Energy Conversion and Management 277 (2023) 116599

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Regionally integrated energy system detailed spatial analysis: Groningen Province case study in the northern Netherlands

Somadutta Sahoo [a,*], Joost N.P. van Stralen [b], Christian Zuidema [a], Jos Sijm [b], André Faaij [b,c]

[a] Department of Spatial Planning and Environment, Faculty of Spatial Sciences, University of Groningen, the Netherlands
[b] Energy Transition Studies, Netherlands Organization for Applied Scientific Research (TNO), Amsterdam, the Netherlands
[c] Energy Research and Sustainability Institute Groningen, Faculty of Science and Engineering, University of Groningen, the Netherlands

ARTICLE INFO

Keywords:
Regional energy system
Integrated energy system modeling
Energy infrastructure
Geographical information system
Renewable resources
District heating

ABSTRACT

Regional level energy system analyses and corresponding integrated modeling is necessary to analyze the impact of national energy policies on a regional level, while considering regional constraints related to energy infrastructure, energy supply potentials, sectoral energy demands, and their interactions. Nevertheless, current literature on energy system analysis largely overlooks the regional level. In response, this study provided a systematic approach to refining and improving the spatial resolution of an existing regional energy system modeling framework. The methodology involved creating regions and nodes within the modeling framework under categories corresponding to land use (cities and other regions), energy supply, and energy infrastructure. We established a unidirectional soft linking with geographical information system-based modeling results allocating spatially sensitive elements, such as renewable resources or heat demand. We provided a detailed breakdown of sectoral energy demand, supply options, and energy infrastructure for electricity and heat, including district heating (DH). This framework explicated regional differences in terms of demand–supply mismatch, supply options, and energy infrastructure. Our case study of the Dutch province of Groningen demonstrated clear differences compared to the previous crude regional model, with, e.g., an increased role of biomass (+460 % change) and decreased role of solar (−59 %), while cities with high heat demand densities and/or compact structures exhibited serious DH penetration, ranging from 11 to 21 %. The systematic steps allow for the replication of the model in other regional analyses. Our framework is complementary for energy system analysis at the national and pan-European levels and can assist regional policymakers in decision-making.

1. Introduction

National targets related to renewable energy addition and emission reduction are stringent within the European Union [1]. Efforts to add infrastructure, particularly related to renewables, need planning at a regional level, especially in densely populated countries such as the Netherlands [2]. A region in this context refers to a geographical area beyond a municipality or city level and to a subnational level. Regional energy system analysis is necessary to understand regional differences in supply sources potential, energy demand, and energy infrastructure, i.e., integrated energy system. In addition, a regional analysis is necessary in the decision-making process related to energy systems, for example, what should be the investment in medium voltage (MV) cables or where should these cables be expanded, i.e., capacity addition [3]. Answering these and other regional energy system-related questions requires an energy system model (ESM) equipped with appropriate spatial detail. This model can act as a regionally-relevant decision support tool related to land use and infrastructure planning. In addition, a regional ESM should have the capability to translate the implications of national policy choices at the regional level.

Regional energy system modeling can be a crucial addition to energy system analysis at a pan-European, national, and local level. In addition, aligning modeling outcomes and inputs of each level allows for a comprehensive analysis of the overall energy system. Currently, regional level analyses and their links with the (inter)national level analyses have received little attention in the energy system-related literature. Regional models are mostly beneficial in identifying regional constraints related to energy infrastructure, renewable energy supply potentials, and their interactions. A regional model can support decision-making upon future policies, both regarding energy systems and the spatial and environmental context in which these are embedded. In response, developing a

* Corresponding author.
E-mail address: somadutta.sahoo@rug.nl (S. Sahoo).

https://doi.org/10.1016/j.enconman.2022.116599
Received 7 September 2022; Received in revised form 2 December 2022; Accepted 14 December 2022
Available online 12 January 2023

Nomenclature

Acronyms

BE	Built Environment
CAPEX	Capital Expenditure
CBS	Central Bureau of Statistics
CHP	Combined Heat and Power Plant
DH	District Heating
ESM	Energy System Model
FBI	Food and Beverage Industry
GBPV	Ground-based Photovoltaics
GIS	Geographical Information System
HP	Heat Pump
HV	High Voltage
IWH	Industrial Waste Heat
KEV	National Energy Outlook (in Dutch)
KNMI	Royal Netherlands Meteorological Institute (in Dutch)
MV	Medium Voltage
MSW	Municipal Solid Waste
NG	Natural Gas
OPERA	Option Portfolio for Emission Reduction Assessment
O&M	Operation and Maintenance
OPEX	Operational Expenditure
RNL	Rest of the Netherlands
STEG	Steam and Gas Turbine (in Dutch)

Units

GW	gigawatt
km	kilometer
km^2	square kilometer (km*km)
M€/year	million euro per year
PJ	petajoule

Formulas

CO_2	carbon dioxide
H_2	hydrogen

regional ESM can greatly benefit if it allows for the inclusion of spatially sensitive parameters, which may be informed by policy considerations.

Spatially sensitive parameters that have a strong impact on ESM results, for example, sectoral heat demand or renewable energy potential, cannot be properly captured with a low spatial resolution [4]. Similarly, having a high spatial resolution leads to computational complexity and issues with getting high quality data related to the regional allocation of parameters within an ESM, for example, related to the built environment (BE) energy demand in every region [4]. The spatial resolution should be appropriate to represent regional differences in energy demand–supply mismatches, renewable potentials, and energy infrastructure, particularly related to district heating (DH), which can significantly impact overall regional energy balances, infrastructure costs, and planning. Additionally, renewable spatial potential can vary significantly under different spatial policies and land-use constraints at a regional level [5]. Our literature review into regional energy system modeling revealed a lack of information and guidance on choosing appropriate spatial resolutions for analyzing various important components of a regionally integrated energy system. Similarly, our review indicated a gap in providing guidance on systematic steps to incorporate these regional spatial categorizations into an ESM.

Ideally, regionally integrated energy system models should simultaneously analyze heat and electricity, and their corresponding infrastructures, with high and low spatial resolutions, respectively. For example, the national or European level is typically considered suitable for analyzing electricity infrastructure [6], whereas heat network analyses, particularly those related to low temperature DH, are highly geographically detailed and demand regional or local analysis [7]. DH network feasibility and corresponding investments are dependent on the spatial proximity of demand and supply due to huge transmission losses [8]. Again, our literature review showed that regional energy infrastructure analyses simultaneously considering different spatial domains and resolutions are currently lacking, which provides us yet another research gap.

1.1. State-of-the-art review

A geographical information system (GIS)-based tool helps perform a detailed and spatially sensitive energy system analysis. Some integrated ESMs and related literature do exist that allow for interaction with GIS. However, this application is more common in energy infrastructure analysis. Review of the state-of-the-art shows GIS and the energy system model MARKAL were linked to study the feasibility of hydrogen (H_2) infrastructure at the pan-country level [9], for example. Similarly, GIS and the ENERGYPLAN model combination have been used to understand the DH expansion potential within Denmark [10,11]. GIS was applied to identify locations for installation of heat pumps (HPs) in Denmark in combination with the TIMES-DK model [12]. Furthermore, GIS and the MARKAL model have been combined to identify the potential of the carbon dioxide (CO_2) infrastructure in the Netherlands, including offshore [13,14]. These abovementioned studies, however, do not explain their choice for a certain spatial resolution or geographical scope. Similarly, they lack interaction of an ESM with other aspects of an integrated energy system, such as various sectoral demand or supply options.

Recent literature at varied geographical scopes were reviewed to further identify GIS and energy system model interaction on other aspects of energy system mentioned before. Most of this literature focused on a city level. For example, a GIS-based platform was conceptualized [15] and utilized [16] for city where electricity generation and consumption were simulated, along with storage under different scenarios. Similarly, GIS interacted with thermal and electricity energy system models to identify energy savings and emission reduction potential of buildings on a city district level [17]. GIS was coupled with a system dynamics model to identify wind capacity potential in Latvia [18]. Modeling results from these analyses are focused on a single topic rather than on holistic approach towards analyzing the entirety of energy system.

There have been regional analyses at a country level within an ESM environment. For example, in Italy, analyses have been performed on power and mobility sector [19], mobility infrastructure [20], renewables deployment [21], and deep decarbonization [22]. Similarly, related to Great Britain, studies have been performed with emphasis on analyzing uncertainties related to meeting decarbonization targets [23], investigating supply sources for power sector [24], and exploring the role floating offshore wind within electricity system in 2050 [25]. Considering other countries, researches have been carried out with emphasis on the mobility sector in Germany [26] and focus on renewables penetration in the electricity supply within Greece [27]. Studies with only regional analysis have been performed with emphasis on waste and energy crops in central Sweden [28], for example. Models have also been developed for an analysis of multiple energy demanding sectors, but the regional categorization is rather crude, for example, [29]. Literature such as [30] acknowledge the need for regional energy system analysis to understand the potential of locally available resources, such as geothermal, or identify regional constraints imposed by spatially-sensitive parameters. Readers are directed to [4] for a review on further studies related to national models with multi-regions and

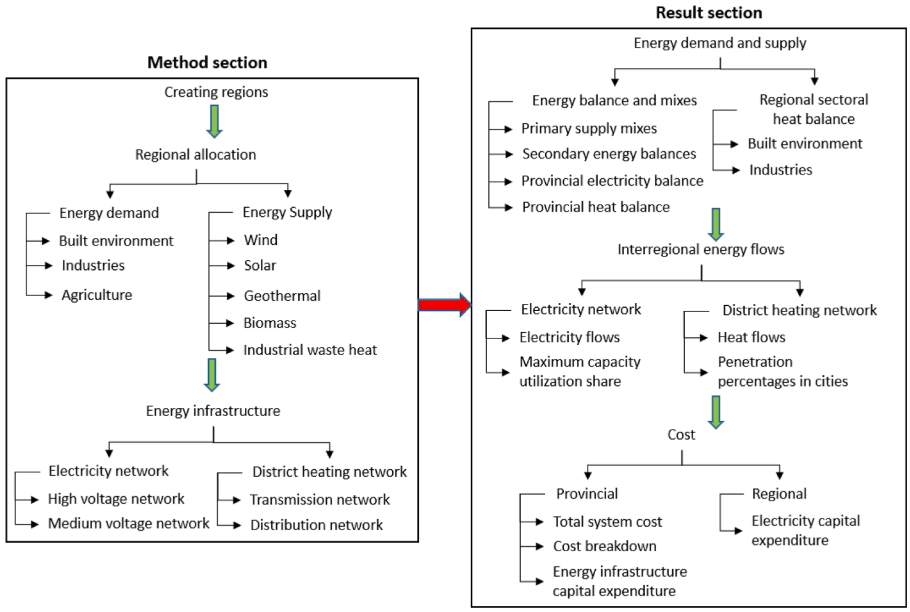

Fig. 1. Structure and flow of the method and results section.

fully regional models. Still, not all aspects of energy system are covered simultaneously, including spatial and land-use planning-related issues. In response, our methodological approach offers novel suggestions upon how to respond to this gap. Our focus is on a regional integrated system analysis linked to a national energy system, the advantages of which have already been documented in [4].

Our research add to GIS-based independent studies that identify future variable spatial potentials for renewable energy deployment considering land-use or planning-related constraints, for example for solar [31], wind [32], and biomass [33]. This addition is not only to identify capacity potentials, but also to incorporate these spatial potentials into an integrated ESM. Such a linkage allows for studying the feasibility and constraints of renewable energy deployment and for realizing their potentials in relation to other parts of the energy system, such as, regional energy infrastructure or sectoral demand.

1.2. Research objective and questions

Based on the literature, state-of-the-art review, and the research gaps identified, our objective was to develop a systematic approach that allows for performing a detailed spatial analysis of a regional energy system within a national integrated modeling context. This was done by refining and improving the spatial resolution of an existing regional energy system modeling framework through capturing the key regional spatial parameters via land-use regions or nodal segregation with detailed emphasis on energy demand, supply options, and infrastructure. With this objective, the following research questions were formulated:

- How can a regional ESM be developed that captures detailed spatial constraints and boundary conditions regarding sectoral energy demand, supply potentials, energy infrastructure, and their interactions, while targeting both heat and electricity along with their different preferred spatial resolutions?
- What are the significant differences between a high spatially detailed ESM and an existing ESM (with a low spatial detail) on regional energy balances, energy carrier flows, and cost structures?

A key novelty of our method is improving the spatial representation of a regional ESM taking into account all the specifics of regional demand, energy supply potentials, energy infrastructure, and associated costs. While doing so, our regional ESM is linked to national and pan-European level for electricity infrastructure, allowing the analysis of different future configurations or scenarios on the regional scale. As such, another key novelty is that our method allows for analyzing the potential impact of various policies and regional constraints on the regional energy system and spatial claims, including network capacities, sectoral demands, and supply potentials. Therefore, this study is a major improvement in the methodological approach to understanding the regional energy system. Our regional ESM can function as a key decision making tool for both energy policies and spatial policies at a national and regional level.

This paper takes a major step toward improving the state-of the-art of the integrated energy system modeling and analysis through detailed regional modeling. Methodologically, this study is novel in offering information on how to identify an appropriate spatial resolution for investigating energy infrastructure, land-use, and energy supply regions. Replicability is also facilitated through introducing a systematic approach for inclusion of relevant spatial detail on the abovementioned aspects. Key novelties include the creation of a DH network with a new unique infrastructure on a pan-provincial level, considering future city planning regarding placing corresponding centralized heat technology options. Novelty also lies in soft linking a detailed GIS-based analysis [5] with an existing crude regionally categorized energy system model [4] to create a spatially-detailed regional energy system model covering most of the aspects of a regionally integrated system. Result-wise, appropriate spatial detail allowed us to observe significant differences in overall regional energy balances, energy demand, and supply potentials. Additionally, our regional ESM spatially represent the primary energy supply mix, interregional electricity flow, and investment in infrastructure, particularly in the DH network. Thus, our regional ESM can provide explicit and detailed inputs for both national and provincial energy system and spatial policies, beyond what was possible through previous ESMs.

This study used the regional Option Portfolio for Emission Reduction Assessment (OPERA) model which is a Dutch-based model, already available, and has a modeling structure for regional and nodal categorization [4]. Our case study was the province of Groningen in the northern Netherlands. Section 2 presents the proposed method with a detailed representation of the modeling framework. Section 3 describes the modeling results related to regional analyses. Section 4 presents a critical discussion on our methodology and results. Finally, Section 5

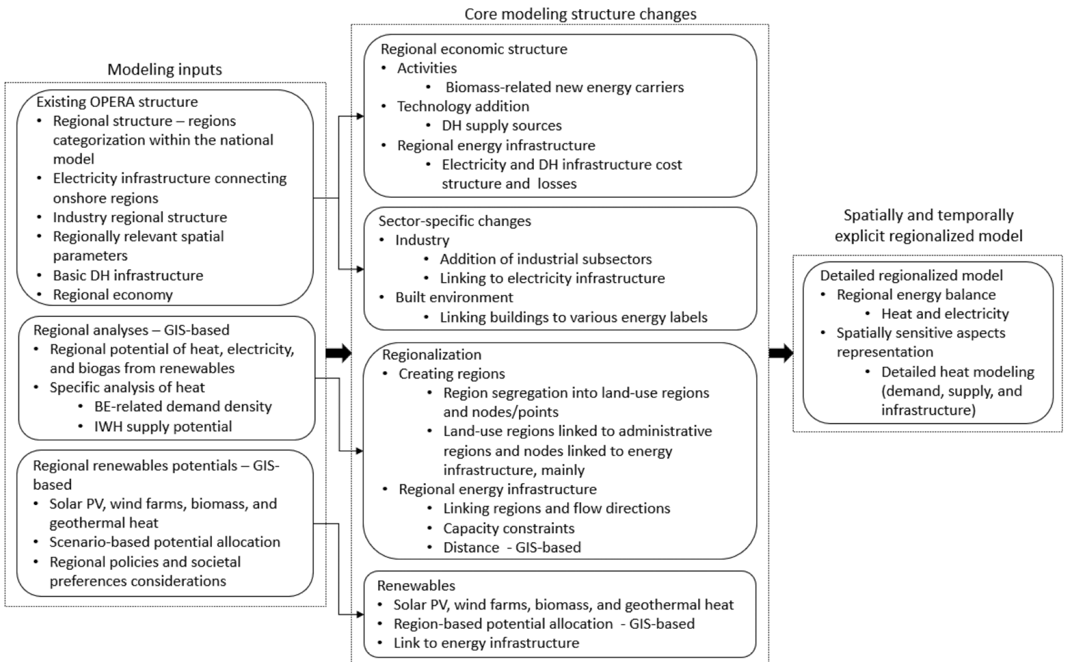

Fig. 2. Methodological framework for this study.

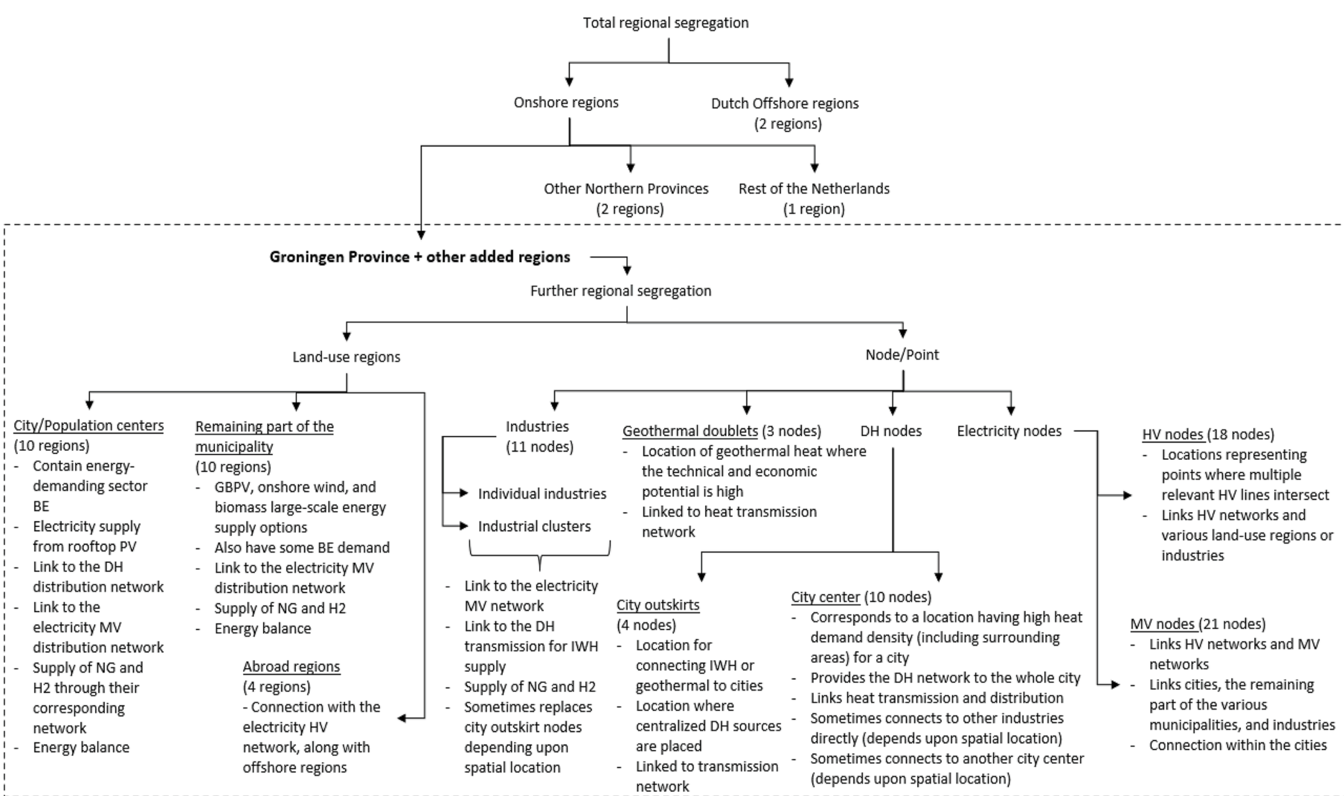

Fig. 3. Categorization of regions and nodes created in OPERA, illustrating what these regions represent, what they contain, and what major OPERA activities are performed in these regions. Numbers within parenthesis represent the number of regions/nodes in each category. Regions explicitly created for this study are provided inside the dashed square.

presents our conclusions and future work. Fig. 1 illustrates the structure and flow of the method and results section.

2. Method

Our modeling method is based on the use of the optimization model OPERA [34], which was developed in AIMMS 4.84 software [35], whereas our GIS model is based on QGIS 3.10 [36] and ArcMap 10.5

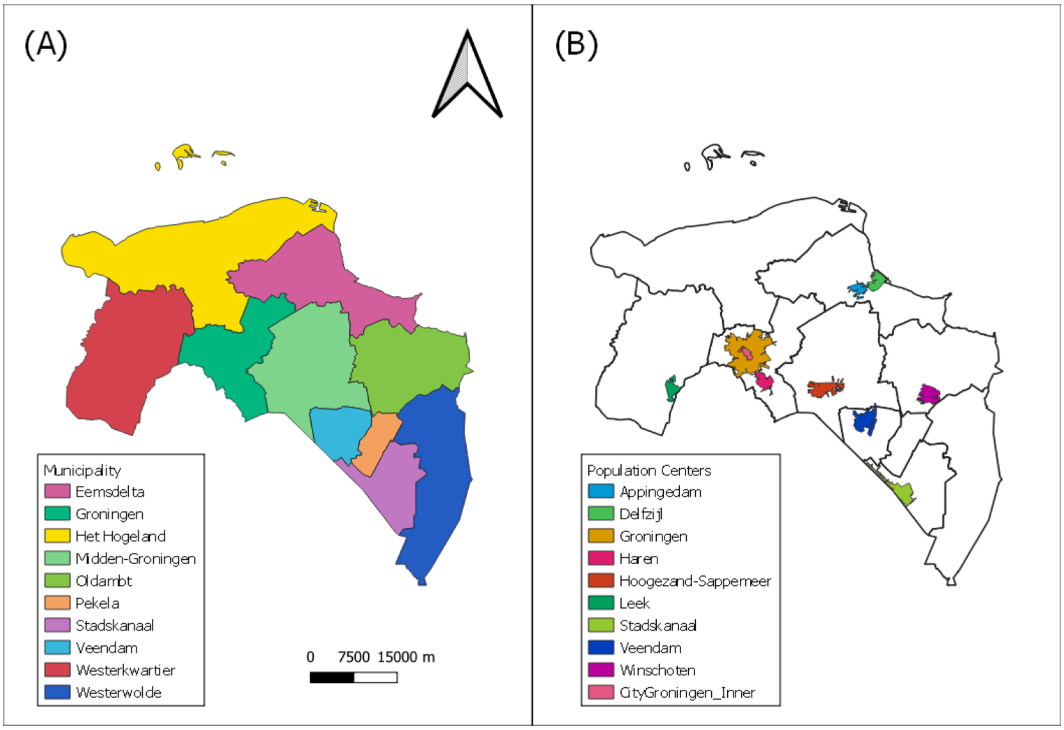

Fig. 4. (A) Categorization of the province of Groningen municipalities; (B) Shortlisted population centers for analysis.

