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An innovative approach for estimating energy demand and supply to inform local energy transitions

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ABSTRACT

A vital first step for regional energy transitions is to develop an understanding of the current energy balance and related carbon dioxide emissions. However, there is a lack of clarity within existing literature on how best to determine a complete regional energy balance including industry, residential, services, agriculture, and transport sectors. This paper identifies four key limitations in the literature: over-reliance on simple population-based proportioning, a narrow focus on building energy, subsequent omission of transport energy in the majority of studies and a lack of transparency in a significant number of studies. This paper proposes a novel conceptual framework to address these gaps using a combination of local energy usage indicators and national unit energy consumption statistics. The authors apply this multi-dimensional approach to a rural case study region, carefully examining the range of energy usage indicators in each sector before selecting the most suitable. The results quantitatively demonstrate the value of this approach, with the final energy demand in some sectors varying by as much as double or threefold compared with a population weighting. Focusing on the socio-economic drivers of energy demand in this manner provides useful insights into the local context that defines the energy system.

1. Introduction

The majority of energy system modelling techniques seek to inform strategies to meet emissions reduction targets at a national or multi-national level, however, there has been a growing call for local efforts addressing climate change. These sub-national efforts at climate change action fall under a variety of spatial scalings; regional, municipal and city or town [1]. While key elements like infrastructure developments and institutional frameworks (such as building codes and planning laws) must be stepped up and managed at a national level, there is an increasing need for the involvement of local stakeholders, especially local authorities, in the design and planning process [2]. This has been prompted by the ever-increasing levels of renewable generation shifting the balance of the energy system from the conventional centralised model towards one that is more decentralised. Supported by policy seeking to pilot/model exemplar areas in order to showcase and promote the energy transition process [3], along with changing governance and institutional structures in support of greater community involvement [4].

A prevalent characteristic of some of the exemplar regional energy transitions such as Güssing, Austria [5], Samsø Island, Denmark and Feldheim, Germany [6] has been their rural and isolated nature. For these communities, suffering from economic decline, the opportunity of new employment and a reduction in imported fossil fuels underpinned a strong unifying vision [7]. It has been shown that in times of economic crisis, investments in sustainable energy is an effective means of driving job creation and industrial development [8]. Emanating from this is the concept of regional energy autarky or energy independence that seeks to replace imported fossil fuels with local renewable sources [9]. This brings ecological, social and economic benefits, which are particularly important in peripheral, rural and declining regions.

The practice of municipal-level energy planning has existed within European countries such as Sweden [10] and Denmark [11] for a number of decades. Thus, it was expected that there may be a

Abbreviations: BEI, baseline emission inventory; BER, building energy rating; CSO, Central Statistics Office; EUI, energy usage indicator; GVA, gross value added; LPG, liquid petroleum gas; NACE, nomenclature of economic activities; NUTS, Nomenclature of territorial units for statistics; SEAI, Sustainable Energy Authority of Ireland; SEAP, sustainable energy action plan; UEC, Unit energy consumption.

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number of useful examples for how to determine local energy and demand supply across multiple sectors. However, it was found that the means by which initial estimates of energy supply and demand can be determined lacks coverage in literature to date. From the studies reviewed, four clear trends emerged. An over-reliance on simple one-dimensional population based proportioning, which fails to account for regional deviations such as the levels of industrial activity or access to public transport. A focus on urban building and in particular housing stock models, which is not suitable in rural areas. The omission of transport energy in the majority of studies, despite it likely being a significant source of energy demand. In 2017, transport accounted for 31% of the total energy demand within the EU28 [12]. Finally, there was a lack of transparency in the majority of studies on how the energy balance had been determined, with most relying on external reports from the area. This missing information makes it difficult for the studies to be replicated and undermines the analysis carried out.

This paper seeks to build on the breadth of literature in this field (highlighted in Section 2), by outlining some of the current gaps, providing an alternative approach that can help to address these limitations and also reflecting on the areas of improvement for future work. The authors take a multi-dimensional approach to the development of a regional energy balance covering energy demand and supply across the five sectors of Agriculture and fishing, Industry, Residential, Services and Transport. In doing so, a novel conceptual framework that combines local energy usage indicators (EUIs) and national unit energy consumption statistics was developed. The authors then apply this approach to an isolated rural case study, comparing and contrasting the range of possible EUIs available in each sector, ensuring that the approach may be easily replicated in other regions. The paper compares the energy balance generated using this framework with a simple population weighted (per capita) estimate to highlight its value.

The paper is structured as follows. Section 2 provides an overview of literature on the topic. Then in Section 3 the chosen case study region is introduced. Section 4 gives an outline of the multi-dimensional approach proposed, including some examples of energy demand and supply calculations. The resultant estimates of energy demand, assessment of the different EUIs and energy supply are all discussed in Section 5. Finally, Section 6 reflects on the ways in which the approach could be improved and considerations for future work.

2. Literature review

This literature review focuses on studies examining subnational energy systems. The criteria for selection was that the study in some way analysed a regional energy system, allowing for the scale of the region to be any sub-national area (county/municipality or city/town).

A vital first step for these sub-national efforts is to develop an understanding of the current energy balance and related CO_2 emissions [13]. This is highlighted by the requirement when joining the Covenant of Mayors to commit to the development of a Baseline Emission Inventory (BEI) as a pre-requisite for the creation of a Sustainable Energy Action Plan (SEAP) [14]. While this requirement provides a good precedent, the supporting documentation fails to provide reasonable explanation or guidelines for the development of a regional energy balance [15]. The approach outlined focuses on urban/city development and in particular building stock models. It relies on the gathering of data from energy suppliers and grid operators or through the distribution of a survey to determine the current energy balance.

