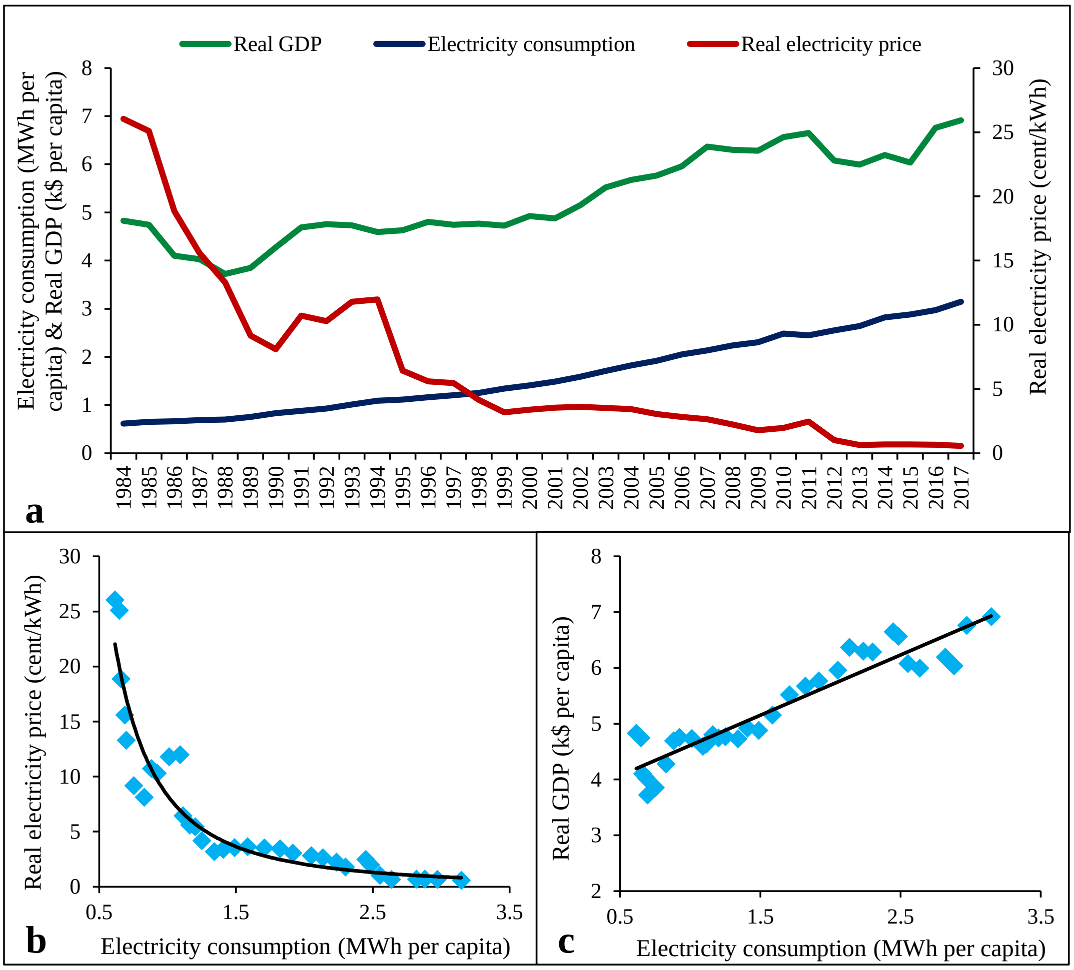

Figure 5-4. Demand-side data and their relationship (MOE, 2017; CBI, 2021)

5.3.1.2 Required data for MESSAGE model

Fossil fuel prices and the techno-economic characteristics of technologies are found in Table 5-2 and Table 5-3. Technologies connect two energy levels and are introduced by two main features: activity and capacity. The former involves input and output energy flows, energy efficiency, and variable operation and maintenance costs. The latter involves the existing installed power plants, investment cost, fixed operation and maintenance costs, plant factor (availability factor), construction time, and plant life. The economic model has projected the annual electricity demand for various scenarios. MESSAGE also considers the electricity demand variation within a year. To model the temporal variations, each year is subdivided into 36 load regions: each month of the year is divided into one day, and each day includes three segments (base, intermediate, and peak load). The corresponding share of electricity demand in each load region is estimated using the analysis of actual hourly electricity consumption.

Table 5-2. Fossil fuels prices during the study period (EIA, 2014; 2015; 2021)

	Natural gas (USD cent/m^3)	Fuel oil (USD cent/lit)	Gas oil (USD cent/lit)	Coal (USD/ton)
1983 (base year)	2.5	12.0	17.3	11.9
1984	2.5	6.5	9.3	11.9
1987	2.5	7.4	10.5	14.6
1990	3.2	4.7	6.7	13.1
1993	4.1	5.7	5.9	14.2
1996	3.4	4.5	6.4	10.2
1999	4.9	6.0	8.6	10.6
2002	13.1	13.9	18.6	18.1
2005	13.1	17.7	25.3	25.3
2008	6.0	17.3	28.7	38.9
2011	9.5	19.0	27.7	38.9
2014	9.5	19.0	27.7	38.9
2017	11.2	31.3	41.5	40.7

[a] Nuclear fuel cost is assumed to be 1 cent per kWh of generated electricity

Table 5-3. Techno-economic specifications of the electricity generation technologies (Manzoor *et al.*, 2017)

Technology	Construction time (Year)	Lifetime (Year)	Plant factor (%)	Efficiency (%)	Capital cost [a] ($1983/kW)	Fixed O&M cost ($1983/kW)	Variable O&M cost ($1983/MWh)
Steam power	4	35	70	37	347	1.94	0.02
Gas turbine	2	15	50	32-35	176	0.65	0.07
Gas engine	1	15	70	39	329	4.50	2.81
Combined cycle	4	40	67	45	267	0.70	0.05
Diesel generator	2	15	70	33	347	6.94	0.03
Coal-fired	5	30	75	35.3	434	0.69	0.23
Nuclear	8	40	80	31	912	13.68	1.74
Hydropower	5	50	20	-	335	0.00	1.59
Wind turbine	1	20	30	-	694	7.20	-
Solar photovoltaic	1	25	18	-	4050	8.10	-
Concentrating solar power	2	30	40	-	3500	8.67	-

[a] It is assumed that capital costs for the wind turbine, solar photovoltaic, and concentrating solar power have decreased at a rate of 0.5%, 5.4%, and 1.5% annually, respectively (Manzoor and Aryanpur, 2017).

5.3.2 Scenario description

Three main scenarios and four alternative cases are defined for this analysis. The main scenarios are as follows:

- **Actual development scenario:** It shows the power sector's historical development and thus, reflects the actual generation mix to cover the real demand during the study period.
- **Reference scenario:** It shows how a cost-optimal power generation mix might have met the actual demand. It also uses real fuel and technology investment costs and can introduce an optimal pathway that could have been implemented. This scenario is the basis for proper long-term least-cost energy planning.

- **Subsidy elimination scenario 1990 (SE1990):** The Iranian government had suggested energy subsidy reforms since the early 1990s when the first and second national development plans were introduced. However, the reforms have not been effectively pursued. This scenario assesses techno-economic and environmental benefits that could have been realised through a 5-year subsidy removal plan starting from 1990. Figure 5-5 shows the subsidy level in the actual and reference cases during the planning horizon. It also indicates how subsidy in the SE1990 scenario is phased out from 1990 to 1995. It is worth mentioning that the subsidy level indicates the difference between electricity generation costs and what consumers have paid. The generation cost is estimated using international fossil fuel prices.

In fact, the Reference scenario involves optimising the supply side using ESOM without incorporating the soft-link approach. On the other hand, SE1990 encompasses both supply-side optimisations and demand-side modifications, including the utilisation of soft-link techniques. The actual scenario shows the real-world energy system development and can be compared to the modelled scenarios, the reference scenario represents a cost-optimal trajectory (i.e. if the electricity supply had followed a least-cost pathway), and SE1990 shows what could have been happened if subsidies had been removed in 1990. This comparison indicates the deviation from the cost-optimal condition. In other words, it can estimate the benefits that could have been achieved through a commitment to long-term energy planning. Then, four alternative cases are defined. In these cases, energy subsidies are phased out with a 5- to 20-year delay: **SE1995**, **SE2000**, **SE2005**, and **SE2010**. These additional scenarios explore how the delay in subsidy removal could change the results.

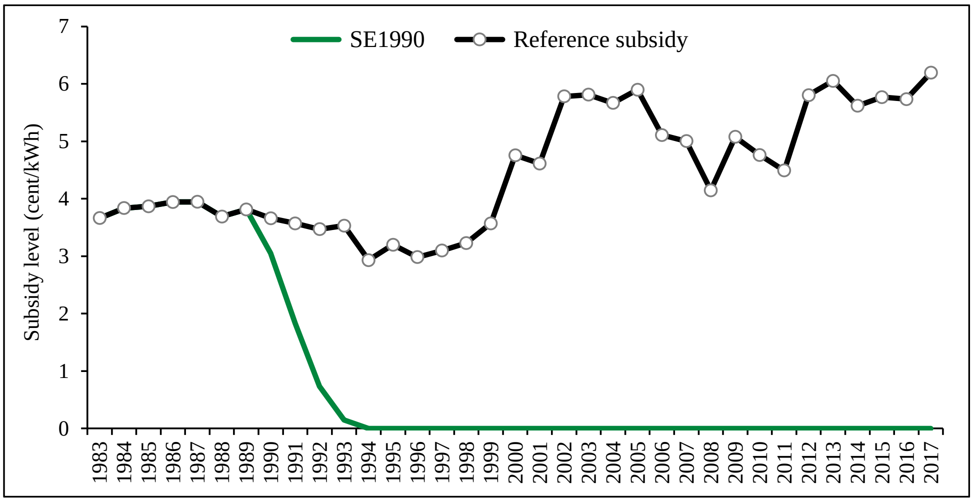

Figure 5-5. Subsidy removal in reference and SE1990 scenarios

5.4 Results

In this section, the results from both models are compared to quantify the potential advantages of commitment to subsidy removal plans and long-term power planning.

5.4.1 Electricity demand estimation

As discussed in the methodology section, after confirming the instability of the parameter using the Hansen test, we can apply the Kalman filter to estimate time-varying coefficients of electricity demand. The results of the Hansen test show that the test statistic is 0.53 with a p-value of 0.03. Thus, the null hypothesis is rejected at a 5% level of significance, and the parameters are not stable and change over time. Figure 5-6 compares the predicted electricity demand in main scenarios versus the actual values during the study horizon. It shows that there is a minor difference between the prediction and the actual statistics, and the Mean Absolute Percentage Deviation (MAPD) is 2.1%. In other words, the estimated demand function very closely follows real-world consumption. Comparing electricity demand projection in the reference and SE1990 scenarios shows that subsidy reform could have changed the direction of electricity demand over time. In the reference scenario, the annual growth rate of total electricity consumption during the study period was about 6.5%, which rose from 30 TWh in 1983 to 253 TWh in 2017 (from 0.68 MWh to 3.12 MWh per capita). However, in the SE1990 scenario, the average power consumption would have reduced by about 22% across the study period. The removal of electricity subsidies could have changed the direction of its demand in the long run. This reduction in electricity demand could have positive consequences on the supply-side, either in terms of investment costs, reducing fuel consumption and environmental pollutants.

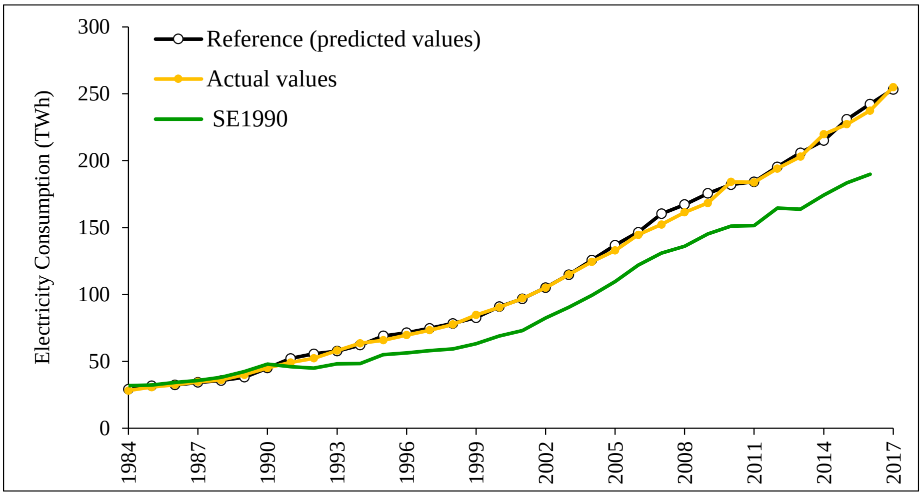

Figure 5-6. Forecasted electricity demand versus the actual consumption (Actual values (*TAVANIR*, 2015; MOE, 2017))

The dynamic effect of price and income on electricity consumption in the reference scenario is shown in Figure 5-7. Figure 5-7a presents the electricity demand's income elasticity experienced a downward trend that depicts real GDP's effect on electricity consumption. The results show that an increase in income by 1% leads to 0.2% to 0.4% increase in electricity consumption, which indicates that electricity is a normal good in Iran. In Figure 5-7b, the price elasticity of electricity demand has always been negative and less than one (in absolute value) over time. This indicates that electricity demand has low elasticity in Iran. That is, a 1% increase in electricity prices is typically associated with a reduction in the quantity of electricity consumption of lower than 1%. To put it another way, the absolute value of the price elasticity has dropped over time, and it has approached zero. It means that keeping electricity subsidies and the downward trend in the real electricity prices have led to the inelasticity of electricity demand. It is also worth noting that under the SE1990 scenario, the average value of the price elasticity could have almost doubled compared to the reference one.

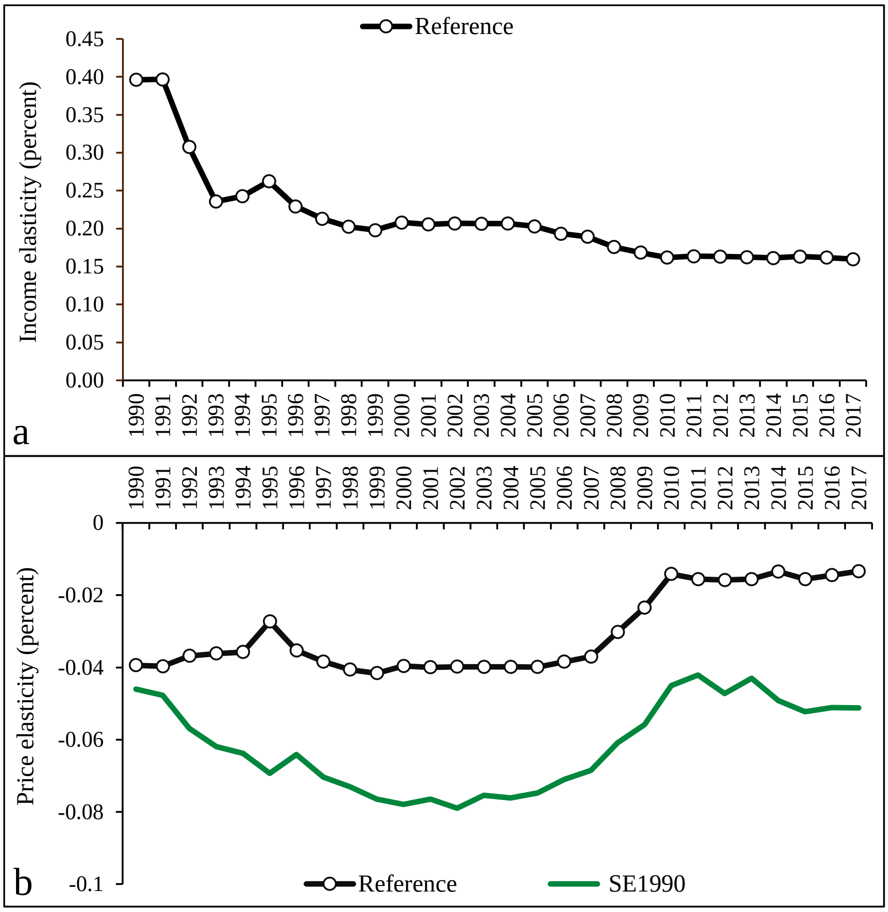

Figure 5-7. Elasticities in the reference and SE1990 scenarios (a) income elasticity, and (b) price elasticity

5.4.2 Electricity supply system

5.4.2.1 Capacity

Figure 5-8 compares total installed capacity under three main scenarios. In the actual case, the total capacity reached 78.96 GW in 2017, and the share of renewable and fossil fuel power plants were about 15.9% and 82.8%, respectively. The remaining was the nuclear unit. The cost-optimal pathway in the reference case could increase the renewable share to 21.3% by the same year. Adding subsidy reform to this pathway (as in SE1990) reduces total demand, and therefore, 62.85 GW capacity might be sufficient to meet power demand. Fossil-based technologies could be meaningfully reduced in the SE1990 scenario, increasing the renewable share to 25.3%. Despite similar demand assumptions both in the actual and reference scenarios, the total installed capacity would have risen to 82.42 GW in the reference case. Higher installed capacity is the direct outcome of higher wind turbine installation with a lower availability factor. Therefore, the model should provide more capacity to meet the same demand.

The reference scenario offers an additional 18.98 GW combined cycle and a 5.25 GW wind turbine compared to the actual historical case. On the other hand, the total installed capacity of gas turbines would have phased out in 2017, while in the actual case, there was 25.92 GW. Also, the model proposes about 6.90 GW coal-fired power stations and distributed gas engines. Coal power plants are mainly suggested due to the lower coal price and the higher efficiency compared to the gas turbines (compare fuel price and techno-economic parameters in Table 5-2 and Table 5-3). However, they were not part of the historical investment portfolio. The total proposed steam power plant capacity is 14.84 GW in 2017, about 1.00 GW less than the actual case. Compared with the actual case, the SE1990 scenario could have used 4.24 GW and 25.92GW fewer steam power stations and gas turbines by 2017. The proposed capacity of coal-fired power plants and gas engines in this scenario is the same as the reference one. Regarding coal-fired power plants, low coal prices compared to other fossil fuels are the main reason for their presence in the reference and SE1990 pathways. Nevertheless, due to abundant natural gas and liquid fuels availability, coal power plant development has ceased in the actual development (Manzoor and Aryanpur, 2017).

