

Regionalized decision-supporting tool application for scenario analyses considering stakeholder interactions: A case study of the Groningen province in the northern Netherlands

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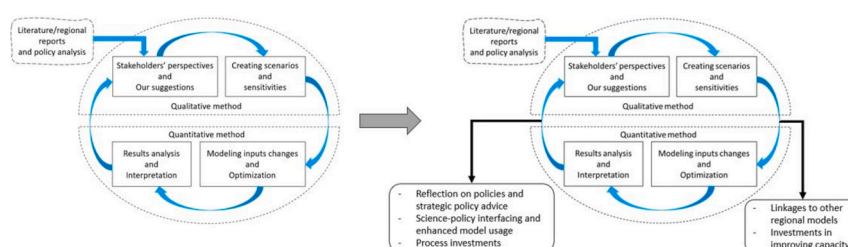
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HIGHLIGHTS

- Multiple scenarios were created using the perspectives of different stakeholders.
- Major cost, supply mix, and energy balance differences exist between scenarios.
- Our decision-supporting tool systematically analyzes regional energy system.
- Stakeholder interactions highlighted the importance of the science-policy interface.

GRAPHICAL ABSTRACT



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ABSTRACT

Regionalized integrated energy system models considering stakeholder inputs are uncommon in the literature. This study tested and validated an existing quantitative optimization-based OPERA regional modeling framework. Stakeholder responses to surveys resulted in multiple future scenarios and sensitivities, applied to the Dutch province of Groningen energy transition. Stakeholder reflections in a workshop confirmed the potential of the model as a strategic decision-supporting tool. The tool successfully analyzed trade-offs, compromises, and complementarities regarding the different choices of stakeholders. The study reflected on the modest role of solar photovoltaics, which supplied 6.6–17.5 % of the primary energy, in comparison to policies and stakeholder assumptions. Biomass energy, at 18.2–28.5 %, was more prominent than expected. Similarly, choosing a scenario close to the current policy implied a strong dependency on imports, with net imports constituting 50 % of the energy supply. On the other hand, regional self-sufficiency implied spatial implications beyond stakeholder expectations. For example, land use associated with onshore wind energy was ~13 % of the provincial land. The stakeholder interaction process highlighted capacity investments via other harmonized model linkages and the importance of the science-policy interfaces. Compared with contemporary models, the major advancements are spatial interfacing and the inclusion of land-use planning and policy constraints.

Abbreviations: BE, Built Environment; CAPEX, capital expenditure; CCTS, carbon capture transport and storage; DH, district heating; DSO, distribution system operator; EU, European Union; GBPV, Ground-based photovoltaics; GIS, Geographic Information System; GHG, greenhouse gas; HV, high voltage; IWH, industrial waste heat; LV, low voltage; MV, medium voltage; NG, natural gas; OPERA, Options Portfolio for Emission Reduction Assessment; TSO, transmission system operator.

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1. Introduction

In line with the European Union (EU) targets for 2050 [1], the Netherlands aims to reduce emissions and deploy renewable energies [2]. A high population density in the Netherlands imposes challenges on existing landscapes with multiple spatial claims besides those related to energy transitions [3]. Most energy system models omit spatial constraints or characteristics related to sectoral demands [4,5] or renewable energy deployment measures [6–8], which are important for developing spatial policies [9,10] and determining spatial aspects of energy transition [11]. In addition, strategic spatial planning specifically targets local and regional levels, whereas most energy models operate at national [12] or highly local levels [13], with few targeting regional levels below the country level [14]. This study shows how a regionalized national energy system model [15] can assist in pursuing regional targets while considering land use, cost, sustainability, efficiency and energy-saving measures, and renewable implementation-related spatial constraints [16].

Regional modeling studies often target specific sectors, such as the built environment (BE) [17,18], the power and mobility sector [19], and mobility infrastructure [20]; energy supply options, such as solar [21], wind [22], and biomass energies [23]; or specific infrastructures, such as carbon dioxide [24,25] or hydrogen infrastructures [26]. Although others approach more integrated modeling, they target a limited set of spatial parameters [27,28]. Furthermore, integrated scenario studies that include contrasting policy ambitions and preferences are often conducted at the national level [29–33]. Regional cases include Västmanland in Sweden [34] and the southwest region of Ireland [16]. However, they only consider sectoral priorities, relevant energy supply options, or related energy infrastructures, lacking simultaneous analyses of these aspects in combination.