The limitations of this are outlined in literature on the topic. Coelho et al. [16], reviewing Portuguese cities found that only 50% had submitted a SEAP and BEI with detailed data. They highlighted the challenge of data availability, which is even greater in isolated rural areas where there is a reliance on surveys of individual households and businesses. Surveys of this manner are unlikely to receive a significant response rate, and as a result will not deliver an accurate energy balance. For example, Schmidt et al. received only a 1% response rate from business establishments when conducting a survey of energy demand and fuel consumption in an Austrian region [17]. This emphasises, as noted by Marinakis et al., following a review of SEAPs in rural regions that; *"there is the need for a methodology, appropriately customised to the rural communities"* [18]. Rural communities are at a distinct disadvantage and thus require easy-to-use tools to support local energy planning [19]. While most sub-regional analyses focus on the future of cities and urban areas, 26% of the European population currently lives in rural areas. Although this share is expected to fall due to the increasing levels of urbanisation, recent projections indicate around 20% will still be living in rural areas by 2050 [20].

As can be seen in Table 1 below, the majority of studies reviewed lacked transparency on how the energy balance had been determined. In a significant number of cases the current energy demand was taken from previous reports on the region. Some had access to data on building energy demand or the electricity system profile. Other studies derived the regional energy balance from state statistics but provided no explanation of how this had been done. In another example, a comprehensive list of EUIs and references is given but no explanation is provided of how these were used to determine the energy demand of the municipalities examined [24]. Some examples from Denmark looking at only heat demand made use of GIS-based 'heat atlases' to map out building heat demand and identify supply options, with a particular focus on district heating [38]. Sperling and Möller assess the district heating potential of an urban building stock [39], while Petrović and Karlsson investigate the potential of the residential building stock for an entire region [40] .

A summary of the methods found during the review can be seen in Table 2, listed from most recent to oldest publication date. The approaches used for estimating the energy demand by sector can be categorized as either top-down or bottom-up. A top-down (or downscaling) approach uses statistical indicators to estimate the proportion an area is responsible for out of the national energy balance, while bottom-up builds an aggregated model based on an energy usage profile of buildings or vehicles within the area. Only four studies were found to detail a top-down approach for the whole energy system with the five sectors taken for this study. In the other top-down approaches one study omits transport, another two omitted agriculture and one omitted both agriculture and transport. Others focused solely on the building stock using a bottom-up approach at a city level include a variety of different scales, with some just covering residential while others include residential, services and industrial buildings. In cases were a top-down proportioning approach was used only the relevant statistic is highlighted, while greater explanation is provided for the bottom-up approaches in order to accurately present the variation across studies.

The lack of consistency across the literature highlights the absence of a standard methodology for estimating sectoral energy demand at a regional level. It may also demonstrate how different approaches are suitable for different scales and regions; for example municipal regions versus rural agricultural ones. One of the reasons for this variation may be the limited amount of data available and differing datasets available in different countries/regions. Something that became apparent was the different levels of data reporting and recording present. In addition, the approach will vary based on the purpose of the analysis. The majority of studies

Table 1
Sources of initial energy demand estimate in studies reviewed.

Study	Source of initial energy demand estimate
INSMART—Insights on integrated modelling of EU cities energy system transition [25]	sustainable energy action plan
Investigating long-term energy and CO2 mitigation options at city scale: A technical analysis for the city of Bologna [26]	
Modelling the energy system of Pécs — The first step towards a sustainable city [27]	
A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass [28]	strategic energy plan
Planning regional energy system with consideration of energy transition and cleaner production under multiple uncertainties: A case study of Hebei province, China [29]	
Regional level approach for increasing energy efficiency [28]	
Energy systems modelling to support key strategic decisions in energy and climate change at regional scale [30]	regional energy environmental plan
The role of decentralised generation and storage technologies in future energy systems planning for a rural agglomeration in Switzerland [31]	previous municipal report
Cost optimal urban energy systems planning in the context of national energy policies: A case study for the city of Basel [32]	national/local statistics with no explanation of methodology
Energy supply modelling of a low-CO2 emitting energy system: Case study of a Danish municipality [33]	
An integrative analysis of energy transitions in energy regions: A case study of ökoEnergieland in Austria [34]	
Assessing energy performances: A step toward energy efficiency at the municipal level [35]	
Energy modelling towards low carbon development of Beijing in 2030 [36]	
Transitioning Island Energy Systems—Local Conditions, Development Phases, and Renewable Energy Integration [37]	data available
The role of municipal energy planning in the regional energy-planning process [13]	
Municipal scale scenario: Analysis of an Italian seaside town with MarkAL-TIMES [21]	
Balanced renewable energy scenarios: a method for making spatial decisions despite insufficient data, illustrated by a case study of the Vorderland-Feldkirch Region, Vorarlberg, Austria [22]	
Local authorities in the context of energy and climate policy [23]	

Table 2
Summary of methods for developing a regional energy balance from literature reviewed.

Study	Agriculture	Industry	Residential	Services	Transport
Identification of potential off-grid municipalities with 100% renewable energy supply [41]	NA	Weighted matrix from area, population, number of companies/employees, as well as salaries	Weighted matrix from area and population	Weighted matrix from population and employee salaries	NA
Optimal carbon-neutral retrofit of residential communities in Barcelona, Spain [42]	NA	NA	3 regional specific building archetypes used	NA	NA
A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale [43]	NA	NA	dwellings by type and age aggregated based on average demands and floor area	NA	NA
Assessing the contribution of simultaneous heat and power generation from geothermal plants in off-grid municipalities [44]	NA	database of building typologies used to simulate energy demand data			NA
Downscaled energy demand projection at the local level using the Iterative Proportional Fitting procedure [45]	NA	gross domestic profit	population	population	number of vehicles per category [b]
Automatised and georeferenced energy assessment of an Antwerp district based on cadastral data [46]	NA	energy performance variables (i.e. building age, building use, floor area, height/number of floors and volume) used in combination with heating and cooling degree hours			NA
A renewable energy system for a nearly zero greenhouse city: Case study of a small city in southern Italy [47]	utilized agricultural land area	employees	population	number of active units	number of vehicles per category [b]
Energy planning of low carbon urban areas - Examples from Finland [48]	NA	NA	dwellings by type and age aggregated based on average demands and floor area	NA	NA
The use of energy system models for analysing the transition to low-carbon cities—The case of Oslo [49]	NA	population	number of people and floor area per dwelling, as well as energy service demand (kWh/m2)	population	vehicle km
A city scale degree-day method to assess building space heating energy demands in Strasbourg Eurometropolis (France) [50]	NA	NA	energy performance variables (i.e. building age, housing types, floor area and inhabitant density, type of the heating system and fuels) applied to housing stock	NA	NA
Bioenergy villages in Germany: Bringing a low carbon energy supply for rural areas into practice [51]	utilized agricultural land area	employees	number/size of households	employees	population, private car only
Investigating 100% renewable energy supply at regional level using scenario analysis [52]	population	population	population	population	population, private car only
Towards an energy sustainable community: An energy system analysis for a village in Switzerland [53]	NA	buildings grouped by purpose and construction period then floor area, U-values, and assumed air change rates used for simulation of hourly energy demand			NA
	employees	employees		employees	NA