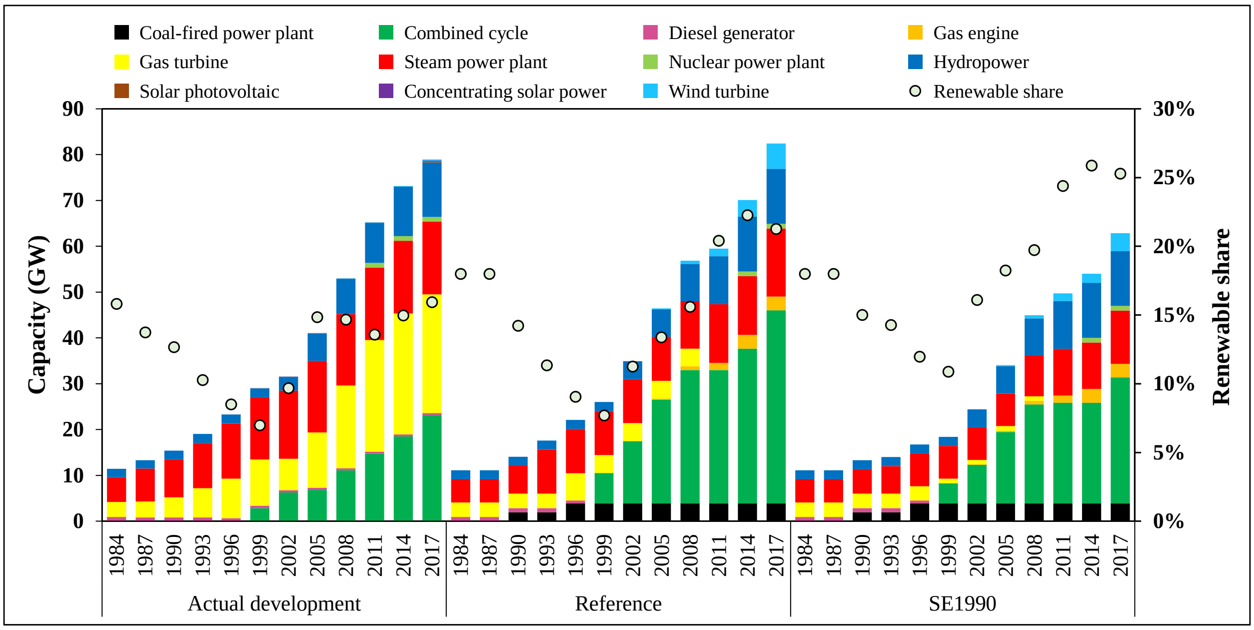

Figure 5-8. Total installed capacity in different scenarios (Actual scenario from (*TAVANIR*, 2015; MOE, 2017)).

5.4.2.2 Power generation

Figure 5-9 indicates the electricity generation mix in three scenarios in 2017. Power generation has experienced a 9-fold increase in the historical capacity expansion. However, subsidy removal in the SE1990 scenario could constrain this radical expansion to about 6-fold. In the reference and SE1990 scenarios, the generation from fossil-based power plants compared to the actual case in 2017 could reduce by 38.7 TWh and 110.8 TWh, respectively. However, the generation is dominated by combined cycle power plants in all scenarios. The conventional steam power plants fuelled by natural gas and fuel oil hold the second-largest share in the actual case. In the alternative scenarios, about one-third of steam power plants generation could be replaced by coal-fired units. While alternative cases allow 11%-14% electricity generation from wind turbines and gas engines, these technologies have a marginal share of 0.1% in the actual transition.

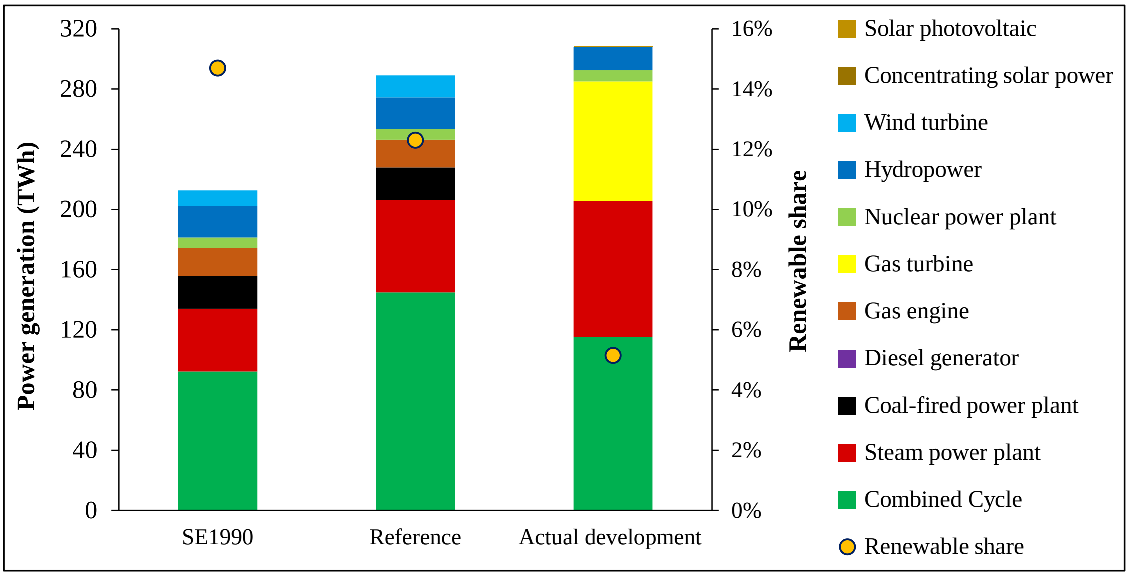

Figure 5-9. Power generation mix in different scenarios in 2017

5.4.2.3 Fuel consumption

Figure 5-10 demonstrates total fuel consumption for power generation. In the actual case, the average annual growth rate of fuel consumption was about 6.9% during the study period. Natural gas has gradually dominated fuel share. Compared to the actual pathway, the cumulative fuel consumption in the alternative scenarios would have been reduced by 23% and 41%. In other words, this difference of these alternative scenarios with the actual conditions could have declined demand for natural gas by 41% and 58%, respectively. In the SE1990 scenario, it is remarkable that it has the lowest fuel usage per unit of electricity generation. This is due to the utilisation of more efficient technologies along with the deployment of renewable technologies.

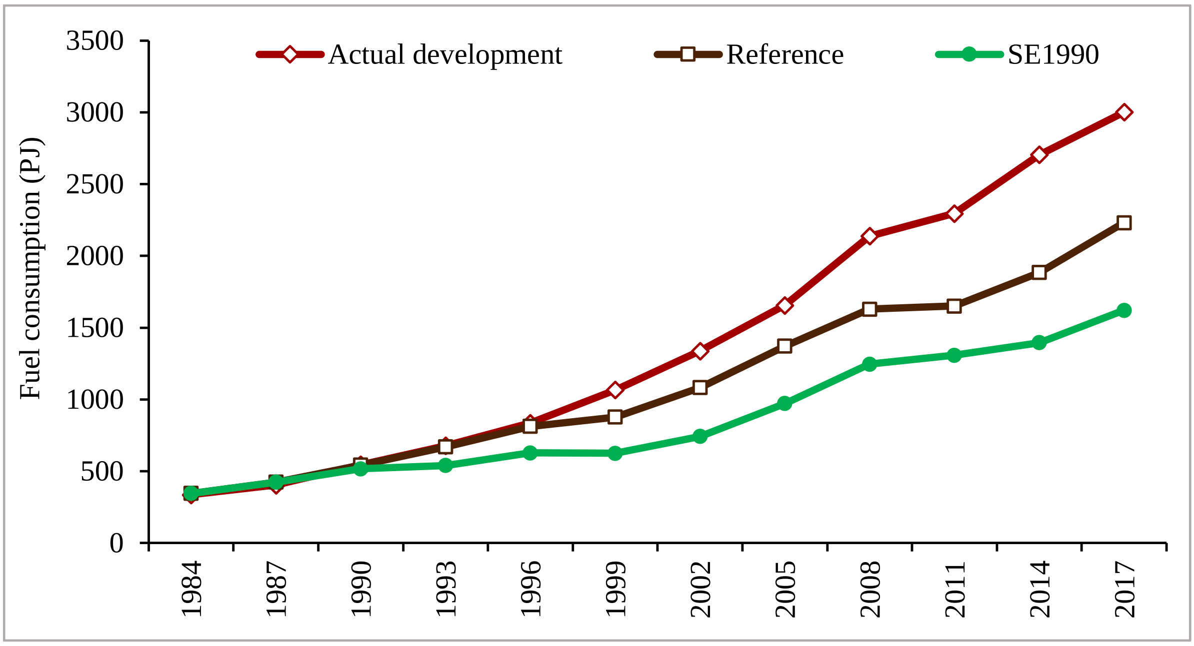

Figure 5-10. Fuel consumption for electricity generation in various scenarios (Actual scenario from (*TAVANIR*, 2015; MOE, 2017)).

5.4.3 The impacts of delay in subsidy reform

This section explores how delays in energy subsidy reforms can affect power demand, total costs, and CO_2 emissions. Figure 5-11a presents the level of subsidies in the reference case. It also illustrates several elimination pathways. Figure 5-11b reveals that the subsidy removal scenario increases consumers' sensitivity to electricity prices. Their reaction varies over time, so that the sooner the subsidy is eliminated, the greater the effect on reducing demand and vice versa.

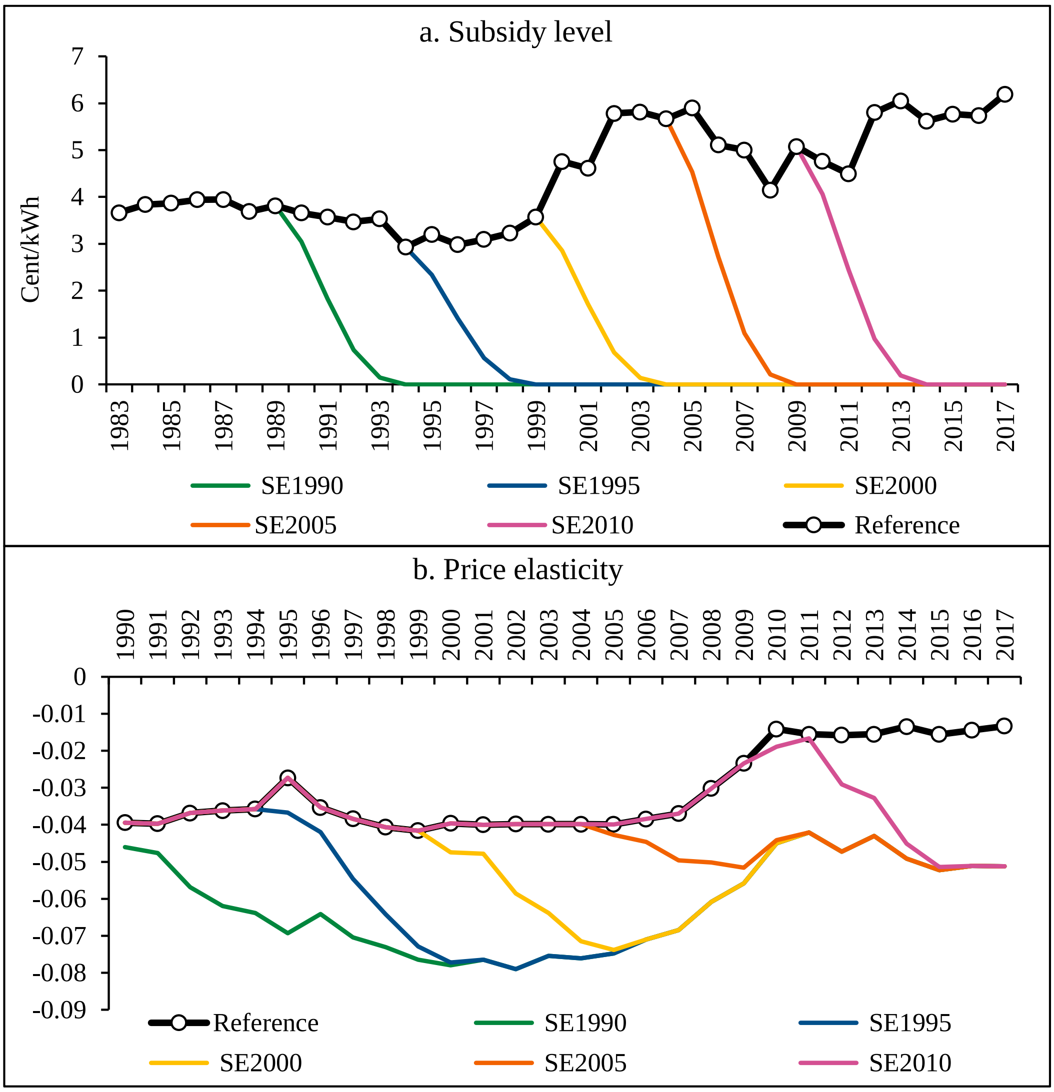

Figure 5-11. Level of subsidies and price elasticities in different scenarios

5.4.3.1 Techno-economic implications

Subsidy removal scenarios reached similar electricity demand in 2017. It can be said that price reform at different times has a similar effect on electricity demand. However, from the data in Figure 5-12, it is apparent that the cumulative impacts of these scenarios will be different. The SE2010 scenario, by 7% reduction, has the lowest reduction in electricity consumption. As expected, the sooner the subsidy elimination is performed, the lower the electricity is consumed during the study period. For instance, subsidy removal in 1990 could avoid 22% electricity consumption, while implementing subsidy reform in 2005 might only prevent 12% of the cumulative consumption.

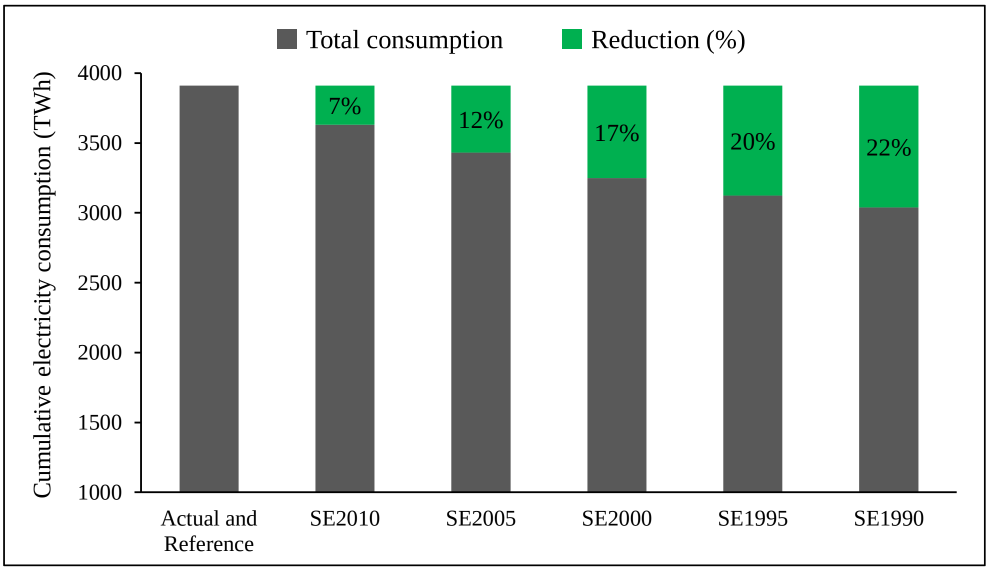

Figure 5-12. Cumulative electricity consumption in different scenarios.

Figure 5-13 presents the total electricity generation costs during the planning horizon in each scenario. The total costs consist of investment, fuel, and O&M costs. The overall cumulative costs of electricity in the reference, SE2010, SE2005, SE2000, and SE1995 scenarios would have been \$41, \$52, \$60, \$66, and \$68 billion lower than the actual transition pathway, respectively. Fuel costs dominate the total costs in all conditions. Comparing the real pathway and the reference case discloses that utilising more efficient renewable technologies could reduce total costs by 27%. A further decrease is expected from subsidy removal scenarios, between 7% to 19%. The accelerated subsidy reform (as performed in the SE1990) could further reduce the costs by about 20%. The investment costs proportion is about 20% of the total system cost in the reference and all the subsidy reform scenarios, while it is 12% in the actual case. The main driver for this growth is increasing the share of capital-intensive technologies in alternative scenarios.

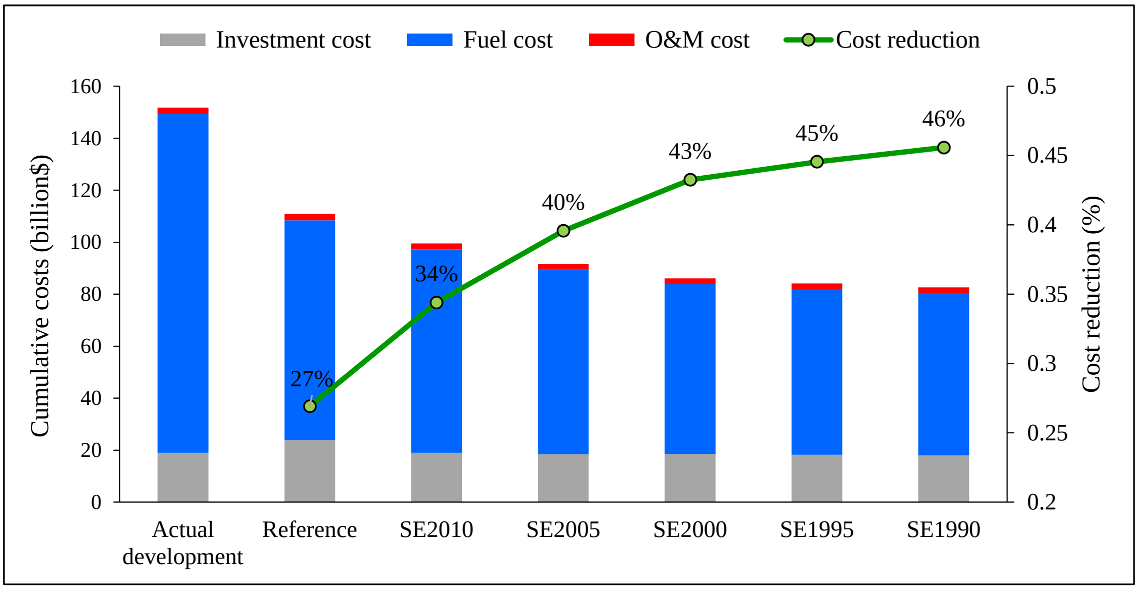

Figure 5-13. Cumulative electricity generation costs in different scenarios.

5.4.3.2 Environmental implications

The annual amount of CO_2 emissions depends on the fuel consumption (MJ/year) and the corresponding emission factors (g CO_2/MJ). The emission factors are from the IPCC guidelines for national GHG inventories (IPCC, 2006). As displayed in Figure 5-14 cumulative CO_2 emissions from power generation activities are calculated in various scenarios. In the actual transition, the total amount of CO_2 emissions has increased from 23 million tons in 1984 to 171 million tons in 2017. Total emissions in the reference and the SE1990 scenarios could be cut by 15% and 33%, respectively. In other words, cost-optimal supply planning could individually reduce the emissions by 15% during the study period. When this planning is combined with the demand-side policies (as reflected in the SE1990), it could further decrease the cumulative emissions by 18%.