In addition to the lack of regional-level modeling, limited focus has been put on incorporating stakeholder perspectives, which are important for supporting strategic, regional, and spatial planning. Scenarios can capture stakeholder preferences absent in current policies [35]. Stakeholder inputs improve data quality and make scenarios more robust and reliable [36]. Furthermore, stakeholder preferences can be compared between scenarios [37], allowing for the identification of conflicts, complementarities, and trade-offs in future energy developments [38,39]. Thus, integrating stakeholder inputs allows for the testing and validation of a regionalized decision-supporting tool.

Focusing on decision-supporting tools, an optimization modeling framework was used for decision support to study the national level [40]. Decision-support tools have been used for renewable energy planning for Ireland [41]. The challenges related to decision-support systems were analyzed, focusing on the agricultural sector [42]. Multi-criteria decision-making methods were reviewed for the household sector related to renewable energy technologies [43]. A decision-support system was developed to analyze the energy sector without specifically analyzing any region [44]. These tools do not analyze the impact of interactions at multiple geographical levels, such as regional and national, which we intend to do.

Energy modeling studies that include stakeholder input remain limited and often target specific topics, such as offshore wind energy in the North Sea [45,46], power generation [47], and hydrogen transition [48], and energy-demanding sectors, such as agriculture [49], residential households [50], and industries [51]. In addition, some of these studies are unclear in defining the geographical scope, sectors, or energy supply options [52,53]. A decision-making approach was used to create a hybrid renewable microgrid without emphasis on spatial planning and stakeholder engagement [54]. These studies lack a simultaneous analysis of an integrated energy system, spatial policies and regulations, and land use and infrastructure planning.

Spatial decision-support tools are necessary for tackling socio-political challenges with increasing land-use demands and renewables planning [41]. Wind energy potential was analyzed at Alborz Province

in central Iran using a multi-criteria decision-support tool [55]. Existing energy system models fail to sufficiently support spatial and planning decisions [56]. Current decision-support tools have limited input from relevant stakeholders [41].

This study developed, analyzed, and discussed scenarios with stakeholders and performed sensitivity analyses using a previously developed spatially sensitive integrated energy system model [15]. The model supports policymakers and key stakeholders on spatial and energy policies and ambitions by combining analyses of existing spatial and environmental policies and regulations related to integrated energy systems. After presenting the methodology in Section 2 and the scenario results in Section 3, Section 4 discusses the overall process of stakeholder interactions reflecting energy-related policies and spatial planning. The conclusions and policy implications are presented in Section 5.

2. Methodology

The approach is a mixed method, as shown in the conceptual map (Fig. 1) and methodological framework (Fig. 2). Section 2.1 describes the regionalized model used in this study. A questionnaire was used to collect shareholder perspectives, which were used to create scenarios and perform sensitivity analyses (Section 2.2). A quantitative method involving modeling and result analyses was then employed (Section 2.3), leading to discussions with stakeholders to gain insights and provide them with suggestions (Section 2.4).

2.1. Regionalized OPERA model

The Options Portfolio for Emission Reduction Assessment (OPERA) model is a Dutch-based national optimization model that represents energy-demanding sectors, energy supply options, energy infrastructure, and emissions [57]. OPERA regionalization [58], followed by a detailed spatial geographical information system (GIS)-based analysis [3], led to a regionalized OPERA model capable of supporting decisions on energy systems, targeting an example case from the Groningen province [15]. Appendix A provides a detailed description of this model.

The method involves five systematic steps (Fig. 3). Stakeholder inputs on key regional and spatial energy systems were collected via a survey in the first step. The second step developed scenarios for a future energy system by compiling and processing the inputs. Step 3 involved modeling changes to accommodate all scenarios. Step 4 analyzed the scenarios and interpreting the results related to infrastructure, costs, and space. Finally, Step 5 consisted of discussing the results with a focus group in a workshop, leading to the formulation of a final set of sensitivity analyses and reflections on regional policies and targets. The following section discusses these steps in detail.