[37] software. OPERA is a Dutch-based national integrated energy system model, where regions within the country are inherent, i.e., hard-linked, to make it a regional model [4]. The major fundamental operation of this paper are creating regions and nodes to spatially represent land-use regions, industries, geothermal doublets, and energy infrastructure explicitly under corresponding categories.[1] The second major operation is soft linking GIS modeling results with the regionalized OPERA model. These two contributions were essential to allow for a detailed spatial analysis on regional energy balances, regional primary energy supply mixes, regional cost structure, and interregional energy flows for the province of Groningen. Our modeling framework development consists of three core activities: (1) creating regions in OPERA, which is described in Section 2.1, (2) providing regional allocation for energy-demanding sectors and supplying options, which is described in Section 2.2, and (3) energy infrastructure modeling along with related nodal categorization in Section 2.3. Fig. 2 illustrates the methodological modeling framework used in this study.

2.1. Region creation

The allocation of regions needs to consider both data availability and computational complexity. Too high a resolution can lead to difficulties in data availability and allocation, while extra effort is needed to connect these regions through appropriate energy infrastructure for linking demand and supply. Even when data is available and a GIS-based analysis can provide a high spatial resolution with a large number of similar regions, these may not necessarily be sensible to use as explicit regions within a regionally integrated energy system analysis. The computational complexity increases as more regions are added; for example, the number of variables increases exponentially in an ESM with the addition of regions. Hence, combining regions from a GIS analysis may be preferable. For finding a balance between spatial detail, data availability, and computational complexity, approximately 100 land-use regions and nodes were included for the province of Groningen, an area of 3000 square kilometers (km^2) and about 600, 000 inhabitants, in this study (Fig. 3). The regions mostly correspond to energy demand and supply, whereas the nodes are mainly linked to energy infrastructure. Nodal structure creation and addition techniques in ESM have been previously applied [4,6].

Data availability is an important criterion for creating regions. In the Netherlands, government agencies such as the Central Bureau of Statistics (CBS) [38] produce data at a minimum resolution of a municipality level. Therefore, the ten municipalities in the province of Groningen were first considered as a set of independent land-use regions (ranging from 50 to 200 km^2, which can vary in other regional contexts) – see Fig. 4 (A). Subsequently, within a municipality, all population centers with over 10, 000 inhabitants were considered as distinct regions, i.e., municipalities containing such centers would be split into multiple regions consisting of a city (the population center) and the remaining part of the municipality (municipality rest) – see Fig. 4 (B). We did so as these centers had much higher population densities and had large pockets of land having a heat demand density greater than 1200 gigajoule per hectare [5], which may allow for creating a DH network as suggested by Persson *et al.* [39] (Table 1). Furthermore, BE-related demand data are available for these current centers from CBS as most of these centers were municipalities in the past (see Table 1). Nine independent population centers were selected and Groningen city (230, 000 inhabitants) was split into two population centers: Groningen inner city and outer city, as the inner city has a much higher heat demand density compared to the outer city, which is relevant for our DH analysis (see Section 2.3.2).

Each land-use region was balanced for net heat and electricity demand in each time slice (Fig. 3). Our regional map were created in GIS, in line with OPERA, by intersecting maps of population centers and municipalities. Groningen inner city was manually delineated by overlaying the heat density map from [5], the open street map, and the building map of Groningen city.

In addition to creating these land-use regions using OPERA, other onshore regions that were created in [4] were included, namely Drenthe,

[1] Regarding time resolution, OPERA (and in this paper) uses a time slice approach where hours (within a year) having similar characteristics of energy demand and supply are grouped together – see [34] for further details.

Table 1
Categorizations of regions or nodes created using the OPERA model with information on the number of regions and nodes created, the underlying reasons for such a categorization, and their selection criteria.

Category	Reasoning and selection criteria (if required)
Municipality	This level was selected as most of the regional data for the Netherlands is available at this level. Further, adding ten municipalities present within the province of Groningen in OPERA did not present major issues considering computational time requirements. In addition, some decision-making related to investments in infrastructure related to energy, renewables, and building stocks takes place at the municipality level. Municipalities also have a say in the future creation and demolition of buildings stocks. Also, installing infrastructure related to wind and solar requires clearance from the municipality [40].
Cities or population centers	Larger population centers have been identified in our study as these have a high concentration of the BE, and a high BE heat demand density allows us to study the feasibility of a DH network on a city level. A threshold of 10, 000 inhabitants was set as a criterion for shortlisting cities for analysis. This led to a selection of 9 centers, which is still manageable in terms of both data collection and computational time. Furthermore, these cities have a future heat demand density greater than 1200 gigajoule per hectare (based on [5]) which is in line with what Persson *et al.* [39] considered to be suitable for DH networks. In addition, CBS provided historical sectoral demand data on these regions as CBS provides data on the municipality level as the lowest level of categorization, and these centers are mostly ex-municipalities or the only major energy-demanding regions within a municipality.
The remaining part of a municipality	These represent regions of a municipality outside of population centers. If a municipality does not have a center, then the whole municipality comes under this category. Therefore, ten regions were created related to the municipality rests. On the supply side, these regions have centralized renewable infrastructure related to mainly electricity production, namely ground-based photovoltaics (GBPV) and wind, which are expected to be located in this region in the future. Additionally, biomass, such as forest, nature, and wet manure are associated with this region. Infrastructure related to renewables is suitable in this region. Furthermore, these regions have the BE, which is not a part of any city, and are scattered throughout the municipality. No attempt has been made to consolidate them into new population centers.
Offshore regions and abroad	Two offshore regions were created with their explicit wind profiles. These regions' segregation is based on planned offshore wind farms in the Dutch part of the North Sea [4]. Abroad regions were created for accommodating their electricity import/export profile with the Netherlands based on a pan-European electricity market model COMPETES – see [4] for further detail. A total of four abroad regions were created.
Industry	The industry represents distinct nodes in our research. important and relevant regional industries were identified based on [4] and current research. These industries are scattered throughout the province of Groningen and exist in clusters or as individual industries (also see Fig. 5). A total of eleven industrial nodes were created based on their spatial location. Creating these explicit nodes allows us to link energy infrastructure, particularly electricity (Section 2.3.1), and identify their energy demand structure (Section 2.2.1). Fixing their locations also helped us to link their industrial waste heat (IWH) potentials to cities with the help of DH networks (Section 2.3.2). Having industries as separate nodes allowed us to investigate secondary energy balances and primary energy use of each of these nodes.
Geothermal doublets	Geothermal heat potential in the province of Groningen, and the Netherlands, is suitable for spatial heat applications of the built environment (BE) [41]. Therefore, we planned to link these regions to major population centers through the DH network for the supply of low temperature heat to the BE (Section 2.3.2). For DH linking purposes, we needed specific geothermal locations, or geothermal doublets, rich in technical potential with low economic costs. Currently, there are no doublets in the province and no concrete plans are there to set up doublets in the near to medium future [42]. Therefore, technical potential and economic cost maps available from ThermoGIS [43] were used to find suitable doublet locations and identify their potential. Overlaying these maps showed that only a small region in Het Hogeland municipality is suitable from technical and economic viewpoints. A doublet effective distance is a range of 2–3 kilometers (kms) [44] also accounting for the distance between production and reinjection wells. These nodes were created manually by carefully aggregating the technical potentials of cells surrounding potential doublets. The technical and economic potential of various locations were manually calculated by trial and error method within the feasible region to pinpoint the locations of geothermal doublets. Three doublets were created based on space limitations due to technical and economic constraints. Having three doublets is also manageable for linking heat infrastructure in the OPERA model.
Electricity nodes	Electricity nodes, both high voltage (HV) and medium voltage (MV), were created to adequately represent electricity infrastructure. HV nodes were used for connecting cities or population centers, major industrial clusters, and connections to centralized electricity supply sources in the remaining part of municipalities. MV nodes were used for making the final connections to the abovementioned regions as the HV network cannot be directly connected to most of these regions. We created a total of 18 and 21 HV and MV nodes, respectively. Section 2.3.1 details the spatial locations and connections of these nodes.
DH nodes	Explicit DH nodes were created to make appropriate DH connections to the whole of each city or population center, shortlisted in this research, starting from their respective city centers, which were ten in number. Additionally, a few additional nodes were created, a total of four in number, as explicit centralized DH supply source locations. Section 2.3.2 explains their locations. For the remaining cities, either an industrial node was used as a supply source location, or a heat connection was established via another major adjoining city.

Friesland, and the rest of the Netherlands (RNL). Additionally, the model included the Dutch part of the North Sea, i.e., the northern and western parts of the region (Fig. 3). Adjoining countries, namely, Germany, Norway, and Denmark, were created as land-use regions because of their high voltage (HV) electricity connections with Groningen. These cross-border connections through electricity infrastructure are described in detail in Section 2.3.1.

2.2. Regional allocation

All land-use regions created in this study need regional allocation for OPERA demand and supply-related activities. Accordingly, this section categorizes sectoral demand (Section 2.2.1) and supply options (Section 2.2.2).

2.2.1. Energy demand

We considered the regional allocation for three energy-demanding sectors: BE, industries, and agriculture. Mobility is allocated based on the regional population distribution, similar to [4]. The energy demand

Table 2
Sectoral distribution of activity along with regional allocation method and criteria for these activities (data requirements for these activities and assumptions associated with methods are provided).

Sector	Activity name/ category	Data requirement/ availability	Regional allocation method and criteria	Major assumptions
Households	Apartments (start label GFE) Apartments (start label DC or B) Apartments (start label A/A+) Terraced Houses (start label GFE) Terraced Houses (start label DC or B) Terraced Houses (start label A) Terraced Houses (start label A+) Others (Start label GFE) Others (Start label DC and B) Others (Start label A) Others (Start label A+)	- GIS regional map - the household building level map with building types, energy labels, and construction year categorization- CBS data (2013–2020) regional, historical trend for dwelling construction and demolition, including cities and municipalities- National Energy Outlook (KEV, in Dutch) 2021 household data on future projections at the national level	- First, we intersected the regional and dwelling maps that categorized dwelling types and energy labels - Next, building level data was aggregated on dwelling types and energy labels toward the regional level using MS Excel - Next, future regional projections were made based on the historical trend - As neither the construction nor the demolition of dwellings in various municipalities in the province of Groningen followed a linear pattern historically, we considered the average of these activities. For generating projections, we prioritized the demolition of the other dwelling type as these buildings have the highest average energy consumption, particularly heat, followed by the demolition of terraced houses. - Finally, the projection in each region was corrected based on the national projection. KEV 2021 provides data until 2040. We linearly projected this data until 2050 for each region. - We used the current provincial dwelling share for calculating provincial future total dwellings. For the province of Groningen, this number directly matched the aggregate of all added regions. For other provinces and the RNL, the construction and demolition data were adjusted to match provincial data based on KEV 2021.	- In GIS, for 10 % of the dwellings, no energy label was mentioned. This group used the year of construction as a proxy for the energy label, based on the input from a household sector expert from the Netherlands Organization for Applied Scientific Research Energy Transition Studies - The same construction equivalent was assumed for all dwelling types - For future demolition projection, we considered only existing GFE dwellings as they have the highest heat demand. - For Groningen city, the demolition of terraced houses is distributed with 16 % and 84 % between the inner and outer cities, respectively, based on their current distribution share.
Services	Offices Education Industrial Halls Hospitals Others	- GIS regional map - the service building level map with building types, energy labels, and construction year categorization - KEV 2021 data on future projections	- First, the regional and service building maps were intersected - Next, building level data on dwelling types and energy labels were aggregated toward the regional level using MS Excel - Finally, we made future regional projections based on the national projections	- In GIS, service buildings with multiple activities were allocated to the "other building" category.
Industry	Starch (food and beverage (FBI)) Malting (FBI) Methanol (Chemicals) Solid board (Remaining industries) Glass fiber (Remaining industries)	- MIDDEN reports for current main product production volume - The SAVE production model database for future projections	- First, industries added in this study and [4] were linked with various industry regions created in the OPERA model (Fig. 3). The method related to industry additions is provided in [4]. - For existing activities,	- The assumptions are the same as those made in [4]

(continued on next page)

Table 2 (*continued*)

Sector	Activity name/ category	Data requirement/ availability	Regional allocation method and criteria	Major assumptions
			production volumes and energy production per unit volume were updated - Only for the newly added activities in the OPERA database, reference production processes were introduced. These processes competed with generic sectoral energy supply options.	
Agriculture	Heat demand Electricity demand Mobile machinery	- CBS regional data on greenhouse areas - 2050 data on arable land from [5] - GIS regional map - CBS data on arable land	- CBS municipality level data on greenhouse areas is linked to various municipality rests. The heat and electricity regional demand share is similar to the regional greenhouse share and corresponds to that in [4] - Intersecting the arable land map 2050 with the regional map to obtain regional arable land and correcting for mismatch with the projection of CBS arable land historical data. - Mobile machinery energy demand is proportional to the regional arable land share	- Agriculture is assumed to be absent in cities

in the province of Groningen is dominated by the BE and industrial sectors, and both are highly spatially explicit. Agricultural demand is low, but still spatially explicit. Table 2 lists the details of the regional allocation method for each energy-demanding sector under various categories/activities defined in OPERA, along with the data requirements and major assumptions.

Built environment

The population centers received the majority of the BE energy demand. The building types and energy labels were taken from [4] and were regionally allocated based on current (2019 latest data available) spatial distribution. For this study, GIS maps were available at the individual building level, including growth projections (see Table 2 for details). Modeling-wise, GIS tools were used to intersect the GIS map with our regional categorization and building maps to segregate buildings in each region, while do so separately for both households and service buildings. Data were aggregated in MS Excel spreadsheets within a land-use region and transferred to the OPERA database.

Energy label categorization GFE (highly inefficient) to A+ (highly efficient) was followed, similar to [4]. The major difference is that [4] considered energy efficiency measures that could theoretically allow any energy label dwelling to move to label A+, which is unrealistic in practice. This paper allowed the energy labels of the dwellings to improve toward certain predefined labels based on the suggestions of sectoral experts. For instance, GFE label buildings can move one label up to DC or two labels up to B. The investment costs associated with energy label changes were considered from [4] explicitly for households and the services sectors.

Construction and demolition rates at the municipality level were considered while making future projections on household buildings – see Appendix A for region-specific detailed data and analysis. One of the major assumptions was future apartments constructed in cities will be only A + energy labeled as this dwelling and energy label is expected to dominate in future construction within cities (also see Section 4). The future number of dwellings for each energy label for other provinces and the RNL was calculated based on the current share of different dwellings and energy labels, as in [4]. For services, the aggregation level of buildings in our defined regions is similar to that of household buildings. For other provinces and the RNL, the data on service buildings was taken from [4].

Industries

New nodes were added for industries having significant impacts within the Netherlands or Groningen in terms of energy demand, emissions, or industrial waste heat supply potentials (see Section 2.2.2). These nodes accommodated either individual industries or industrial clusters, depending upon their spatial locations (Figs. 3 and 5). In terms of modeling, these nodes were allocated future production volumes of the main products or activities related to the industries located at these nodes along with their energy demand per unit activity. The model determined the final net demands of various energy carriers based on optimization. The production volumes and final energy demand of each activity was based on the method suggested in [4] and their future production volumes were updated as per the latest production data. For electricity supply to the node, we considered the current network structure, particularly the MV network (see Section 2.3.1). Currently, any specific energy supply infrastructure for other carriers are not considered. For Groningen, eleven independent industrial nodes were created based on the industries identified in the previous study [4] and some newly added industries in our current analysis (see Table 1 and Section 2.3.2 for the node selection method).

The new activities included are methanol, starch, malting, glass fiber, and solid board productions, which are categorized under various industrial subsectors (Table 2) – refer to Appendix A for region-specific details. There might be seasonal industries within a node, such as the sugar industry located in the Groningen city industrial cluster. A demand profile was created according to the production season of a sugar plant, that is, from September to mid-January.

Agriculture

Agriculture is considered to be present only in the remaining part of each municipality. The energy demand in each of these regions is based on the greenhouse area as these activities are responsible for the majority of energy demand [4] (see Table 2). Additionally, the mobile machinery used in agriculture was regionally allocated considering the regional share of arable land in each municipality as this land influences the energy used in corresponding machinery. For this purpose, 2050 arable land availability obtained in [5] was considered.

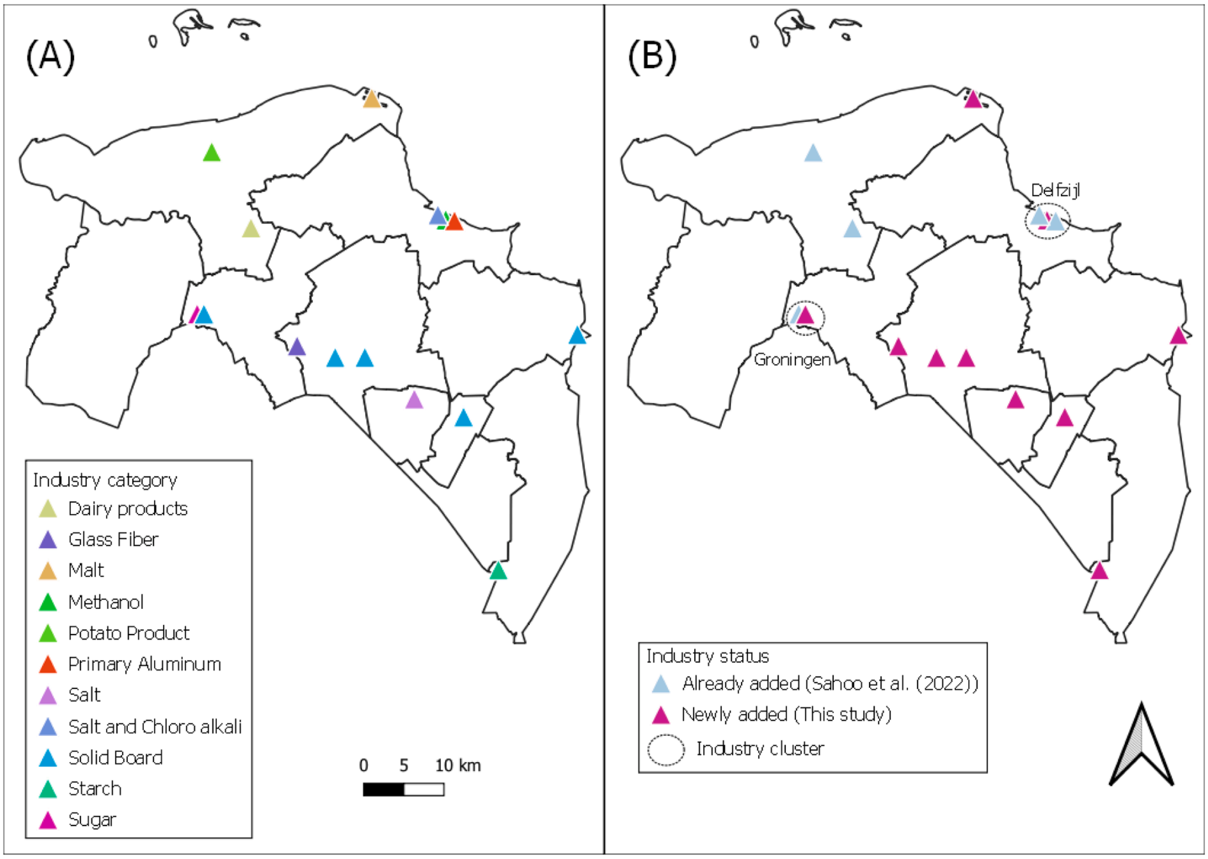

Fig. 5. (A) Industrial activity category used in this study and (B) Segregation of already added industries in [4] and newly added industries in this study, showing industrial clusters, created using OPERA.

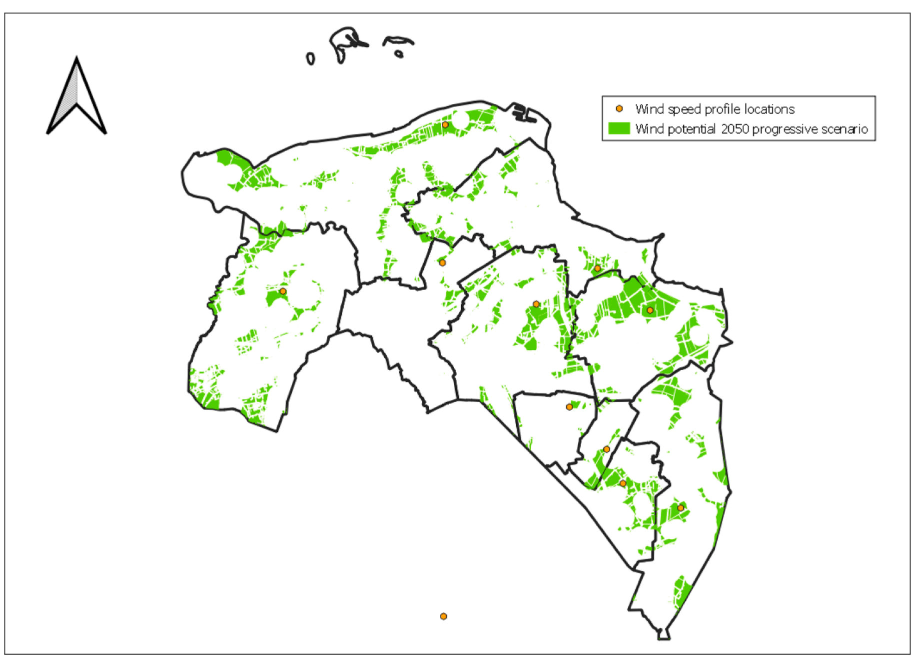

Fig. 6. Locations where wind speed profiles were considered, overlaid on the wind 2050 progressive scenario map obtained from [5].