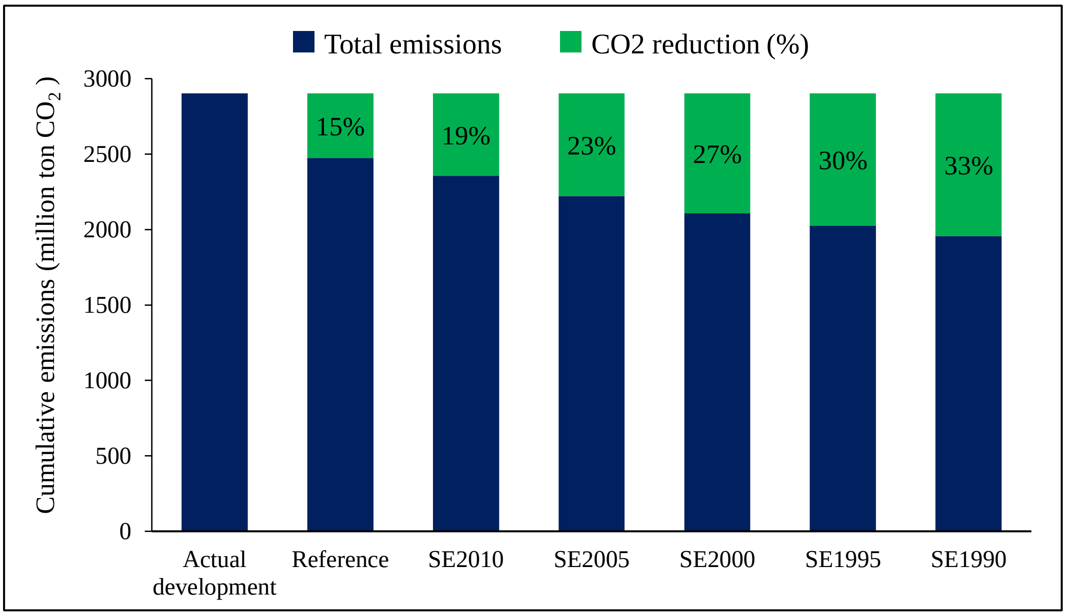

Figure 5-14. Cumulative CO_2 emissions in different scenarios.

5.5 Discussion

5.5.1 Lessons for future modelling

The ex-post modelling of Iran's power sector shows that the cost-optimal modelled scenarios are different from the real-world energy system development. During a period of 33 years, the total investment costs in the cost-optimal reference scenario exceed the actual transition costs by 26%. However, the total energy system costs were reduced by 27% in the cost-optimal scenario. The deviation between the cost-optimal modelled scenarios and the real-world energy system development, as evidenced by the higher investment costs in the cost-optimal reference scenario compared to the actual transition costs, can be justified by several factors:

Firstly, the cost-optimal reference scenario may have a different financing mechanism, such as lower interest rates or less limitation in availability of funds, which might not have been feasible in the real-world energy system development. Budget constraints, limited access to financing, or competing priorities for investment in other industries may have influenced the actual transition costs, resulting in a deviation from the cost-optimal scenario. Moreover, the decision-making process in the real-world development does not always fully account for lifecycle costs due to a myopic planning strategy, and long-term gains can be underestimated in the decision-making process due to insufficient long-term information.

Secondly, a smooth and efficient implementation process have been assumed in the cost-optimal reference scenario, neglecting potential delays, disruptions, or inefficiencies that can occur in real-world energy system development. Factors such as project management challenges, delays in construction or operation, or unexpected changes in regulations or policies, can affect the actual transition costs and deviate from the cost-optimal scenario. Previous studies confirm that large scale power generation projects often suffer cost overruns and fail to deliver the efficiency aspirations initially expected (Sovacool *et al.,* 2014; Callegari *et al.,* 2018).

Thirdly, the cost-optimal reference scenario has assumed the availability and accessibility of certain technologies or resources at based on average international costs, which might not have been fully realised in the real-world energy system development. Technological constraints, resource limitations, or unforeseen changes in technology costs or resource availability can influence the actual transition costs and deviate from the cost-optimal scenario.

Lastly, the reference scenario has assumed a regulatory environment that could facilitate the implementation of optimal transition pathways. However, changes in policy priorities, regulatory frameworks, or political dynamics during the real-world energy system development may have influenced the actual transition costs.

Policymakers could have potentially reduced the overall cost of the transition in three areas. (1) They could have explored options to secure lower interest rates or increased availability of funds to finance the energy system transition. (2) They could have considered the full lifecycle costs of the energy system transition and incorporated long-term gains into their decision-making process. By taking a more comprehensive and forward-thinking approach to planning, policymakers could have potentially identified cost-saving opportunities. (3) They could have implemented strategies to ensure an efficient process of implementing the energy system transition. This could have included effective project management and operation processes, and proactive measures to address potential delays, or regulatory changes. However, other factors such as resource limitations and resource availability, technological constraints or changes in technology costs, and regulatory environment may have been beyond the control of energy policymakers, resulting in deviations from the cost-optimal scenario. Changes in policy priorities, or political dynamics may have also influenced the actual transition costs. These factors highlight the complex and dynamic nature of real-world energy system development, where policymakers may face challenges and limitations in implementing a cost-optimal scenario.

Ex-post modelling exercises can be conducted to measure the success rate of previous policies (Dennehy and Ó Gallachóir, 2018; Liu *et al.*, 2019; Valentová *et al.*, 2019; Trotta, 2020). For instance, Iranian policymakers have always paid particular attention to improving the efficiency of power generation and consumption. The actual development of more efficient power plants (combined cycle gas turbines) is relatively comparable to that suggested by the modelled cost-optimal scenarios. However, total electricity consumption has consistently increased in the actual development, while subsidy removal scenarios could control the trend. This shows that, unlike the supply-side policies, the demand-side ones were unsuccessful. The results in different scenarios show that the reference case can better approximate the real-world pathway, and the highest deviation is observed in the SE1990. This is due to the fact that only supply-side policies are optimised in the reference case while the SE1990 is assessed based on both supply- and demand-side strategies. In fact, the former focuses on relatively few actors (electricity suppliers), but the latter cope with many different actors (consumers and suppliers) and thus higher uncertainty that need to be considered for modelling the future energy transition. A recent study by Trutnevyte (2016) mentioned that the ex-post analysis can help identify what modelling framework works better under what circumstances.

This exercise can help decision-makers better understand if a policy intervention has reached the original goals it aimed to obtain. The main objectives of energy subsidies by the Iranian government were to improve economic growth, employment rate, social equity, and control inflation. Nevertheless, no compelling evidence confirms these improvements were achieved (Farajzadeh and Bakhshoodeh, 2015). Moreover, such subsidies benefit high-income households who usually utilise more energy-intensive goods and services (Victor, 2011). As a result, universal subsidies can be replaced by alternative policy measures such as well-targeted and transparent financial support for protecting vulnerable groups (IEA, 2011). This may significantly reduce the fiscal burden on the government, which in turn accelerates the low-carbon transition.

Scenario analysis using energy systems modelling tools can show how current decisions shape the future. However, out-of-ordinary extremes affect the future, such as unanticipated political decisions and unexpected energy requirements (Pilavachi *et al.,* 2008; Trutnevyte *et al.,* 2016), technological innovation, financial shocks, and weather events (McCollum *et al.,* 2020). The extremes can increase the deviation of the real-world development from the cost-optimal scenarios. The deviation can also be intensified by the ambitious mitigation target of limiting global temperature increase to 1.5°C envisaged in the Paris agreement. In other words, without considering the extremes, energy systems modelling is less likely to present a realistic picture of the future. This calls for strengthening the construction and application of energy models to produce cost-optimal energy scenarios under parametric uncertainties (Trutnevyte, 2016). To embrace the substantial future uncertainties that are inherent in the energy transition, scenario developers can explore them by using complementary off-model analyses (McCollum *et al.*, 2020), qualitative method (Gambhir, 2019), robust decision-making (Lempert *et al.*, 2006), and simulation approach (Schweizer and O'Neill, 2013) (see more details in (Trutnevyte, 2016; Yue, Pye, *et al.*, 2018)).

Last but not least, it is worth discussing the structure of the power sector market. The type of ownership of companies (public versus private) will significantly impact production costs and efficiency. Iran's Ministry of Energy (MOE) is responsible for the development and implementation of policies for, and the regulation of, electricity supply. Two main holding companies supervised by the MOE coordinate the design, installation, management, and operation of power system facilities. Iran's Ministry of Petroleum is responsible for supplying natural gas, and oil products. During the last two decades, the power sector has gradually been restructured. In fact, the privatisation and changes to the governmental monopoly model were officially started in the early 2000s (Nazemi and Mashayekhi, 2015; Yousefi *et al.*, 2017), and the private sector provided about 50% of total electricity generation at the end of this study period (MOE, 2017). It is important to note that almost all the large-scale power plants were built using public funds, and during this period Ministry of Oil fully subsidised all natural gas and liquid fuels consumed for power generation. In fact, the government does not charge the generators for fuel consumption but purchases electricity from independent producers. These producers bought the existing power plants, and they have not built new power plants using self-generated finance. Iran has also experienced sustained high inflation that has increased the payback period for investors. Inflation also increases the cost of living. To support low- and medium-income groups, the government has not increased electricity prices in proportion to inflation. Therefore, the amount of subsidies paid by the government increases over time, and the power sector demands more subsidies from the government to cover their non-fuel operation costs. The fiscal deficit is another outcome of this subsidy regime. As a consequence, the government cannot timely satisfy the producers. This results in the effective discouragement of investors who may wish to build new electricity generation, and the existing power plants are continuously dependent on fossil fuel subsidies. In brief, this mechanism totally distorts the market, increases inefficient consumption, and removes any potential for foreign investors to develop new infrastructure.

5.5.2 Limitations of the study

The current ex-post modelling has some limitations that need to be addressed in future studies. The presented system boundaries only consider electricity supply and demand, while interacting with other sectors can influence the results. Both energy systems and economic models could be extended to analyse the impacts of subsidy reforms in other sectors such as oil products consumption in the transport sector and the corresponding supply system from petroleum refineries. Future research can extend the time period of the current research to investigate the impacts of the COVID-19 pandemic on the energy system. The lack of spatio-temporal resolution also limits this study. The higher resolution can capture the variability of renewable energy sources and demand fluctuations (Collins *et al.,* 2017; Aryanpur *et al.,* 2021). Future research might explore to what extent a higher resolution changes the results. This investigation does not engage with the bi-directional causal relationship between electricity consumption and GDP. In future investigations, it might be useful to use the causal relationship between economic growth and electricity consumption (Chen *et al.,* 2007; Al-Mulali *et al.,* 2013; Abbasi *et al.,* 2021; Arčabić *et al.,* 2021).

Another area of future research would be to investigate how other policy measures such as carbon-pricing policy and subsidising the deployment of low-carbon technologies (Meckling et al., 2017) could decarbonise energy systems. This could help policymakers prioritise and then apply the most cost-effective measures for the future. Furthermore, the present study focused on electricity generation subsidies. However, the electricity supply system comprises transmission and distribution networks simplified in our analysis that needs to be considered. More research is required to better understand to what extent subsidy removal from those networks would change the results.

Finally, it is worth noting that savings that could have been made by removing subsidies may not be realistic due to the factors beyond the control of policymakers. As discussed in the previous section, there are several reasons why policymakers may not have been able to achieve the cost savings in the real-world transition, such as resource limitations, technological constraints, regulatory environment, and political dynamics. However, quantifying the realistic savings in these areas is challenging due to the lack of data and complex interactions. For instance, obtaining comprehensive and accurate information on resource limitations during the real-world energy system development is difficult, as can understanding the interactions between resource availability and technology costs. Given these challenges, quantifying the realistic savings that could have been achieved in the real-world transition may not be feasible within the scope of this study. It is important to note that future studies may be able to quantify realistic savings by considering a wider range of factors and using more comprehensive data. As a result, this area can be considered as an agenda for future research efforts.

5.6 Conclusions

Energy subsidies help encourage inefficient electricity generation and wasteful consumption. They also impose a substantial financial burden and environmental costs. This chapter quantifies techno-economic and environmental benefits that would have been achieved through the implementation of energy subsidy reforms. It provides evidence from ex-post Iran's power system modelling during the period 1984-2017. A time-varying econometric (state-space) model estimates electricity demand under different subsidy removal scenarios, and an energy systems optimisation model identifies the cost-optimal transition pathways. Although the proposed method is used for the case of Iran, it can be used to support subsidy reform policies in other countries. The modelled pathways were compared to the actual transition.

The results show that subsidy removal could have reduced the total cumulative electricity consumption by 22%. The reforms combined with a cost-optimal generation pathway would have saved \$69 billion and avoided 944 million tons of CO_2 emissions. This amount of emissions reduction is almost equivalent to 3 percent of total global emissions in 2020 (see (IEA, 2020a) for comparison). It shows the potential contribution of subsidy reforms in preventing global warming.

The findings show that the supply-side policies could reduce the emissions by 15% during the planning horizon. In contrast, the demand-side policies (i.e., subsidy removal in this study) could even further mitigate the cumulative emissions. Moreover, implementing the former policies requires more investment in capital-intensive technologies, whereas the latter could be achieved via the same level of investment that the government really expends. It can be concluded that demand-side policies meet a similar GHG mitigation goal in a more cost-effective way than supply-side ones.

According to this analysis, lower energy subsidies would have reduced electricity consumption. However, it is important to note that the implications of this reduction in consumption may vary depending on the context and specific circumstances of the population and industry. Reduced electricity consumption could lead to lower energy costs for consumers, which may increase their disposable income and potentially improve their overall well-being. It could also incentivise energy efficiency measures, such as investment in energy-saving technologies or behavioural changes, which could result in long-term cost savings and environmental benefits. Lower electricity consumption could also have negative impacts on certain industries that rely heavily on electricity for their operations. It could increase production costs, reduce competitiveness, and potentially result in job losses. It could also affect vulnerable populations who rely on electricity for basic needs, such as cooling and heating, and may face challenges in adjusting to lower energy consumption. Therefore, it is important to carefully assess and consider the potential implications of reduced electricity consumption resulting from lower energy subsidies on both the population and industry.

Finally, the delays in subsidy reform led to huge technical-economic and environmental costs. It is worth noting that the continuation of the current regime in subsidy payment leads to the formation of inappropriate consumption behaviour. Modifying this behaviour will be more complex over time so that long-term delay in subsidy reform can turn it from a socio-economic concern to a socio-political and security challenge. When social resistance to energy subsidy reforms is assessed to be small, a politically strong government can adopt rapid reform. Otherwise, gradual subsidy reform in line with well-targeted and transparent financial supports for protecting low-income groups is recommended.

6 How energy subsidy reform can drive the Iranian power sector towards a low-carbon future

Abstracts:

Substantial energy subsidies are recognised as the leading cause of Iran's inefficient electricity generation and consumption. This chapter investigates the impacts of subsidy removal on future electricity demand and the required generation mix. A hybrid modelling framework is developed to analyse supply and demand sides under harmonised assumptions. An autoregressive distributed lag (ARDL) model combined with an autoregressive integrated moving average (ARIMA) model forecast electricity demand under subsidy removal scenarios at different paces. A partial equilibrium energy systems model (MESSAGE) offers a cost-optimal configuration of power generation technologies to meet the forecasted demand during the period 2017-2050. The findings demonstrate that energy subsidy reforms can reduce total electricity demand by 16% and could ensure a 31% cut in cumulative CO_2 emissions. The scenario analysis also shows that under an early and steady reform scenario and with gradual removal, the development of renewable energy technologies and energy efficiency plans become cost-competitive. In contrast, the late and rapid subsidy removal path should tackle the lock-in effect's risk. This reveals that the early action in energy subsidy reform should be considered a priority over the removal speed. Finally, this research discusses the potential policy implications beyond Iran.

Keywords: Energy subsidy reform; Integrated energy-economy modelling; Power sector; Subsidy removal scenarios, Optimisation; Low-carbon future

6.1 Introduction

Energy subsidies are government interventions that serve to, in general, keep prices below the market rates (IEA, 2006; Cheon *et al.*, 2013). The primary goals of energy subsidies are to support industrial and rural development (Gangopadhyay *et al.*, 2005; Petkova and Stanek, 2013), assist domestic producers against international competitors (Lin and Jiang, 2011), and improve the security of energy supply (IEA, 2011; Schwanitz *et al.*, 2014). The global fossil fuel subsidy was about $320 billion in 2019 (IEA, 2019). This amount of energy subsidies puts financial pressure on the governments (Farajzadeh and Bakhshoodeh, 2015), reduces energy prices and encourages excessive consumption (Lin and Li, 2012; Rentschler and Bazilian, 2017), increases CO_2 emissions (Li and Sun, 2018), and decreases the competitiveness of investing in renewable energy technologies (Wesseh *et al.,* 2016).

According to the IEA (2021), Iran is one of the most extensive energy subsidy providers globally. Iran’s energy subsidies have fluctuated between $30-$137 billion during the last decade. This IEA estimation is based on a price-gap approach, and thus, this vast variation is mainly driven by the variation in fossil fuel prices in the international markets. Subsidies for electricity, Natural Gas (NG) and oil products are $12.5, $12.2, and $5.0 billion in 2020. This shows that the power sector has become Iran’s most significant energy subsidy flow component. The country has a high potential for renewable energy sources, especially solar and wind (Ghorbani *et al.,* 2020). Nevertheless, due to large-scale fossil energy subsidy schemes, the market equilibrium has been corrupted, and the development of energy efficiency plans and renewable energy technologies have remained uncompetitive. In this situation, incumbent fossil-fuel-based technologies dominate the electricity generation mix. This sector released over 170 million tons of carbon dioxide in 2017 (Aryanpur *et al.,* 2022). In addition, the low energy prices have caused low productivity in the industrial sectors, budget deficit and deviation in economic policies (Taiebnia and Barkhordari, 2022). As a result, the analysis of energy subsidy reform in a country with the highest subsidy flow is a crucial case study.

A considerable amount of literature has used top-down tools to simulate the economic impacts of energy subsidy removal. Socio-economic implications of energy subsidy reform have been analysed in China (Jiang *et al.,* 2015; Lin and Kuang, 2020), Argentina (Giuliano *et al.,* 2020), Ecuador (Schaffitzel *et al.,* 2020), Egypt (Breisinger *et al.,* 2019), Latin America and the Caribbean (Feng *et al.,* 2018), India (Acharya and Sadath, 2017), and Iran (Khalili Araghi and Barkhordari, 2012; Breton and Mirzapour, 2016). They indicate that energy subsidy reform usually causes a fall in GDP during the short-term period. However, reallocating a part of a subsidy revenue may increase overall welfare. Their findings also suggest a targeted subsidy scheme as an efficient way to support low- to medium-income families. The economic-wide analyses also show that subsidy removal would positively impact GDP (Timilsina and Pargal, 2020), improve efficiency and drive economic diversification (Shehabi, 2020). These studies have mainly focused on the demand-side and energy consumption. But, the supply-side has often been analysed in an aggregated fashion. It is because the traditional top-down economic models alone have many limitations for examining complex systems as they usually have a limited connection with the supply sectors (Monasterolo and Raberto, 2019).