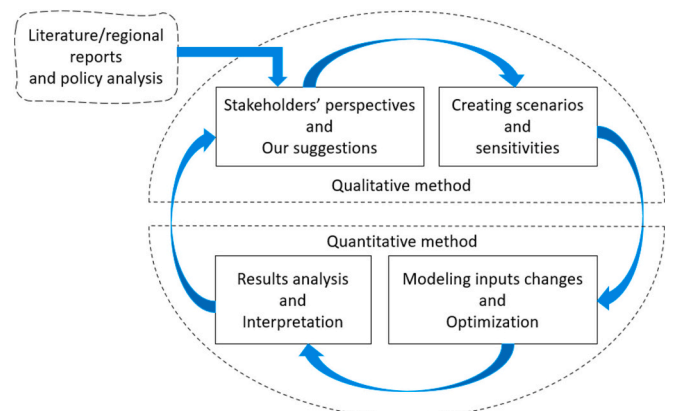


Fig. 1. Conceptual map of the method.

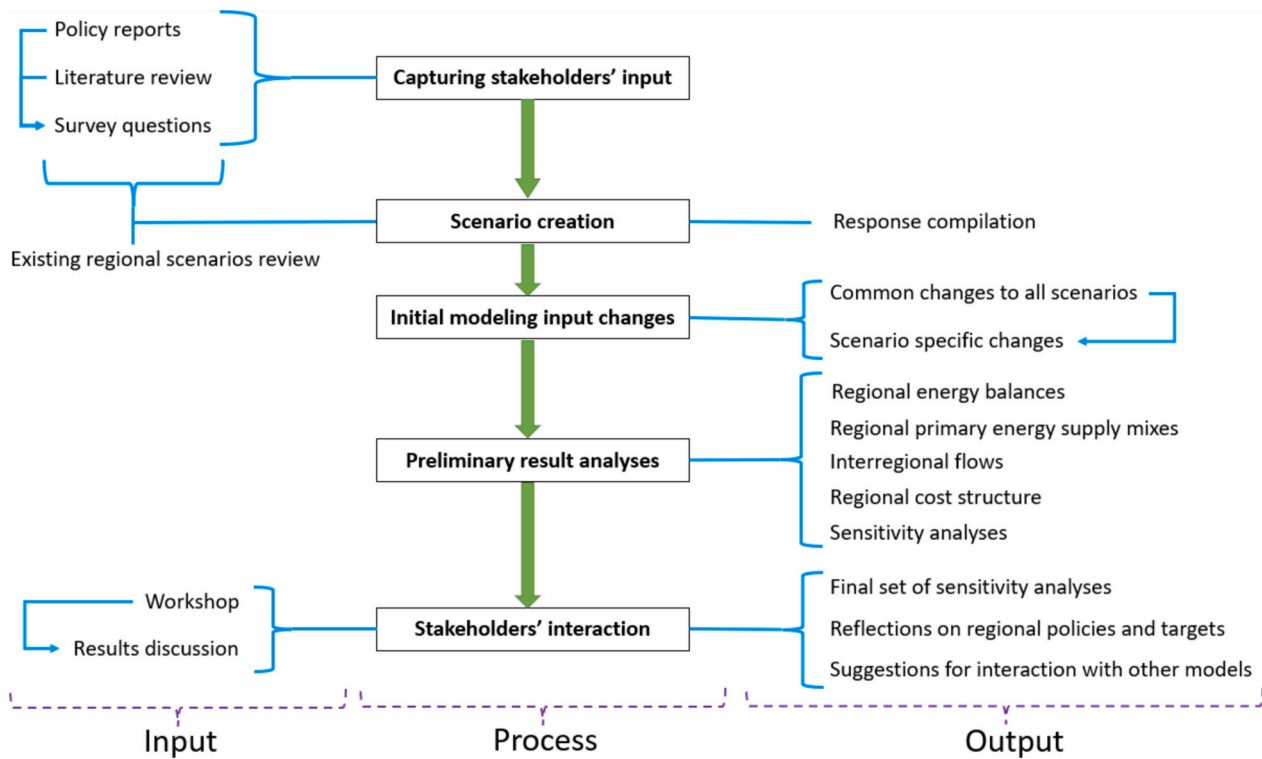


Fig. 3. Step plan for the method.

operator (DSO) were included.

2.2.2. Step II: Scenario development

Three scenarios were formulated based on stakeholder perspectives and expectations (Fig. 4), embedded in a wider consideration of reports on provincial policy reports [62,63], energy infrastructure [64], and industries [65]. These scenarios differed primarily in the land use related to renewable energies, capacity and spatial distribution of energy infrastructure, and other supply options and infrastructures. Appendix Table C1 in Appendix C details these scenarios.