2.2.2. *Energy supply*

In this section, we provide regional allocations for energy supply options linked to the following renewables: solar PV, wind, geothermal, and biomass. We also describe some major energy supply technology options that produce a variety of secondary carriers not using the abovementioned renewables. Additionally, we investigate the IWH potential of the industries analyzed in Section 2.2.1. We directly used inputs from our previous study on renewable energy potentials for these

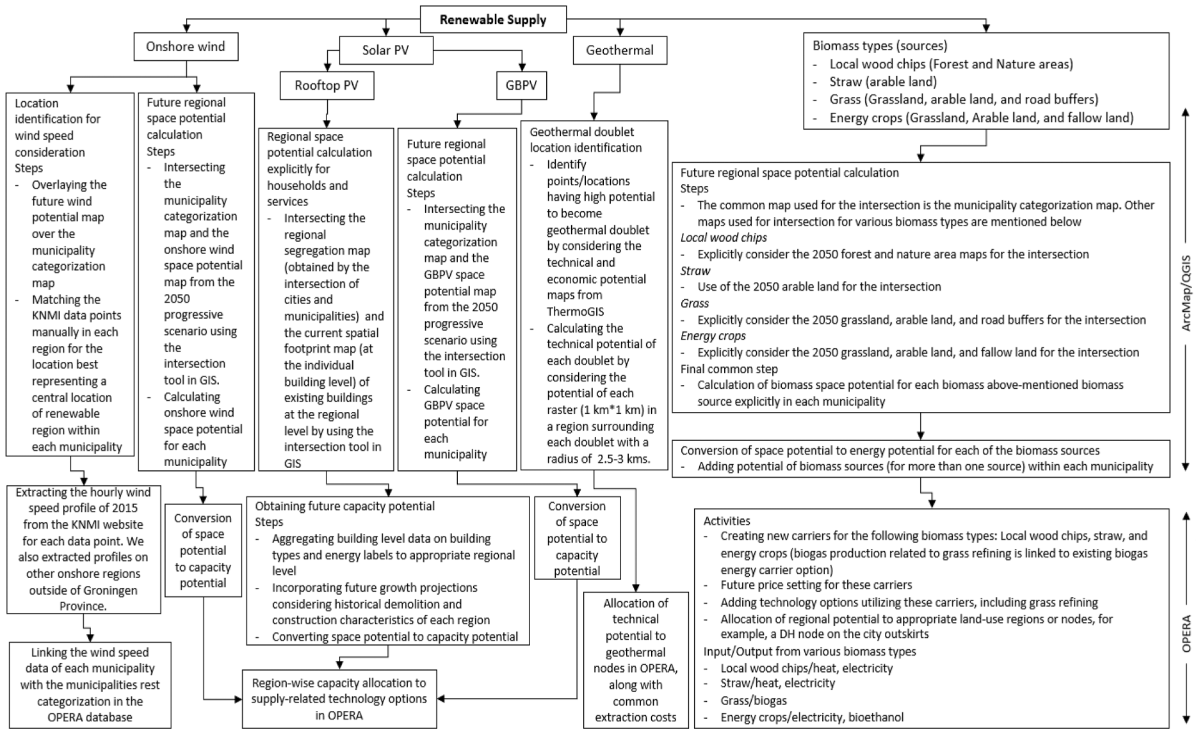

Fig. 7. Summary of unidirectional information flows from GIS to OPERA for renewables on the supply side. GIS and OPERA interlinking activities are illustrated in detail for renewables. The 2050 renewable potential maps were obtained from [5].

resources, which was based on considering the existing and future developments in land use and spatial policies influencing what may be possible in the province [5]. We used the most optimistic (least constrained) 2050 progressive scenario from this previous study. No additional region or node was created for energy supply, except for geothermal. For regional allocation of renewables (except geothermal), we intersected the progressive scenario and GIS municipality maps, and the potentials were allocated to the remaining part of each municipality (Fig. 7) unless stated otherwise. The energy potentials for regions outside the province of Groningen remained the same as those in [4].

Wind

Apart from the regional distribution of wind future spatial potential from [5], an additional methodological step was introduced to estimate the wind speed profile for the remaining part of each municipality (Fig. 7). For this, one location was identified, which would represent the central location of the onshore wind feasible region in each municipality (Fig. 6). These locations should coincide with Royal Netherlands Meteorological Institute (KNMI, in Dutch) data points [45], where KNMI refers to the meteorological agency of the Netherlands.[2] Explicit data points were considered instead of the average wind profile of each feasible region because averaging leads to compromise of actual peaks and ebbs at various time periods which would have led to a poor estimation of wind farm capacity and wind energy supply potential – refer to Appendix A for detailed analysis on this method.

Solar

For solar ground-based photovoltaics (GBPV), a common and existing profile[3] for the whole of the Netherlands was used as the solar spatial potential does not vary as much as the wind potential. Regional BE buildings mapping was used for rooftop PV allocation. The projected rooftop space of the current buildings was calculated using the area function in GIS. The method used in [5] was applied for future projections. Inland floating PVs, mainly on stagnant water bodies, are gaining attention in the Netherlands. Therefore, regional allocation of floating PV potential was calculated based on the current inland standing water proportion, assuming that this space will not change in the future – see Appendix A for region-specific potential calculation. The potential of other PV types included in OPERA is considered the same as in [4], and no attempt was made to regionally allocate these PVs. In addition to the above-mentioned electricity-producing PV options, OPERA considers heat production from solar thermal options in different sectors. However, no regional allocation is made for this option.

Geothermal

The Upper Rotliegend geothermal stratigraphic layer was considered for analysis as this is the only shallow layer available for the province of Groningen with high heat potential [41]. A maximum of three probable geothermal doublet locations were manually identified as they have high potential compared to the surrounding locations within the province by overlaying the potential recoverable heat and economic potential maps provided by ThermoGIS [43]. Table 1 further details the selection criteria of these doublet locations, and Fig. 10 shows these locations. In terms of modeling, each doublet was made an individual node in OPERA and linked to the created DH network (see Section 2.3.2). Additionally, these nodes were connected to the MV network (Fig. 3) for providing electricity to pumps responsible for extracting heat – see Appendix A for further detail.

Biomass

Before this study, biomass production-related activities were not well represented in OPERA. All biomass type energy balances occurred at the national level. A variety of biomass types were introduced in [5] which could not be tackled by existing biomass-related energy carriers and the corresponding technology options in OPERA. Four biomass-related energy carriers were introduced in OPERA: wood chips incorporating forest and nature biomass, biomass straw, energy crops, and grass incorporating grass refining in arable land and grassland, along

[2] This organization is responsible for the Dutch national weather forecasting service. The primary tasks of KNMI are monitoring of climate changes, weather forecasting, and monitoring seismic activity.

[3] This profile is the same as the profile used in [4]. The source of this profile is [75].

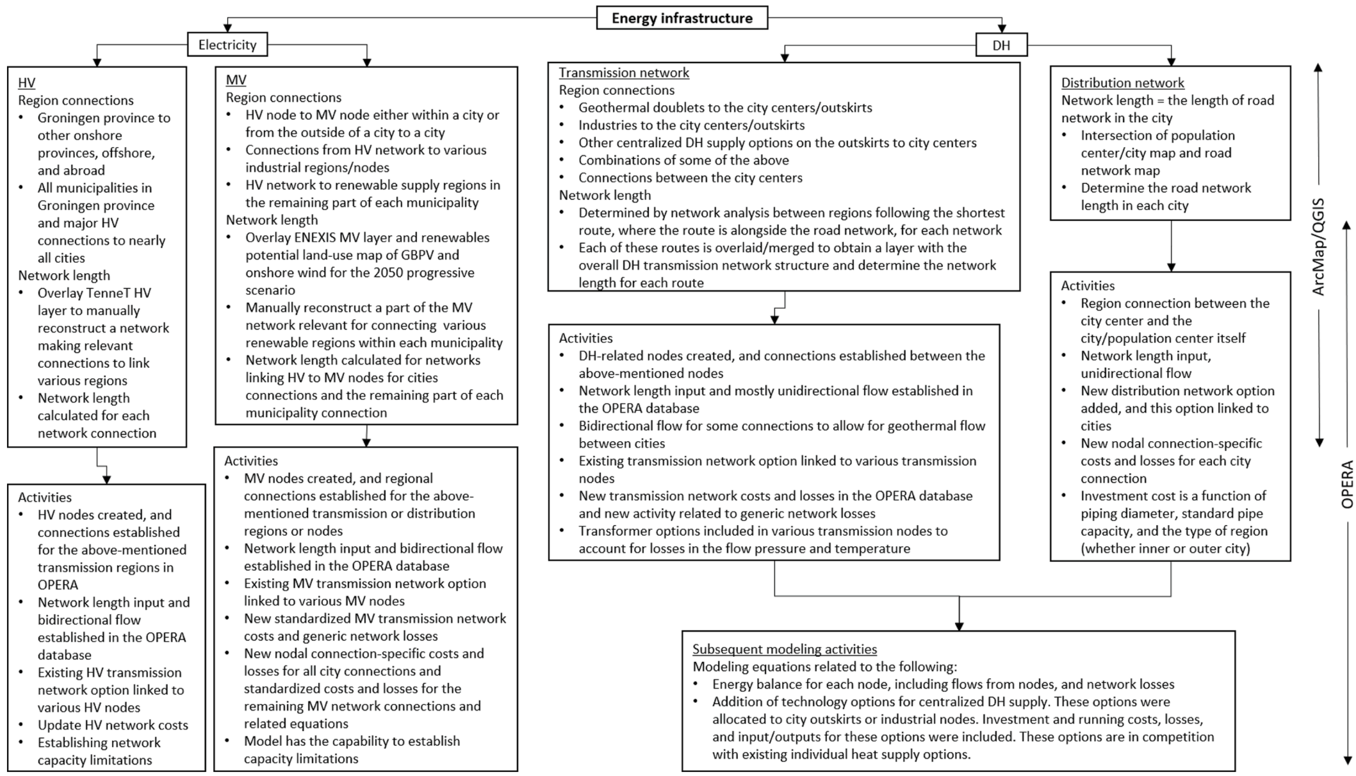

Fig. 8. Summary of unidirectional information flows from GIS to OPERA for energy infrastructure. GIS and OPERA interlinking activities are illustrated in detail related to energy infrastructure.

with verge grasses (Fig. 7). Energy carriers related to manure, both dry and wet, already existed in OPERA.

All newly added energy carriers were regionally balanced, where a region is a municipality with a movement distance of 5–25 kms. The conversion from land-use related to these energy carriers to biomass energy content is based on [5]. The production costs of each of these carriers were determined based on a literature review of biomass wood chips and straw [46], energy crops [47], and grass [48]. Technology options utilizing these energy carriers were introduced, along with their technical characteristics, inputs/outputs, and cost structure. The outputs and the corresponding technology options from energy crops, wood chips, and straw were heat boilers or combined heat and power plants (CHPs). Additionally, energy crops can produce ethanol. Grass was converted into biogas using specific grass-based digesters. These biomasses were allocated to municipality rests or industrial nodes because biogas can be utilized by the BE or industries. The preferred location of energy crops was industrial nodes and grass and wet manure were municipality rests. Biomass wood chips and straw were linked to DH energy supply-related nodes (see Section 2.3.2). As dry manure has a low production volume at the municipality level, it was not allocated to any particular region or node, but was considered within the entire province and was balanced at the national level. GIS-based regional allocation was performed for most of the carriers (Fig. 7). Household and municipal solid waste (MSW) produced within the province of Groningen were allocated to the Delfzijl industrial node because the only MSW incinerator in the province is located at this node.

Other energy supply technology options

These options can be divided into two categories. (1) These options are not a part of any energy-demanding sector. For example, electricity is produced from an H_2 steam and gas turbine (STEG, in Dutch), which is a highly efficient electricity-producing turbine with H_2 as the input. Similarly, technology options associated with centralized heat supply to a DH network are also a part of this category. (2) These options are a part of energy-demanding sectors and are responsible for meeting the sectoral energy demand. For example, heat is produced from options such as HPs, hybrid boilers, and electric boilers in the BE or industrial sectors (see [4] for more details).

Industrial waste heat

The province of Groningen has a strong potential for IWH because of the presence of a variety of industrial clusters and individual industries at various spatial locations. IWH can make a significant contribution to a provincial DH network – see Appendix A for IWH potential calculation method. Data for newly added industries in our analysis rely on existing industrial subsector categorization as it is difficult to find IWH-related literature for each activity. Glass fiber is a specific case that is not covered by existing categorization and has a high IWH potential owing to its high operating temperatures. A separate industrial subcategory was created in OPERA for glass fiber and calculated its IWH potential based on a case study in Germany [49] and adjusted the production volumes according to our case.

2.3. Energy infrastructure analysises

Every land-use region and node were connected using energy infrastructure. Fig. 3 illustrates the detailed OPERA activities related to energy infrastructure in different nodes and Table 1 lists their selection criteria. The electricity network is already represented in OPERA [4], although not in significant spatial detail, as discussed in Section 2.3.1. For the heat network, no modeling structure is available, particularly related to DH, which we modeled, including the key technical and economic constraints (Section 2.3.2). Fig. 8 illustrates the GIS-related activities and their interlinkages with OPERA in detail.

2.3.1. Electricity network

The electricity network within Europe is interconnected. Therefore, electricity flows in the Netherlands are affected by adjoining European countries with which the Netherlands is connected via the HV network. As OPERA is an integrated energy system model of the Netherlands, it

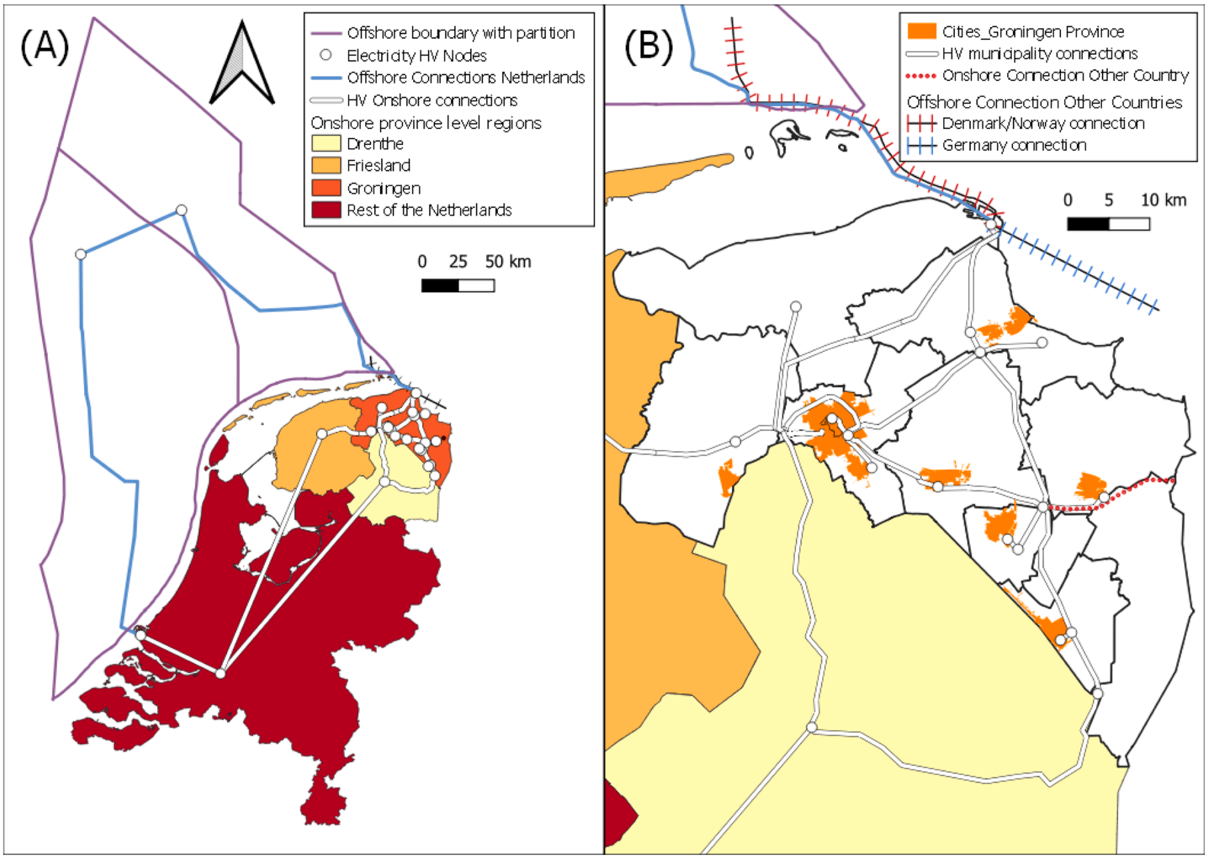

Fig. 9. (A) Onshore HV connections of the province of Groningen with other provinces in the northern region of the Netherlands and the RNL with the Dutch offshore part of the North Sea and the partition related to regional allocation towards the province of Groningen and the RNL and offshore HV connections to this region. (B) Enlarged view of the province of Groningen, representing onshore HV connections between municipalities, along with the onshore HV connection between Germany and the province of Groningen, and the offshore HV connections between the province of Groningen and Denmark/Norway and Germany. Municipalities with shortlisted cities have nodes closer to these cities.

does not perform pan-European power flow analysis. To consider electricity import–export profiles with these countries, OPERA is soft-linked with a pan-European electricity market model, COMPETES [6]. For consistency purposes, a similar high renewable scenario (see [4]) is considered in both models. For the adjoining countries that were added in this study (see Section 2.1), electricity import–export profiles of these countries were used from the COMPETES model run. OPERA does analyze electricity flows at the regional and the national level. The network spatial categorization and representation is presented in more detail below.

High voltage network

Earlier, OPERA incorporated the HV network cost as a function of distance, along with capacity constraints between regions and network losses [4], although these distances were simple straight-line connections between nodes. This study improved the spatial representation of the network for the province of Groningen based on the actual physical electricity network through GIS (Fig. 8). In OPERA, the province of Groningen has HV network connections with multiple regions within the Netherlands and with the Dutch part of the North Sea. Therefore, the deployment of renewables in Groningen will impact the network capacity of other regions. Henceforth, the capacity ranges for the whole of the Netherlands were improved, i.e., 1.25 times of the current capacity (latest values on current capacity was obtained from the HV network service provider for the Netherlands [50]), to accommodate an increase in capacity due to the deployment of large scale renewables. The model determined the actual increase in various connection capacities through energy system optimization. This increase was compared with the planned capacity addition of these connections so that network capacity shortages or constraints can be better identified.

For HV network connections, the priority was to connect all municipalities by creating at least one HV node in each of them. The emphasis was on nodes representing actual major interconnections, which were responsible for electricity supply to cities via the MV network, electricity supply from renewable regions located in the remaining part of municipalities, electricity supply to industrial clusters, and connection to the offshore electricity network. A total of 18 nodes was created for the HV network for the province of Groningen (Fig. 9). Appendix A further details these connections and nodes for the province of Groningen.

Nodal connections in GIS was relied on maps from Dutch transmission system operator, TenneT, for onshore regions [51] and a future scenario analysis developed by the Netherlands Environmental Assessment Agency for offshore regions [52] - Fig. 9(A). These maps were overlaid and manually constructed network connections linking HV nodes to determine various network lengths in GIS.

Medium voltage network

Before this study, the MV network in OPERA was represented as a copper plate at the national level, i.e., demand and supply were met within the country without consideration of network distances. A framework for MV, similar to HV, was created in this paper, including network costs and losses as a function of distance. Additionally, constraint characteristics and region/node-specific connection types were introduced, all of which are major modeling framework improvements on a regional level. The MV network is important on a regional level because large scale deployment of renewables, growth of cities, and electricity demand due to electrification will significantly

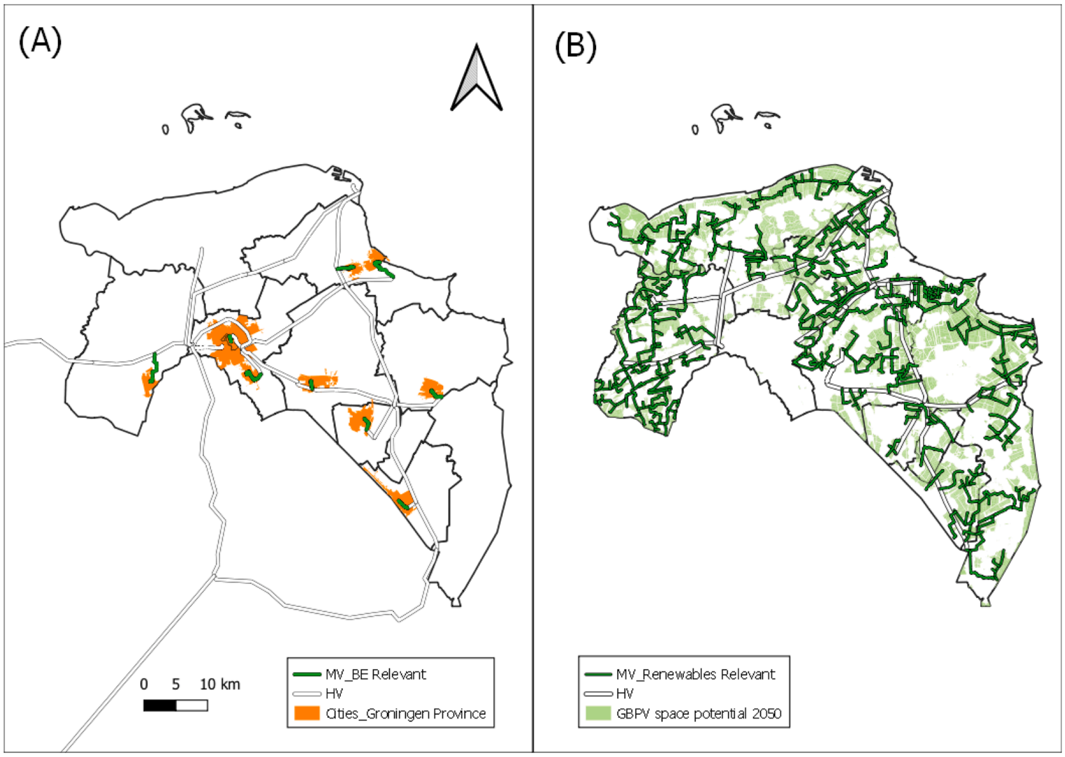

Fig. 10. (A) MV network connections linking various cities (i.e., BE relevant, within the province of Groningen) and (B) MV network connections relevant for renewables (overlaid on GBPV future (2050) space potential based on [5]).

affect the future MV capacity and its spatial structure.

The MV network was divided into two major categories in this study. First, an MV connection was established from an HV network to the municipality rests for supplying renewable energy to the electricity grid. The MV network map was obtained from the MV transmission and distribution system operator for the province of Groningen, ENEXIS [53]. A part of this network that will be nearer to the space suitable for GBPV and onshore wind in the 2050 progressive scenario [5] was manually reconstructed and the network lengths were calculated in GIS (Fig. 10). The renewable regions within each municipality are directly connected to an MV network because these sources are large and centralized. As every municipality has a positive potential for renewables, we created ten MV nodes to establish MV connections from HV nodes.

As cities cannot be connected directly with an HV network, additional MV network connections were created to supply electricity to cities. Establishing this connection through the MV node is helpful in future situations wherein the electricity demand of the cities increases owing to, for example, increased electrification to meet heat demand in the BE. Similarly, the electricity supply can also increase due to the presence of more BE-related rooftop PVs. This demand and supply may not occur within the same time interval. By creating an MV network connection to the cities, the energy-demanding/supplying regions were segregated from the energy infrastructure, which is our research contribution. MV connections were established between city MV nodes and an HV node located in the municipality (Fig. 10). An additional MV connection was provided to the Delfzijl industrial cluster through a corresponding node because of the presence of a large number of industries, and a direct HV connection could not be provided to these industries. Thus, a total of 21 MV nodes were created in OPERA for Groningen (Fig. 3).

The MV network does not have a single standardized cost as an MV network can be responsible for transmission or distribution depending on the region or connection to which it supplies electricity [54,55]. Therefore, a region connection-specific database was introduced in the OPERA. Different cost and loss characteristics were set for cities and other connections [56] as listed in Appendix B. Capacity limits for the MV network could not be implemented because of a lack of data availability on the current network capacities in various regions, although the modeling structure allows us to incorporate these limits. Nevertheless, the inclusion of network costs provides a primary, yet simplistic, representation of the additional investments required to potentially expand the MV network if needed (see Section 4). The MV network connection with the HV network allows us to understand how the impact of electricity transmission at the national level may be translated to electricity distribution at the regional level.