(continued on next page)

Table 2 (*continued*)

Study	Agriculture	Industry	Residential	Services	Transport
Regional energy autarky: Potentials, costs and consequences for an Austrian region [17]			estimated with a heat demand model based on the size and age of buildings		
Technical and economic aspects of municipal energy planning. International journal of sustainable development and planning [54]	NA	NA	dwellings by type and age aggregated based on average demands and floor area	population	NA
Regional energy planning methodology, drivers and implementation – Karlovac County case study [55]	NA	NA_d	thermal energy based on the age of the building, heating area, isolation, and standard of living	NA_d	NA
An energy balance and greenhouse gas profile for county Wexford, Ireland in 2006 [56]	utilized agricultural land area	fuel spending	number of households/oil boilers	proportioned fuels based on national ratio to electricity $consumption_a$	number of vehicles per $category_b$

Note a – Public sector building energy usage recorded as per requirement under EU Energy Performance of Buildings Directive 2010. This was the only study to distinguish between commercial and public services.
Note b – Those that state number of vehicles considered both cars and freight, otherwise when stated just cars the study only considered private car travel. All studies only accounted for fuel supplied in the region so neglected other transport demands such as aviation, fuel tourism and rail.
Note c – NA; Not Applicable as it was omitted from the study.
Note d – obtained from an external source.

that involved building stock models did so because they were focused on heat energy demand, while others covering all (or most) sectors looked at all or multiple elements of the energy system.

3. Case study

To address the literature gaps highlighted in Section 2, a case study region was chosen in order to investigate the process of developing a regional energy balance. As noted in Section 1, some exemplar regional energy transitions have been isolated rural areas. This is quite apparent from two prominent exemplars of regional energy transitions; Güssing, Austria [5] and Samsø Island, Denmark [6]. In Ireland, similar challenges can be seen throughout rural areas within the Border, Midlands and Western regions. One particularly interesting region is the Dingle peninsula (highlighted area in Fig. 1), a small isolated 583 km^2 peninsula about 50 km long and 15 km wide, with a population of 12,500 [57], located in County Kerry (dotted line in Fig. 1), Ireland. Due to the absence of a gas grid and its highly dispersed population, the region spends a significant amount on the import of oil and electricity as in the cases of Güssing and Samsø.

Despite or perhaps because of its isolation, the Dingle peninsula has established itself as an extremely popular tourist destination [58], estimated to host roughly a million visitors each year [59]. While this is a significant source of income for the area, it brings with it some challenges. The Dingle peninsula housing stock contains a significant amount of holiday homes at 25% of dwellings compared to 11% in Co. Kerry and 3.2% nationally [57]. In addition, the limited employment opportunities outside of the hospitality sector and an increasing number of tourists makes the area less attractive for young families to settle there. This is reflected in population/demographic statistics, with 41.1% of the population over 50 [57] compared to 30.4% across the state [60].

In the context of the energy transition, the Dingle pensinsula presents a particular challenge. The highly dispersed nature of the households limits the options available for heating and transport. Existing initiatives in the area see electrification forming a large part of the solution [61]. However, the area currently relies on a single electricity 110 kV line, which already struggles to maintain a reliable supply of electricity, and will experience increased difficulty as heating and transport are electrified.

The selection of the Dingle peninsula as the case study for this paper is based on its similarity to the examples of regional energy transitions outlined; firstly given the socio-economic context and secondly, the current dependence on imported energy and significant challenges decarbonisation poses. In addition, the choice of an isolated rural area highlights the issues around data availability and necessitates the study of transport energy demand, which was seen

Fig. 1. Map of Ireland highlighting areas of interest; Co. Kerry (broken line) & Dingle peninsula (shaded).

to be generally neglected in the literature.

In obtaining data for the Dingle peninsula, it was found that the majority of relevant statistics were only available at a county level, so Co. Kerry's energy balance was also determined. This usefully demonstrates the scalability and replicability of the approach derived. For the purpose of demonstration, this paper applies the approach to a small isolated rural area within Ireland, but it has applicability for any scale region. In the following sections, the Dingle peninsula will predominantly be referred to simply as Dingle, while when referring to the small town within the region, Dingle town shall be used. Likewise, County Kerry will be referred to simply as Kerry.

4. Multi-dimensional approach

This section will outline the multi-dimensional approach that was developed through this study. A key issue that emerged from the literature review (Section 2) was that while a range of top-down and bottom-up approaches already exist there is a lack of clarity and transparency in existing literature with no clearly defined best practice for how to estimate a subnational energy balance. The conceptual framework and approach proposed seeks to address this by offering a means to standardize the practice of subnational energy planners. It involves five key elements;

1. Data collection
2. Engagement with local and national stakeholders
3. Determining energy demand
4. Assessment of the representativeness and quality of the socio-economic indicators available and careful selection of method for each sector
5. Determining energy supply and associated CO_2 emissions

The novelty of this approach is as follows; clearly outlining the selection of method and EUIs with a range of options being explored in each sector, building a detailed understanding of the local context and determining a complete energy balance covering agriculture, industry, residential, services and transport sectors.