Energy systems development can be analysed using bottom-up Energy Systems Optimisation Models (ESOMs). They can comprehensively represent the energy system from resources to end-use technologies and suggest cost-optimal capacity, generation and fuel mix to meet a given set of demands (Connolly *et al.,* 2010). Several attempts have applied ESOMs to explore the development of power generation technologies in Iran (Shafiei *et al.,* 2009; Manzoor *et al.,* 2014; Aryanpur and Shafiei, 2015; Ghorbani *et al.,* 2017, 2020; Atabaki and Aryanpur, 2018; Aryanpur *et al.,* 2019; Atabaki *et al.,* 2022). Yet, the demand-side projections in these studies are defined exogenously and based on historical trends or hypothetical scenarios. Hence, there is a lack of an integrated modelling approach that can address a broader picture of the energy-economic system. In addition, there is a consensus that energy subsidy reforms can reinforce economic development (Taiebnia and Barkhordari, 2022). But to the best of the authors' knowledge, no reliable evidence assesses the economic benefits of energy subsidy reform policies at different paces.

A few efforts have developed a hybrid modelling approach (bottom-up linked with top-down) to capture the interactions between the energy system and the rest of the economy. For example, the hybrid approach has been used to assess national energy and climate policies (Krook-Riekkola *et al.,* 2017), the environmental co-benefits (Yang *et al.,* 2021) and the economic impacts of low-carbon energy pathways (Taliotis *et al.,* 2020; Timilsina *et al.,* 2021). However, the impacts of subsidy removal have remained underexplored in this group of studies.

This research develops an integrated approach by linking a bottom-up ESOM to an economic model. The economic model predicts future electricity demand under various subsidy reform scenarios, and the energy model finds the optimal generation mix to meet the projected demand from 2017 to 2050. This chapter aims to (1) investigate how energy subsidy reform at different paces can impact electricity demand, generation mix, fuel consumption, and CO_2 emissions, (2) determine how delays in subsidy removal may affect capacity expansion and investment needs.

This chapter is organised as follows: first, the models and the hybrid modelling process are discussed. Then, the development of subsidy reform scenarios based on historical electricity price and supply costs is presented. The following section provides the required data and outlines how the model is developed, calibrated, and used for Iran's power sector. Subsequently, the main results and lessons learned from hybrid modelling are discussed.

6.2 Methodology

As shown in Figure 6-1, Auto-Regressive Integrated Moving Average (ARIMA) and Auto-Regressive Distributed Lag (ARDL) models are used for forecasting energy demand. These couple of models estimate electricity demand projections. An energy systems partial equilibrium, bottom-up engineering optimisation model is employed for electricity supply planning. It examines the power supply configuration during the study period. Energy prices play a central role in this analysis as they are used for scenario development. These scenarios are built based on eliminating energy subsidies at different paces and are the basis for running two models. The electricity demand function is endogenously estimated via reformed electricity price. The estimated demand under various subsidy removal scenarios is used as an input for the energy model. This model suggests an optimal generation mix. This linkage allows to simultaneously capture the impacts of subsidy reform in both supply and demand-side models and run them with harmonised assumptions.

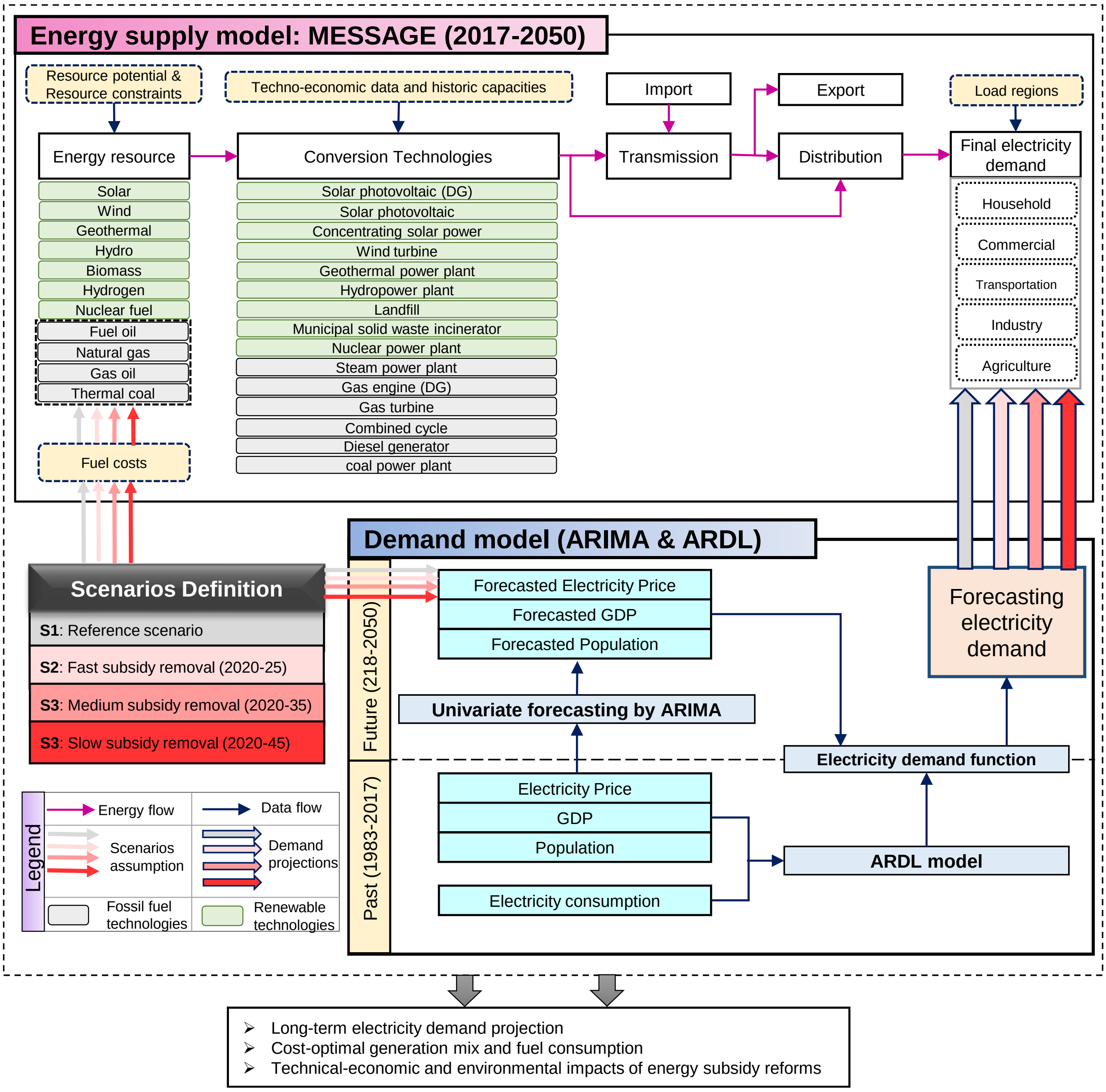

Figure 6-1. Methodology: an energy-economy modelling framework

6.2.1 Demand-side modelling: ARDL and ARIMA models

Energy demand forecasting models can be classified into three main groups (Adom and Bekoe, 2012; Suganthi and Samuel, 2012): extrapolation, bottom-up, and econometrics methods. Extrapolation is the simplest method and is appropriate for short-term forecasts. Bottom-up models employ end-use accounting methods and require significant data, and their application is usually challenging due to the limited data availability. Econometric models are based on consumer behaviour theory that is generally affected by electricity price and socio-economic pathways.

The main purpose of the demand-side modelling is to explore the effect of subsidy reform on future electricity demand. For this purpose, the ARDL model has been used as an econometric model to predict electricity demand, where a forecast of electricity demand is obtained. Estimating the long-run relationship between electricity demand and its determining factors is necessary, especially its own price. Therefore, the demand side is modelled in two steps. First, the factors influencing the electricity demand (explanatory variables) are identified, and the ARDL model estimates the demand function to know the data generation process (DGP). The DGP describes how each observation in electricity consumption was produced in the past (1983-2017). If we had known the DGP, we could have correctly forecasted the future of electricity consumption by explanatory variables. Thus, the ARIMA model forecasts the explanatory variables in the second step. Finally, the electricity consumption is obtained based on the predicted values of the explanatory variables during 2018-2050.

Electricity demand (ED_t) in this study is estimated based on demand theory and empirical studies (for details, see (Zachariadis, 2010; Adom and Bekoe, 2012; Arisoy and Ozturk, 2014; Kaytez, 2020)). As shown in equation (1), it is a function of the real electricity price (PE_t), real gross domestic production (GDP_t), and population (POP_t). All variables are expressed in natural logarithms and estimated coefficients indicate elasticities, where β_1, β_2, and β_3 represent price, income, and population elasticities, respectively.

$$lnED_t=\alpha + \beta_1 lnPE_t + \beta_2 lnGDP_t + \beta_3 lnPOP_t + \varepsilon_t \qquad (1)$$

The ARDL model is applied to estimate the elasticities and electricity demand function. One of the advantages of the ARDL is that it has consistent estimates of long-run coefficients regardless of the variables are stationary, I(0), or non-stationary, I(1) (Adom and Bekoe, 2012). Also, in this model, short- and long-run elasticities are estimated. The general equation of ARDL is as follows:

$$\Delta lnED_t = \alpha_0 + \sum_{i=1}^{p} \beta_{1i}\, \Delta lnED_{t-i} + \sum_{i=0}^{q1} \beta_{2i}\, \Delta lnPE_{t-i} + \sum_{i=0}^{q2} \beta_{3i}\, \Delta lnGDP_{t-i} + \sum_{i=0}^{q3} \beta_{4i}\, \Delta lnPOP_{t-i} + \varphi_1 lnED_{t-1} + \varphi_2 lnPE_{t-1} + \varphi_3 lnGDP_{t-1} + \varphi_4 lnPOP_{t-1} + e_t \qquad (2)$$

The first part of the equation with β_1 to β_4 presents the short-run coefficients of the model and the second part, including φ_1 to φ_4 represents the long-run coefficients. The optimal lag lengths (p,q1,q2,q3) are determined by information criteria such as AIC (Akaike Information Criterion) and SBC (Schwarzs Bayesian Criterion). The bound test is used to check the relationship between the dependent variable and a set of regressors (Pesaran *et al.*, 2001). The null-hypothesis of the bound test is H_0: $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = 0$. There will be a long-run relationship if null-hypothesis rejects (Ziramba, 2008). The ARDL model captures the DGP of electricity consumption by explanatory variables over the past three decades. Thus, the trend of future electricity consumption depends on the predicted values of the explanatory variables, which are predicted separately by the ARIMA model. In ARIMA modelling, time series must be either stationary or become stationary after one or more differencing (Bowden and Payne, 2008). The general equation of ARIMA (p, d, q) is as follows:

$$\Delta_d y_t = \mu + \sum_{i=1}^{p} \beta_i \Delta_d y_{t-i} + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} + \varepsilon_t \qquad (3)$$

Where, y_t indicates real gross domestic production (GDP_t), and population (POP_t), which are estimated separately in the form of equation 3. Here p, q and d indicate the order of the autoregressive part (AR), moving average part (MA), and the amount of differencing (Δ_d) to make it stationary, respectively. β_i and θ_i are the AR and MA coefficients, and μ is the constant term (Jamil, 2020). The optimal lag length of AR and MA are selected based on the AIC and SBC.

6.2.2 Supply-side modelling: MESSAGE model

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental impact) is a process-based linear optimisation model. The model was originally developed by the International Institute for Applied System Analysis (IIASA) during the last four decades (Huppmann *et al.,* 2019). The International Atomic Energy Agency (IAEA) added a user interface to facilitate its application (IAEA, 2013). This model is used for medium- to long-term energy planning, energy policy analysis, and scenario development (Messner and Strubegger, 1995). The model's principal basis is the minimisation of an objective function under a set of techno-economic constraints to meet the demand (Riahi and Roehrl, 2000). The objective function is the present value of total system costs during the planning horizon covering investment costs, non-fuel operation costs, fuel costs and any additional costs (such as energy imports and carbon tax) (IAEA, 2009). To calculate the present value, all costs are discounted to the base year of the case study. Various technologies and commodities are modelled at different levels depicting a Reference Energy System (RES) from primary sources to final or useful energy demand (Messner and Schrattenholzer, 2000; Huppmann *et al.*, 2019). As such, MESSAGE determines optimal energy mixes and investment needs to satisfy a given demand at the least cost (Horak *et al.*, 2021).

In this research, Iran's power system is modelled using MESSAGE. This system includes different levels, commodities, and technologies. The resource level incorporates fossil and non-fossil fuel energy resources currently used or have enough potential for commercial electricity generation in Iran. The conversion level includes fossil-based power plants, renewable technologies, and nuclear units. The base year is calibrated using existing power plants and actual fuel consumption (MOE, 2017; TAVANIR, 2020). Aggregated distribution and transmission networks connect power plants to several consumers. Power trades are modelled at the transmission level.

General data such as discount rate, planning horizon, and energy conversion units are defined to build the model. Then, the power sector supply structure, including energy levels (from resource to demand), energy carriers in each level, and different technologies are defined. Technologies are characterised by fuel input and output and their techno-economic characteristics. Next, annual demand (from the economic model) and their fluctuations are added. Finally, fuel share constraints, trades, renewable potentials, and operational constraints are captured. Furthermore, the base-year model results are compared with the actual official statistics to ensure that the model is well-calibrated. These basic steps construct a reference case, and the alternative scenarios are developed based on this case.

6.2.3 Scenario definition

Energy prices play a crucial role in determining energy demand. As shown in Figure 6-2, electricity subsidies in Iran have increased from 3.7 cents/kWh in 1983 to 6.2 cents/kWh in 2017. The average electricity consumption has increased 7% per year during the same period. Also, there is a significant gap between the average electricity price and the average supply cost. It can be said that the selling price is about 22% of the supply cost.

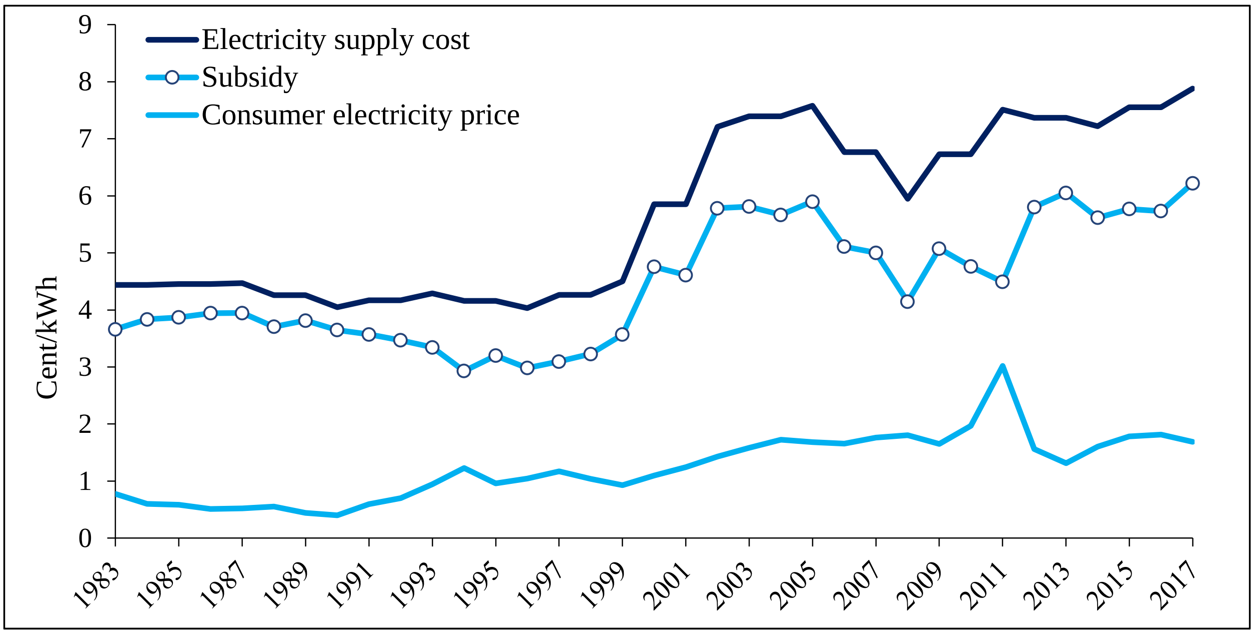

Figure 6-2. Historical price, electricity supply cost and subsidy level in Iran (MOE, 2017)

Subsidy removal is the critical parameter in scenario definition, impacting both models. In the economic model, the removal affects the electricity price, which, in turn, changes the electricity demand. In the energy model, subsidy reform affects the price of fossil fuels used for power generation. A reference case, as well as three alternative scenarios characterised by the different speeds in subsidy reforms, are as follows:

- **Reference:** This scenario represents a business-as-usual situation without subsidy reform. The energy subsidies are assumed to be the same as the base year and kept constant over the study period.
- **Fast subsidy removal:** It reflects a rapid subsidy removal condition starting from 2020, and then, over five years, the subsidy is linearly phased out so that electricity price reaches supply cost in 2025. In the supply model, fossil fuel subsidies are fully eliminated during the same period, and thus, the energy model uses unsubsidised fossil fuels (as in international markets) from 2025.
- **Medium subsidy removal:** Subsidies are moderately removed over 15 years.
- **Slow subsidy removal:** Subsidies are removed very mild over 25 years.

Similar to the previous chapter, in the Reference case, the optimisation of the supply side is carried out using ESOM without incorporating a soft-link with the demand model. However, in the removal scenarios, the soft-link approach is utilised. Finally, four sensitivity cases are defined to explore the implications of delays in the implementation of subsidy reform. The subsidy removal postpones by 5 to 20 years to compare early versus late actions. For instance, SR2025 shows a subsidy removal plan starting from 2025, and then, over five years, the subsidy is removed so that electricity price reaches supply cost in 2030. Table 6-1 summarises the assumptions of the main scenarios and sensitivity cases.

Table 6-1. Subsidy removal in different scenarios

<table>
<tr><td>Category</td><td>Focus</td><td>Scenario name</td><td>Removal period
(Start year-end year)</td><td>Removal duration</td></tr>
<tr><td rowspan="4">Main scenarios</td><td rowspan="4">Speed of removal</td><td>Reference</td><td>Without subsidy reform</td><td>NA</td></tr>
<tr><td>Fast removal</td><td>2020-25</td><td>5</td></tr>
<tr><td>Medium removal</td><td>2020-35</td><td>15</td></tr>
<tr><td>Slow removal</td><td>2020-45</td><td>25</td></tr>
<tr><td rowspan="4">Sensitivity cases</td><td rowspan="4">Early and late actions</td><td>SR2025</td><td>2025-30</td><td rowspan="4">5</td></tr>
<tr><td>SR2030</td><td>2030-35</td></tr>
<tr><td>SR2035</td><td>2035-40</td></tr>
<tr><td>SR2040</td><td>2040-45</td></tr>
</table>

6.3 Data

6.3.1 Demand-side

As shown in Table 6-2, historical electricity consumption has increased almost ten times from 1983 to 2017, while the price of electricity, GDP, and population has nearly doubled. The Augmented Dickey-Fuller (ADF) test shows that all variables are non-stationary at levels. The first difference of variables is stationary, which implies that the variables are integrated of order one, I(1). Therefore, it is necessary to use the first difference of the variables in the ARIMA model.