2.3.2. *District heating network*

DH network is not common in the Netherlands and has only recently gained importance as a possible future heat supply option. In the province of Groningen, the municipality of Groningen is the most active region, and it is developing a DH network for approximately 10,000 households. The DH structure was almost nonexistent in OPERA. This study performed the following DH-related activities: adding heat supply sources, establishing network connections, and modeling DH, all of which are discussed in the subsequent sections, thereby making a significant improvement to the OPERA modeling framework related to the DH representation. Another major research contribution is the creation of a pan-provincial DH network spatial structure not found in any DH-related literature studies or integrated energy system models. In addition, improving the technical details of this network within the context of regional energy system modeling is a major step as heat gets less attention at higher geographical levels.

Heat supply sources

Various centralized heat supply sources and technology options can potentially support DH networks in the province of Groningen, ranging from geothermal, and IWH, to HPs. Future geothermal heat and potential IWH locations were fixed, as discussed in Section 2.2.2. The focus was centralized heat supply options that could provide heat to the whole city and added those options to the OPERA database, based on [57], as the existing DH options were insufficient. New nodes were created in

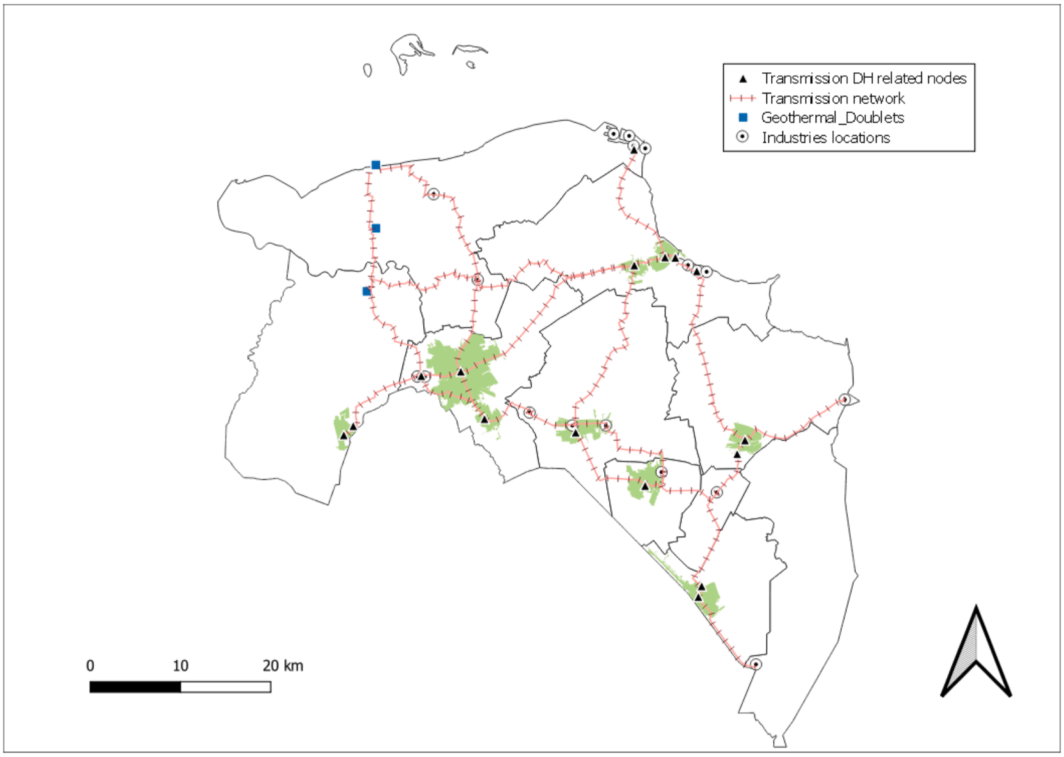

Fig. 11. Transmission DH network for the province of Groningen, including industries (as some connections are exclusively for individual industries), geothermal doublets locations, and DH nodes used to represent the city center, city outskirts, or industry clusters.

OPERA to spatially allocate these options. From a city planning perspective, it likely that these nodes would not be positioned within city centers, notably because of their spatial and environmental implications. Therefore, all of these centralized options were placed at a single location on the current outskirts of the cities to ensure proximity to demand and represented that location as a new node. While doing so, further considerations were made on whether industries might be located close to a city, as they are a source of IWH.

If a single industry is located on the city outskirts, then the location of all heat supply sources is shifted to that location to reduce the additional piping costs associated with connecting IWH with a DH network. For multiple industries, a centralized location or node was identified, and a DH network connection was established. This process identified four cities without any industries located on the city outskirts, thereby creating four additional nodes on the city outskirts for Groningen (Fig. 3). Cities that were too close to one another within a municipality were awarded one node on the outskirts of the larger city. For example, Haren and Appingedam cities had no nodes as these are closer to Groningen and Delfzijl cities, respectively, within the same municipalities. All these activities assisted in reducing the number of DH-related explicit nodes.

DH network connections

The route for the DH network is along the road network to avoid the pipelines laid in undesirable areas, based on [58]. The existing road network map for the Province of Groningen was used for calculating network lengths. The DH network is constructed to connect cities to energy-supplying options, which include the geothermal doublets and industrial locations for IWH, implemented as nodes in the model. Constraints were imposed, for example, related to the capacity or energy potentials of supply options and related to the capacity and flows of energy (heat) infrastructure, and in the process, our first research question was answered. For DH, two types of network connections were created and used in this paper: distribution DH and transmission DH.

The distribution DH is useful for short connections within cities and were added to all included cities for this paper. For all cities, the distribution network starts from the city center where the heat demand density is the highest [5] and expands radially outward towards low density areas, as this structure is identified to be the shortest possible network length [59]. Hence, starting from the city center also leads to least heat losses. Ten nodes were created in OPERA to account for the center of each city (also see Fig. 3). The length of the network was determined using the intersections of the road infrastructure and population center maps in GIS (Fig. 8). The overall DH network length of each city was reduced by 30 % to account for the repetitive nature and bi-directionality of the road network.

The transmission network for DH is useful for long network connections, say > 10 kms, but also short unobstructed connections of a few kms. Compared to a distribution network for DH, a transmission network has relative lower losses and investment cost per unit of distance, as well as higher heat flow capacity. These aspects are important to transport heat over longer distances. The transmission network created for this paper connects population centers and DH supply sources such as geothermal doublets or industries for waste heat. Modeling-wise, the GIS network analysis tool with the shortest route (road network) criteria [60] was used to obtain the minimum connection lengths between two DH-related nodes linked to the DH transmission network, for example, geothermal doublets, industries, and city outskirts. All possible connections between these were created without repetition by utilizing the same connections wherever feasible and allowing the OPERA model to choose cost-effective routes through optimization. The planning related to network connections can be divided into four categories. (1) Connections were established from geothermal doublets to city centers or outskirts (whichever was nearer), either directly or via industries depending on the spatial location of the cities, including connections between doublets. (2) Connections were established from industry to city centers or outskirts, with a preference to outskirts. (3) Connections were established between industries and between doublets with an emphasis to reduce overall transmission network length. (4) Connections were established from city outskirts to city centers, including connections between city centers, for example,

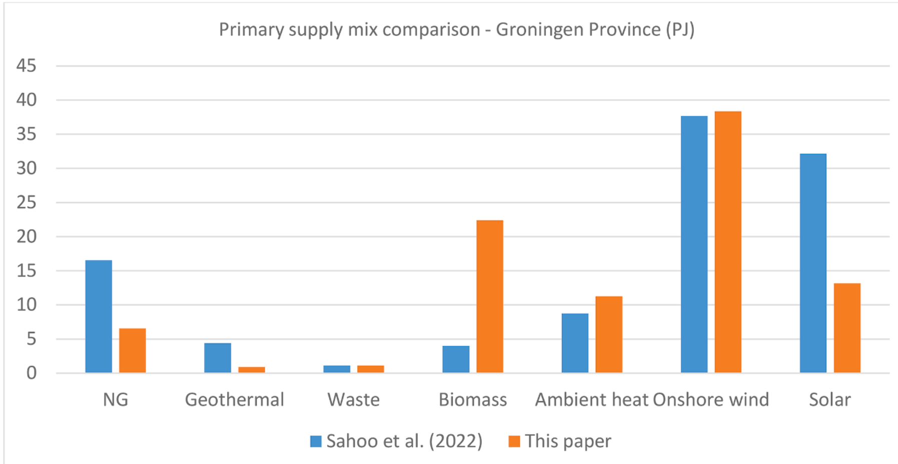

Fig. 12. Primary energy mix comparison (data in PJ) between the results of Sahoo et al. [4] and this study for the aggregate of all regions within the province of Groningen.

between Haren and Groningen city and between Appingedam and Delfzijl city. Transmission DH connected the source to distribution DH unidirectionally in the OPERA model. Fig. 11 shows the transmission DH network created in GIS which is used as the input in OPERA.

This study is a first-time attempt to spatially connect a whole province of 3000 km^2 through a DH transmission network. Even though the province of Groningen does not have any concrete plan on the layout of a DH network, a recent provincial planning document on heat [61] suggested that transmission lines could come up from Delfzijl industrial cluster to Groningen city, which we have also included. Such policy developments signify that a regional energy system model for analyzing regional DH networks is indeed a sensible addition to the toolbox of energy system analysis.

District heating network modeling

The DH model structure was created similar to the electricity network to avoid adding too many equations in OPERA. The major differences are that the cost and losses are dependent in a non-linear manner on the capacity of the pipeline (or pipe diameter). In addition, unlike the electricity network, the flows are sequential and unidirectional which is distinguished in the database. The model allows bidirectional flows, but the redundant connections are discarded in the model preprocessing run. Differences exist between DH activities within a region/node and between nodes, as shown in Figs. 3 and 8. A generic cost and loss structure was used for transmission, whereas a connection-specific structure was used for distribution. Appendix C presents a detailed description and modeling equations related to the new DH structure addition in the OPERA model.

3. Results

The scenario definition is similar to that in [4] and emphasizes extensive renewable deployment and national self-sufficiency in 2050[4] [62]. The renewable potential of the province of Groningen is based on [5], and those for the other regions are similar to [4]. The sectoral demands of the province of Groningen and other regions are the same as in [4]. The total greenhouse gas emissions at the national level were restricted to zero in the scenario definition.[5] Some emissions, particularly non-CO_2, indirect, and process emissions, were difficult to avoid. In OPERA, the balance of these emissions occurs at the national level. Therefore, the energy demand and related costs associated with the processes or technology options responsible for negative CO_2 emissions (and related infrastructure) were excluded from our regional analysis.[6] These processes and related costs were allocated to the RNL, instead, and the interregional electricity flows and electricity imports to the province of Groningen were adjusted.

The results of this study were compared with those in [4] to understand the impact of detailed spatial segregation on energy balances and costs. For consistency in the comparison of results, similar databases were used for [4] and this study. The results are further categorized into energy demand and supply (Section 3.1), interregional energy flow analyses (Section 3.2), and cost analyses (Section 3.3).

3.1. Energy demand and supply

Section 3.1.1 compares [4] and this study regarding the primary energy supply mix, followed by overall heat and electricity energy balances, for the province of Groningen. Heat balances for the BE and industrial sectors were analyzed in all land-use regions and industrial nodes in Section 3.1.2 to illustrate the model capabilities regarding the sector-specific detailed spatial analysis. Section 3.1.3 focused on the capacity potential of spatially sensitive renewables and their utilization shares in the regions and nodes mentioned above.

3.1.1. Primary energy mix and secondary energy balances

The changes in the contribution of some primary energy carriers in this study compared to [4] were significant (Fig. 12). For example, biomass supply in this study was 18.4 petajoule (PJ) higher (approximately 460 %) than that in [4] due to the availability of a variety of biomass types, such as grass and energy crops, in almost every

[4] Apart from renewables mentioned in the method section, fossil fuel-based resources, such as coal, oil, natural gas, and uranium, are part of the national energy system and are nationally balanced. For some of the processes or technology options, particularly related to industries, these resources are necessary, and, for some other processes, these might be cost-effective. Hydroenergy is another renewable option available, which was not discussed in the method section due to its limited availability in the Netherlands. In addition, a variety of biofuel options, such as bioethanol, biodiesel, and bio benzene, are available in this scenario. These options have common utilization in the mobility and industrial sectors.

[5] This does not mean that the province of Groningen has zero net emissions. We did not regionally balance CO_2 emissions.

[6] We did not model the CO_2 network in this study. Neither did we allocate spatial locations for CO_2 storage. The model finds it convenient to allocate greater than50% of the CO_2 consuming process and related infrastructure to the province of Groningen owing to its close connection to the North Sea for cheap electricity. In reality, this might be an overestimation, as a singular province might not agree to share such a high proportion of emission reduction share.

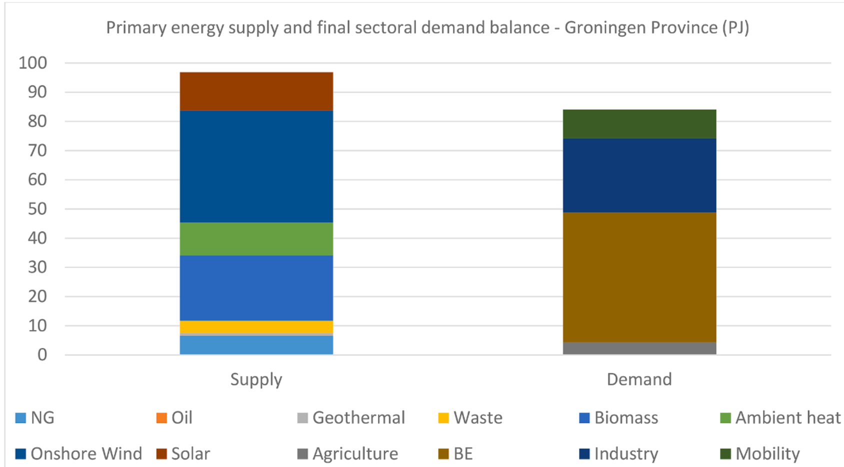

Fig. 13. Primary energy supply and final sectoral demand balance for the province of Groningen (data in PJ).

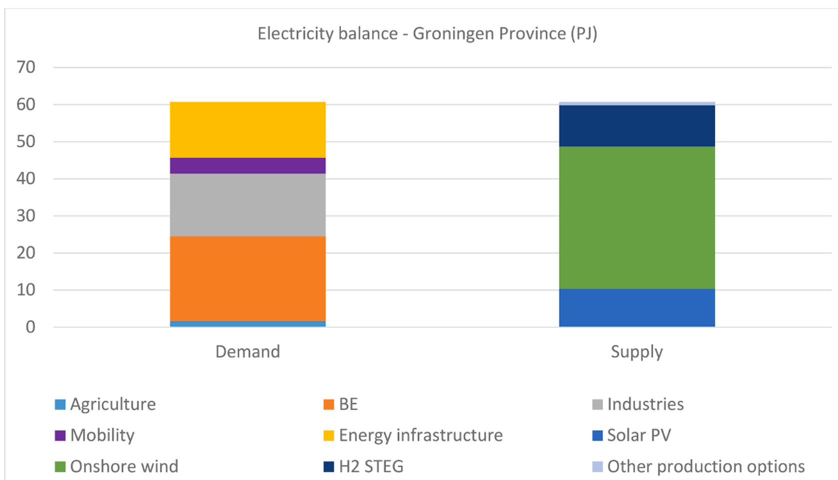

Fig. 14. Electricity balance for the province of Groningen (data in PJ). H_2 STEG is a highly efficient electricity-producing turbine with H_2 as input.

municipality and their utilization within the corresponding region. In addition, our analysis demonstrated that the regional biomass potential is higher than that of [4] and is cheaper to utilize. The contributions from onshore wind increased slightly (2 % increase), whereas the solar PV contribution decreased significantly (59 % decrease). In contrast to [4], the geothermal heat contribution is negligible because geothermal energy is suitable for the BE or horticulture applications in the Netherlands [41]; however, geothermal applications are restricted owing to the presence of natural gas (NG) fields in the province of Groningen, the extraction of which can make the land susceptible to earthquakes. Therefore, geothermal heat had limited application in horticulture. Additionally, geothermal doublets have less use in the BE because of high DH network costs owing to large distances from population centers (Fig. 11). As expected, the onshore wind potential (38.3 PJ) is significantly higher compared to the provincial government assessment for 2030 (the latest year for which the assessment is made) [63], i.e., 9.5 PJ. Similarly, the large-scale photovoltaic potential in this report is 1.8 PJ which is much lower compared to 13 PJ of solar potential in our analysis.

Biofuels, other renewables, such as hydro-energy, and oil have negligible contributions. Other primary sources, such as synthetic fuels and coal, have no contributions. The final energy mix is not represented separately because this mix is almost similar to the primary energy mix, as no major conversion process occurs in the province of Groningen, such as refineries, fuel-based power plants, or electrolysis. NG is utilized in processes such as methanol production (Bio-MCN plant in Industry Delfzijl node), although the utilization volume is slightly lower than that in [4] (Fig. 12). Fig. 13 shows the primary energy supply and final sectoral demand balance for this study. The demand was dominated by the BE (44 PJ), followed by industries (25 PJ).

The BE (23 PJ) and industrial (17 PJ) sectors were responsible for the majority of the sectoral electricity demand (Fig. 14). Most of the electricity demand was met by renewable energy supply options, namely, onshore wind (38 PJ) and solar PV (10 PJ).[7] The heat demand was dominated by the BE (38 PJ) for the province of Groningen in this study (Fig. 15). Among the heat supply options, electric boilers made a significant contribution (14 PJ), followed by hybrid boilers (13 PJ) and HPs (7 PJ).

3.1.2. *Sectoral heat balances*

Each land-use region has a distinct share of various technology options for heat supply to meet the heat demand of the BE sector (Fig. 16). For example, Groningen outer city had the highest heat supply from HPs (2 PJ), followed by DH (1.2 PJ), whereas Appingedam city had the

[7] The role of flexibility options related to power flow, such as batteries or thermochemical storage, is minimal at the geographical resolution considered for our analysis. Therefore, these options are neither mentioned in the method nor reflected in the results related to electricity.

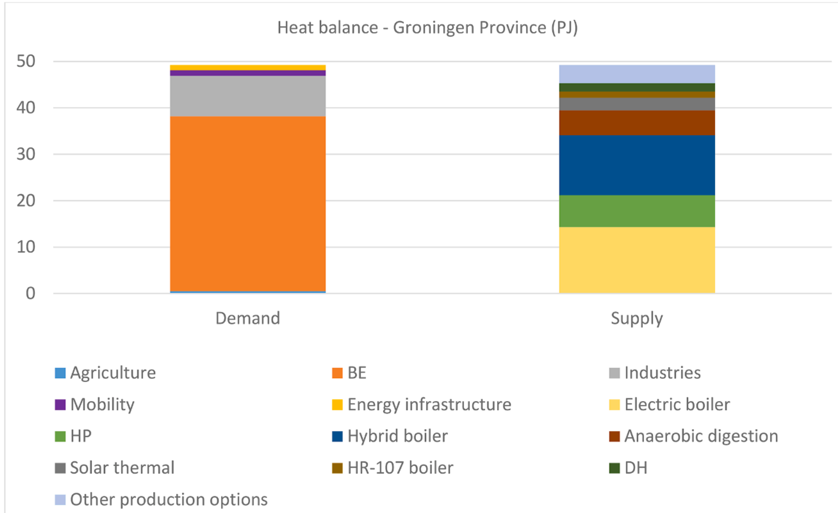

Fig. 15. Heat balance for the province of Groningen (data in PJ). The hybrid boiler has two components: the major component produces only heat and a minor component produces both electricity and heat, and the HR-107 boiler is a high-efficiency boiler.

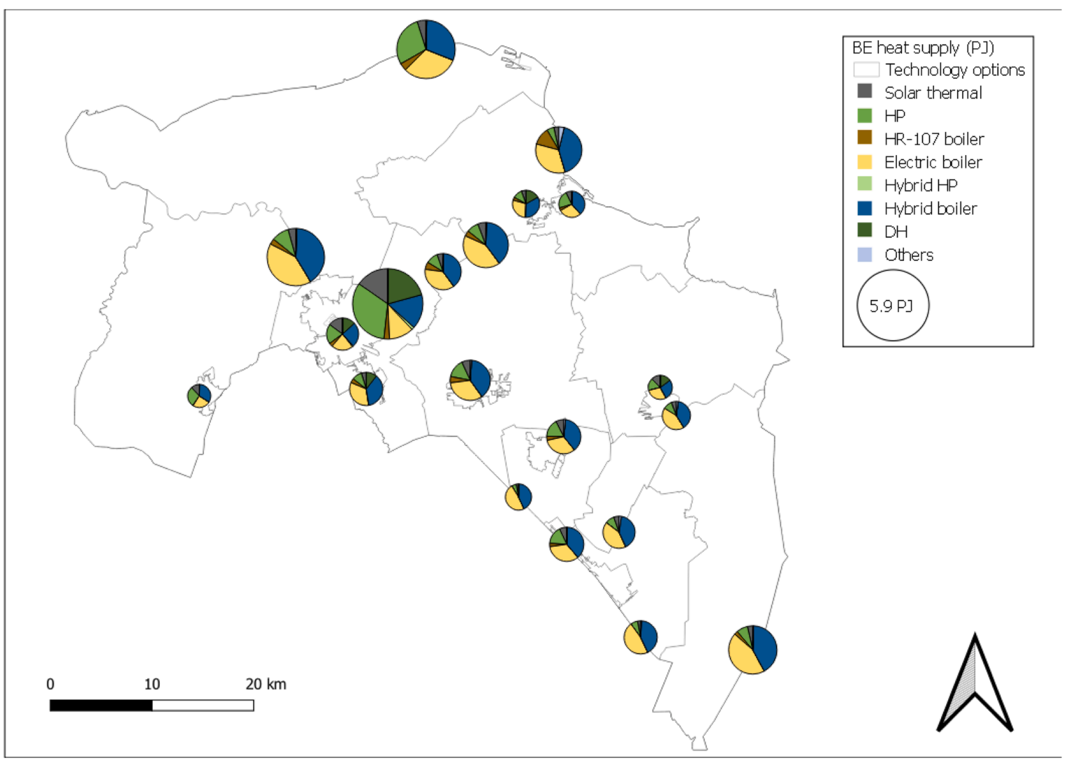

Fig. 16. Heat supply technology options for meeting heat demand of the BE in all the land-use regions in the province of Groningen. The area of the pie represents energy supply volume in PJ.

highest supply from hybrid boilers (0.3 PJ), followed by electric boilers (0.25 PJ). Overall, hybrid boilers made the highest contribution (13 PJ), followed by electric boilers (12 PJ). CHP did not contribute as the investment cost is high, and the co-produced electricity is not cost-effective compared to electricity produced from renewable resources. Groningen outer city had the highest BE heat demand (6 PJ), followed by Het Hogeland municipality and the rest of Westerkwartier municipality (4 PJ each).

Various industrial nodes have distinct heat demands from different industrial subsectors and are supplied by diverse technology options (Fig. 17). The industry Delfzijl node had a variety of heat supply sources that are not present in other locations, such as MSW incineration, methanol production, and oil boiler pyrolysis. The overall heat demand was the highest for the Groningen industry cluster (1.93 PJ), followed by the Avebe starch FBI in Ter Apelkanaal (1.3 PJ). The sectoral heat demand was the highest in the FBI (4.7 PJ). On the supply side, anaerobic digestion resulted in the highest overall contributions (5.3 PJ or 60 % of the total contribution), followed by electric boilers (2 PJ). Some heat produced in Delfzijl remained unutilized (0.3 PJ) because heat production exceeds the demand in this node and the DH heat transmission to the nearby cities is costly.