2.2.2.1. Autarkic. The autarkic scenario targeted regional self-sufficiency with a regional greenhouse gas (GHG) emission reduction of 100 %, with a national emission reduction target of 95 % compared to the 1990 levels (Fig. 4). General assumptions were no net energy dependence on other regions, including North Sea, and no reliance on

fossil fuels. The scenario targeted sustainability, even if the total system cost was high. Hence, the autarkic scenario allowed for the highest stakeholder estimates regarding rooftop solar energy (60 % of roofs), available land for GBPV energy (5 % of the agricultural land), wind farms (everywhere except no-go zones), biomass (30 % of the agricultural land covered with miscanthus and willow [66,67] and 40 % of grass refining used for energy production), and utilizing residues of nature management and agriculture. The autarkic scenario also assumed the small buffer zones (+500 m) from the survey answers.

Regarding the energy infrastructure, a pan-provincial DH network with connections to geothermal doublets and industries (for residual heat) was included (Fig. A-2 in Appendix A). The capacity of high voltage (HV) electricity infrastructure increased by 20 % compared to the current capacity.¹ Hydrogen and NG produced in the province must be used locally and the capture of CO₂ was only allowed from provincial point sources.

2.2.2.2. Least constrained. The least-constrained scenario targeted a low total system cost at the national level (where the progressive scenario from Sahoo et al. [3] was considered for renewable energies) without considering additional regional constraints (Fig. 4). This scenario assumed a lower pressure on renewable energy capacity compared to the autarkic scenario, taking the median of stakeholder estimates regarding rooftop solar (50 % of roofs), available land for GBPV energy (1.3 % of agricultural land), biomass (for example, energy crops on 10 % of the agricultural land and 10 % of grass refining were used for energy production), and the use of residues from nature management and agriculture. Only for wind energy did it assume high estimates (everywhere except no-go zones) because of the climatic suitability of Groningen for wind energy. However, larger buffer zones (+1000 m) are used between wind farms (and the GBPV farms) and sensitive areas.

Table 1

List of stakeholders included for our analysis.

	Organization	Area of interest	Filled in survey	Joined workshop
1	Province of Groningen	Spatial policies	✓	✓
2	Province of Groningen	Economy	✓	✓
3	Province of Groningen	Spatial & environmental policies	✓	✓
4	Municipality of Groningen	Urban municipality	✓	X
5	Municipality of Hogeland	Rural municipality	✓	✓
6	Gasterra	Gas company	✓	X
7	Groningen Seaports	Industry/Energy	✓	X
8	LTO Noord	Agriculture	✓	✓
9	Natuur & Milieufederatie	Environment, Nature	✓	✓
10	Enexis	DSO	✓	✓
11	Tennet	TSO	✓	X

¹ MV capacity addition is also included in the modeling framework, and its investment and other costs are included. However, the capacity change is unrestricted in the scenarios.