Table 6-2. Descriptive statistics of variables and unit root tests, 1983-2017 (CBI, 2021; MOE, 2017)

Variable	Mean	Max	Min	Average growth rate per year	Ratio 2017/1983	ADF test
ED (TWh)	110	255	25	7%	10.1	I(1)
PE (cent/kWh)	1.2	3.1	0.4	2%	2.2	I(1)
GDP (billion $)	356	561	193	2%	2.3	I(1)
POP (million people)	63.9	81.1	44.1	3%	1.8	I(1)

6.3.2 Supply-side

The fossil-based power plants and hydropower units account for 83% and 15% of the total installed capacity, respectively. The rest is mainly from nuclear and variable renewable energy sources. The total installed capacity increased sevenfold from 11 GW in 1983 to 79 GW in 2017. Fossil fuel-fired power generation is from three sources in 2017 (TAVANIR, 2020): NG (84.8%), gas oil (8.3%), and fuel oil (6.9%). The proportion of NG to oil products has gradually risen (Manzoor and Aryanpur, 2017); however gas turbines and steam power plants use liquid fuels for power generation in cold seasons (Kachoee *et al.,* 2018). In line with the electricity consumption growth, fossil fuel consumption has increased, and CO_2 emissions soared (Vahid Aryanpur and Shafiei, 2015). The average yearly growth rate of CO_2 emissions is 6% in this period, and the total emissions of power generation activities reached 171 million tons in 2017 (2.12 tons CO_2/capita).

This study's time horizon is from 2017 to 2050 (33 years) with a 3-year step and six 5-year time steps. Therefore, the model is calibrated for 2017, and the 2020 results are compared with the actual statistics. The comparison helps to modify the deviations and better adjust the operational parameters. Previous studies show that for the economic assessment of power sector projects in Iran, a discount rate of 10% is appropriate (Aryanpur and Shafiei, 2015a). Table 6-3 lists the international prices of fuels during the planning period. Based on historical information, NG has the highest share (at least 75%) among the fuels used by power plants (Manzoor and Aryanpur, 2017). The techno-economic specification of power generation units relies on actual data (such as capacity factors for solar and wind) for the current technologies and the best available alternatives. Table 6-6 displays these data for representative technologies.

The predicted electricity demand by the economic model is one of the inputs of the MESSAGE model. Electricity demand also fluctuates per year. MESSAGE simulates these fluctuations based on load regions (Fairuz *et al.,* 2013). In this study, 36 sub-annual load regions are considered, including 12 months, a typical day, and each day involves three hourly base, medium, and peak loads (see the details in Table 6-5).

Table 6-3. Fuel prices in the base year and their annual growth rate (OPEC, 2017; IEA, 2020b)

Fuel (unit)	Price	Average annual growth rate (%) [a]
Fuel oil (cent/lit)	28.7	2.5
Natural gas (cent/m^3)	21.9	3.3
Gas oil (cent/lit)	40.5	3.3
Thermal coal ($/ton)	47.6	1.0

[a] Based on the growth of fuel price in the reference scenario of the World Energy Model (IEA, 2020b). It is assumed that oil products price growth follows crude oil price growth.

Table 6-4. Techno-economic information of power generation technologies (Tsiropoulos et al., 2018; IEA, 2020b)

Technology	Fossil fuel input	Investment cost ($/kW)[b]	Fixed cost ($/kW)[b]	Variable cost (S/kWyr)	Efficiency (%)[c]	Capacity factor (%)	Plant life (Years)	Construction time (Years)
Solar photovoltaic	-	1243-611	49-32	-	-	20	25	1
Solar photovoltaic (DG[a])	-	1510-744	49-32	-	-	18	20	0.5
Concentrating solar power	-	5860-2431	64	-	-	40	30	2
Wind turbine	-	1500-1077	48-40	-	-	30	20	1
Geothermal	-	4100-3440	84-70	-	-	80	30	6
Small hydropower	-	2000	14	-	-	40	50	3
Large hydropower	-	1500	10.8	-	-	20	50	8
Pumped Storage	-	2000	14	-	80	80	50	7
Landfill	-	2352-1655	20-17	130	-	80	20	2
Municipal solid waste incinerator	-	5570-3918	557-275	-	-	80	20	3
Nuclear power plant	-	5000	69	4	33	85	40	7
Steam power plant	NG, Fuel oil	900	9	4	41.2	76	30	5
Steam power plant (conventional)	NG, Fuel oil	-	9	4	37	76	30	5
Gas engine (DG)	NG	800	8	44	41-45	80	10	1
Gas turbine	NG, Gas oil	550	4.4	5.6	34.7-38.9	70	12	2
Gas turbine (conventional)	NG, Gas oil	-	4.5	5.57	29.5	69	12	2
Combined cycle	NG, Gas oil	760	4	4	49	73	30	5
Combined cycle (conventional)	NG, Gas oil	-	5	3.6	44.7	73	30	5
Diesel generator	Gas oil	550	8	38	33	75	10	2
Coal power plant	Coal	1600	64	-	35	85	30	5
Advanced coal power plant	Coal	2169-1696	64	-	46	85	40	5
Electricity transmission	-	-	-	71.25	96.3-97.5	-	-	-
Electricity distribution	-	-	-	66.89	86-92	-	-	-

[a] DG stands for distributed generation and is a power plant directly connected to the consumers.
[b] Left values represent investment cost and fixed cost in the base year, and the right values are expected for 2050.
[c] Left values represent the base year efficiencies, and the right ones are for 2050.

Table 6-5. Load regions within a year (TAVANIR, 2015)

	Base	Peak	Medium
January	0.024	0.014	0.035
February	0.024	0.014	0.035
March	0.023	0.013	0.034
April	0.023	0.010	0.036
May	0.024	0.011	0.045
June	0.025	0.030	0.040
July	0.028	0.035	0.046
August	0.028	0.039	0.041
September	0.027	0.037	0.039
October	0.030	0.015	0.036
November	0.023	0.013	0.034
December	0.024	0.014	0.034

6.4 Results and discussion

6.4.1 The effects of subsidy removal on power demand

Table 6-6 indicates the results of the ARDL model. All the estimated coefficients show the expected signs and are statistically significant. Moreover, both income and population positively affect electricity demand, while the real price of electricity has the opposite effect. Also, there is a long-run relationship among variables, and the electricity demand is more elastic in the long-run than in the short-run. The price elasticity indicates that a 10% increase in electricity price leads to a 0.2% and 0.9% fall in electricity demand in the short-run and long-run, respectively. To confirm the goodness of fit in the ARDL model, diagnostic tests examine the serial correlation as well as heteroscedasticity associated with the model. As a result, 99% of the variations in the electricity demand are explained by the electricity prices, income and population.

As mentioned before, to predict electricity consumption, the future value of the explanatory variables (PE, GDP, POP) has been forecasted by applying ARIMA to each of the series. As shown in Table 6-7, the ARIMA forecasting equation for the variables is formulated by first-order difference because stationarity is necessary for ARIMA modelling. Finally, the forecasted values of the explanatory variables are embedded in the electricity demand function and predict the electricity consumption.

Table 6-6. Long- and short-run elasticities of electricity demand by ARDL Model

Variables	Long-run	Short-run
Price elasticity	-0.09	-0.02
	(-1.71) *	(-1.63) *
Income elasticity	0.62	0.18
	(7.63) ***	(6.68) ***
Population elasticity	2.77	1.65
	(14.69) ***	(1.59) *
Error correction term	--	-0.29
		(-7.34) ***
Adjusted R-squared	0.99	
Serial correlation test	0.58 (prob= 0.56)	
Heteroscedasticity test	1.46 (prob= 0.22)	
Bound test	F-stat= 28.74	
	F[I(0)]= 2.37	F[(I(1)]= 3.2

Numbers in parentheses represent t-statistic, and symbols *** and * indicate the level of significance of 1% and 10%, respectively.

Table 6-7. Forecasting equations for the variables

Variables	*Model*	*Forecasting Equation*
Forecasting explanatory variables		
LnGDP	ARIMA (0,1,1)	$dLnGDP_t = 0.03+0.41\ \varepsilon_{t-1} \Rightarrow LnGDP_t^f = LnGDP_{t-1} \times (1 + dLnGDP_t)$
LnPOP	ARIMA (1,1,0)	$dLnPOP_t = 0.02+0.94\ \mathrm{dLPOP}_{t-1} \Rightarrow LnPOP_t^f = LnPOP_{t-1} \times (1 + dLnPOP_t)$
LnPE	Variable Scenario	$LnPE_t^f = Ln[Cost_{t-1} - SR(i)],\ i =$ Reference, Fast, Medium and Slow.
Forecasting dependent variable		
LnED	ARDL (1,0,0,1)	$LnED_t^f = - 8.32 + 0.70\ LnED_{t-1}^f - 0.02\ LnPE_t^f + 0.18\ LnGDP_t^f + 1.65\ LnPOP_t^f - 0.83\ LnPOP_{t-1}^f$

SR(i) shows the difference between the electricity generation cost (Cost) and the selling price under different subsidy removal scenarios.

Indeed, the electricity demand function (ARDL model) shows that electricity consumption is a function of consumption habits (first lag of electricity consumption), real electricity price, GDP, population, and first lag of population. Because these explanatory variables have been able to explain 99% of the electricity consumption pattern in Iran over the past three decades, it is assumed that the future trend of electricity consumption (2018-2050) will follow this pattern. Therefore, the accuracy of electricity consumption forecasting depends on the prediction values of the explanatory variables. Based on the results of the ARIMA as shown in Figure 6-3, the average annual growth rate of real GDP (economic growth) and population are predicted to be about 2.9% and 0.8%, respectively[1]. It is worth mentioning that the main purpose of the demand-side modelling in this study is to predict the long-term trend of variables, and it does not consider the short-term fluctuations. However, as touched upon in the previous section, the supply-side model captures demand variability and inflexibility by analysing hourly electricity consumption during recent years.

[1] According to the statistical research centre (Fathi, 2020), Iran's annual population growth rate is predicted to be 0.75% in 2016-2050. The average long-term GDP and GDP per capita growth rate over the period 2025-2050 is estimated at 3.1% and 2.9% per year (Pwc, 2017).

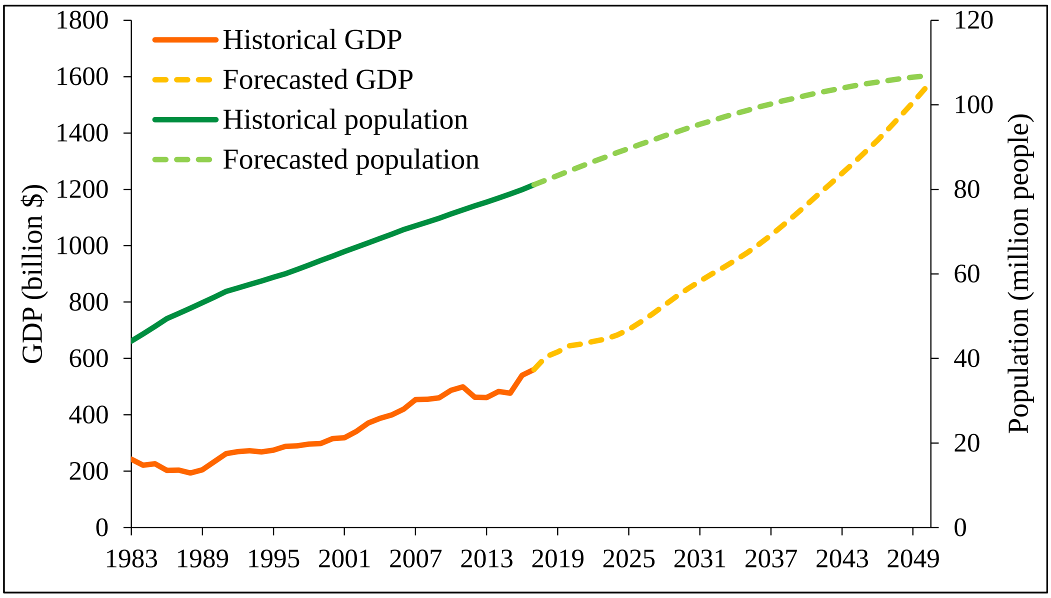

Figure 6-3. Historical and forecasted GDP and population (Historical from CBI, 2021)

As illustrated in Figure 6-4, the projected electricity demand in the alternative scenarios diverges from the beginning of the planning period because the electricity price varies between scenarios during the subsidy reform period. Of course, an overlap is observed towards the end of the study period. As shown in Figure 6-2, the level of subsidy is assumed to be constant throughout the planning horizon, so that after subsidy elimination, electricity prices reach generation costs and equalise across all scenarios. Consequently, all the explanatory variables (electricity prices, GDP, and population) are the same after the elimination of subsidies, and electricity demand converges.

As shown in Table 6-7, the electricity demand equation is a linear first-order difference equation because it contains a lagged dependent variable as an explanatory variable. In this equation, the coefficient of lagged electricity consumption (φ) captures the impact of past consumption on current consumption. As a result, a positive and significant coefficient is consistent with the hypothesis that electricity consumption is a habit. Also, this coefficient plays a key role in examining the consequences of explanatory variables such as electricity price, GDP and population on electricity consumption. In fact, the responses of electricity consumption to variations in explanatory variables such as electricity prices are dependent on the coefficient of lagged values of electricity consumption. When the absolute value of this coefficient is smaller than one, the consequences of a given change in explanatory variables will eventually die out and decays geometrically toward zero. Since in the estimated demand function, the coefficient of lagged electricity consumption is smaller than one ($\varphi = 0.7$), so the impact of price changes caused by subsidy reforms on future electricity consumption will decrease geometrically and the values of electricity consumption converge at the end the periods for all scenarios[1]. Economic models show that by maintaining the current level of energy subsidy flow in the Reference scenario, the electricity demand will be almost fourfold by 2050 and grows at an average rate of 4.2% per annum. The power demand in previous studies is projected to annually grow by 6.0% (Shafiei *et al.*, 2009a, 2009b), 3.8% (Shafiei *et al.*, 2014; Atabaki and Aryanpur, 2018), 3.0% (Aryanpur and Shafiei, 2015a), 2.6% (Ghorbani *et al.*, 2020) and 2.3% (Tavana *et al.*, 2019). This range is mainly driven by different socio-economic assumptions, extrapolation based on short-term growth rates and average international growth rates in previous studies.

The final electricity demand in the alternative scenarios is 19.8% lower than the Reference case in 2050. Furthermore, the cumulative electricity demand will reach 19415 TWh in the Reference scenario. Nevertheless, the rapid removal in the Fast scenario can reduce the cumulative demand by 16%, and the average annual growth rate will reach 3.5%. The decelerated subsidy removal in the Medium and Slow scenarios may increase the cumulative consumption by 2%.

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[1] As shown in Table 6-7 electricity demand function is $LnED_t^f$ = - 8.32 + 0.7 $LnED_{t-1}^f$ -0.02 $LnPE_t^f$ + 0.18 $LnGDP_t^f$ + 1.65 $LnPOP_t^f$ -0.83 $LnPOP_{t-1}^f$. The following equation is a simplified representation of the demand function and w_t incorporates the effects of all the input variables:

$LnED_t^f = \varphi LnED_{t-1}^f + w_t$

Where $\varphi = 0.7$ *and* $w_t =$ -8.32-0.02$LnPE_t^f$+0.18$LnGDP_t^f$+1.65$LnPOP_t^f$-0.83$LnPOP_{t-1}^f$. By solving the difference equation, the value that $LnED_t^f$ takes on at period t can be described as a function of its initial value ($LnED_0^f$) and the history of w between 0 and period t:

$LnED_t^f = \varphi^{t+1} LnED_0^f + \varphi^t w_0 + \varphi^{t-1} w_1 + \varphi^{t-2} w_2 + \cdots + \varphi w_{t-1} + w_t$

It should be noted that the calculations would be exactly the same if the simulation were started at date t; then the electricity consumption for the j[th] future value ($LnED_{t+j}^f$) could be described below:

$LnED_{t+j}^f = \varphi^{j+1} LnED_0^f + \varphi^j w_t + \varphi^{j-1} w_{t+1} + \varphi^{j-2} w_{t+2} + \cdots + \varphi w_{t+j-1} + w_{t+j}$

Thus, the effect of w_t on $LnED_{t+j}^f$ is given by $\frac{\partial LnED_{t+j}^f}{\partial w_t} = \varphi^j$

So, if $|\varphi| < 1$, the system is stable; the consequences of a given change in w_t (like $LnPE_t^f$) will eventually die out and decays geometrically toward zero. Now, the effect of electricity price at period t on the future value of electricity consumption is given by $\frac{\partial LnED_{t+j}^f}{\partial LnPE_t^f} = \frac{\partial LnED_{t+j}^f}{\partial w_t} \times \frac{\partial w_t}{\partial LnPE_t^f}$ = -0.02 (0.7)^j.

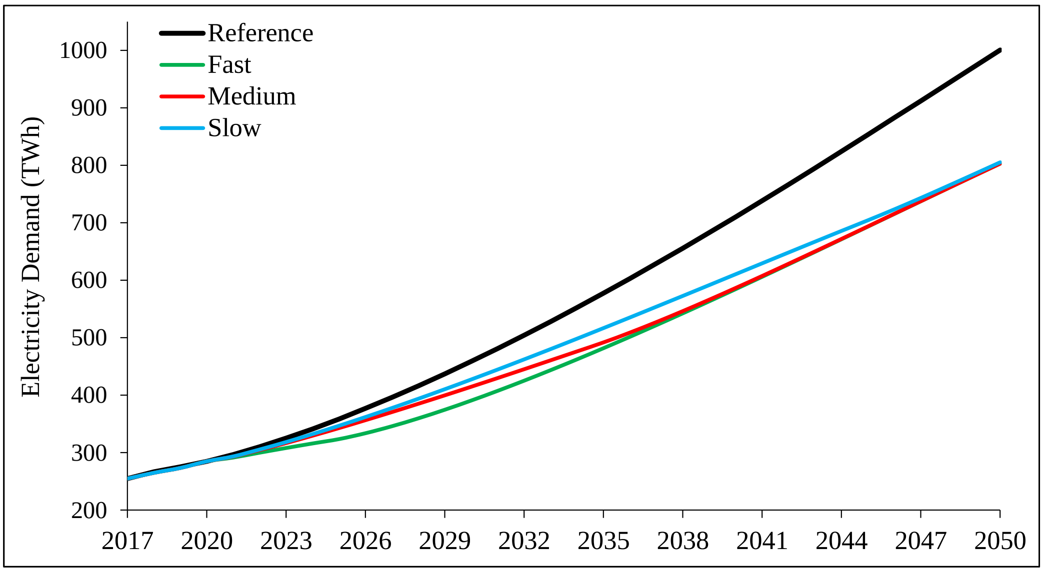

Figure 6-4. Forecasted electricity demand in different scenarios

6.4.2 The effects of subsidy removal on the generation mix

Figure 6-5 depicts the electricity generation mix in two main scenarios. Total power generation in 2020 is 338 TWh and the actual generation in the same year is about 343 TWh (lower than a 1.5% deviation). This limited divergence between the model results and the real world transition shows that the model has been properly calibrated. In the Reference case, the generation gradually increases at an average annual growth rate of 4.0%. Combined cycle units dominate the mix. However, fast to respond gas turbines and hydropower units are offered to meet the load changes. On the other hand, the average growth rate of generation will reach 3.3% per annum in the Fast removal scenario. With subsidy removal, highly efficient combined cycle power plants still play a pivotal role. Electricity generation from solar photovoltaics, concentrating solar power, and wind power plants will be significant in this scenario. At the end of the planning horizon, renewables produce 2.5% of the total electricity in the Reference case, while 48.5% comes from renewables in the Fast removal one. This substantial difference is because the fossil fuel subsidies reduce the total generation costs of fossil-based power plants. As a result, the removal policy radically increases the competitiveness of investing in renewable energy sources. In other words, in the Fast subsidy removal scenario, the operational costs of fossil-fired power generation soar due to higher fuel costs. Consequently, the model offers more efficient technologies, and the development of renewable energy sources radically increases to cut the reliance on fossil fuels.