Detailed spatial modeling of land-use regions and industrial nodes provided the sectoral heat balance insight that was not possible to obtain via crude spatial regional segregation, as performed in [4]. The regional

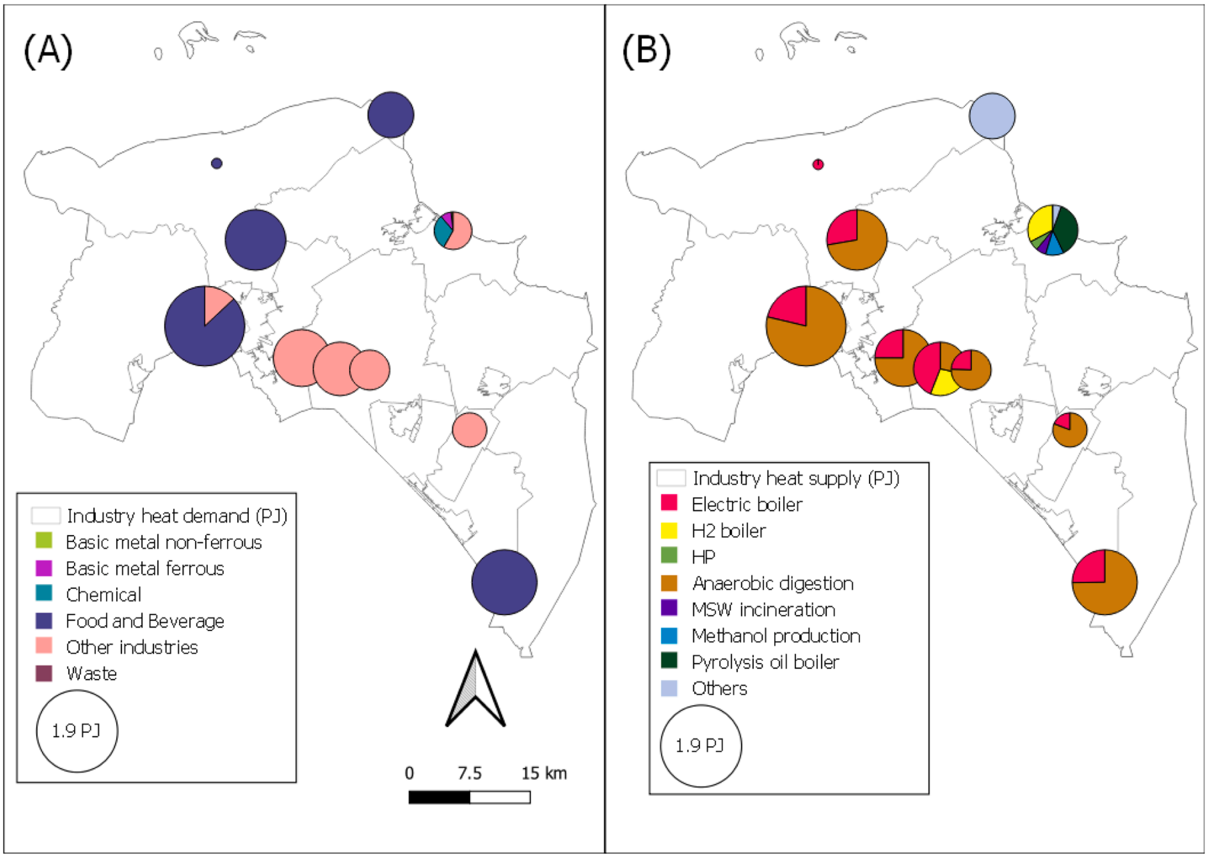

Fig. 17. Heat balance for industries. (A) and (B) represent the heat demanding industrial subsectors and heat supplying technology options, respectively, for the province of Groningen. The area of the pie represents demand or supply volume in PJ.

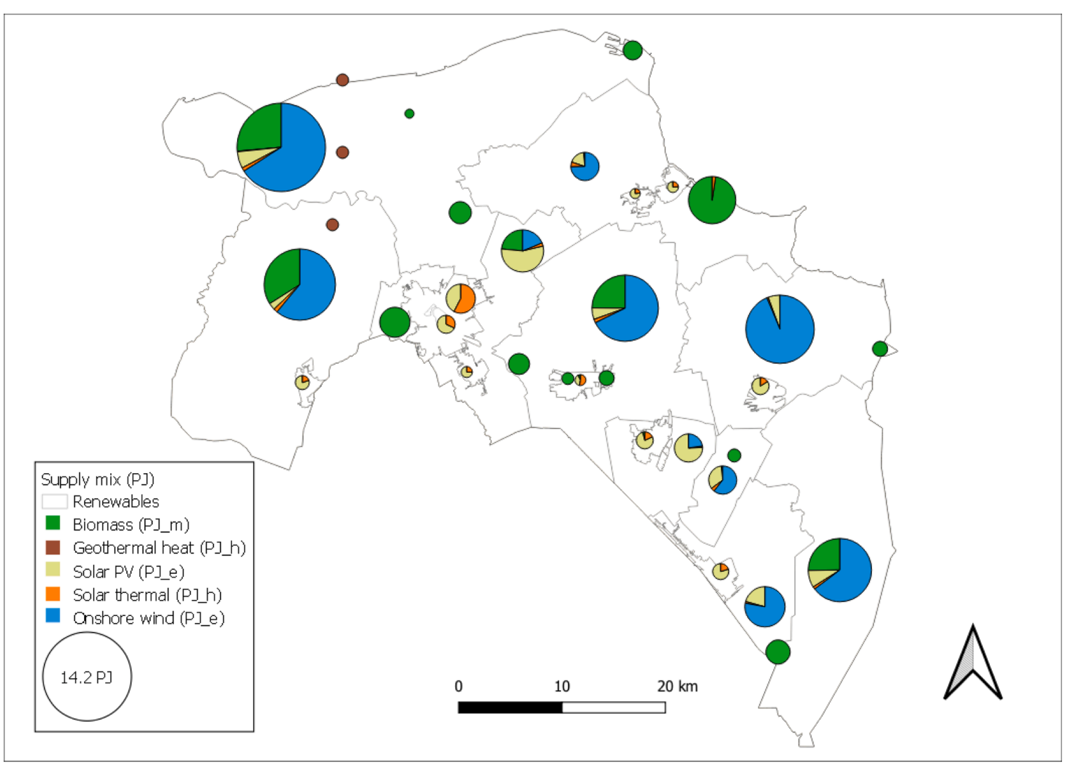

Fig. 18. Renewable energy supply mix in each land-use region and industrial node in the province of Groningen. Here, m, h, and e represent multiple, heat, and electricity energy carriers, respectively. The area of a pie represents energy supply volume in PJ.

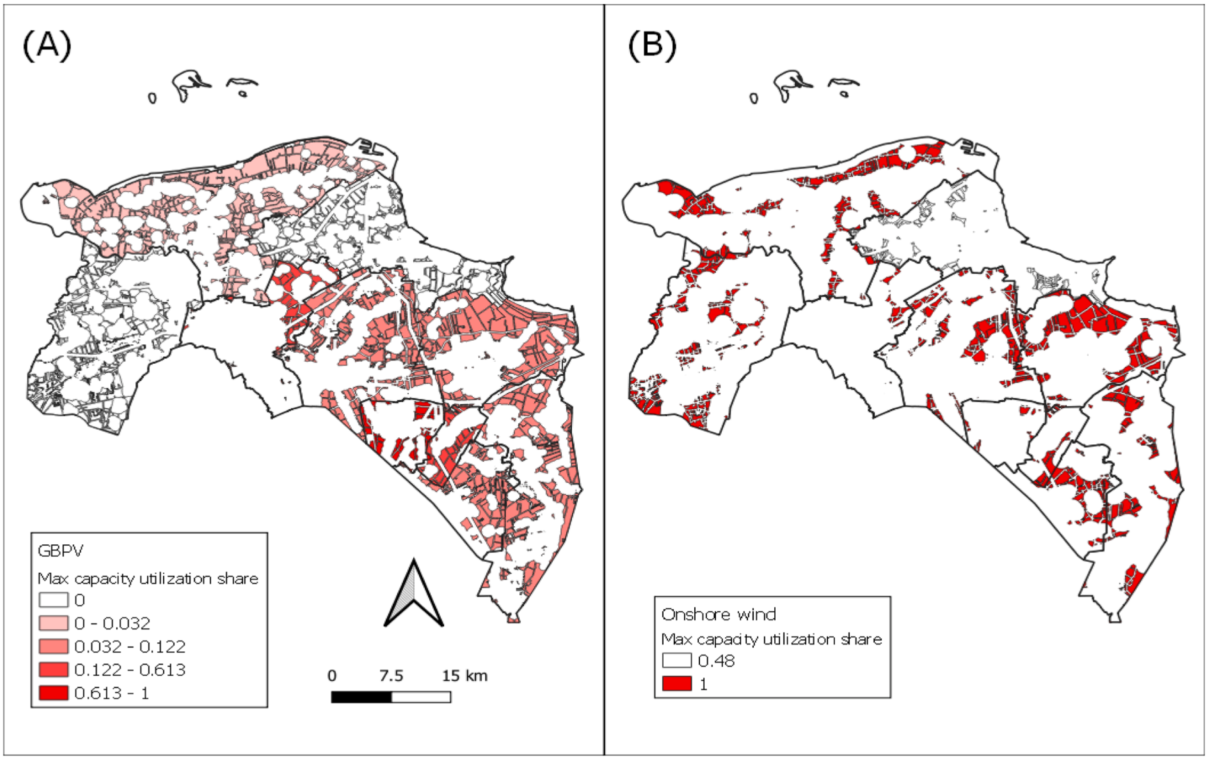

Fig. 19. Analysis of capacity utilization share for GBPV and onshore wind in (A) and (B), respectively, for the remaining part of each municipality within the province of Groningen.

heat balance analyses of the BE and industrial sectors are illustrative examples of the regional OPERA model capabilities. Similar balances can be conducted on other energy carriers, such as electricity, within the province of Groningen. Therefore, our modeling framework allowed us to understand the mechanisms of demand and supply of various energy carriers within an integrated system with spatial details. Even though some of the overall balances are similar between our spatially-detailed modeling and crude modeling in [4] on some of the supply options, these detailed land-use region balances provided insights and deviations that were not possible to identify before. In addition, similar spatially-detailed energy balance analyses can be performed for other regions following our method.

3.1.3. *Regional renewable supply mix capacity potential utilization shares*

The renewable energy supply mix was diverse in all land-use regions and industrial nodes within the province of Groningen in this study (Fig. 18). The supply mix of cities was dominated by rooftop PV (approximately 70 % contribution), followed by solar thermal (29 %), with the remainder coming from biomass. The predominant renewable source in the remaining part of each municipality was onshore wind, with the highest contribution from Het Hogeland municipality (9.4 PJ). In addition, Het Hogeland municipality had the highest overall renewable contribution (14.2 PJ) among all regions and nodes. Geothermal heat made a negligible contribution only to Het Hogeland municipality. Floating PV, agricultural PV, and industrial PV had negligible contributions within the province of Groningen. The detailed biomass-related regional analysis of sources and energy carriers, including capacity utilization share, is presented in Appendix D.

In the latest report on the Provincial Strategy for renewables [64], the cumulative contribution of the municipality Het Hogeland onshore wind and GBPV is 6.3 PJ for 2030 (this is the latest future year for which provincial planning has been made), which is 3.6 PJ less compared to our calculation for 2050. In addition, the provincial strategy report did not show contributions from any other renewables that were considered in our analysis. This report [64] also shows the overall provincial energy supply of wind and GBPV is 23 PJ, which is significantly lower compared to our case of 43 PJ. This suggests that significant efforts are needed to improve the contribution of wind and GBPV after 2030 towards 2050 if ambitious renewable targets are to be met. The province should also seriously consider including other renewables in the primary energy supply mix, for example, biomass, as this will provide more options and some of these options have high regional potential as we calculated.

There was a difference between the available capacity and utilization potentials of renewables in various regions. For example, GBPV exhibited an average utilization share of 0.21 for all the remaining parts of municipalities, with the highest share for Veendam (1.0) and the lowest for Eemsdelta and Westerkwartier (zero utilization) – Fig. 19 (A). Our GBPV capacity potential utilization of 1.3 GW (GW) is within the capacity range of 0.7–3.8 GW suggested by [65] and slightly lower than 1.5 GW considered in the national management scenario in [5,62] for the province of Groningen in 2050. The maximum capacity potential of onshore wind was fully utilized in all the remaining parts of municipalities, except Eemsdelta, where the utilization share is 0.48 – Fig. 19 (B). This suggests that onshore wind provides a cost-effective solution as a renewable source for meeting future electricity demands as also identified in [4]. Our onshore wind capacity potential utilization of 2.5 GW for the province of Groningen is comparable to 2.24 GW considered in the same scenario as GBPV in [5] and slightly higher than that of [65], where the capacity potential range identified is 0.6–1.7 GW. These comparisons confirms the reliability of our data and results. The rooftop PV regional capacity utilization share is detailed in Appendix D.

3.2. *Interregional energy flow analyses*

This section includes analyses of electricity flow volumes in the Netherlands, including offshore, with a focus on the province of Groningen (Section 3.2.1). Furthermore, the HV network capacity potential utilization share is included in this section. Section 3.2.2 details DH flows including flow volumes toward various cities from DH supply points and DH penetration in cities.

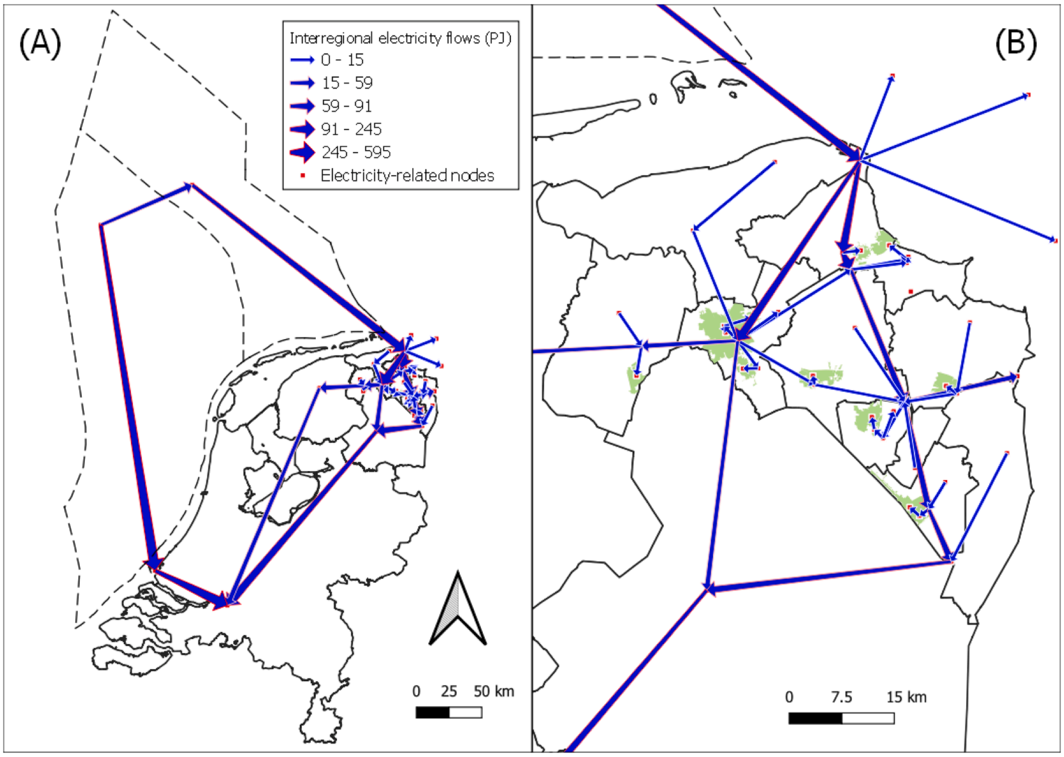

Fig. 20. Interregional net annual electricity flows obtained from the optimization modeling results for the HV and MV networks with the arrow width representing the net annual flow volumes in PJ, and the arrow directions representing the net flow directions. (A) Flow in the Netherlands including offshore regions. (B) Enlarged view of flow in the province of Groningen.

3.2.1. *Electricity*

Our modeling framework of the electricity system considers the whole of the Netherlands, including the Dutch offshore part of the North Sea and adjoining countries linked via the HV network. This allowed us to perform electricity flow analysis on a national scale, along with cross-border electricity trade. Fig. 20 presents the electricity network flows as a result of optimization modeling.[8] A large volume of electricity flowed from the northern Dutch part of the North Sea (245 PJ) – Fig. 20 (A). A majority of this flow is directed toward Groningen municipality (118 PJ), followed by Eemsdelta municipality (105 PJ), with the rest exported abroad – Fig. 20 (B). A net annual total of 144 PJ of electricity was exported from the province of Groningen to Drenthe and 43 PJ to Friesland. The model also allowed us to investigate the electricity flows from supply regions via the MV network, which was not possible in the earlier crude modeling.

Measuring and analyzing the future utilization of the available HV network capacity is necessary to understand which network needs to be strengthened if the aim is to achieve a cost-efficient integrated energy system at the national level. Our model indicated that some network maximum allocated capacities were fully utilized such as the connection between municipalities Eemsdelta and Groningen with a capacity of 0.4 GW (Fig. 21). There are no plans for actual capacity improvement of this network, at least until 2045 based on European electricity network planning database, which is concerning given the fact that this connection supplies electricity to the largest city in the province, Groningen city.

The connection between Eemsdelta and Het Hogeland (offshore connection) municipalities has a current connection capacity of 7 GW. Our analysis depicted that the network will fully utilize its maximum capacity of 8.8 GW; however, the Dutch transmission system operator, TenneT, does not plan to expand this connection until 2045. Similarly, the maximum connection capacity between Groningen and Het Hogeland (offshore connection) municipalities of 4 GW was also fully utilized. This raises concerns because these connections are responsible for transporting electricity from the Dutch north offshore and from other countries to the province of Groningen towards Drenthe and Friesland. Future offshore wind capacity additions without fast and significant upgrades to these network capacities can lead to network congestion and unexpected price hikes. In addition, as maximum network capacities are utilized for certain network connections, the model might not find it cost-effective to invest in renewables, particularly GBPV, in these regions (Fig. 19) because the corresponding additional electricity produced cannot be transferred over these networks.

3.2.2. *District heating*

Even though DH network was considered in all the cities included in our modeling framework, the regional model (after optimization) found five cities to have feasible DH supply, among which Groningen outer city had the highest penetration (1.2 PJ or 21 %), followed by Appingedam city (0.14 PJ or 17 % penetration) (Fig. 22). These penetration volumes are significantly higher than the current penetration of < 1 % [66]. However, these values are lower than that in [7], which obtained an average penetration of 21 % for various cities in the Netherlands, including Groningen city. Even though all the cities investigated in our study demonstrate high heat demand densities [5], cities with DH contributions are either highly compact with less distribution DH lengths or have higher average heat demand densities compared to other cities. In general, the distribution DH cost per unit length and losses are considerably higher than the transmission DH cost per unit length and losses. Another reason for the low DH penetration is heat savings associated

[8] The OPERA model optimization details at the national level, including algorithm, design variables, and constraints, are presented in [34]. This is applicable for the electricity network. Additionally, objective function including regions and nodes, energy balances at the national and regional levels, related constraints are documented in [4]. This includes electricity network connected structure and the corresponding optimization.

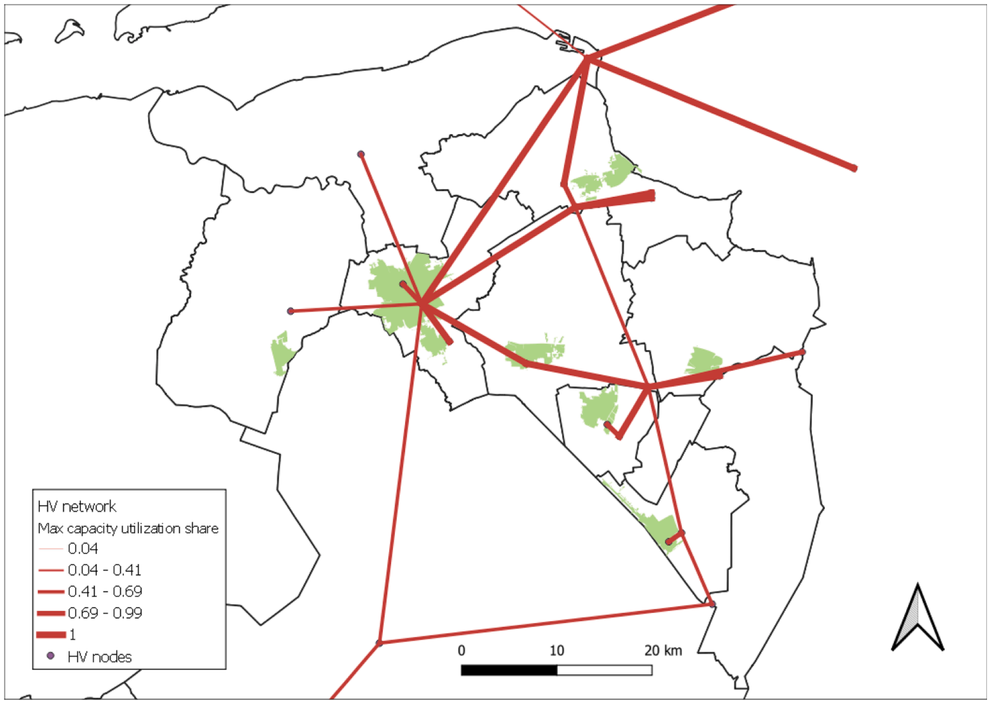

Fig. 21. Utilization share of the maximum capacity of the HV network in 2050 for the province of Groningen. The thickness of the line represents the share of the maximum HV network capacity utilized.

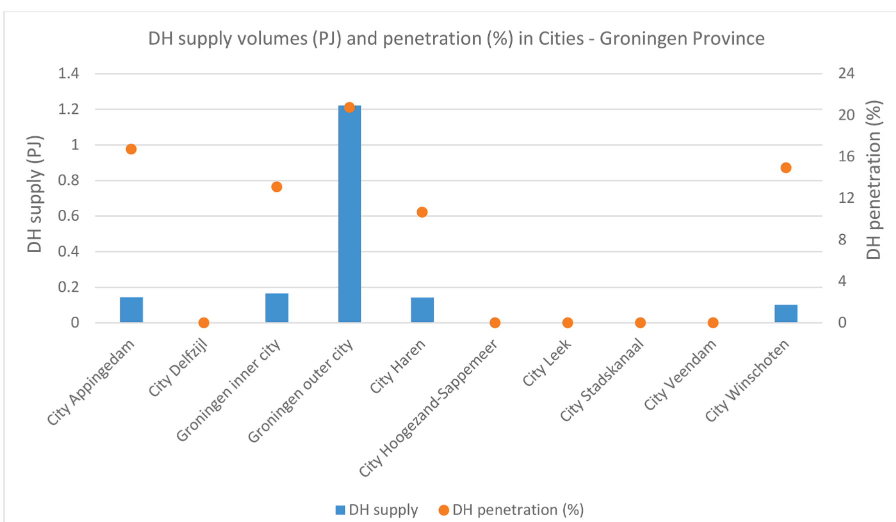

Fig. 22. DH supply (data in PJ) and % DH penetration of cities (included in our study) in the province of Groningen.

with changes in energy labels reduce the net heat demand density and make investing in a citywide DH network less cost-effective. The findings of our study demonstrate that a DH network might be cost-effective in small pockets of high heat demand densities within cities, such as Groningen inner city. However, it was not possible to analyze all of these pockets within the geographical resolution of our research. The framework offers the possibility to perform a more detailed spatial analysis, though. This study spatial resolution is still too low for estimating the true potential of DH networks in cities or population centers.