4.1. Data collection

A range of EUIs were gathered, those that had been identified in the literature review (Section 2), as well as some others found to be available such as the unladen weight of fishing boats or tonne km of freight vehicles. The granularity of data available was an issue throughout the calculations. Some are only available at the NUTS 3 (Nomenclature of Territorial Units for Statistics third level, developed by the European Commission) defined region of the Irish South West (including both County Kerry and Cork), while others are only available at a county level. The data collection and preparation process is outlined in detail within the accompanying Data in Brief [62].

4.2. Engagement with key local and national stakeholders

Throughout the data collection and analysis researchers engaged extensively with key stakeholders. Firstly, national and local organisations were contacted in efforts to improve the quality of the data, meetings were held with the Central Statistics Office and Kerry County Council. Secondly, in line with the review of academic literature of the topic, existing studies in Ireland were investigated and meetings held with experts in the field to discuss the approaches taken and data that was available. Finally, the analysis has been a collaborative effort with other members of the 'Dingle Peninsula 2030' partnership established [63]. Most notably the lead author sat on the Dingle Peninsula 'Sustainable Energy Community' steering group, which oversaw the development of an Energy Masterplan for the area informed by this analysis. This not only ensured the research was of value to the case study community but also provided a useful opportunity for researchers to gain a better understanding of the socio-economic context of the area.

4.3. Determining the energy demand in each sector

As stated above in Section 2, approaches for estimating the energy demand by sector can be categorized as either top-down or bottom-up. Firstly, a bottom-up approach involves building an aggregate model of energy demand based on energy benchmarks such as energy per metre squared of different building types and local statics such as the total floor area of a building type. For example:

$$\textit{energy benchmark} \cdot \textit{regional statistics} = \textit{regional energy demand} \tag{1}$$

$$\textit{average kWh} \Big/ m^2 \cdot \textit{average } m^2 \cdot \textit{No. of dwellings}_{(\textit{per age group})} = \textit{residential energy demand} \tag{2}$$

Secondly, in the absence of the data necessary for a bottom-up approach, a top-down approach may be used. This involves proportioning (or downscaling) national energy data based on local statistics. It is based on the assumption that the energy demand will correspond to socio-economic drivers [41]. For example:

$$\textit{regional share} \cdot \textit{national energy demand} = \textit{regional energy demand} \tag{3}$$

$$\frac{\textit{regional indicator}}{\textit{national indicator}} \cdot \textit{national energy demand} = \textit{regional energy demand} \tag{4}$$

$$\%\ \textit{share of population} \cdot \textit{national energy demand} = \textit{regional energy demand} \tag{5}$$

Eq. (6) was re-arranged as follows;

$$\textit{national unit energy consumption} \cdot \textit{regional energy usage indicator} = \textit{regional energy demand} \tag{6}$$

$$\frac{\textit{national energy demand}}{\textit{national statistic}} \cdot \textit{regional statistic} = \textit{regional energy demand} \tag{7}$$

$$\textit{MWh} \,/\, \textit{capita} \cdot \textit{population of the region} = \textit{regional energy demand} \tag{8}$$

By re-arranging the equation in this manner the national unit energy consumption (UEC) values and local energy usage indicators (EUIs) can be displayed. This enables the repetition of the approach in another region within the same country simply by gathering the relevant local statistics, which would help to greatly reduce the workload in preparing a regional energy balance. Similar to the work of Weinand et al. [64], a database could be developed for the country that would generate a regional energy balance for any given subnational area. For repetition in a different country, the national unit energy consumption figures would have to be determined based on the relevant statistics to get the most accurate results. A further benefit of this would be the ability to compare and contrast these energy indicators across regions and countries, as suggested by Ref. [19].

4.3.1. Top-down approach calculation

For the majority of calculations, excluding the residential sector where a bottom-up approach (as discussed below in Section 4.3.2) was taken, the energy demand in each sector was determined using a top-down approach. The following examples will cover how this was carried out. Although a range of different indicators were used (as outlined in Table 4) the calculation follows two possible paths. Firstly, in cases where the data was available at the local level, the calculation is quite simple, for example using the number of employees in industry.

$$National\ UEC = \frac{industry\ energy\ demand}{number\ of\ employees\ in\ industry} \tag{9}$$

$$National\ UEC = 28,435.4\ GWh/210,059 = 135.4\ MWh/employee \tag{10}$$

$$Energy\ demand\ in\ region = national\ UEC \cdot number\ of\ employees\ in\ the\ region \tag{11}$$

$$Energy\ demand\ in\ Kerry = 29.494 \cdot 5,695 = 770.9\ GWh \tag{12}$$

$$Energy\ demand\ in\ Dingle = 29.494 \cdot 433 = 58.6\ GWh \tag{13}$$

For other indicators that first had to be estimated before the energy demand calculation could be performed, the method was as per the following example using gross value added for industry;

$$National\ UEC = \frac{industry\ energy\ demand}{gross\ value\ added\ of\ the\ sec\ tor} \tag{14}$$

$$National\ UEC = 28,435.4\ GWh/\notin 94,455\ million = 301.1\ MWh\ /\notin million \tag{15}$$

$$Energy\ demand\ in\ region = national\ UEC \cdot gross\ value\ added\ in\ the\ region \tag{16}$$

$$Kerry\ industrial\ energy\ demand = 301.1 \cdot 1468 = 441.8\ GWh \tag{17}$$

$$Dingle\ GVA\ 2016 = Kerry\ GVA\ 2016 \cdot \%\ share\ of\ employees \tag{18}$$

$$Dingle\ GVA\ 2016 = 1,468 \cdot (433\ /\ 5695) = \notin 111.6\ million \tag{19}$$

$$Dingle\ industrial\ energy\ demand = 301.1 \cdot 111.6 = 33.6\ GWh \tag{20}$$

For Services and Industry in Dingle, the proportion of Kerry's employees was used to determine estimates for GVA and number of buildings, while in agriculture the hectares of farmland was used to get the share of the GVA. The tonne km in road freight was determined for Kerry based on the share of km travelled in the South West region originating there. For transport in Dingle, public service vehicles were proportioned based on the number of employees, while tonne km and km travelled in road freight was based on the share of GVA estimated.