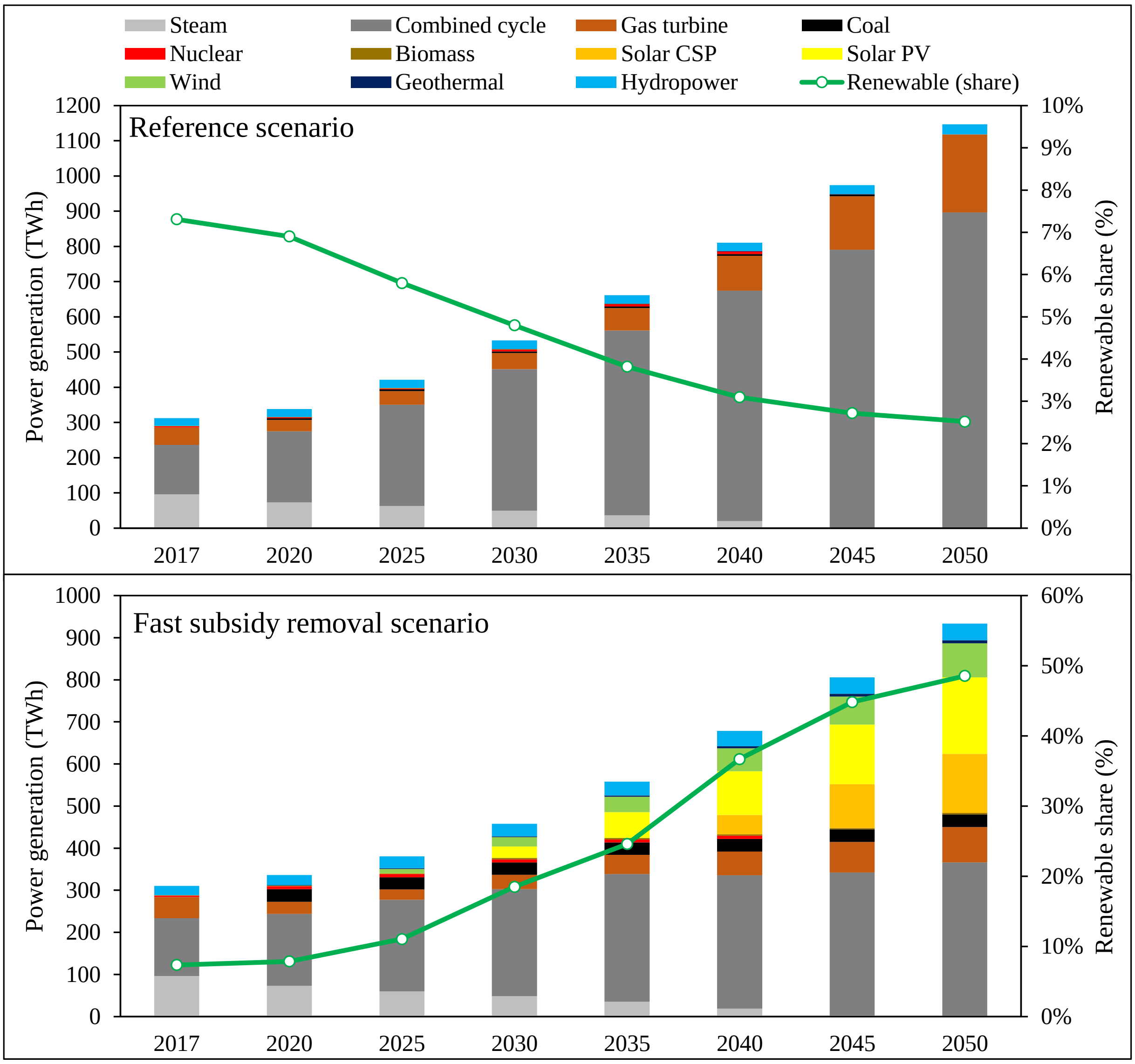

Figure 6-5. Electricity generation mix and renewable share in the Reference and Fast removal scenarios

Figure 6-6 shows how the current installed capacity evolves from medium to long-term. Power capacity grows at an annual rate of 3.7% in the Reference case. Despite the lower demand in the Fast removal scenario, this rate reaches 4.4%. The difference stems from the development of renewable power plants. They have a lower capacity factor than fossil-based technologies (compare 18-40% for variable renewable energy sources with 70-85% for fossil-fired). The model does not offer steam power plants in both scenarios; however, the gas turbine's capacity has increased compared to the existing capacity. As discussed in (Aryanpur and Shafiei, 2015a), they are suggested to meet the peak load demand. Moreover, In the Reference case, combined cycle power plants dominate total installed capacity, while solar panels overtake within the Fast removal scenario.

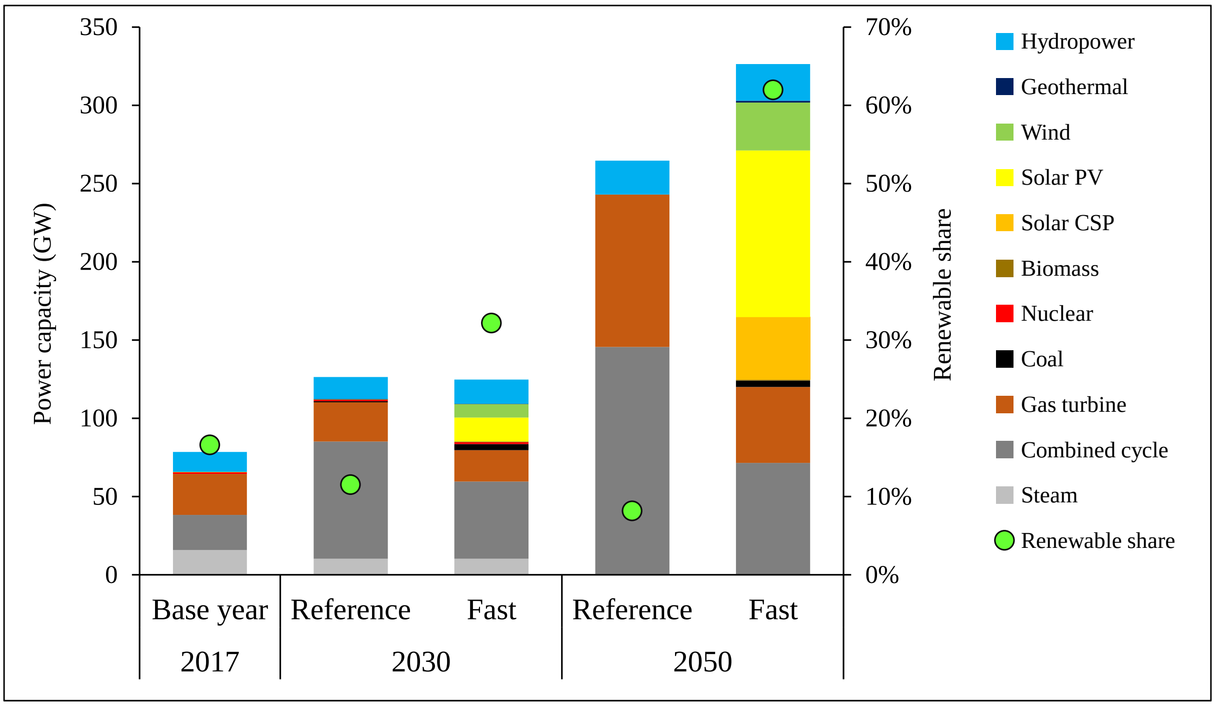

Figure 6-6. Total installed capacity and renewable share in the Reference and Fast scenarios

As shown in Figure 6-7, the cumulative fuel consumption has reached 157 EJ in the Reference case. Accelerated subsidy removal could cut this level of fuel consumption by one-third. The average annual growth rate of fuel consumption is 3.6% in the Reference case, while it reaches 1.0% in the Fast removal scenario. NG dominates fuel consumption in all scenarios. In the best condition, eliminating subsidies could reduce 40% and 8% of cumulative NG and liquid fuels consumption, respectively. The NG saving equals around 33 to 48 billion cubic metres per year (bcm/yr). Due to the lower electricity demand, total fuel consumption for power generation has declined in the alternative scenarios by 22-34%.

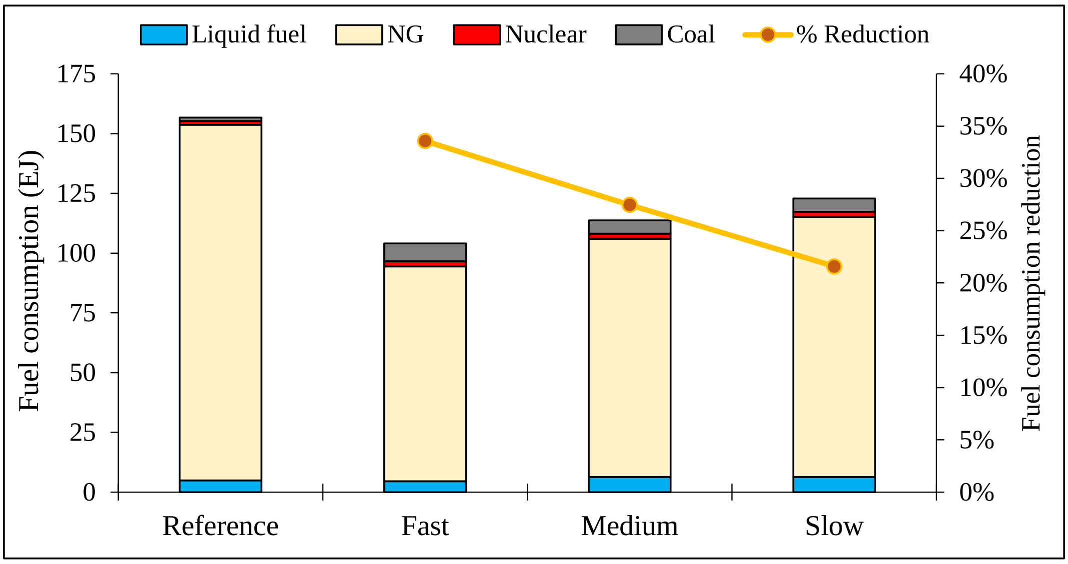

Figure 6-7. Cumulative fuel consumption from 2017 to 2050 in different scenarios

As shown in Figure 6-8, total costs consist of investment costs for building new capacities and operating costs. The investment costs are the product of newly installed capacities in each period (offered by the MESSAGE model during the planning period) and the related investment costs. The operating costs are mainly from fossil fuel consumption and are calculated based on the fuel costs. To estimate the non-fuel operating costs, the generation mix in each year is extracted from the energy model and then multiplied by the fixed and variable costs of different power plants.

Fuel consumption accounts for between 69% and 88% of the total costs across different scenarios. Therefore, the total system costs are noticeably affected by fuel costs. The share of investment cost is between 10% to 23%, and the rest is from non-fuel operation & maintenance costs. Compared to the Reference case, Slow and Fast subsidy removal can reduce the total costs by about 18% to 25%. The main reason for these reductions is lower electricity demand in the removal cases. Consequently, lower installed capacity and lower fuel are required to meet the demand. However, total investments are triggered in the subsidy removal scenarios by the substantial deployment of more capital-intensive renewable energy technologies.

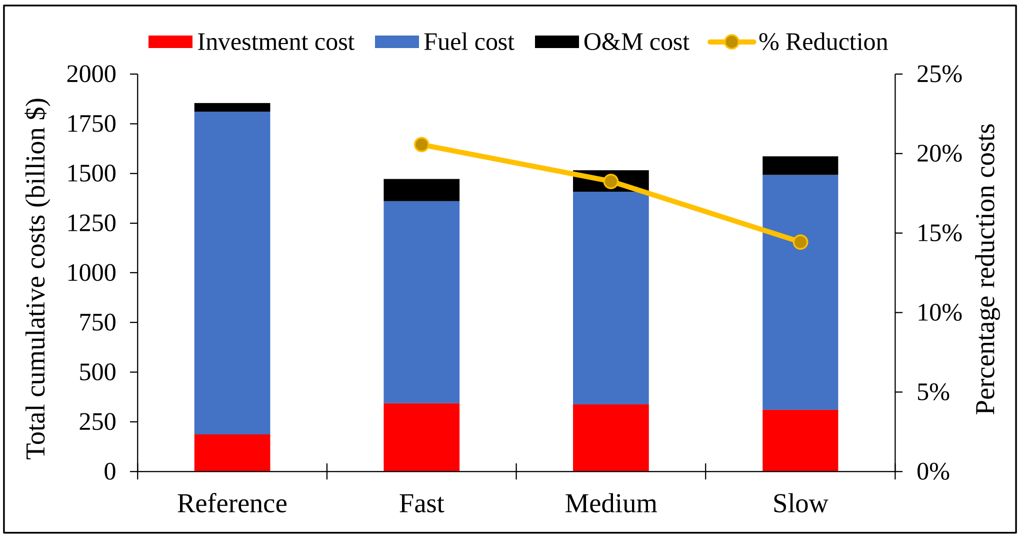

Figure 6-8. Total costs of electricity generation in different scenarios

6.4.3 Environmental effects

The cumulative carbon emissions in different scenarios are shown in Figure 6-9. In the Reference scenario, CO_2 emissions have reached 8.9 Gt. It is almost equal to one-fourth of the total global emissions (IEA, 2021c). In the Fast scenario, the rapid elimination of subsidies would reduce the emissions by 31% compared to the Reference case. The diffusion of renewables and lower electricity demand drive this reduction. As illustrated, even a very mild subsidy removal over 25 years (i.e., the Slow scenario) can significantly reduce CO_2 emissions because the cost-optimal solution does not necessarily offer the development of renewable energy sources after full removal in 25 years. This reveals that renewable energy sources become cost-competitive under partial subsidy removal.

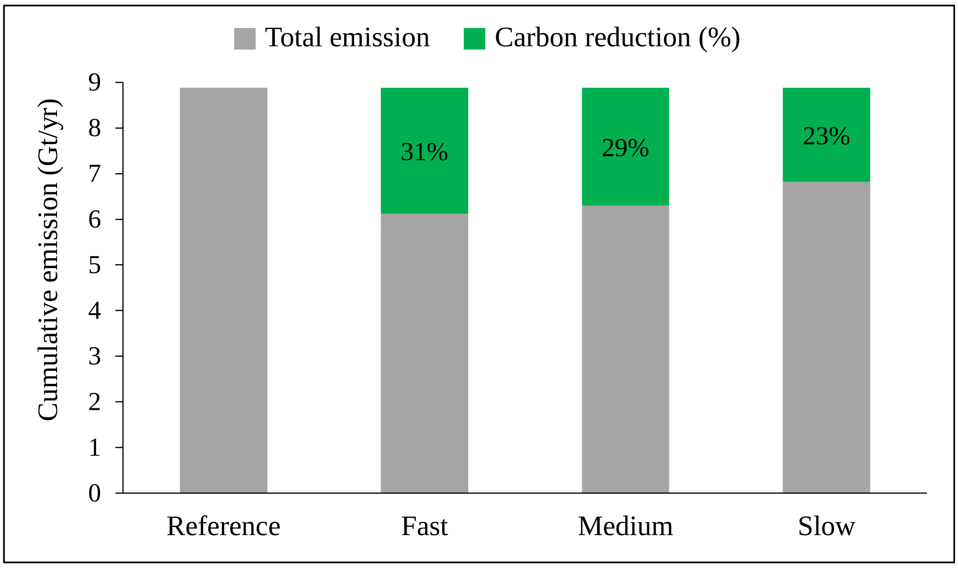

Figure 6-9. Total CO_2 emissions in different scenarios

6.4.4 Sensitivity analysis

This section conducts a sensitivity analysis to explore how early and late subsidy removal can impact the main results. The effect is investigated by delaying the Fast reform pattern by 5-20 years. Figure 6-10 demonstrates cumulative reduction compared to the Reference case. As previously displayed in Figure 6-4, the system rapidly reacts to subsidy removal. When the removal postpones by five years (SR2025: removal starts in 2025 instead of 2020), the power system tends to develop less efficient conventional technologies during the delayed period to meet the demand that consistently increases and replace the retired capacities. This situation will expand the conventional technologies. On the other hand, the lifetime of these technologies is usually more than two decades, and the government often commits to purchasing their generation over the long term. Therefore, the consequences of a five-year delay in subsidy removal will remain for at least two decades. This analysis helps understand the "lock-in effect" given by the existing power generation infrastructure. Every five-year delay in eliminating the subsidy will emit about 300 million tons more CO_2. It is equal to 10% of the total EU emissions in 2021 (IEA, 2021b). It highlights the urgency of subsidy removal, especially for implementing decarbonisation policies.

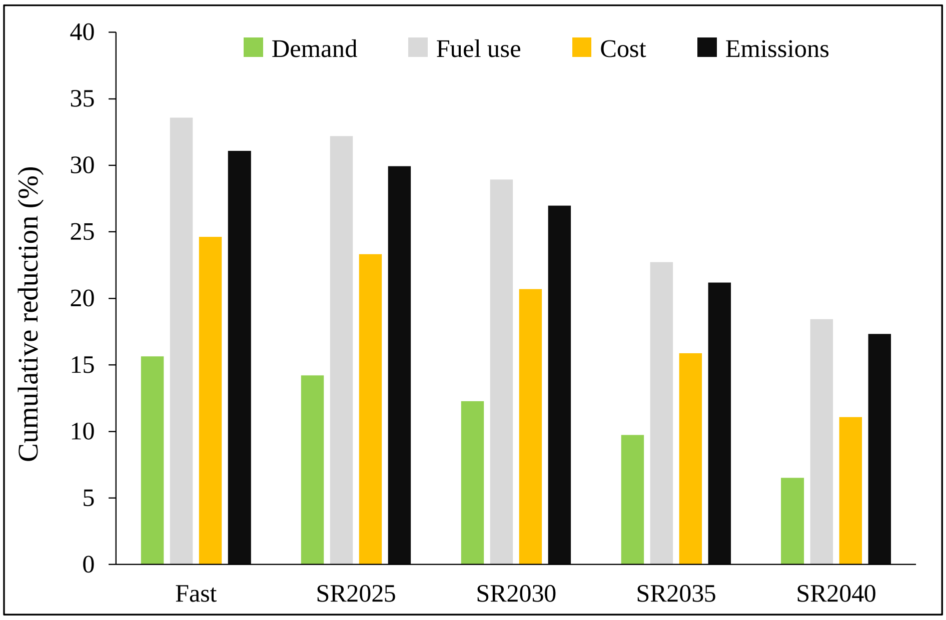

Figure 6-10. The cumulative reduction compared to the Reference scenario

6.4.5 Potential impacts beyond Iran

This section analyses the benefits of fossil fuel subsidy reform beyond Iran and explores potential impacts on global energy security and the interactions with climate change. The coincidence of rising energy demand in the post-COVID period and constrained supplies has unprecedentedly triggered energy security concerns (Khan, 2022). In this condition, an energy exporter country can play a critical role in alleviating the global energy crisis (Yergin, 2006). Iran, as the holder of the second-largest NG reserves after Russia (BP, 2021), is expected to be a central player in the global gas market. As shown, NG is the main source of power generation in Iran and subsidy reform policies could reduce domestic consumption well above 30 bcm/yr. It is equal to the potential capacities that the EU can import from non-Russian gas sources, including the global LNG market, increased production inside the EU, and pipeline imports from Norway and Azerbaijan (IEA, 2022). On the other hand, a tight gas market could negatively affect global gas demand and shift the gas-importer countries towards more emission-intensive domestic energy carriers such as coal and oil products. This would postpone clean and sustainable energy transition and threaten climate goals.