Even though a pan-provincial DH network having a dense spatial spread was created (Fig. 11), the network obtained as a result of optimization was sparsely spread throughout the province (Fig. 23), suggesting that most of the potential network routes are not cost-effective due to long transmission network distances and related high costs and losses. Considering the interregional DH flow volumes, a significant net annual flow occurs through the transmission network from the Industry Groningen node to the Groningen inner city transmission node (1.7 PJ), followed by the flow from Groningen inner city to outer city (1.5 PJ). IWH has the highest contribution to DH (0.6 PJ) because it is available for “free,” subject to DH costs and losses. The results demonstrate significant losses in the distribution network; for example, the Winschoten city distribution DH network has a loss of approximately 19 % compared to the net transmission heat supply at the Winschoten city center. These results show that technically-detailed DH network analysis can be performed at a city level using our regional model along with provincial analysis.

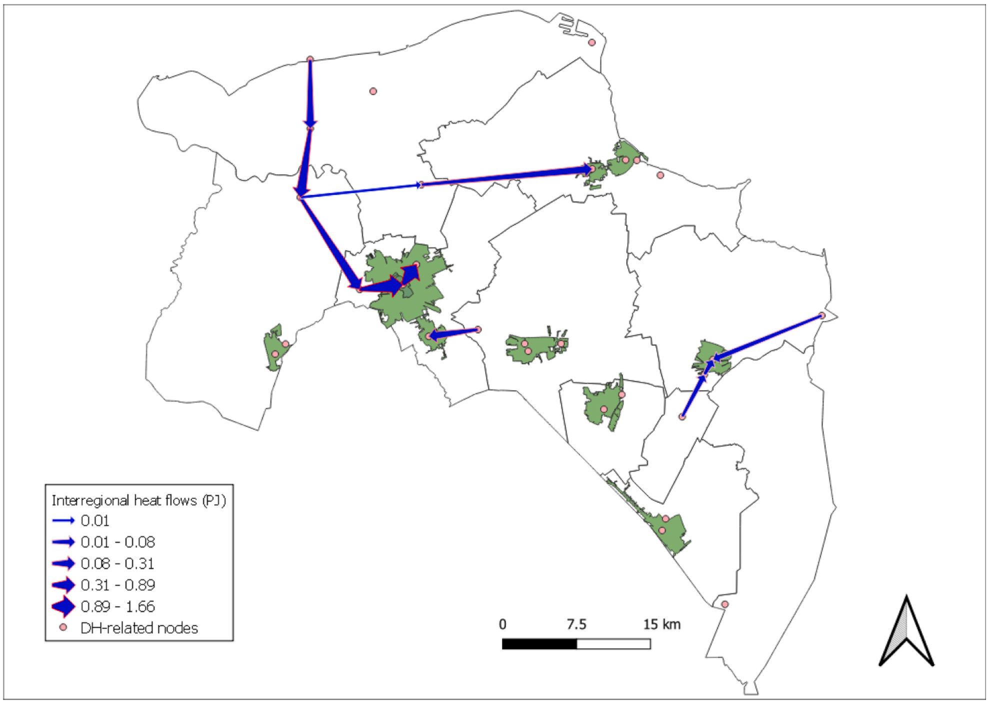

Fig. 23. Net annual heat flows in the DH network within the province of Groningen. The thickness of the arrow represents the annual net flow volumes in PJ, and the direction represents the net flow direction.

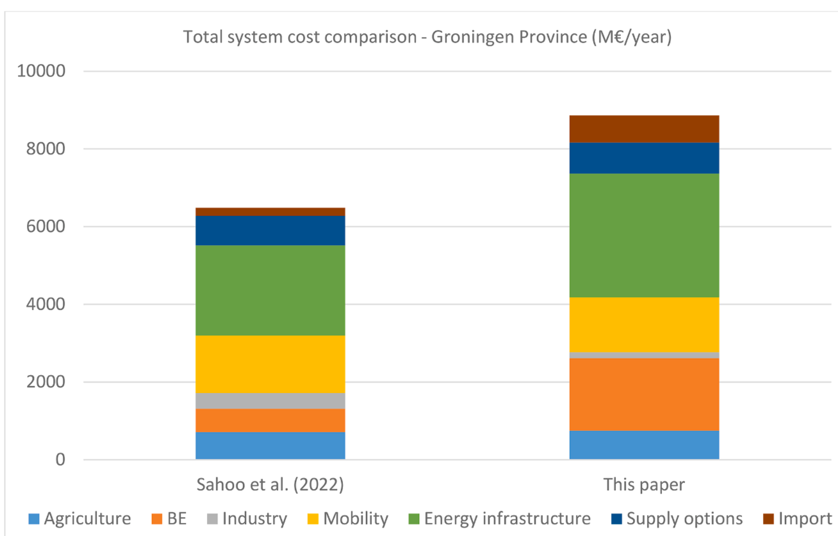

Fig. 24. Total system cost comparison between [4] and this study (data in M€/year).

3.3. Cost analysis

Fig. 24 shows the total system cost comparison between that reported in [4] and this study for the province of Groningen. This cost is further broken down into energy-demanding sectors, namely, agriculture, BE, industry, and mobility, energy supplying options, such as large-scale onshore wind and GBPV, energy infrastructure, and net import of secondary energy carriers,[9] such as electricity, H_2, and NG, to the province of Groningen. The cost associated with these secondary carriers are taken from Appendix B. The difference in the total system cost between this study and [4] was the highest for the BE sector, this difference is 1260 million euro per year (M€/year), which is 208 % more than that obtained in [4]. The main reason for the difference in the BE sector is that the model in this paper finds it more cost effective to invest in additional insulation measures, reflected in upgrade of energy labels. The upgrade of energy labels is so significant that the difference in investment related to only energy label change is 807 M€/year. Detailed analysis of spatially explicit data of various regions within the province of Groningen shows that a large proportion of buildings has low energy

[9] We fixed the annual costs of these energy carriers' (see Appendix B for costs) and multiplied the annual net import of these carriers to determine the overall annual import cost.

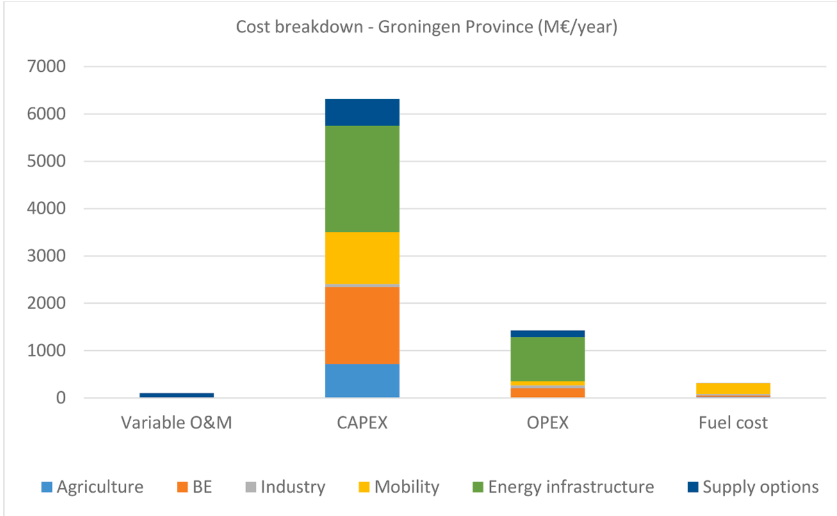

Fig. 25. Cost breakdown into variable O&M, CAPEX, OPEX, and fuel costs for this study (data in M€/year).

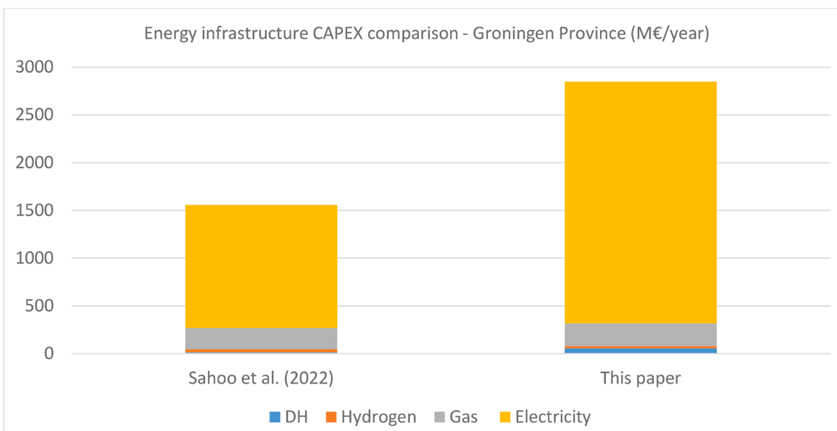

Fig. 26. Energy infrastructure CAPEX comparison between [4] and this study (data in M€/year).

labels, such as GFE or DC labels, and improving these labels to the next-level labels are cheap compared to improving DC or B labels to the highest level labels such as A or A+[4].[10] The model as used in [4] could not pick this regional specificity due to crude regionalization. Therefore, the model in this paper suggests more investments in the BE compared to [4] as this is the cost effective solution, even though the overall cost is higher. Differences in energy infrastructure costs is the second highest, i.e., 863 M€/year or 37 % more than the previous study. The main reason for this positive difference in energy infrastructure is additional investment associated with predominantly MV electricity and DH infrastructure. These networks are not spatially well developed in [4], and hence could not pick the related investment and operation costs. To illustrate, in [4], MV network only considers average investment cost as a function of energy flows and not as a function of distance. Similarly, for DH network cost, only marginal cost associated with heat flows are considered and not investment costs per unit distance. Further explanation on energy infrastructure is provided in the subsequent paragraphs. The aggregated cost associated with the net regional import of energy carriers, such as, electricity and H_2, is also higher for this study, accounting for 697 M€/year, which was 205 M€/year in [4]. This suggests that more import is required to meet regional energy demand, compared to [4], as regional supply is less and it is less cost effective to use own supply options.

Fig. 25 shows a further breakdown of total system cost to variable operation and maintenance (O&M) cost, capital expenditure (CAPEX), operational expenditure (OPEX), and fuel costs for energy-demanding sectors, energy infrastructure, and supply options in the province of Groningen.[11] CAPEX cost was the highest (6704 M€/year), followed by OPEX (1789 M€/year). Energy infrastructure CAPEX and OPEX played a major role, followed by the energy-demanding sector BE. Appx. Fig. A4 in Appendix D illustrates the abovementioned cost components' comparison between [4] and this study.

The energy infrastructure cost for various energy carriers (heat, hydrogen, gas, and electricity) were compared between [4] and this

[10] OPERA can calculate the changes in energy labels and the corresponding changes in investment costs, without considering the costs associated with the entire building stock. This aspect is consistent in both [4] and this study.

[11] Variable O&M costs refer to the operation and maintenance expenses that vary with the amount of production of the main product for a process or technology option. CAPEX represents the expenses associated with adding new equipment within a process or upgrading a technology option. OPEX or fixed O&M costs represent auxiliary expenses associated with technology options, such as the expenses in staffing and maintenance or research and development. Both CAPEX and OPEX are considered over multiple years and annuity is applied for calculating the cost equivalent for a single year. Fuel costs are the costs of fuel used as inputs to processes or options.

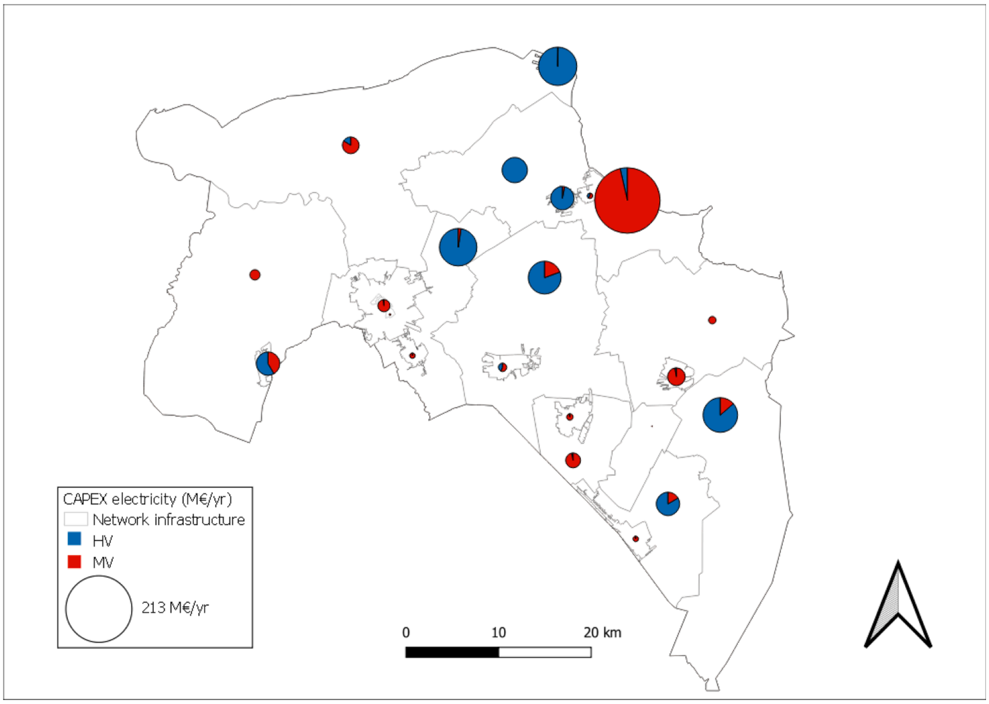

Fig. 27. CAPEX distribution for land-use regions and industrial nodes for electricity network infrastructure within the province of Groningen. The area of the pie represents the cost in M€/year.

Table A1
MV network connection costs applied to this paper based on [56].

MV network type	CAPEX (Euro/m/MW)	Fixed O&M (Euro/MW/year)	Loss (%)	Explanation
1–5 MW capacity, suburban	16	2570	3	We multiplied CAPEX with the length of each MV network to obtain cost in Euro/MW. This cost applies to all cities, except Groningen inner city.
5–25 MW capacity, city	6.76	2747	2.25	This applies only to Groningen inner city as Groningen inner city has a dense MV network structure compared to other cities.
Main distribution, 50/60 kV electricity	3.9	21.2	0.3	This cost applies to all other MV network connections. Fixed O&M cost is per unit meter. The losses in these networks are low as they are meant for transmission purposes, for example, a connection to large-scale GBPV or onshore wind farms.

Table A2
Various energy carriers and their net annual price, along with their cost reference or explanation.

Energy carrier	Price [€_2015/GJ]	Cost reference or cost explanation
NG	6.667	Berenschot and Kalavasta report [62], considering the national management scenario
Electricity	12.419	This data is obtained from the COMPETES model run for the TRANSFORM 2021 scenario [72]. This scenario is very similar to the national management scenario from [62].
Hydrogen	18.255	Hydrogen cost is derived from electricity. Since hydrogen is mainly produced from large-scale electrolyzers in the Netherlands, we applied electricity price and the efficiency of hydrogen conversion, i.e., 1/1.47.

study for the province of Groningen (Fig. 26) because this cost is a major component of the system cost. The heat and electricity CAPEX costs increased when compared to [4] owing to a high investment in detailed spatial structure of these infrastructures with the corresponding cost increased by 42 M€/year (or 330 % increase) and 1243 M€/year (96 %), respectively. DH CAPEX cost for transmission and distribution networks are 8.3 M€/year and 46.2 M€/year, respectively, in this study, whereas the corresponding costs were 12.7 M€/year and zero, respectively, for [4]. The results of this study are likely to be more realistic, as one would expect DH distribution costs to be much higher than DH transmission costs. Our detailed DH modeling allowed for better cost allocation in the spatial structure of heat and electricity networks.

These results show that creating a large number of regions (and nodes) allowed us to distinguish spatially between energy-demanding regions, supplying options, and energy infrastructure, which was not possible in the earlier study. In our previous crude regionalization study, demand and supply were met within the larger region wherever feasible and possible without the need of energy infrastructure. In our study, the mismatch between energy demand and supply within a region is met by energy infrastructure, thereby increasing the utilization of infrastructure and optimizing its investment cost. Currently, the regional distribution system operator and the province of Groningen also consider an increased need and related expansion of MV [67] and DH [61] networks, respectively, on a regional level. Additionally, the discrepancies in the spatial distribution of energy supply sources within the province are better captured by adding spatial detail, leading to greater differences in primary energy supply mixes as reflected in our model. Our spatially-detailed model can make a more accurate estimation of future regional energy supply potentials, particularly related to renewables,

Table A3
Definitions of variables, parameters, and indices related to equations 1 to 11.

Variables		Parameters		Indices	
FlowHeatInterRg	The flow of heat between regions or nodes (interregional/internodal)	**AF**	Availability per time slice [0,1]	*ts*	Time slice
CapFlow	The capacity of transmission or distribution pipe	**C2A**	Capacity to availability conversion factor	*rhtn, rhtn1*	Transmission-related DH nodes
FlowIn	Amount of heat that enters a node	**LossInterRg**	Interregional/internodal heat losses, for example, between transmission nodes or between a transmission and a distribution node	*otdh*	Option for transmission network related to DH
FlowHeatIntraRg	The flow of heat from supply option to transmission option or from transmission option to distribution option within a node (intraregional/intranodal)	**LossIntraRg**	Intraregional/internodal heat losses, for example, transformer stations	*ohsdh*	Heat supply sources in DH, including geothermal doublets and IWH
FlowOut	Amount of heat that exits a node	**Y**	Fraction of hours assigned to a time slice	*rhdn*	Distribution-related DH node
CostDH	DH-related total infrastructure cost, does not include costs associated with centralized heat supply options	**a**	Annuity factor. A discount rate of 2.25 % was considered	*oddh*	Option for distribution network related to DH
CostTrans	Transmission network cost	**InvestmentTrans**	Capital expenditure (CAPEX) cost of the transmission network	*obe*	End-use option in the BE
CostDistri	Distribution network cost	**VarO&MTrans**	Variable operation and maintenance (O&M) cost of the transmission network		
		InvestmentDistri	CAPEX cost of the distribution network		
		VarO&MDistri	Variable O&M cost of the distribution network		
		$\mathbf{C_1}$	Construction cost constant (€/m)		
		$\mathbf{C_2}$	Construction cost coefficient (€/m^2)		
		$\mathbf{D_d}$	Diameter of the distribution pipe (m)		
		$\mathbf{Capa_d}$	Standard capacity of the distribution network		

Table A4
Lookup table for calculating DH pipe loss, cost, water flow, and capacity ().

Sl. No.	DN	Loss (kWh/(m*yr.))	Cost (€/m)	Water flow (m/s)	Capacity (MW)
1	32	186	195	0.9	0.2
2	40	214	206	1	0.3
3	50	239	220	1.2	0.6
4	65	281	240	1.4	1.2
5	80	289	261	1.6	1.9
6	100	302	288	1.8	3.6
7	125	350	323	2	6.1
8	150	413	357	2.2	9.8
9	200	448	426	2.5	20
10	300	494	564	2.7	45
11	400	509	701	2.8	75
12	500	720	839	2.9	125

Source: [58,73]

Table A5
Fixed parameters values for different region types for the DH distribution network based on [7].

Region type	C_1(€/m)	C_2(€/m^2)
Inner city areas	286	2022
Outer city areas	214	1725

whereas crude spatial modeling might lead to overestimation or underestimation of these potentials depending upon the scenario.

The CAPEX[12] costs associated with the HV and MV networks were further investigated with a detailed spatial resolution (Fig. 27) as the electricity infrastructure has a high CAPEX cost (Fig. 26). The HV and MV network combined CAPEX cost was the highest for the Industry Delfzijl node, 213 M€/year, of which the MV network cost was 205 M€/year, as this node was responsible for connecting the Delfzijl industrial cluster via an MV network. The HV network exhibited the highest cost contribution in the Het Hogeland offshore connection, 74 M€/year, owing to the important connections within the province of Groningen and abroad, including offshore (Fig. 20).

Our regionalized model, with an emphasis on spatial disaggregation, enabled the investigation of network capacity additions with a detailed geographical resolution. This showed that national or regional expenses in energy infrastructure, particularly those related to electricity, will play a major role in the regional energy system. Regional disaggregation further demonstrated that investments in efficiency improvement in various building types within the BE are cheaper than investments in the DH infrastructure. This detailed insight is not possible with low spatial resolution regional modeling. The diverse set of results, thus, provide a novel view on the regional energy system, signifying the added value of our spatially-detailed modeling framework.

4. Discussion

Central to interpreting the modeling results presented in this study is to discuss uncertainties regarding some of the assumptions made regarding the future development of energy demand, supply, and infrastructure. To begin with, the model results demonstrated a significant potential role of industrial waste heat (IWH) in providing heat to a district heating (DH) network, as they could be linked to nearby population centers. However, there are uncertainties regarding the IWH potentials from various industrial activities as final product demand projections and their corresponding energy use may change in the future. The continued existence of key industries and their exact energy use cannot be simply assumed in the long term. In addition, energy carriers, technology options, and processes can change, affecting the IWH potentials from various activities. The model is robust in accommodating such future changes, though. For example, inputs related to

[12] In OPERA, the investment cost of a network between two nodes is equally allocated to these nodes. It is the case for losses as well. However, in the case of the connection between the Het Hogeland offshore node and the northern North Sea, the HV network CAPEX cost is completely allocated to the northern North Sea offshore region to keep the offshore connection costs separate from the regional costs.