4.3.2. Bottom-up approach calculation

The residential sector was the only case with the data needed to take a bottom-up approach. Combining the age profile of the housing stock in the region of interest (which was available at the Small Area) with known values for the energy demand and average floor area by household age can provide an estimate of energy demand as follows.

$$Energy\ demand = No.\ of\ dwellings\ in\ age\ category\ x\ Avg.\ m2\ x\ Avg.\ kWh/m2 \tag{21}$$

An issue that emerged, as is documented in literature on the topic [65], was the fact that the energy rating doesn't reflect actual energy demand. Using the Irish Building Energy Rating (BER) database to determine the values for energy demand per metre squared will likely produce an overestimate. This was confirmed by applying the values to the national housing stock and comparing to the reported figures, which was found to have been overestimated by 57%. It was addressed by deriving a simple correction factor as follows.

$$Correction\ factor = \frac{estimated\ energy\ residential\ demand}{reported\ residential\ energy\ demand} \tag{22}$$

$$Correction\ factor = \frac{31,448}{49,245} = 0.6386 \tag{23}$$

Given the limited data on the housing stock in the case study region, this was deemed sufficient. However, for future analysis a more detailed housing stock model could be developed using different correction factors for each energy rating category as developed in Mac Uidhir et al. [65].

4.4. Assessment of socio-economic energy usage indicators

In order to decide the most appropriate EUI in each sectors, a representativeness and quality index was developed. For representativeness, this looked at the ability of the EUI to account for the size, level of activity and type of activity in the region. The quality was based on the granularity of the data available and if it came from the relevant year (2016). The selection of EUIs is discussed in Section 5.2.

4.5. Determining energy supply and associated CO2 emissions

As with the determining of energy demand, there is little data

Table 3
Primary heating fuel in non-domestic buildings Ireland and Kerry 2016 [66].

	Ireland	Kerry	Difference
Gas	25%	0%	−25%
Oil	10%	24%	14%
Electricity	62%	69%	7%
LPG	2%	6%	4%
Solid Fuel	1%	1%	0%

available on energy supply below national level. At a county level industry and service sectors are grouped as non-residential buildings. To address this issue, the national share for the sector was adjusted based on changes in the overall heating system fuel share. There is no natural gas grid in Co. Kerry, and according to the Non-Domestic BER database shown in Table 3, it was replaced as follows.

$$\begin{aligned}&\mathit{Share\ of\ gas\ use\ replaced\ in\ heating}\\&= \mathit{increase\ in\ fuel\ use/national\ share\ of\ gas}\end{aligned} \tag{24}$$

$$\mathit{Share\ of\ gas\ use}\ \text{covered by}\ \mathit{Oil} = (14+4)\ /\ 25 = 72\% \tag{25}$$

$$\mathit{Share\ of\ gas\ use}\ \text{covered by}\ \mathit{Electricity} = 7/25 = 28\% \tag{26}$$

$$\begin{aligned}&\mathit{Adjusted\ fuel\ share\ of\ total\ energy\ demand} = \mathit{original\ fuel\ share}\\&\quad + \mathit{share\ of\ gas\ use\ replaced}\end{aligned} \tag{27}$$

$$\mathit{Adjusted\ Oil\ value} = 20\% + (0.72\ x\ 32.9\%) = 43.7\% \tag{28}$$

$$\mathit{Adjusted\ Electricity\ value} = 35.3\% + (0.28\ x\ 32.9\%) = 44.5\% \tag{29}$$

The associated CO_2 emissions are then determined by applying national conversion factors [67].

5. Results

This section outlines the resultant energy demand per sector (agriculture and fishing, industry, residential, services and transport) in the case study region. Firstly, the selection of the most appropriate indicators using an index for representativeness and quality is detailed in section 5.1. Then in Section 5.2, the range of energy demand values in each sector is provided in Fig. 2, as well as the final chosen values based on the findings of Section 5.1, which are shown in Table 5 and Fig. 3.

5.1. Analysis and choice of the energy usage indicators

During the literature review, the reasons for selecting commonly used indicators did not become apparent. It was found that in the vast majority of studies no explanation was given for why the chosen indicators had been used, other than it was the data available. To address this issue, an index was devised to objectively assess the representativeness and quality of the indicators, as displayed in Table 4. Each indicator was rated out of a total of 8 points, which were allocated as follows;

- Representativeness (1 point each)
  - o Asserted in literature – it was noted as a commonly used indicator in the literature reviewed
  - o Size of sector – it can give an indicative gauge of the share of that sector contained within the region of interest
  - o Level of activity – differing to size as a measure of how much activity takes place in the region of interest. For example, the number of enterprises can tell you the level of activity but gives no indication of how large the buildings are.
  - o Type of activity – can account for the different types of activity within a sector, i.e. different farming outputs, more energy intensive industry, freight carrying bigger loads.
- Quality
  - o Spatial quality – determined by the granularity of the data, if it was available for the area of interest by aggregating the relevant Small Areas it got 2 points, whereas those only available for County Kerry got 1 point
  - o Correct year (1 point)
  - o Accuracy (1 point) – a measure of confidence in the data. This was primarily an issue with employee statistics. As the data comes from a Census survey, it will reflect the occupancy of people living in the area but may not be the number of actual employees located there if people commute outside of the area for work.