6.4.6 Lessons learned and modelling limitations

This section discusses lessons learned and the challenges of the hybrid modelling approach in this study.

First, demand projection in a stand-alone modelling framework is often from official references (see, e.g., Ghorbani *et al.,* (2020), Aryanpur and Shafei (2015)), and thus, the assessment of the underlying demand assumptions is generally difficult (Krook-Riekkola *et al.,* 2017). But a hybrid modelling framework in the present analysis allows us to run both energy and economic models with consistent and harmonised assumptions. The consistency not only provides a more transparent scenario analysis but also facilitates the understanding of the critical drivers of the results. For example, the current research shows to what extent and how energy prices can impact total electricity demand and the generation mix to meet the demand. However, answering those questions from previous exercises based on a single modelling approach is challenging. Therefore, the hybrid modelling explicitly captures the energy demand evolution while addressing cost-optimal technology configuration and confidently informing the decision-making process.

Second, the results of the hybrid modelling under subsidy removal scenarios show that, the total investment costs are expected to be almost double compared to the reference case. As expected, the availability of sufficient and timely investment plays a crucial role in the transition from fossil fuel to a renewable-based energy system. On the other hand, an ex-post analysis (Aryanpur *et al.,* 2022) introduces insufficient financial resources as one of the barriers to energy transition in Iran. As a result, the required capital costs from the energy model would dramatically change investment flows or might not be feasible in the future. The availability of financial resources was not addressed during this exercise and needs further investigations.

Last, one of the challenges in this hybrid modelling is the calculation of subsidy level during the planning horizon. The initial subsidy level is carefully estimated based on the difference between the average generation costs in the base year and consumers' actual price. However, the future generation cost depends on the future generation mix that has not happened yet. The energy model can estimate the future generation cost. On the other hand, running the energy model depends on the inputs from the economic model, and thus, both models are dependent on inputs from each other. The base year subsidy level is extrapolated to the future to avoid the dependency issue in the present analysis. Our method would be improved through an iteration and convergence procedure, starting from the economic model. Adding a stop parameter as used in Fortes et al. (2013, 2014) will be required to cease the iteration.

6.5 Conclusions and policy implications

Significant energy subsidies are recognised as one of the major reasons for Iran's inefficient consumption. In addition, the development of energy efficiency plans and renewable energy technologies has remained uncompetitive. This article examines the impacts of subsidy removal on electricity demand and the required generation mix. An economic model predicts electricity demand, and a bottom-up energy systems model offers the optimal configuration of the power sector from 2017 to 2050. The hybrid modelling approach allows us to perform the analysis with harmonised assumptions both for supply and demand. The economic model has richer information on the whole economy, and the energy model is characterised by its technology richness. This hybrid modelling explicitly captures the evolution of energy demand while addressing cost-optimal technology configuration and informing the decision-making process more reliable. Multiple scenarios investigate how subsidy removal speed can impact power demand and supply. The findings are as follows:

- From an energy systems perspective, this study demonstrates that subsidy removal can reduce electricity demand by 16%. The electricity demand decline and the uptake of renewable energy technologies could ensure a 31% cut in CO_2 emissions over the projected period. Moreover, the cumulative total electricity system costs would decrease by about \$480 billion. These results show that policymakers can see energy subsidy reforms as a fiscal relief measure and an opportunity to reduce CO_2 emissions. Even though there is no obligation to implement subsidy reforms in the Paris Agreement on climate change, the reforms appear as a prerequisite for designing national climate policies.

- Finding the optimal rate of energy subsidy removal can be a controversial question for policymakers. However, scenario and sensitivity analyses in the present study reveal that the urgency of energy subsidy reform is more important than the removal speed to achieve long-term decarbonisation targets. It is because, under the early and steady path (even with gradual subsidy removal), the development of renewable energy technologies and energy efficiency plans become cost-competitive. In other words, partial subsidy reform would be adequate to enhance their economic competitiveness. Furthermore, gradual early removal can avoid the lock-in effect. In contrast, the late and rapid subsidy removal path should tackle the lock-in effect's risk over a couple of decades. Last but not least, gradual and early subsidy removal can prevent the political economy challenges of subsidy reform.
- This analysis also shows how efficiencies from energy subsidy reforms can support the UN's sustainable development goals. These efficiencies could deliver significant natural gas to a gas-constrained world and thus would enhance access to secure and affordable energy supplies (SDG7). Furthermore, a secure international gas market can prevent shifting from natural gas to more emission-intensive domestic energy sources. This can help to achieve climate goals (SDG13).

The article illustrates several areas of possible further research. One potential area would be to investigate efficiency improvements of end-use technologies to fulfil the aspirations for a low-carbon economy. Further research could examine how the resulting savings from energy subsidy reforms can be used for public investment and may improve economic growth. Moreover, the demand-side findings of this research are subject to at least three limitations. First, explanatory variables, i.e. GDP, population, and electricity price, are assumed to follow their past trends in the future. Second, electricity demand's price and income elasticities have been kept constant over time. Third, a uni-directional causal relationship between GDP and electricity consumption has been used. Future investigations might analyse the impact of time-varying assumptions and bi-directional causal relationships. The lack of spatio-temporal resolution limits the current study. It would be interesting to address demand fluctuations and the intermittency of renewable energy sources through higher resolution (Collins *et al.*, 2017; Aryanpur *et al.*, 2021). Finally, the future costs are a source of uncertainty that can impact optimal long-term investments in the present research. A future study might investigate the uncertainties associated with fuel and investment costs.

7 Iran's potential impact on global energy security under subsidy reform policies

Abstracts:

Despite having huge gas and oil reserves, Iran is no longer a key player in the international energy markets. We show how synergies and efficiencies from Iran's energy subsidy reforms and lifting its sanctions could enhance global energy security, with a focus on natural gas.

7.1 Introduction

Global energy markets have experienced significant volatility during the post-COVID-19 pandemic economic recovery, and this has been amplified by the recent Russian invasion into –Ukraine, which has sent gas and oil prices to record high levels in many parts of the world (Khan, 2022). The coincidence of rising demand, constrained supplies, and supply interruptions from the conflict has dramatically triggered energy security concerns and in response, the European Union has committed to phasing reliance on Russian energy before 2030. Experience shows that supply diversification is a crucial element in maintaining energy security (Yergin, 2006), and in this context, the International Energy Agency (IEA) estimates that non-Russian gas sources can offset Russian imports into the EU by an additional 30 billion cubic metres per year (bcm/yr). This additional supply comprises a combination of greater access to the global LNG market, increased production inside the EU and larger pipeline imports from Norway and Azerbaijan (IEA, 2022). This estimated additional 30 bcm/yr accounts for one-sixth of the EU gas imports from Russia in 2020 (BP, 2021). While the EU also plans to accelerate energy efficiency and renewable energy supply, they will also need to find further gas suppliers from other regions in order to completely phase out dependence on Russian imports.

Iran holds the world's second-largest natural gas proved reserves (17% of total) (BP, 2021) and is expected to be a central player in the global gas market. Despite the enormous hydrocarbon resources, two key circumstances currently impede the country from actively contributing to the global market: firstly, substantial domestic natural gas consumption and secondly economic sanctions. The first is mainly due to domestic policies within Iran that subsidise fossil fuel consumption and discourage both efficient energy consumption and renewable energy deployment (Moshiri, 2015; Barkhordar *et al.*, 2018). The second disconnects the country from international trades and blocks foreign investment that can help the development of modern energy infrastructures. As a result, removing domestic subsidies and international sanctions would allow Iran to contribute again into the global gas market. This return could improve the worldwide supply of natural gas.

7.2 Method and scenarios

This analysis investigates the synergies that can arise from changes to domestic Iranian energy policies and to successful international negotiations. It draws on a body of research into Iran's domestic energy policies (Shafiei *et al.,* 2014; Aryanpur and Shafiei, 2015a; Aryanpur *et al.,* 2017, 2019; Aryanpur *et al.,* 2022), where an integrated system-wide energy modelling framework was developed and applied to assess different aspects of Iran's energy supply and demand. Figure 7-1 shows how energy modelling results are used to estimate increased gas export potentials across different scenarios.

Iran is deemed to be the most extensive energy subsidy provider globally. The heavy subsidies are acknowledged as the leading cause of Iran's inefficient energy consumption (Aryanpur *et al.,* 2022). An analysis drawing from five Integrated Assessment Models (IAMs) confirms that removing fossil fuel subsidies in energy-exporting regions would encourage energy efficiency plans and substantially decrease their overall consumption and GHG emissions (Jewell *et al.,* 2018). Thus, we assess the demand-side growth in gas consumption with and without the energy subsidy removal under two scenarios:

- Business as Usual (BAU): The existing energy subsidies are kept; consumer behaviours and technology levels remain unchanged (average growth rate of 3.5%/yr (Shafiei *et al.,* 2014))
- Energy Subsidy Removal (ESR): Energy subsidies are phased out; the growth rate of energy demand is reduced (average growth rate of 2.1%/yr (Shafiei *et al.*, 2014; Aryanpur *et al.*, 2022)), and the development of renewable energy supply becomes cost-competitive. In this scenario, non-fossil fuel technologies are anticipated to supply well above half of the total electricity generation over the next decades (Saeid Atabaki, Mohammadi and Aryanpur, 2022).

The energy modelling exercises produce cost-optimal energy system evolution pathways that also consider supply which is constrained due to economic sanctions. After the United States' withdrawal from the Joint Comprehensive Plan of Action (JCPOA) (also known as the nuclear deal) in 2018, Iran lost access to international markets. This led to delays in upstream energy activities due to a lack of investment (Jalilvand, 2018) in a manner that has limited pipeline export to neighbouring countries after the withdrawal. As a result, we also assess the supply-side under two different scenarios:

- Sanctions remain: The sanctions remain, and the maximum growth rate of natural gas production equals the production level growth during the sanction period (i.e. 3.6%/yr during 2018-2020 (MOE, 2022)).
- Relaxed sanctions: Sanctions are lifted, and the development of natural gas production fields is accelerated through infrastructure investment and modern offshore gas production technologies (using pre-sanction rates of 8.2%/yr from 2015 to 2017 (MOE, 2022)). In other words, the supply-side development would be improved due to lifting sanctions. This improvement is because of sufficient and timely financial resources and the possibility of collaborations with drilling and LNG producer companies.

The combined impact of supply-side and demand-side factors results in four distinct scenarios that serve as inputs for the comprehensive energy system analysis. These factors encompass the implementation of subsidy removal or retention in the demand-side module, as detailed in Chapter 5. Projections for final energy demand are estimated under scenarios with and without subsidy reform. Additionally, simulations are conducted to assess the potential of gas extraction from onshore and offshore reservoirs to meet domestic demand. The availability of financial resources and modern offshore gas production technologies are crucial inputs for controlling gas production pathways. Finally, the maximum gas export potential in this study is determined as the difference between maximum gas production and consumption. These scenarios and simulations form a comprehensive framework for evaluating the impacts of subsidy reform on the energy system, considering both supply-side and demand-side dynamics.

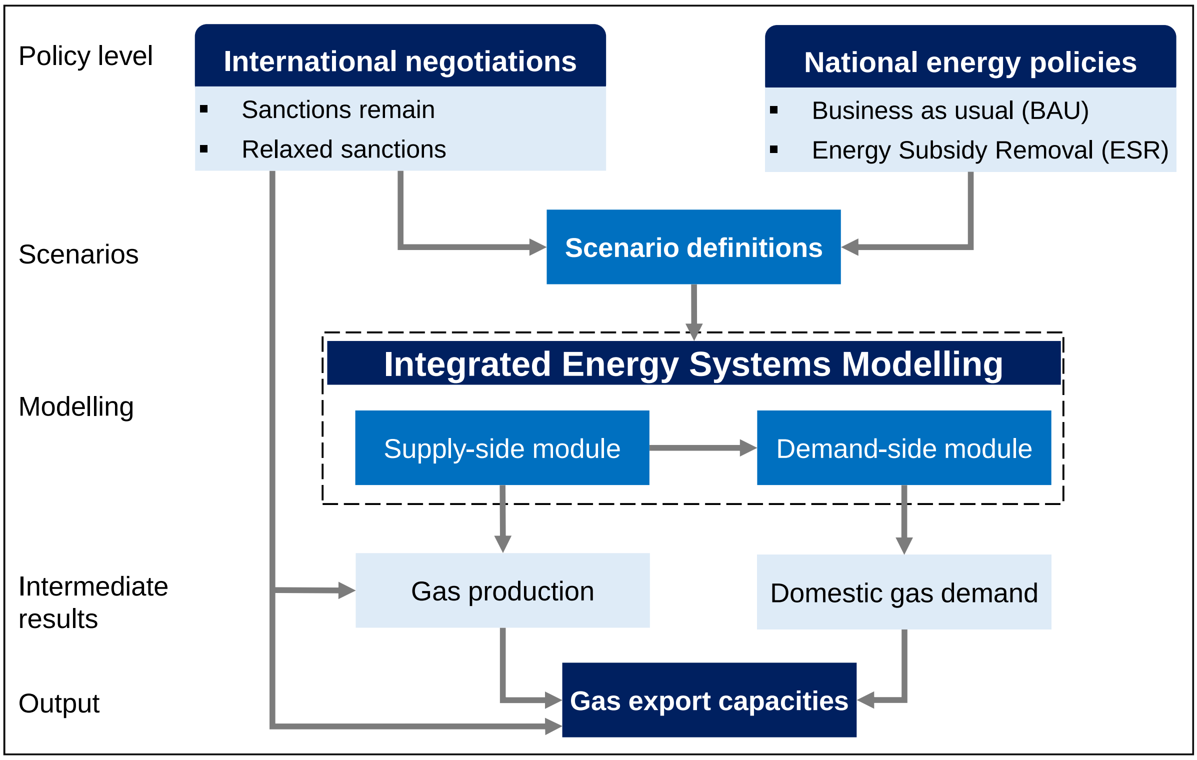

Figure 7-1. Flowchart depicting the approach to calculate gas export capacities under various national and international policies

7.3 Opportunities for global energy security

Taking into account the present limitations of export infrastructure, the potential impact of removing sanctions on global energy security needs to be analysed in different timeframes. In the short-term, the increase in gas exports may be limited due to the existing export infrastructure constraints. However, in the medium-term, there may be potential for higher gas exports as Iran develops its domestic gas production capacities.

Figure 7-2 illustrates the variations in total gas export potential under different scenarios, including the combined impact of energy subsidy reform and relaxed economic sanctions (ESR+Relaxed sanctions). This scenario shows that gas exports from Iran could reach 90 bcm/yr by 2026, but then decline to over 70 bcm/yr by 2030 due to reaching maximum production capacity and increasing domestic gas demand. The export potential associated with domestic energy subsidy reform alone also grows steadily over the period, reaching over 50 bcm/yr by 2030, even in the absence of relaxed economic sanctions (ERS+Sanctions remain). On the other hand, relaxing economic sanctions in the absence of energy subsidy reform (BAU+Relaxed Sanctions) may result in a more rapid initial increase in gas exports (reaching 65 bcm/yr by 2026), but followed by a reduction (to 24 bcm/yr by 2030) due to increased domestic gas consumption limiting additional exports. If there are no changes in energy subsidy reform or economic sanctions (BAU+Sanctions), the gas export capacity is not expected to exceed 5 bcm/yr. In sum, while there are limitations in export infrastructure in the short-term, the medium-term prospects for increased gas exports from Iran are influenced by various factors, including energy subsidy reform, economic sanctions, and domestic gas production capacity.

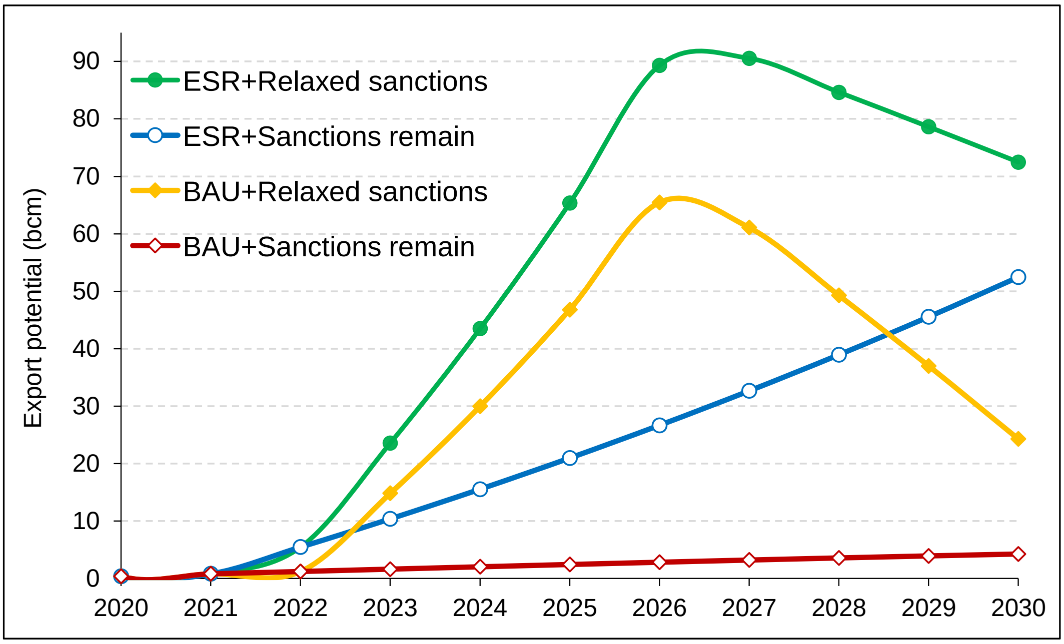

Figure 7-2. Potential of natural gas export under different scenarios

One of the critical questions is how in practice could Iran step up as a significant gas exporter? One option would be for Iran to export gas via existing active pipelines to Turkey and Iraq, up to 21 bcm/yr (Aryanpur *et al.*, 2017). However, due to consistent growth in domestic consumption and restricted upstream development after reimposing sanctions, Iran could only utilise a limited part of its capacity. These two countries have imported over 25 bcm of LNG in 2020 (BP, 2021). Iran could also expand exports to Pakistan by pipeline already in place near the borderline. Pakistan imported around 11 bcm LNG in 2020 (BP, 2021). In this way, Iran could indirectly reduce the demand for the global LNG market by about 32 bcm/yr via pipeline export to these three neighbouring countries. This amount is equal to the total potential that the IEA estimated for gas supply from non-Russian sources to the EU.