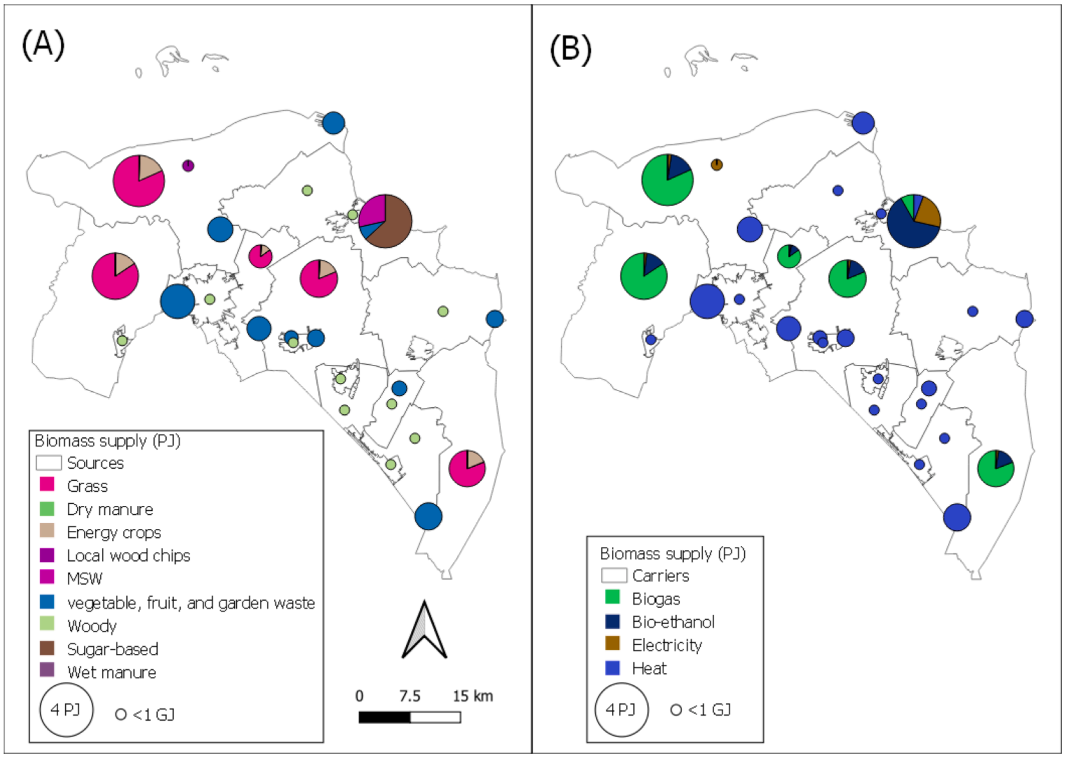

Fig. A1. Detailed analysis of biomass supply in land-use regions and industrial nodes within the province of Groningen. (A) and (B) Supply sources and secondary bio-energy carriers resulting from these sources, respectively. The area of the pie represents the energy volume in PJ. The size of smaller pies (<1 GJ) has been increased for representational purposes.

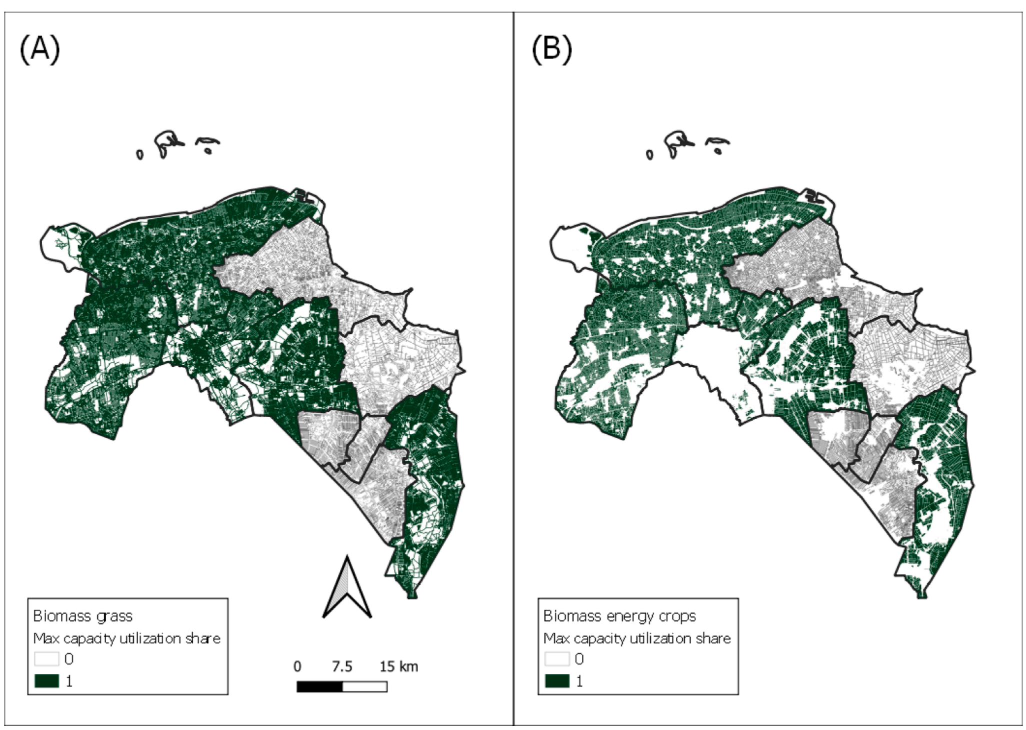

Fig. A2. Analysis of utilization share for biomass grass and energy crops in (A) and (B), respectively, within the province of Groningen. Cities show biomass grass in (A) because of the presence of verge grass alongside roads [5]; however, all the allocations were made to the rest of the municipalities.

final products demands can be easily adjusted in the database and the model can calculate the corresponding changes in processes, capacity of technology options, and IWH potentials accordingly. Hence, it is feasible to run the model under different assumptions in scenarios and to perform detailed sensitivity analyses if needed. Considering changes in IWH potentials maybe highly policy relevant as these changes are reflected in the feasibility of regional DH network linkages to industries which are currently considered in policies. The integrated nature of our

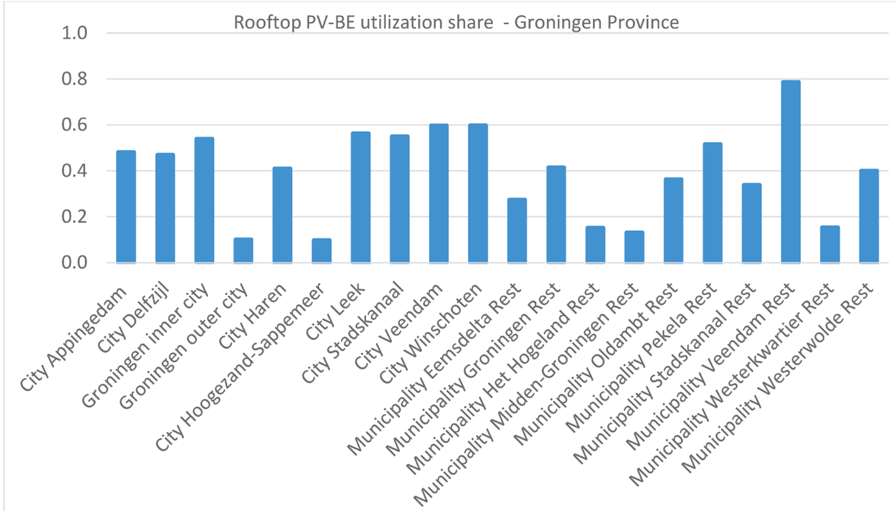

Fig. A3. The utilization share of the maximum capacity potential of rooftop PV in the BE within the province of Groningen for every land-use region.

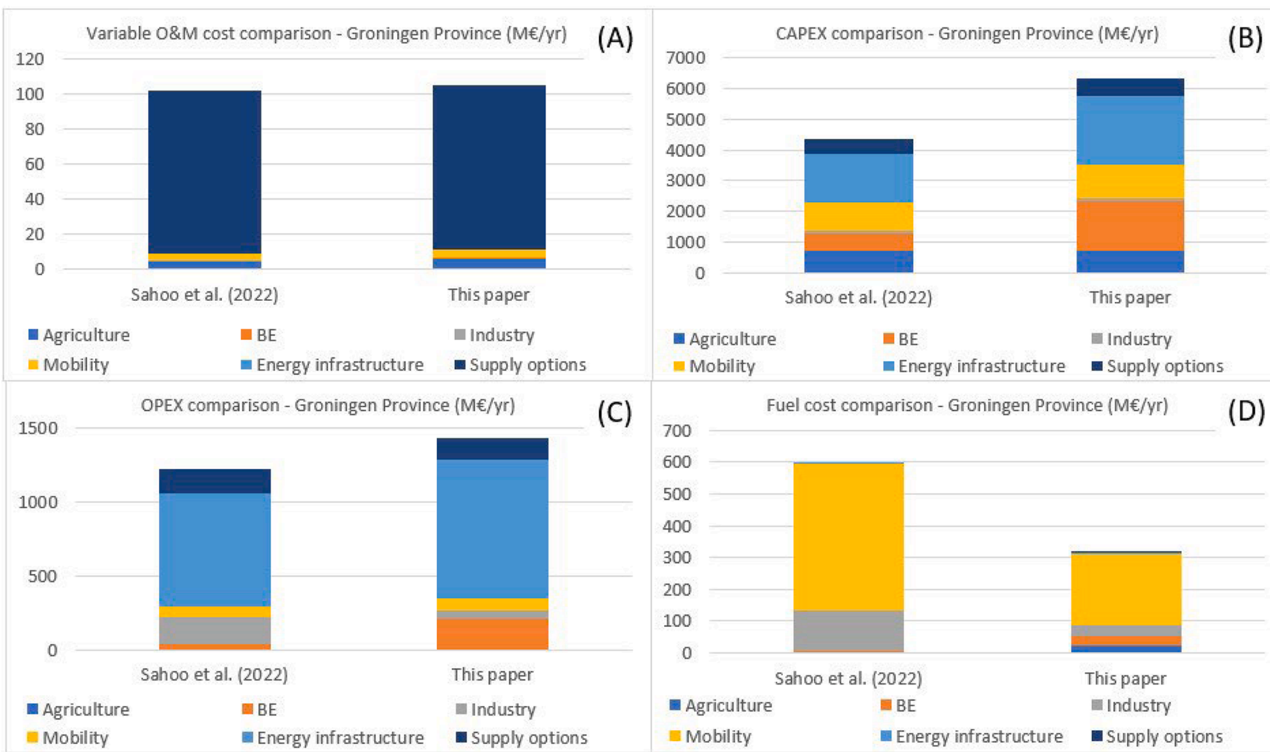

Fig. A4. Various cost components' comparison between [4] and this paper for the province of Groningen (data in M€/year). (A), (B), (C), and (D) are variable O&M, CAPEX, OPEX, and fuel cost comparison, respectively.

modeling framework would allow for studying this feasibility under different scenarios.

Secondly, geothermal heat contributed minimally to the DH network, even though the model allows us to do so. Geothermal-related technology options may develop in the future and become cheaper, which may improve corresponding heat contributions. Notably, serious increases in natural gas (NG) prices provides a scope for geothermal heat as most of the current built environment (BE) heat demand is met by NG in Groningen, which can be analyzed either through sensitivity analyses or creating scenarios within the modeling framework.

Thirdly, ground-based photovoltaics (GBPV) and rooftop photovoltaics (PVs) contributions are expected to increase due to current policy instruments [68], which might lead to congestion problems of both the low voltage and medium voltage (MV) network. Our model does not consider the low voltage network as it is considered relevant mostly for modeling at a city or district level. Hence, further analysis on the role of the low voltage network may either urge for expanding the proposed modeling framework or linking to other energy system models working on a local scale. Regarding the MV network, a large number of nodes were created in our model to represent the MV network with spatial and technical details to also assess the possible role of grid congestion. Nonetheless, access to data on current MV capacity was lacking, implying the model cannot fully incorporate this role. In response, only additional costs (capital and operational expenditure) of transporting electricity were imposed so as to represent the need for additional investments in the grid. Therefore, as a key aspect for improvement, our framework does allow including a better representation of the technical characteristics and constraints of an MV network, and can also identify locations where MV capacity increases significantly.

Of course, there are other assumptions that may warrant detailing or further exploration. Examples include the rates of demolishing and constructing in the build environment, the use of greenhouse area as proxy for agricultural demand or the 30 % reduction of the district heating distribution network length network to account for the repetitive nature and bi-directionality of the road network. Rather than discussing these in detail, it is important to indicate that the modeling framework allows for such choices to be swiftly changed, represent them in scenarios or do sensitivity analyses with them. Our framework, therefore, is robust in allowing these changes quickly. Hence, our modeling approach of regional integrated energy analysis can also be easily replicated in other regions, subject to data availability. Tweaks can be made to the model depending upon the type of data available, though. As such, our systematic approach is a potentially valuable addition to the toolbox for performing energy system analysis on a regional level, next to a range of national and international modeling tools, along with geographical information system-based tools. Our results also confirms that such an addition may well be crucial, as it produced quite different results than our previous study using a more crude regional representation of the province of Groningen.

Further improvements in modeling framework can include response to developments regarding the regional policies and incorporate new features. For example, the model currently follows national emissions reduction targets. Regional policies incorporate additional regional emission-related targets, which are not yet integrated into the modeling framework. Additionally, based on the current discussions in the Netherlands, the model could be expanded so as to investigate the applicability of salt caverns for the storage of hydrogen, which is a spatially-dependent feature and is available within the province. Additionally, regional infrastructure related to carbon capture and storage is worth analyzing. Finally, regional policies currently point to becoming (nearly) self-sufficient regarding energy in the future, while various stakeholders look quite differently at which technology options and where they may be used to do so. Inputs from stakeholders on the above-mentioned aspects can make our modeling framework more robust, flexible, and dynamic. The impact of these multitude of aspects on the regional energy balances and costs, for example, can be analyzed by creating scenarios and performing sensitivity analyses. This also shows that, although a variety of spatially sensitive aspects of the regional energy system analysis were covered in this paper, more regional energy system-related topics need to be investigated.

5. Conclusions and future work

This study focused on improving a regional energy system integrated modeling framework by providing systematic steps to add relevant spatial detail. The methodology involved creating regions and nodes within the modeling framework under categories corresponding to differences in land use (cities, industry, geothermal doublets, and other regions), energy supply, and energy infrastructure. Furthermore, the methodology involved a unidirectional soft linking with geographical information system-based modeling results. As a result, the modeling framework allows for regionally allocating spatially sensitive elements, such as renewable resources or heat demand. A detailed breakdown was provided for sectoral energy demand, supply options, and energy infrastructure for electricity and heat, including district heating (DH). Our regional energy system model (ESM) can translate the impact of national and international energy-related planning and policy decisions to a regional level, in addition to implementing regional policies. They included policies and regulations of, for example, energy infrastructure, spatial constraints for renewables, and renovations of the built environment (BE). Linkages with other models at higher geographical scales were established.

Important modeling results are as follows:

- Compared to the crude spatial modeling results, our detailed spatial modeling showed significant changes in renewable supply mix, such as, an increased role of biomass, 18.4 PJ increase (+460 %), and decreased role of solar, 19 PJ decrease (−59 %). The detailed spatial modeling has nearly 100 regions and nodes categorization, compared to only two in the crude modeling case for the province of Groningen.
- The capacity potential of onshore wind was fully utilized in every remaining part of the municipalities, except for Veendam (a utilization potential of 2.5 GW (GW) from a total of 2.6 GW for the province of Groningen). However, neither rooftop PVs (1.8 GW from a total of 6.1 GW) nor ground-based photovoltaics capacity (1.3 GW from a total of 16.6 GW) potential was fully utilized in any land-use region. This shows onshore wind has a higher utilization potential compared to photovoltaics in our regional modeling context.
- Important high voltage (HV) network connections within the province of Groningen were between Het Hogeland (offshore connection) and Eemsdelta municipality and between Het Hogeland (offshore connection) and Groningen municipality, as demonstrated by the utilization of their maximum future capacity potential of 8.8 GW and 4 GW, respectively.
- Cities with high heat demand densities and/or compact structures had high DH penetration, such as, Groningen outer city (20.1 % penetration), Appingedam (16.7 %), and Winschoten (14.9 %).
- The capital expenditure costs of the regional HV and MV electricity networks demonstrated that the HV network was dominant in the Het Hogeland (offshore connection) which has links with abroad and the North Sea, contributing 74 M€/year, and the MV network connected to the Delfzijl industrial cluster, contributing 205 M€/year.

The method and results demonstrated that this paper filled a major research and knowledge gap on the regional level. Adding spatial detail has several benefits, such as a better understanding of renewable energy supply potentials and mixes due to regional spatial policies and circumstances, an understanding of regional sectoral demand differences, e.g., related to the BE, industries, and agriculture, identifying constraints and costs related to energy infrastructure, and identifying possible demand and supply mismatches. While the province of Groningen was tested, the modeling framework has a wide applicability in other regions if sufficient data is available. The flexibility of our approach also allows for use on a geographical scale somewhat higher or lower than in our case. The model has a strong potential for use in reflecting on and providing input to regional policies, both regarding spatial and energy planning. Our modeling framework is a useful addition to already existing tools at the national and European levels.

We intend to test our modeling framework using inputs from various regional stakeholders. Policymakers at various regional scales are expected to play a major role in deciding the future of a regional energy system modeling framework, along with energy infrastructure and environmental experts. These inputs will aid in fine-tuning our model and produce multiple scenarios in synchronization with stakeholders' expectations and regional policy reports. Scenarios can be used to analyze the impacts of increasing citizen participation, sustainability, circularity, or lowering cost solutions. Scenarios can include significant fossil price rises which can occur due to international political developments as now in the case of natural gas. Similarly, sensitivity analyses can include choices related to the use of hydrogen-related technology options and increase in DH penetration in population centers. Our modeling framework has provisions to incorporate all these changes in future research.

CRediT authorship contribution statement

Somadutta Sahoo: Conceptualization, Methodology, Resources, Formal analysis, Data curation, Visualization, Validation, Writing – original draft, Writing – review & editing. **Joost N.P. van Stralen:** Conceptualization, Methodology, Resources, Software, Validation, Supervision. **Christian Zuidema:** Writing – review & editing, Supervision. **Jos Sijm:** Writing – review & editing, Supervision. **Andre Faaij:** Conceptualization, Methodology, Resources, Validation, Writing – review & editing, Project administration, Funding acquisition.

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.

Data availability

Data were collected from Open Sources only and appropriate references were made to them throughout the manuscript.

Acknowledgements

We acknowledge the support provided by the ESTRAC Integrated Energy System Analysis Project financed by the New Energy Coalition (finance code: 656039).

Appendix A. Detailed Groningen and other region-specific data and analysis

Sectoral demand

Built environment

For the province of Groningen, municipality level construction and demolition projection was based on 2013–20 historical data from CBS [38] (see Table 2). For Groningen city, the construction of apartments was distributed by 20 and 80 % between the inner and outer cities, respectively, based on their current apartment distribution share.

Services buildings were segregated based on activity solely dedicated to offices, education, industrial halls, and hospitals in GIS, as these are independent building type activities in OPERA (Table 2). The remaining buildings types were allocated to “other” service buildings. We calculated the floor area of these buildings based on the effective area dedicated to that activity within a building (the BAG area). Building level aggregation toward regions was similar to that of household buildings.

Industries

For salt, an additional industry, Nedmag in Veendam, was included compared to the previous study [4], as this industry, even though has less annual production volume compared to other salt producing industries in the province of Groningen, is important in a detailed spatial analysis due to high energy demand and industrial waste heat (IWH) supply potential. The procedure for adding a new industrial activity is explained in the previous study [4] and Table 2. For newly added activities, the model can choose between the current technology option or processes (free of cost) and generic options available within the subsector to meet future energy demands (including costs).

Energy supply

Wind

KNMI is the meteorological agency of the Netherlands providing wind speed profiles at the center of a $2 \times 2\,km^2$ square mesh for the whole of the Netherlands for various hub heights and years [45]. We considered wind energy annual profile at location/point which coincided with KNMI data points and are almost in the central location of region/municipality suitable for wind power production in 2050. For this, we manually matched these data points with the central locations of each region. For onshore regions outside the province of Groningen, we considered a location closer to the centroid of these regions. We used a MATLAB script to extract hourly wind speed profiles at 150 m hub height for 2015 from a large dataset in KNMI and used MS Excel spreadsheets for these profiles, from where they were uploaded to the OPERA database (Fig. 7).

Solar

Currently, the province of Groningen does not have any examples of floating PVs. Because the data related to the conversion of inland water space potential into floating PVs potential was not available in OPERA, we used an upcoming project in Ubbena, Drenthe, as an example in our research. In that project, 28 hectare of inland water space is planned to be utilized in a given space of 50 hectare, with a solar PV capacity of approximately 25 MW [69]. The inland water PV average capacity is estimated to be higher than that on land [70]. Other regions might have different potentials than what we calculated.

Geothermal

For each of the geothermal doublets or node, we calculated recoverable heat [41] considering the technical potential by aggregating the potential values of each $1 \times 1\,km^2$ cell surrounding the doublet for 2–3 kms. In addition, we estimated the investment costs in technology related to geothermal heat extraction based on [48,71] and applied a learning curve.

Industrial waste heat

We calculated the IWH potentials of various industrial activities added in [4] and in this study (see Table 2). The method associated with calculating the IWH potential for most industries is described in [5]. IWH production from various industrial activities is dependent on the energy input associated with related technology options. The IWH production volumes per unit final main product were included in the energy balance of the corresponding technology options for various activities in the OPERA database.

Energy infrastructure

Electricity network

Each municipality within the province of Groningen through their respective HV nodes, except Pekela, (Fig. 9 (B)) which has no nodes, as this municipality is small with no distinct activities allowing reliance on an MV connection. Some cities have additional HV connections because of the peculiarities of the existing HV network structure, the need to make an additional node to connect the city via an MV network, or the relative importance of the city. This includes Delfzijl, Groningen, Haren, Hoogezand-Sappemeer, Stadskanaal, and Veendam. There are two additional HV nodes for establishing connections specifically to the Delfzijl industrial cluster and the Het Hogeland offshore connection (responsible for abroad connections and the North Sea offshore connection) – Fig. 9.

Appendix B. Miscellaneous costs

Tables A1 and A2

Appendix C. Detailed modeling of DH network

As mentioned in Section 2.3.2, the equations below are written in the OPERA model in a general way, i.e., flows are non-sequential and bidirectional. The distinction related to flow direction is made in the database to reduce the number of variables and constraints the model needs to solve. There are two types of flows: inter-regional/nodal and intra-regional. Inter-regional connection is responsible for the connection between nodes and intra-regional is responsible for the connection between technology/options within a region/node. Appx. Table A3 provides definitions of variables, parameters, and indices used in the equations.

The heat flow through a transmission network (from node *rhtn* to *rhtn1*) is

$$FlowHeatInterRg(otdh, rhtn, rhtn1, ts) \leq \boldsymbol{AF}(otdh, ts)^{*}CapFlow(otdh, rhtn, rhtn1)^{*}\boldsymbol{C2A}(otdh)^{*}\boldsymbol{Y}(ts) \tag{A1}$$

The above-mentioned equation is used to determine the capacity of the network *CapFlow*. Readers are directed to refer Joost et al. [34] for a detailed description of parameters **AF**, **C2A**, and **Y**.

The amount of heat that enters a heat transmission node in *rhtn* is

$$FlowIn(otdh, rhtn, ts) = \sum_{rhtn1} FlowHeatInterRg(otdh, rhtn, rhtn1, ts)^{*}(1 - \boldsymbol{LossInterRg}(otdh, rhtn, rhtn1, ts)) + \sum_{ohsdh} FlowHeatIntraRg(otdh, ohsdh, rhtn, ts)^{*}(1 - \boldsymbol{LossIntraRg}(rhtn, otdh, ohsdh, ts)) \tag{A2}$$

where *FlowInterRg(otdh, rhtn, rhtn1, ts)* represents heat flow from transmission node *rhtn* to node *rhtn1* in a unidirectional manner (see also Section 2.3.2), within transmission network (*otdh*). *FlowHeatIntraRg*(*otdh*, *ohsdh*, *rhtn*, *ts*) represents heat flow from heat supply source (*ohsdh*) within the node *rhtn*. The parameter **LossInterRg** is dependent on the pipe length along with capacity (diameter). **LossIntraRg** corresponds to losses in piping or transformers, which are not included in heat supply source losses. This loss was considered zero in this paper; however, the model now has the capability to include this loss in the future.