As a further assessment of representativeness, a regression analysis was attempted looking at the relationship between the national recorded energy data and EUIs over a 10-year period (2008–2018). However, there was insufficient data on a number of the EUIs to draw any meaningful conclusions from this. For example, population figures and the employees in agriculture/fishing come from the Census of Ireland and thus are only available at 5-year intervals, while the GVA is only available from 2014 to 2018.

Based on the assessment index in Table 4 and some additional assertions, the choice of EUI is outlined below. The index provided useful quantitative figures for comparison, but it should be noted that it doesn't guarantee with absolute certainty the respective representativeness of each EUI. In addition, its not clear if representativeness should be favoured over data quality, if the two are equally important, or vice versa.

- Agriculture/Fishing
  - o Agriculture – Hectare of farmland was the mostly commonly used EUI in the literature and scored the same as GVA in the assessment index. However, GVA was chosen as it may better capture the fact that Kerry has less arable land and dairy farming, the highest earning and most energy intensive.
  - o Fishing – Although scoring lower on quality, gross boat tonnage was chosen over GVA for its representativeness as there will be a clear link between the size of the boats and their fuel consumption.
- Industry – GVA was chosen as it scored highest in this sector and is frequently used as a means of classifying industrial energy intensity [68], altough only one of the studies reviewed made use of it.
- Services -
  - o Commercial – GVA was chosen over employment figures. Although employment figures were available for Dingle from the 2016 census [63], an issue within this sector is that large portion of it will the hospitality sector, which is very seasonal with significant fluctuates in employees over the year. Thus, GVA was favoured as an indicator of the level of activity over the whole year.
  - o Public – As the impact of seasonality on employment would not be an issue for the public services, it was chosen over GVA, given it was the most popular indicator in the literature reviewed.
- Transport

Table 4
Index to assess the representativeness and quality of the energy usage indicators.

Sector	Indicator	Representativeness					Quality					Overall Rating (0–8)
		Asserted in literature	Size of the sector	Level of activity	Type of activity	Rating (0–4)	Spatial quality		Data quality		Rating (0–4)	
							Small Area	**County**	**Correct year**	**Accuracy**		
		1	**1**	**1**	**1**		**2**	**1**	**1**	**1**		
All	Population			1		1	2		1	1	4	5
Agriculture & Fishing	Employees		1	1		2	2		1		3	5
Agriculture	Gross value added		1	1	1	3		1	1	1	3	6
Agriculture	Area of land	1	1	1		3	2			1	3	6
Fishing	Gross value added		1	1		2	2		1	1	4	6
Fishing	Unladen weight of boats		1	1	1	3		1		1	2	5
Industry	Enterprises			1		1		1	1	1	2	3
Industry	Employees		1	1		2	2		1		3	5
Industry	Gross value added	1	1	1	1	4		1	1		2	6
Commercial Services	Enterprises			1		1		1	1	1	3	4
Commercial Services	Employees	1	1	1		3	2		1		3	6
Commercial Services	Gross value added		1	1	1	3			1	1	2	5
Public Services	Enterprises			1		1		1	1	1	3	4
Public Services	Employees	1	1	1		2	2		1		3	5
Public Services	Gross value added		1	1	1	3			1	1	2	5
Residential	Houses		1	1		2	2		1	1	4	6
Transport - Road freight	Vehicles		1	1		2		1	1	1	3	5
Transport - Road freight	Distance travelled		1	1		2		1	1	1	3	5
Transport - Road freight	Weight carried		1	1	1	3			1	1	2	5
Transport - Private car	Vehicles		1			1	2		1	1	4	5
Transport - Private car	Distance travelled		1	1		2		1	1	1	3	5

- o Road freight – Tonne km scored higher on representativeness but lower on quality compared to the distance travelled as it was only available at regional level. However, was still chosen as a good measure of the activity in the sector.
- o Private car – Distance travelled although scoring the same as the number of vehicles because the average km per car per year is only available at a county level, was still considered the best choice of indicator.

5.2. Energy demand per sector and resultant energy balance

The range of energy demand estimates in each sector is shown in Fig. 2. In the majority of sectors, the estimates varied quite significantly, except residential were the difference was minimal.

The energy demand figures based on the selected EUIs can be seen in Table 5. Using a population weighting can provide an indicative gauge of energy demand in a given region, but it is overly simplistic in that it assumes all regions within a country are the same. Without examining local socio-economic statistics, it fails to address deviations across regions such as the level of industrial activity, population density, public transportation infrastructure, age of the housing stock or levels of dependence on private cars. For example, in comparing the energy demand shares by sector shown in Fig. 3, it is clear that the level of activity in Transport and Agriculture/Fisheries sectors is significantly above the national average, whereas there is very little industrial activity.

The overall balance is displayed in Fig. 3, comparing the differences between Ireland, Kerry and the Dingle Peninsula. In the context of the low carbon transition, Dingle's geographical location as an isolated and sparsely populated rural peninsula poses a significant challenge. Kerry is Ireland's fourth least densely populated county at 30.7 people/km^2, while the Dingle peninsula is even lower at 21.5 people/km^2. This is significantly lower than the EU NUTS 3 region average of 117.5 people/km^2 [69]. As a direct consequence of this, the two key sectors that dominate the energy balance are private car travel (accounting for 25%) and residential heating (accounting for 21%). Given to the rural nature of the area, car ownership on the Dingle peninsula is significantly above the national average at 547 cars/1000 inhabitants [57] compared to 428 cars/1000 inhabitants [60], an increase of almost 28%. Likewise, it is above the EU average of 505 cars/1000 inhabitants [70]. Heating also presents a challenge, the area is currently heavily reliant on the import of oil with LPG (liquid petroleum gas) and kerosene boilers representing 71% of central heating systems compared to 41% nationally.