The modelling results also reveal that Iran would have 50-70 bcm of additional gas to export under the subsidy reform scenarios over the long-term. LNG facilities could be developed after lifting sanctions, and therefore, Iranian gas could also be contributing directly to the LNG market from 2024-25. This means that the global market could be further supported by 40 bcm extra gas from the mid-2020s, which is quite significant from an international perspective. Following the EU's decision to phase out Russian gas imports, the EU Member States will negotiate with LNG exporters. The US has committed to supplying the EU with an additional 15 bcm LNG in 2022, including cooperation with international partners (The White House, 2022). However, analysis of the significant LNG-importing regions (mainly East Asian countries) demonstrates that even diverting 20 bcm away from these regions will be extremely challenging (Corbea, 2022) for the following reasons: China has consistently increased LNG import by 10-20 bcm/yr since 2015. Korea and Japan would need to replace gas with coal and nuclear, which seems unlikely. In addition, Qatar's LNG capacity has been locked into long-term contracts with Asian customers. A reduction of Latin American LNG imports would also seem highly uncertain. It depends on multiple factors: resolving gas production problems in Argentina, precipitation in Brazil and US pipeline gas export to Mexico. These shreds of evidence from exporting and importing gas regions indicate that Iran, with 40 bcm of new gas supply potential, could significantly impact the global LNG market in a positive way.

It is also worth noting that Iran's climate conditions result in seasonal variations in domestic gas demand. While the fluctuations pose a severe supply challenge in winter, the global energy market might benefit more during the summer months. Iran can further increase gas export potential via managing gas injection to oil fields (21-32 bcm/yr during the last decade (MOE, 2021)) and utilising underground reservoirs (8 bcm capacity (MOE, 2021)). These can provide a sufficient buffer for the international gas market and reinforce national gas supply security through the heating season.

Energy subsidy reforms could release $30 billion of Iran's national budget that may then be used in more productive sectors of the economy. Furthermore, gas export income could reach about $27 billion (assuming a price of $15/MMBtu and an annual 50 bcm export capacity). It is important to consider of course, that subsidy reform can unduly penalise economic sectors and vulnerable populations (OECD/IEA, 2019). Several technical and empirical studies reveal that redistribution of a part of the revenue from the reform program among disadvantaged and low-income families is required to help shield them from price volatility and to improve overall welfare (Farajzadeh and Bakhshoodeh, 2015; Breton and Mirzapour, 2016). It is worth mentioning also that a prolonged high gas price is not necessarily beneficial for exporters. This can result in many countries replacing gas with coal and oil products or at least delaying LNG imports when the spot prices stay above $20/MMBtu (Siow, 2022). This in turn, could negatively affect a substantial amount of global gas demand and may shift the gas-importer countries towards more emission-intensive domestic energy carriers. This heavy reliance on domestic energy sources can be translated into an ambitious energy independence target. Findings of five global energy-economic models show that achieving ambitious climate targets would indeed reduce energy imports. The corollary is not true however: ambitious policies constraining energy imports would result in insignificant advantages for climate mitigation (Jewell *et al.*, 2016).

7.4 Conclusion

We showed here that Iran could deliver significant additional gas supplies to a gas constrained world, by up to 80 bcm/yr through both pipeline infrastructure and in the form of LNG. These amounts would enhance access to secure and affordable energy supplies, both regionally and globally. However, the opportunities could only be realised through a combination of national energy policy reforms and cross border cooperation in a favourable international environment.

Iran’s onshore natural gas fields have been developed extensively during the last decades; however, many offshore gas fields have remained untapped due to various reasons. Firstly, the complex and costly nature of offshore drilling and production technologies has hindered the development of Iran’s offshore gas reserves. Secondly, economic sanctions have limited access to advanced technologies, financing, and foreign investment. Thirdly, the lack of foreign investment and financing has prevented the country’s ability to develop and expand its natural gas production capacity, including offshore fields and LNG infrastructures. As a result, lifting of economic sanctions could potentially unlock opportunities for foreign investment, advanced technologies, and collaboration with international partners, leading to increased natural gas production in Iran.

8 Conclusions and future perspectives

This thesis aims to improve the robustness of models that inform national energy policy makers in achieving decarbonisation pathways, particularly in the transport and power sectors. Several priorities that need to be developed to improve the realism associated with model dynamics have been highlighted in previous research (Pye *et al.*, 2020; DeCarolis *et al.*, 2017). The present work investigates some critical priorities, including spatial resolution, significance of model skill, heterogeneity of consumers. It also presents potential impacts of mitigation policies on air quality and energy security. These priorities and policy insights are addressed through seven research questions (RQ1-7). In this chapter, the questions are answered, key modelling and policy insights are highlighted, and perspectives for future research are presented.

8.1 Answers to the research questions

RQ1: *When, how, and to what extent does higher spatial resolution impact the results of energy systems modelling?*

The significance of spatial resolution for energy system analysis has recently increased, and it is expected to be a crucial part of energy modelling (Martínez-Gordón *et al.*, 2021). Chapter 2 critically reviews 36 multi-regional ESOMs from 22 countries. The review discloses that finer spatial resolution in ESOMs offers significant added value for regions with heterogeneous renewable potential (see, Miranda *et al.*, 2019; Simoes *et al.*, 2017) or across regions with higher variability in energy service demands (Jalil-Vega and Hawkes, 2018). However, in homogeneous areas, aggregated single-region modelling is more efficient. In other word, heterogeneous regions either in terms of weather-driven variability or higher variability in energy service demands across regions require more disaggregation.

Furthermore, spatially resolved models can significantly change the results of the scenarios with very high shares of variable renewable energies. But it is not straightforward to find a direct relationship between the level of geographic disaggregation and penetration of renewable energies. This trade-off should be explored case-by-case. Total system costs can be under- or over-estimated in various levels of spatial resolutions. Disaggregation of renewable resources leads to lower costs, and disaggregation of transmission grids leads to higher costs.

To show the impact of higher spatial resolution in transport sector, the development of a multi-regional transport sector within TIM was described in Part B. Chapter 3 of this part also reveals that the total number of EVs and their electricity consumption in a single-region TIM is lower than in a multi-region one. This difference is mainly driven by the average values that are used to calibrate a single-region model, while region-specific modelling can better capture spatial heterogeneities. In our case, multi-region case suggests 15-32% more electrified LDVs. Additionally, Chapter 4 estimates that cumulative economic co-benefits of mitigation actions in the multi-region case is 36% more than the single-region one. This difference is mainly driven by the average marginal damage costs. It is since the single-region model hides the higher damage costs in medium and large cities and thus, underestimates total benefits.

RQ2: ***How does heterogeneity in potential car buyers with different income level (variations in consumers' ability to pay higher up-front costs) impact the penetration of EVs?***

The concept of heterogeneity replaces the traditional view of a mean representative agent by taking into account that consumer groups have different preferences toward adopting new vehicles (Venturini *et al.,* 2019; Mccollum *et al.,* 2017). Chapter 3 uses a flexible model with two degrees of consumer aggregation: 1. Homogenous car buyers with identical affordability (ignore variation), 2. Five groups of consumers with different income levels represent the heterogeneity of consumer decisions. The findings show that the model offers fewer EVs in a homogenous case than the heterogeneous one. This difference is mainly driven by the average values used to capture consumer decisions in purchasing new vehicles. In a model with identical consumers, car buyers with higher income rates are aggregated with low-income buyers. It can decrease the attractiveness of EV adoption in high-income families that would otherwise be purchased in the heterogeneous model. In fact, the averaging process hides the tendency of high-income consumers to purchase EVs.

RQ3: ***How can a hybrid energy-economy modelling method with harmonised assumptions improve energy systems analysis?***

Consistent and harmonised assumptions provide a more transparent scenario analysis and facilitate understanding of the results' critical drivers. Hybrid modelling in Chapters 5 and 6 that energy subsidy removal can reduce electricity demand by 16% over a long-term period. Then, the generation mix is endogenously adjusted to meet the modified demand. The findings demonstrate that the removal could ensure about a 20% reduction in total costs. However, answering those questions using a stand-alone modelling framework and exogenous assumptions is significantly uncertain (Krook-Riekkola *et al.,* 2017). The hybrid approach explicitly captures the energy demand evolution while addressing cost-optimal technology configuration. Consequently, hybrid modelling can be used to deal with uncertainty and inform the decision-making process more confidently.

RQ4: ***What potential outcomes could have been realised through the implementation of subsidy reform policies?***

Chapter 5 applies an ex-post modelling exercise to minimise parametric uncertainties around fuel and technology costs and their availabilities. This chapter highlights the significance of the model's ability to accurately and reliably predict energy system behaviour, such as energy demand, supply, and transition pathways, in comparison to actual observed outcomes. The model is run with three decades of historical data and compared with the real-world transition. Due to a myopic planning strategy, the real transition does not account for full lifecycle costs. But a long-term cost-optimal scenario with actual data shows 27% less cumulative costs over three decades than the real development. When the ex-post energy model is linked to an economic model to capture the price-induced demand response, the reduction in cumulative costs could be almost doubled (about 50% less cumulative costs). These results show that the imperfect knowledge of ESOM input values can significantly change the results. The findings highlight that modellers must critically address the uncertainties to know how they can affect the insights and avoid misleading conclusions.

RQ5: ***To what extent can different policy measures support the decarbonisation of LDVs?***

Chapter 3 explores how different monetary (i.e., purchase grant, lower rate of annual motor tax and carbon tax) and non-monetary (i.e., LDV improvements, modal shift, biofuel obligation and occupancy rate) measures can contribute to meeting ambitious mitigation targets. The evidence reveals that subsidy schemes (grants) do impact on EV adoption rate; however, they would not individually be an effective policy to reduce emissions. Multiple scenarios and sensitivity analyses suggest that shift and improve strategies can contribute to about 12% and 14% emissions reduction, respectively. Adding carbon tax may reduce emissions by further 5%. Thus, they together contribute to 31% of total reduction. To meet the decarbonisation target, heavy reliance on EV uptake will be required. It means that the government should keep generous EV incentives until the mid-2020s. Another theoretical option is 80% increase in the the average occupancy rate of private cars which is unlikely to happen. These additional measures demonstrate that the targets reflected in the climate action plans are quite ambitious. The current study's findings support other research results by Daly and O'Gallachoir (2012) and Gaur *et al.* (2022) that without demand-side strategies (i.e., limiting the level of private-car-based mobility), the mitigation goals appear to be unachievable in the Irish transport sector.

RQ6: ***What are the co-benefits of decarbonisation policies on air pollution levels?***

The evidence for climate policy co-benefits is often overlooked in policy-making (Karlsson *et al.* 2020). Chapter 4 estimates the ancillary pollution benefits of the mitigation policies in Ireland. It predominately quantifies the co-impacts of mitigation actions on air pollution levels for PM and NOx. The findings demonstrate that the net-zero emission pathway is accompanied by significant reductions in local air pollutants (85% to 93% in populated areas). This reduction can compensate between 2% to 89% of total mitigation investment costs during the study period. Likewise, Kelly *et al.* (2017) have reported the same trend for NOx reduction and total net-benefits in Ireland. By contrast, PM emissions differ between the previous and the current work. The difference is largely driven by greater use of biomass in earlier study, while the present research depends on renewable-based power generation system.

RQ7: ***How synergies and efficiencies from Iran's energy subsidy reform can assist in decarbonising the power sector? What are the potential impacts on energy security?***

Fossil fuel subsidies incentivise inefficient fuel consumption and impede the transition towards a sustainable energy system (Rentschler and Bazilian, 2017). For instance, a global study estimates that fossil fuel subsidy removal may diminish carbon emissions by 6.4% until 2050 (Schwanitz *et al.,* 2014). Substantial energy subsidies are recognised as the leading cause of Iran's inefficient electricity generation and consumption. Chapter 6 of this thesis demonstrates that energy subsidy reforms could ensure a 31% cut in cumulative CO_2 emissions until 2050 from Iran's power sector. The scenario analysis also shows that under an early and steady reform scenario and with gradual removal, the development of renewable energy technologies and energy efficiency plans become cost-competitive. In contrast, the late and rapid subsidy removal path should tackle the lock-in effect's risk. Finding the optimal rate of energy subsidy removal can be a controversial question for policymakers. However, scenario and sensitivity analyses in this chapter reveal that the urgency of energy subsidy reform is more important than the removal speed to achieve long-term decarbonisation targets. In other words, the early action in energy subsidy reform should be considered a priority over the removal speed.

A further analysis beyond Iran in Chapter 7 shows that fossil fuel subsidy reform could promote energy security and support climate change mitigation on a global scale. Subsidy reforms could reduce domestic consumption well above 30 bcm/yr in Iran. It is equal to the potential capacities the EU can import from non-Russian gas sources. Iran can export gas via existing pipelines to neighbouring countries and reduce the pressure on the global LNG market, thus improving global energy security and helping stabilise the gas price. On the other hand, a tight gas market could negatively affect global gas demand and shift the gas-importer countries towards more emission-intensive domestic energy carriers, which in turn, would postpone clean and sustainable energy transition and threaten climate goals.

In sum, this thesis provides two key takeaways for energy modelling communities and decision-makers. First, energy modellers should improve ESOM analysis to provide valuable insights for designing and implementing effective energy policies. Second, policymakers must accelerate the clean energy transition to protect energy systems against future volatility, reducing CO_2 emissions and local air pollution while mitigating energy security concerns and generating long-term economic benefits.

8.2 Future works

Energy systems are complex, and it is almost impossible to capture all real-world dynamics and build a model with perfect accuracy, although the development of cost optimisation methods, such as those presented in this thesis, can assist the energy policymaking process. The proposed methods in this research could be furthered in the following areas:

- **Improving transport sector within TIM:** Exogenous purchase price assumptions for EVs and their parity with the ICEs are a source of uncertainty that need to be addressed. Moreover, importing second-hand cars will likely change the retirement profile. It would be interesting to explore the efficacy of second-hand car import. Finally, the current study has only examined the historical trend in energy service demand. But different actions can reduce mobility demand: lower travel needs (facilities to reduce business travels, telecommunication mobility services and effect of digitalization, reducing sprawl), shorter travel distances (urban planning), raising the price of travel and transport demand management (dynamic ridesharing). There is, therefore, a definite need for assessing the effects of these actions on energy service demands.
- **Spatial resolution beyond the transport sector:** Spatial resolution could be extended to other sectors, more specifically, to the power sector to capture national grid congestion. Future studies deserve more careful analysis that Ireland should invest in remote low-cost wind energy sources and reinforce its power grids or install wind turbines with higher generation costs close to load centres. The extension can answer two key questions: when and where is additional inter-regional grid reinforcement necessary? Regarding strong transport electrification, some interesting research agendas are exploring optimal charging/discharging of EV batteries and the impacts of vehicle-to-grid technologies. A

high-temporal resolution and detailed operating problems can analyse sector coupling opportunities and challenges. Another improvement is the representation of non-monetary parameters such as range anxiety and charging station availability that might change individual attitudes toward the adoption of modern technologies. The extension may also facilitate the investigation of the co-benefits related to air quality under mitigation policies that were not covered in this thesis (especially in residential and power sectors).

- **Systematic analysis of increased resolution:** High-resolution models can better capture real-world issues but increase the solution time exponentially (Sharma *et al.,* 2019; Panos, 2019). Our analysis shows that existing temporally explicit ESOMs with a single sector coverage can permit regional disaggregation up to the first-level administrative divisions within a country (such as state and province) while maintaining computationally tractable. In fact, computational time and burden are manageable with a normal PC in this group of models. In line with advances in computational capabilities, a more systematic method is required for cost-benefit analysis of increased resolution. It calls for the development of a multi-sector ESOM with high- spatiotemporal details for a long-term period. This model can comprehensively check resolution trade-offs, find out how more spatial resolution actually makes a difference, and show the minimum acceptable level of resolution.
- **Incorporating stakeholder engagement:** ESOMs generally employ a typical single agent to allocate capital on a rational basis (Li *et al.,* 2016). However, developing stakeholder-inclusive approaches for technology pathway assessment is crucial for advancing ESOMs in the future (Pfenninger *et al*., 2014). As discussed in part B, modellers may not directly engage in policy making, but they can inform ongoing climate policies through dialogue with a wide range of stakeholders. The stakeholders can contribute to iteratively refining the model assumptions and scenario definition. This is known as "co-creation" approach and facilitates an evidence-based decision-making process. Further research needs to critically show how capturing multiple stakeholders' interactions, while they have conflicting priorities and objectives, might impact the model development, scenario definition and key results.
- **Transparency and flexibility in model development:** Energy systems models need to be transparent and reproducible through opening up their code, data and documentation (Morrison, 2018). Chapter 3 highlights an example of a best practice standard in software development and open modelling convention. Code and data are publicly available, and other modellers can validate the results, inspire modelling approaches, use data and run

new scenarios. It is a prerequisite for public transparency, scientific reproducibility, model maintenance, and enhancement and verification of results. A Git-centred model development process has been an integral part of the model development approach to enable version control and model management. Along with improvements in management, quality assurance, and transparency this brings, it also allows developers and researchers from different projects to branch research versions of the model to explore innovations and new developments while keeping a secure and stable main version of the model for policy application. At the same time, individual projects and researchers can input their improvements and developments to the core model to enable continuous improvements. It would be interesting to archive those experience and show the benefits that an open-source modelling approach can offer.

Moreover, TIM can run in multiple modes with multiple configurations of regional and temporal resolution, ranging from a single region national model at a single annual time slice, all the way to county level at an hourly resolution where supply-demand data are available at that spatiotemporal granularity. As a result, the modeller can easily switch between single and multi-region options or run them together and compare their results. It is suggested that the benefit of flexibility is investigated in future studies.

- **Extending subsidy reform to whole energy-economy system**: Both energy systems and economic models could be extended to analyse the impacts of subsidy reforms in other sectors such as oil products and gas consumption in the transport and residential sectors and the corresponding supply system from petroleum and gas refineries. Moreover, the demand-side findings of this research are subject to at least three limitations. First, explanatory variables, i.e. GDP, population, and electricity price, are assumed to follow their past trends in the future. Second, electricity demand’s price and income elasticities have been kept constant over time. Third, a uni-directional causal relationship between GDP and electricity consumption has been used. Future investigations might analyse the impact of time-varying assumptions and bi-directional causal relationships between economic growth and electricity consumption.

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