The amount of heat that exits a heat transmission node is the amount of heat flowing to the distribution grid with the same region/node. Heat transmission node does not have a final demand. The heat flowing out of a transmission node is therefore represented as

$$FlowOut(rhtn, otdh, ts) = \sum_{rhtn1} FlowHeatInterRg(otdh, rhtn, rhtn1, ts) + FlowHeatIntraRg(otdh, oddh, rhtn, ts)^{*}(1 - \boldsymbol{LossIntraRg}(rhtn, otdh, oddh, ts)) \tag{A3}$$

where *FlowHeatIntraRg* (*otdh*, *oddh*, *rhtn*, *ts*) represents heat that is transferred from the heat transmission option, *otdh*, to the heat distribution option, *oddh*, at node *rhtn*. **LossIntraRg** in this case represents losses in the transformer responsible for stepping down the flow, which is assumed to be zero in this paper. Then, we have a nodal flow balance equation as

$$FlowIn(rhtn, otdh, ts) = FlowOut(rhtn, otdh, ts) \tag{A4}$$

Heat needs to flow from the transmission node to the distribution node (the city), which happens via the distribution grid. The flow of heat from the heat transmission node, *rhtn*, to the distribution node, *rhdn*, via the distribution option/grid, *oddh*, is (an equation analogous to eq. 1)

$$FlowHeatInterRg(oddh, rhtn, rhdn, ts) \leq \boldsymbol{AF}(oddh, ts)^{*}CapFlow(rhtn, rhdn, oddh)^{*}\boldsymbol{C2A}(oddh)^{*}\boldsymbol{Y}(ts) \tag{A5}$$

The generalized inflow equation for distribution DH is as follows:

$$FlowIn(rhdn, oddh, ts) = \sum_{rhtn} FlowHeatInterRg(oddh, rhtn, rhdn, ts)^{*}(1 - \boldsymbol{LossInterRg}(oddh, rhtn, rhdn, ts)) \tag{A6}$$

The heat that enters the heat distribution node is analogous to Eq. 2, only differences being the distribution has a unique flow from one transmission node and no supply of heat sources to the distribution grid within the heat distribution node. The equation is generalized though where multiple entry points is represented. **LossInterRg** represents heat losses in the distribution network for connection between transmission node, *rhtn*, and distribution node, *rhdn*.

The heat that leaves the heat distribution grid meets the end-use heat demand in the BE sector. The equation is

$$FlowOut(rhdn, oddh, ts) = \sum_{obe} FlowHeatIntraRg(oddh, obe, rhdn, ts)^{*}(1 - \boldsymbol{LossesIntraRg}(oddh, obe, rhdn, ts)) \tag{A7}$$

where **LosssesIntraRg** corresponds to heat exchanger losses before final delivery to the end-use options.

Similar to flow balance in transmission, we have the following balance equation at the heat distribution node *rhdn* as

$$FlowIn(rhdn, oddh, ts) = FlowOut(rhdn, oddh, ts) \tag{A8}$$

The total DH infrastructure cost equation is as follows:

$$CostDH = CostTrans + CostDistri \tag{A9}$$

where transmission DH cost is

$$\begin{aligned} CostTrans = \boldsymbol{a}^* & \sum_{otdh,\ rhtn,\ rhtn1} (CapFlow(rhtn,\ rhtn1,\ otdh)^*(\boldsymbol{InvestmentTrans}\,(otdh,\ rhtn,\ rhtn1))) \\ & + \sum_{otdh, rhtn,\ rhtn1,\ ts} (FlowHeatInterRg\,(otdh, rhtn,\ rhtn1,\ ts)^*\boldsymbol{VarO\&MTrans}\,(otdh, rhtn,\ rhtn1,\ ts)) \end{aligned} \tag{A10}$$

where annuity factor **a** is calculated considering a discount rate of 2.25 % was considered based on the Central Planning Bureau of the Netherlands and a lifetime of 50 years for both transmission and distribution DHs [56]. **InvestmentTrans** and **VarO&MTrans** represent capital expenditure and variable operation and maintenance cost, respectively, associated with the transmission network.

Distribution DH cost is

$$\begin{aligned} CostDistri = \boldsymbol{a}^* & \sum_{oddh,\ rhtn,\ rhdn} \left(CapFlow\,(oddh,\ rhtn,\ rhdn)^* \frac{(\boldsymbol{C}_1(rhtn,\ rhdn,\ oddh) + \boldsymbol{C}_2\,(rhtn,\ rhdn,\ oddh)^*\boldsymbol{D_d}\,(rhtn,\ rhdn,\ oddh))}{\boldsymbol{Capa_d}(rhtn,\ rhdn,\ oddh)} \right) \\ & + \sum_{otdh, rhtn,\ rhtn1,\ ts} (FlowHeatInterRg\,(oddh,\ rhtn,\ rhdn,\ ts)^*\boldsymbol{VarO\&MDistri}\,(oddh, rhtn,\ rhdn,\ ts)) \end{aligned} \tag{A11}$$

where parameters $\mathbf{C_1}$ and $\mathbf{C_2}$ are construction cost constant and construction cost coefficient, respectively – refer Persson and Werner [7] for a detailed description on these parameters (also see the description below for the values of these parameters used in this paper). $\mathbf{Capa_d}$ represents the standard capacity of the distribution cost as obtained from Appx. Table A4, which also presents standard Investment costs and interregional losses. This table represents attributes for piping series 1 and considered assumptions mentioned in the catalog from a pipe producer Powerpipe [73]. The distribution DH capital cost (the first part of the RHS of the above equation) is a modified version of the capital cost mentioned in [58]. For the DH network, we only focused on distribution capital cost as this cost constitutes more than half of the total distribution costs of a standard DH network [7]. **VarO&MDistri** represents variable O&M costs associated with distribution network. Calculating operating costs can be uncertain and would require more detailed modeling of a distribution network, for example including water flow levels, pumping pressure and current, and pressure losses, which are beyond the scope of our paper. The cost equations provide the possibility of including other operating costs, though. We considered a standard capacity pipeline of 125 MW and 45 MW for transmission and distribution DH, respectively.

Appx. Table A5 provides data on fixed parameters used in the distribution capital cost equation for different region types. We used inner city area parameters for Groningen inner city and outer city area parameters for other cities. Other region-specific modeling change is that we divided the Groningen outer city into eight equal parts, along with equal BE demand distribution in each region, because this region is much larger than that of other cities.

Appendix D. Detailed analysis

Biomass has a variety of supply sources and results in different energy carriers (Appx. Fig. A1), hence we analyzed biomass in detail. Biomass grass converted to biogas has the highest contribution, i.e., 9.5 PJ, with predominant contributions from Het Hogeland municipality (3.1 PJ) and the remaining part of Westerkwartier (2.6 PJ) municipality. Industry Delfzijl has the highest biomass supply (4 PJ) due to the presence of a large industrial cluster utilizing various biomass carriers. Regarding conversion, biogas has the highest contribution of 9.8 PJ, which is lower compared to the 15 PJ considered in [74], though [74] considered biogas from sources not included in our study, such as agricultural residues, energy crops, and sea algae. Heat has the second highest contribution of 7 PJ.

Biomass grass and energy crops are either fully utilized within a municipality or completely left out (Appx. Fig. A2). Eemsdelta and Oldambt are amongst municipalities without these sources. Biomass local wood chips and straw are almost completely unutilized in the province of Groningen – also see Appx. Fig. A1. For grass and energy crops utilization within the province of Groningen, we see some municipalities utilize their full potential, whereas neighboring municipalities did not have any utilization as each municipality is a distinct region in our modeling, and the transport between regions of these regional types of biomass is not included in our method.

The average utilization share of rooftop PV-BE capacity potential is higher in the cities (0.44 average) compared to the rest of the municipalities (0.35) - Appx. Fig. A3. Neither cities nor municipalities rest have a full utilization share of rooftop PV. Our rooftop PV capacity utilization of 1.8 GW is higher compared to the range considered in [65] for 2050.

Appx. Fig. A4 represents a cost breakdown for cost of options (energy demand, supply, and infrastructure) and compares between [4] and this study. Variable O&M costs shows supply options making the largest contribution, even though the difference between [4] and this study is minimal, i.e., this paper has a 0.3 M€/year or 0.3 % more contribution compared to [4]. CAPEX graph shows significant difference for the energy-demanding sector BE, for which this study is 1070 M€/year (191 % more) higher than that of [4]. The primary reason for this difference is the changes in the energy labels of the building stocks as mentioned in the main text. CAPEX investment in energy infrastructure is also higher in this paper compared to [4], i.e., 691 M€/year. OPEX investment comparison also shows significant positive difference related to the BE and energy infrastructure for this paper compared to [4]. For example, energy infrastructure has a cost difference of 172 M€/year. Fuel cost comparison shows the BE and agriculture have high cost for this paper compared to [4].

References

[1] Eurostat. Key figures on Europe; 2019. Doi: 0628.
[2] Ministry of Economic Affairs. Energy Agenda. Den Haag; 2017.
[3] Netbeheer E. TenneT, Netbeheer Nederland. Netimpactrapportage RES 2021;1 (in Dutch).
[4] Sahoo S, van Stralen JNP, Zuidema C, Sijm J, Yamu C, Faaij APC. Regionalization of a national integrated energy system model: A case study of the northern Netherlands. Appl Energy 2022:306.
[5] Sahoo S, Zuidema C, van Stralen JNP, Sijm J, Faaij A. Detailed spatial analysis of renewables' potential and heat: A study of Groningen Province in the northern Netherlands. Appl Energy 2022:318. https://doi.org/10.1016/j.apenergy.2022.119149.
[6] Özdemir Ö, Hers JS, Fisher EB, Brunekreeft G, Hobbs BF. A nodal pricing analysis of the future german electricity market. 2009 6th Int Conf Eur Energy Mark EEM 2009; 2009. Doi: 10.1109/EEM.2009.5207112.
[7] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76. https://doi.org/10.1016/j.apenergy.2010.09.020.
[8] Petrovic SN, Karlsson KB. Danish heat atlas as a support tool for energy system models. Energy Convers Manag 2014;87:1063–76. https://doi.org/10.1016/j.enconman.2014.04.084.
[9] Strachan N, Balta-Ozkan N, Joffe D, McGeevor K, Hughes N. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. Int J Hydrogen Energy 2009;34:642–57. https://doi.org/10.1016/j.ijhydene.2008.10.083.
[10] Möller B, Lund H. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. Appl Energy 2010;87:1846–57. https://doi.org/10.1016/j.apenergy.2009.12.001.
[11] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. https://doi.org/10.1016/j.energy.2009.11.023.
[12] Petrović SN, Karlsson KB. Residential heat pumps in the future Danish energy system. Energy 2016;114:787–97. https://doi.org/10.1016/j.energy.2016.08.007.
[13] van den Broek M, Brederode E, Ramírez A, Kramers L, van der Kuip M, Wildenborg T, et al. Designing a cost-effective CO2storage infrastructure using a GIS based linear optimization energy model. Environ Model Softw 2010;25:1754–68. https://doi.org/10.1016/j.envsoft.2010.06.015.
[14] van den Broek M, Ramírez A, Groenenberg H, Neele F, Viebahn P, Turkenburg W, et al. Feasibility of storing CO2in the Utsira formation as part of a long term Dutch CCS strategy. An evaluation based on a GIS/MARKAL toolbox. Int J Greenh Gas Control 2010;4:351–66. https://doi.org/10.1016/j.ijggc.2009.09.002.
[15] Alhamwi A, Medjroubi W, Vogt T, Agert C. GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas. Appl Energy 2017;191:1–9. https://doi.org/10.1016/j.apenergy.2017.01.048.
[16] Alhamwi A, Medjroubi W, Vogt T, Agert C. Development of a GIS-based platform for the allocation and optimisation of distributed storage in urban energy systems. Appl Energy 2019;251:113360. https://doi.org/10.1016/j.apenergy.2019.113360.
[17] Schiefelbein J, Javadi AP, Diekerhof M, Streblow R. GIS supported city district energy system modeling. Proc 9th Int Conf Syst Simul Build; 2014. Doi: 10.13140/RG.2.1.5036.1444.
[18] Pakere I, Kacare M, Grāvelsiņš A, Freimanis R, Blumberga A. Spatial analyses of smart energy system implementation through system dynamics and GIS modelling. Wind power case study in Latvia. Smart Energy 2022:7. https://doi.org/10.1016/j.segy.2022.100081.
[19] Colbertaldo P, Guandalini G, Campanari S. Modelling the integrated power and transport energy system: The role of power-to-gas and hydrogen in long-term scenarios for Italy. Energy 2018;154:592–601. https://doi.org/10.1016/j.energy.2018.04.089.
[20] Colbertaldo P, Cerniauskas S, Grube T, Robinius M, Stolten D, Campanari S. Clean mobility infrastructure and sector integration in long-term energy scenarios: The case of Italy. Renew Sustain Energy Rev 2020;133:110086. https://doi.org/10.1016/j.rser.2020.110086.
[21] Lombardi F, Pickering B, Colombo E, Pfenninger S. Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives. Joule 2020;4:2185–207. https://doi.org/10.1016/j.joule.2020.08.002.
[22] Borasio M, Moret S. Deep decarbonisation of regional energy systems: A novel modelling approach and its application to the Italian energy transition. Renew Sustain Energy Rev 2022;153:111730. https://doi.org/10.1016/j.rser.2021.111730.
[23] Pye S, Sabio N, Strachan N. An integrated systematic analysis of uncertainties in UK energy transition pathways. Energy Policy 2015;87:673–84. https://doi.org/10.1016/j.enpol.2014.12.031.
[24] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Appl Energy 2015;152:83–93. https://doi.org/10.1016/j.apenergy.2015.04.102.
[25] Moore A, Price J, Zeyringer M. The role of floating offshore wind in a renewable focused electricity system for Great Britain in 2050. EnergyStrateg Rev 2018;22:270–8. https://doi.org/10.1016/j.esr.2018.10.002.
[26] Bartholdsen HK, Eidens A, Löffler K, Seehaus F, Wejda F, Burandt T, et al. Pathways for Germany's low-carbon energy transformation towards 2050. Energies 2019;14:1–33. https://doi.org/10.3390/en12152988.
[27] Tigas K, Giannakidis G, Mantzaris J, Lalas D, Sakellaridis N, Nakos C, et al. Wide scale penetration of renewable electricity in the Greek energy system in view of the European decarbonization targets for 2050. Renew Sustain Energy Rev 2015;42:158–69. https://doi.org/10.1016/j.rser.2014.10.007.
[28] Song H, Dotzauer E, Thorin E, Guziana B, Huopana T, Yan J. A dynamic model to optimize a regional energy system with waste and crops as energy resources for greenhouse gases mitigation. Energy 2012;46:522–32. https://doi.org/10.1016/j.energy.2012.07.060.
[29] Limpens G, Moret S, Jeanmart H, Maréchal F. EnergyScope TD: A novel open-source model for regional energy systems. Appl Energy 2019;255:113729. https://doi.org/10.1016/j.apenergy.2019.113729.
[30] Amirhossein F, Manuel SD, Jos S, Germán ME, André F. Measuring accuracy and computational capacity trade-offs in an hourly integrated energy system model. Adv Appl Energy 2021;1:100009. https://doi.org/10.1016/j.adapen.2021.100009.
[31] Marques-Perez I, Guaita-Pradas I, Gallego A, Segura B. Territorial planning for photovoltaic power plants using an outranking approach and GIS. J Clean Prod 2020;257.. https://doi.org/10.1016/j.jclepro.2020.120602.
[32] Watson JJW, Hudson MD. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landsc Urban Plan 2015;138:20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001.
[33] Liu Y, Chen S, von Cossel M, Xu B, Gao H, Jiang R, et al. Evaluating the suitability of marginal land for a perennial energy crop on the Loess Plateau of China. GCB Bioenergy 2021;13:1388–406. https://doi.org/10.1111/gcbb.12865.
[34] van Stralen JNP, Dalla Longa F, Daniëls B, Smekens K, van der Zwaan B. OPERA: A New High-Resolution Energy System Model for Sector Integration Research. Environ Model Assess 2020. https://doi.org/10.1007/s10666-020-09741-7.
[35] AIMMS. AIMMS:: AIMMS Optimization Modeling; 2018. https://aimms.com/english/developers/resources/manuals/optimization-modeling/ (accessed October 9, 2018).
[36] Open source community. QGIS n.d. https://qgis.org/en/site/ (accessed October 5, 2020).
[37] ESRI. Get started with ArcMap—ArcMap | Documentation n.d. https://desktop.arcgis.com/en/arcmap/latest/get-started/main/get-started-with-arcmap.htm (accessed April 11, 2022).
[38] CBS. Dwellings and non-residential stock; changes, utility function, regions; 2021. https://opendata.cbs.nl/statline/#/CBS/en/dataset/81955ENG/table (accessed February 9, 2021).
[39] Persson U, Wiechers E, Möller B, Werner S. Heat Roadmap Europe: Heat distribution costs. Energy 2019;176:604–22. https://doi.org/10.1016/j.energy.2019.03.189.
[40] Provincie Groningen. Verordening van Provinciale Staten van de provincie Groningen houdende ruimtelijke ordening Omgevingsverordening Provincie Groningen 2016 (in Dutch); 2020.
[41] Kramers L, Van Wees JD, Pluymaekers MPD, Kronimus A, Boxem T. Direct heat resource assessment and subsurface information systems for geothermal aquifers; The Dutch perspective. Geol En Mijnbouw/Netherlands J Geosci 2012;91:637–49. https://doi.org/10.1017/S0016774600000421.
[42] Geothermie Nederland. Geothermie locatie van de diverse projecten in Nederland (in Dutch); 2020. https://geothermie.nl/index.php/nl/geothermie-aardwarmte/geothermie-in-nederland/projectoverzicht (accessed April 22, 2022).
[43] TNO. Map Viewer | Thermogis n.d. https://www.thermogis.nl/en/map-viewer (accessed September 2, 2019).
[44] Rivera Diaz A, Kaya E, Zarrouk SJ. Reinjection in geothermal fields - A worldwide review update. Renew Sustain Energy Rev 2016;53:105–62. https://doi.org/10.1016/j.rser.2015.07.151.
[45] KNMI - Koninklijk Nederlands Meteorologisch Instituut. KNW Data | KNW Atlas | KNMI Projects n.d. https://www.knmiprojects.nl/projects/knw-atlas/knw-data (accessed April 5, 2022).
[46] Bang C, Vitina A, Gregg JS, Lindboe HH. Analysis of biomass prices; 2013.
[47] van der Hilst F, Dornburg V, Sanders JPM, Elbersen B, Graves A, Turkenburg WC, et al. Potential, spatial distribution and economic performance of regional biomass chains: The North of the Netherlands as example. Agric Syst 2010;103:403–17. https://doi.org/10.1016/j.agsy.2010.03.010.
[48] Lensink S, Schoots K. Eindadvies basisbedragen SDE++2021; 2021.
[49] qpunkt gmbh. Waste heat recovery systems for the Glass Industry; 2014.
[50] TenneT, Elia, ENTSOE. HoogspanningsNet Netkaart 2021. https://webkaart.hoogspanningsnet.com/index2.php#10/51.3958/4.5483 (accessed November 18, 2021).
[51] TenneT_Nederland. TenneT Assets (hoogspanning) 2020. https://www.arcgis.com/home/item.html?id=646a6dee22bf485587bc4daf98da1306 (accessed March 14, 2020).
[52] Matthijsen J, Dammers E, Elzenga H. De toekomst van de Noordzee. De Noordzee in 2030 en 2050: een scenariostudie; 2018.
[53] ENEXIS. Open data | Enexis - Energie in goede banen (in Dutch) 2021. https://www.enexis.nl/over-ons/wat-bieden-we/andere-diensten/open-data (accessed March 23, 2021).
[54] CEER. 2nd CEER Report on Power Losses; 2020.
[55] ETSAP. Pricing in electricity transmission and distribution. vol. E12; 2014. Doi: 10.1109/melcon.1996.550955.
[56] Danish Energy Agency, Energinet. Technology Data for Energy Transport; 2021.
[57] Danish Energy Agency, Energinet. Technology Data Generation of Electricity and District heating; 2022.
[58] Nielsen S, Möller B. GIS based analysis of future district heating potential in Denmark. Energy 2013;57:458–68.
[59] Nussbaumer T, Thalmann S, Jenni A, Ködel J. Handbook on Planning of District Heating. Networks 2020.

[60] QGIS. Network Analysis; 2022. https://docs.qgis.org/3.22/en/docs/training_manual/vector_analysis/network_analysis.html.
[61] Provincie Groningen. RES Naslagwerk regionale structuur Warmte (in Dutch); 2021.
[62] Berenschot, Kalavasta. Klimaatneutrale scenario's 2050 – Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050; 2020 (in Dutch).
[63] Provincie Groningen. Klimaatagenda Provincie Groningen 2030 (in Dutch); 2022.
[64] Provincie Groningen. Regionale Energie Strategie 1.0 Groningen (in Dutch); 2021.
[65] van der Niet S, Rooijers F, van der Veen R, Voulis N, Wirtz A, Lubben M. Systeemstudie energie-infrastructuur Groningen & Drenthe (in Dutch). Delft; 2019.
[66] CBS. StatLine - Energy consumption private dwellings; type of dwelling and regions 2018. https://opendata.cbs.nl/statline/#/CBS/en/dataset/81528ENG/table?ts=1550249238313 (accessed February 15, 2019).
[67] ENEXIS. Congestiemanagement onderzoeken | Enexis Netbeheer 2022. https://www.enexis.nl/zakelijk/aansluitingen/congestie-onderzoeken (accessed April 11, 2022).
[68] Agency NE. Features SDE++ | RVO.nl 2021. https://english.rvo.nl/subsidies-programmes/sde/features (accessed April 24, 2022).
[69] Energiecooperatie duurzaam Assen, Natuur en Milieu Drenthe, Bronen VanOns, ADAMANT Solar. Bundeling verslagen van en na informatieavonden Zonneplas Ubbena – Assen; 2020.
[70] Choi YK. A study on power generation analysis of floating PV system considering environmental impact. Int J Softw Eng Its Appl 2014;8:75–84. https://doi.org/10.14257/ijseia.2014.8.1.07.
[71] Beckers KF, Performance YKR. Cost, and Financial Parameters of Geothermal District Heating Systems for Market Penetration Modeling under Various Scenarios. 42nd Work Geotherm Reserv Eng 2017:1–11.
[72] Scheepers M, Palacios SG, Jegu E, Nogueira LP, Rutten L, van Stralen J, et al. Towards a climate-neutral energy system in the Netherlands. Renew Sustain Energy Rev 2022;158:112097. https://doi.org/10.1016/j.rser.2022.112097.
[73] Powerpipe. District heating network pipe catalogue; 2016.
[74] Noordelijke Rekenkamer. Energietransitie provincie Groningen (in Dutch); 2016.
[75] European Commission. PVGIS Photovoltaic Geographical Information System. 2022 n.d. https://joint-research-centre.ec.europa.eu/pvgis-photovoltaic-geographical-information-system_en (accessed November 29, 2022).