6. Discussion

The comparison between population weighted and chosen sector estimates (Table 5) shows significant deviations at a sectoral level. Although the total energy demand values are relatively similar, the results in some sectors differ by as much as 60% or 215%. Without access to any recorded energy demand it is not possible to verify the accuracy of these results. However, they still highlight the value of examining the sectors individually and how this multi-dimensional approach can give greater consideration to local deviations and drivers of energy demand. The population weighted

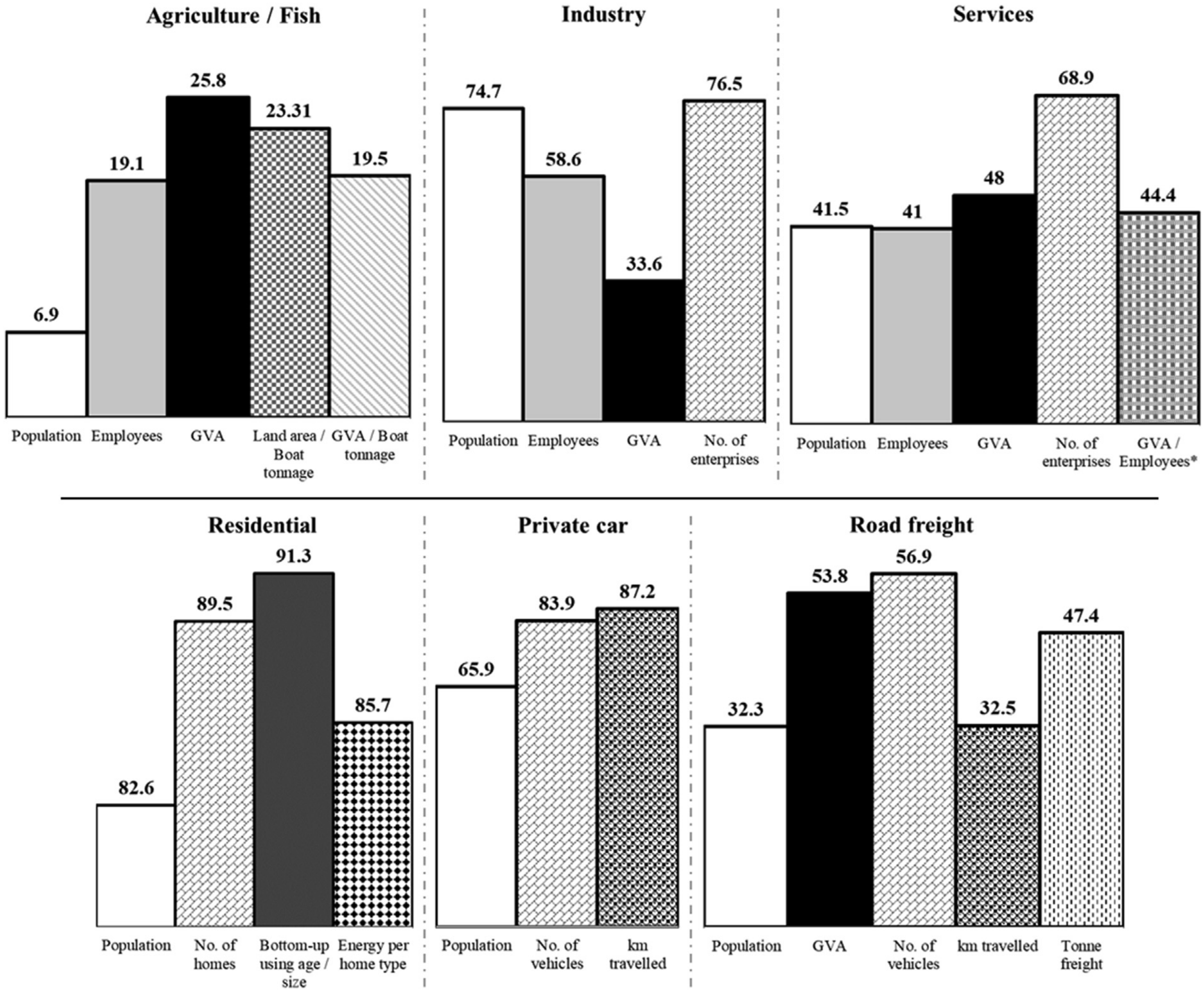

Fig. 2. Range of energy demand estimates by sector and indicator used. *GVA for commercial services/employees in public services.

Table 5
Comparison of population weighted and sector weighted estimates for Co. Kerry and Dingle energy balances in 2016.

	Kerry			Dingle Peninsula		
	GWh		% change	GWh		% change
	population weighted	sector estimates		population weighted	sector estimates	
Agriculture/Fisheries	81.5	135.9	67%	6.9	21.7	215%
Industry	882	441.8	−50%	74.7	30.1	−60%
Residential	975.5	991.3	2%	82.6	91.3	11%
Services	489.5	349.3	−30%	41.5	44.4	7%
Transport	1342	1436	7%	113.6	150.3	32%
Total	3771	3348	−11%	319	340	6%

estimate can be seen to represent the national average, which clearly does not represent the activity in the case study region.

There is scope for refining and improving this approach with better access to both local energy usage indicators and recorded energy data. Firstly, recorded energy data could be used to verify the results, and thus more accurately determine the most appropriate EUI in each sector. Without any recorded energy data it is not possible to properly assess the representativeness of the various EUIs or impact quality has on the results. However, this approach has demonstrated, that the deviation from the actual values could be very large in some cases. Therefore, this needs to be further investigated in future studies. In addition, the rating of the various assessment criteria in the index developed during the selection process outlined in Section 5.2 could also be improved. At present, without a means of validation it is assumed that all the criteria are of equal importance. Secondly, with access to more comprehensive and granular data on key drivers of energy demand such as; the profile of the building stock or vehicle fleet characteristics bottom-up energy demand estimates could be determined. Another important addition would be increased temporal resolution. For example, in order to assess the impact of technologies like heat pumps and electric vehicles on the electricity grid daily load profiles would be needed.