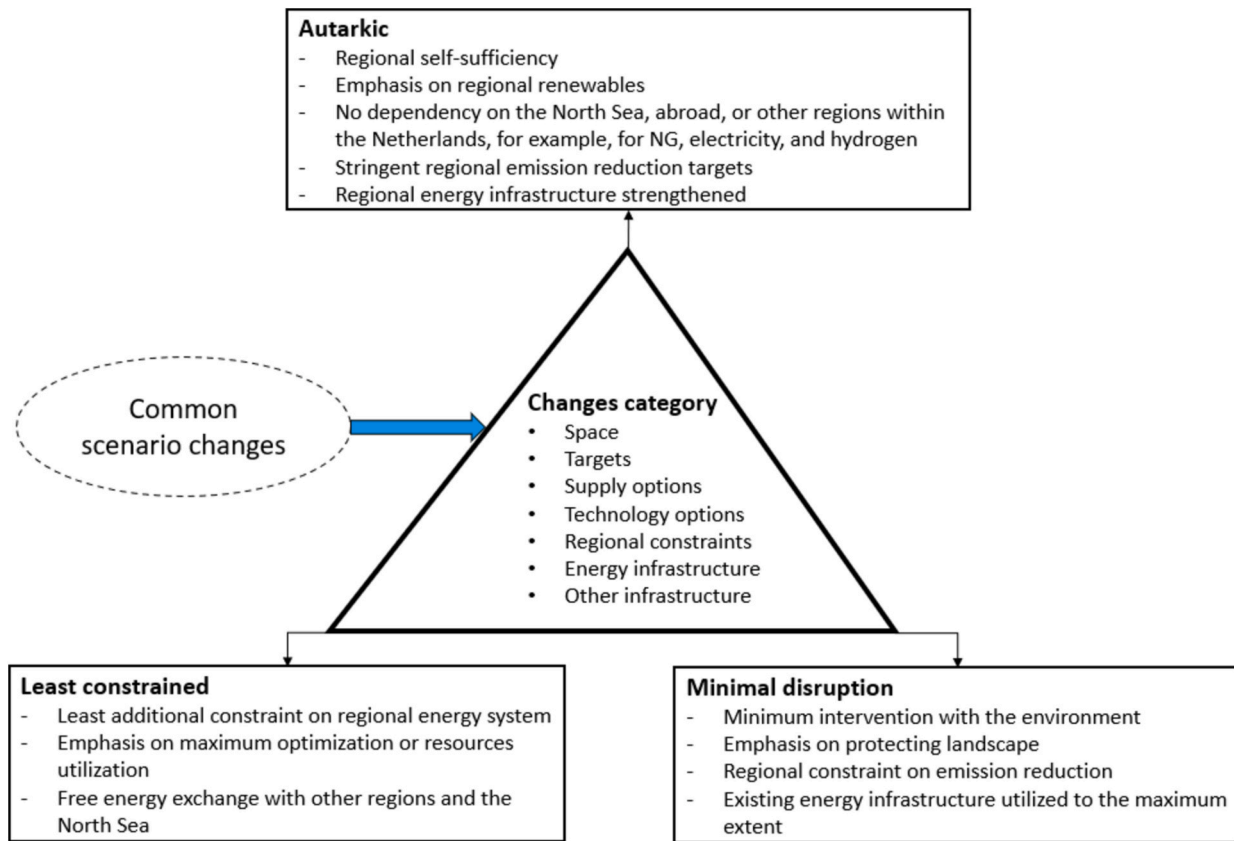


Fig. 4. Overall scenario description.

To avoid constraints on energy transport, high stakeholder estimates for energy infrastructure expansion were considered; for example, the HV network capacity was doubled. Similar to the autarkic scenario, a pan-provincial DH network was included, which also allowed for the net regional import of electricity, NG, and hydrogen.

2.2.2.3. Minimal disruption. This scenario targeted minimal disruption to the landscape and environment (Fig. 4). The aim was to achieve less social controversy, even at the expense of costs and sustainability. In line with the Groningen Regional Energy Strategy Report [61], which does not emphasize GBPV and onshore wind energies, the scenario takes the most prudent stakeholder estimates on both; that is, there was no expansion compared to existing provincial and municipal plans. Assuming that PVs should be placed in the BE to meet the regional energy demand, rooftop solar energy remains significant (50 % of roofs), whereas biomass was moderate to avoid disruption (5 % of the agricultural land was dedicated to energy crops and there was limited use of residues of nature management and agriculture).

A minimal HV capacity was added to avoid the disruption of landscapes and space use [59]. We did not consider a pan-provincial DH network, although city-wide DH networks were allowed. Net regional imports of electricity, NG, and hydrogen were allowed.

2.3. Step III: Modeling activity (phase I)

The modeling activity consisted of two parts: GIS modeling and energy system modeling (Fig. 2). GIS modeling first targeted the creation of buffer zones surrounding the BE and quiet areas for the autarkic and least-constrained scenarios, using GIS model builders created in Sahoo et al. [3]. The minimal-disruption scenario required no GIS modeling because it used existing municipality targets [61,68]. For biomass energy, projected spaces (2050) associated with arable land, grassland,

forest, and nature areas were considered, based on the same study [3]. Excel sheets were used to calculate the percentages of the availability of various biomass types associated with the abovementioned land-use categories, such as agricultural residues or energy crops. The provincial renewable energy potential was converted into capacity or energy potential for each municipality.

Next, the OPERA database was updated with spatially detailed data based on the scenario description and data on renewable energies from the GIS modeling. Additional constraints were included depending on the scenario, including limits on provincial greenhouse gas emissions, net provincial import or export of various energy carriers, and not allowing a pan-provincial DH network to operate in the minimal-disruption scenario. The costs and technical characteristics were updated in relation to the DH transmission and distribution networks, along with centralized heat supply technology options associated with the DH. The hydrogen network is underrepresented in OPERA. In this study, the cost structure of the hydrogen network was improved by the national average cost associated with the hydrogen distribution network, based on the study by Dodds and McDowall [69].