As previously noted in Sections 3 and 4, the approach developed

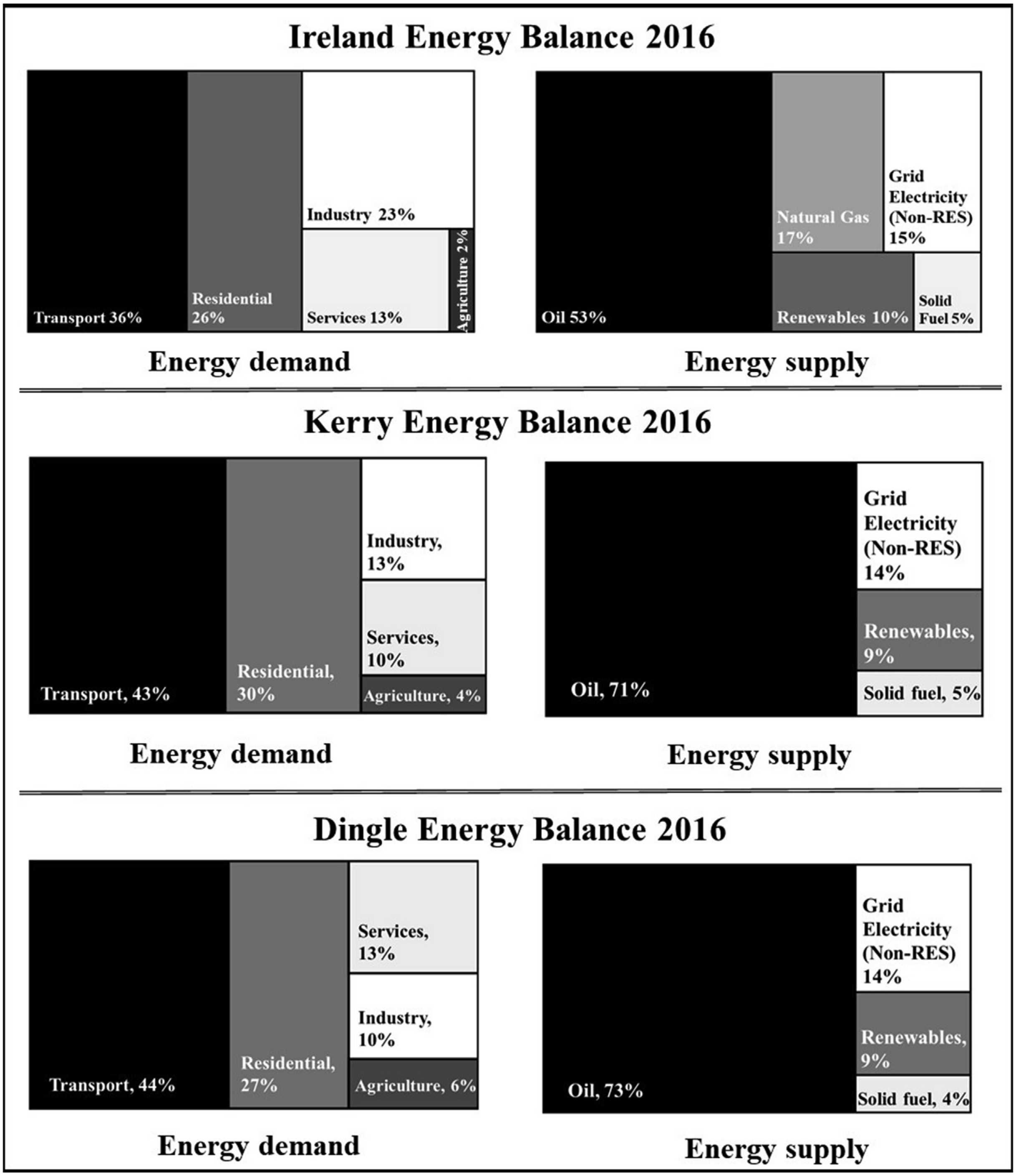

Fig. 3. Energy balance in Ireland, Co. Kerry and Dingle in 2016.

in this paper may be applied to any scale region or area. However, in replicating this approach, the presented unit energy consumption figures should be revised based on the relevant countries national statistics. Not every region will have access to data on the EUIs chosen in this study or may indeed have access to other indicators that were not available in this case. It should be noted that there will likely be regional deviations in the representativeness of different indicators, and thus the choice of indicator might differ based on the region of study. Moreover, as suggested by Weinand et al. [71], an interesting approach may be to look at the use of a weighted matrix with multiple indicators.

This paper has shown that taking a more thorough approach to develop a regional energy balance provides important insights that should be a prerequisite to any energy system analysis. It has illustrated how a valuable understanding of a region's socio-economic topography may be gained by gathering the relevant statistics used to determine the EUIs. The resultant understanding of potential local deviations from the national energy profile can serve to highlight key areas of concern to address. This can enable measures to be more appropriately directed as part of national and local energy planning processes; examining energy demand reductions, efficiency improvements and renewable energy supply options. For example, in the case study region, it is clear that improving the energy efficiency of homes and exploring alternative transport options should be a priority. The transport sector, which was omitted from the majority of studies reviewed, accounts for 43% of the overall energy demand.

7. Conclusion

Across Europe, despite an increasing call for the development of local energy strategies, there is an absence of a standard methodology or guidelines for estimating a regional energy balance. Through the use of an isolated rural case study region this analysis has demonstrated the importance of developing an understanding of a local area's characteristics prior to conducting analysis on the energy system. Taking the time to carefully select the appropriate energy usage indicators and exploring the socio-economic profile of an area is an essential first step in the local energy planning process. However, one prominent issue that emerged throughout the analysis undertaken in this study was the lack of data available below national level, not just with regard to energy data but also socio-economic statistics. This highlights the value of having more decentralised governance in order to facilitate sub-national efforts at energy planning. Furthermore, in order to conduct well-informed energy system analysis, a degree of local knowledge is required, emphasizing the important role to be played by local authorities and other actors.

CRediT author statement

Connor McGookin: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. Brian Ó' Gallachoir: Conceptualization, Methodology, Supervision, Writing – review & editing. Edmond Byrne: Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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