2.4. Steps IV and V: Stakeholders' interaction (phase II)

Step IV was the analysis of scenario results, which were presented for discussion with stakeholders in the analysis in Step V, which is presented in Fig. 3. For that discussion, stakeholders who completed the survey were invited, most of whom were present (Table 1). Presentations were prepared to explain the capabilities and limitations of the regionalized OPERA model, the adopted scenarios and sensitivities, and model results.

The results were categorized into primary energy supply mixes, energy balances, spatially detailed renewable energy supplies, inter-regional flows, and cost considerations. Stakeholders reflected on these

results and discussed land-use choices, infrastructure, and social implications, particularly those related to the deployment of renewable energies. Next, discussions were held on the expected energy infrastructure constraints, particularly electricity, necessary investments, sectoral energy savings and efficiency measures, spatial allocation of technology options and processes, and interactions between energy carriers, sectors, and supply options. Finally, the gaps and discrepancies between existing spatial policies and targets related to renewable energy penetration, efficiency measures, and GHG emissions were discussed. This provided an opportunity to gain insights into potential conflicts, complementarity, and compromise from different future perspectives. Based on these discussions, further sensitivity analyses were performed.

3. Results

The modeling input data related to regions outside the Groningen province were similar to those in the study by Sahoo et al. [58] for all scenarios. We ran the model with the abovementioned scenarios, and the results are presented and analyzed.

3.1. Regional energy analyses

The autarkic scenario showed the highest difference between supply (including regional imports) and demand (24 PJ or 6.7 TWh), followed by the least-constrained scenario (10 PJ), indicating the relative importance of transformation losses (Fig. 5). The wind energy supply was 59 PJ (55 % of the total primary energy supply) in the autarkic scenario, 48 PJ (54 %) in the least-constrained scenario, and 8 PJ (17 %) in the minimal-disruption scenario. The model found it cost-effective to prioritize wind energy over others, such as solar PV.

The renewable energy supply mix varied spatially and was diverse in all scenarios (Fig. 6). For example, the Het Hogeland municipality had the highest renewable energy supply in each scenario: 19.3 PJ (20 % of the total provincial renewable energy supply), 15.8 PJ or 4.4 PJ (22 %), and 8.4 PJ (29 %) in the autarkic, least-constrained, and minimal-disruption scenarios, respectively. Wind energy also had varied contributions between scenarios, as the Westerwolde (16 PJ) and the Het

Hogeland (14 PJ) municipalities had the highest contributions in the autarkic and least-constrained scenarios, respectively. The solar PV range of 2–66 PJ for Groningen is comparable to other studies [70,3,71,72], and for onshore wind, 2050 potential range of 0–49 PJ [3,70,72,71] is near our range of 8–59 PJ.

Contributions varied highly from different technologies and scenarios to meet the BE heat demand for all land-use regions (Fig. 7). Heat pumps were crucial in the BE heat supply in all scenarios, with 10.2 PJ or 2.8 TWh (54 % of the total BE heat supply), 5.7 PJ (29 %), and 7 PJ (36 %) supplies in the autarkic, least-constrained, and minimal-disruption scenarios, respectively. In all scenarios, the outer city of Groningen had the highest supply (and demand), followed by the Het Hogeland municipality. A similar spatially detailed analysis of heat supply can be performed for other sectors, such as industries. In addition, a similar energy balance study can be performed for other energy carriers, such as electricity.

Fig. 8 presents a comparison between scenarios regarding the utilization share of capacity potentials for rooftop PVs in the BE and onshore wind farms for land-use regions within the Groningen province. Notably, the share of GBPV energy is not represented because it is almost negligible for all land-use regions in all scenarios. Rooftop PV was not maximized in any scenario, with capacity potential shares of 0.21, 0.23, and 0.41 for the autarkic, least-constrained, and minimal-disruption scenarios, respectively. The utilization share of the capacity potential of onshore wind farms for each municipality was higher than that of rooftop PVs for all scenarios: 0.63, 0.88, and 0.46 for the autarkic, least-constrained, and minimal-disruption (having only wind farms listed in existing policies) scenarios, respectively. The results from the autarkic scenario show that municipalities that did not maximize wind farm capacity utilization utilize less than 50 % of their capacity, suggesting that they are less optimal for onshore wind farms (Fig. 9). Except for Westerwolde, the least-constrained scenario nearly maximized the use of the available capacity potential in each municipality. The Eemsdelta municipality had a low utilization share in all scenarios suggesting that it is cost-ineffective for wind farm installation because of the capacity limits of the projected electricity infrastructure.

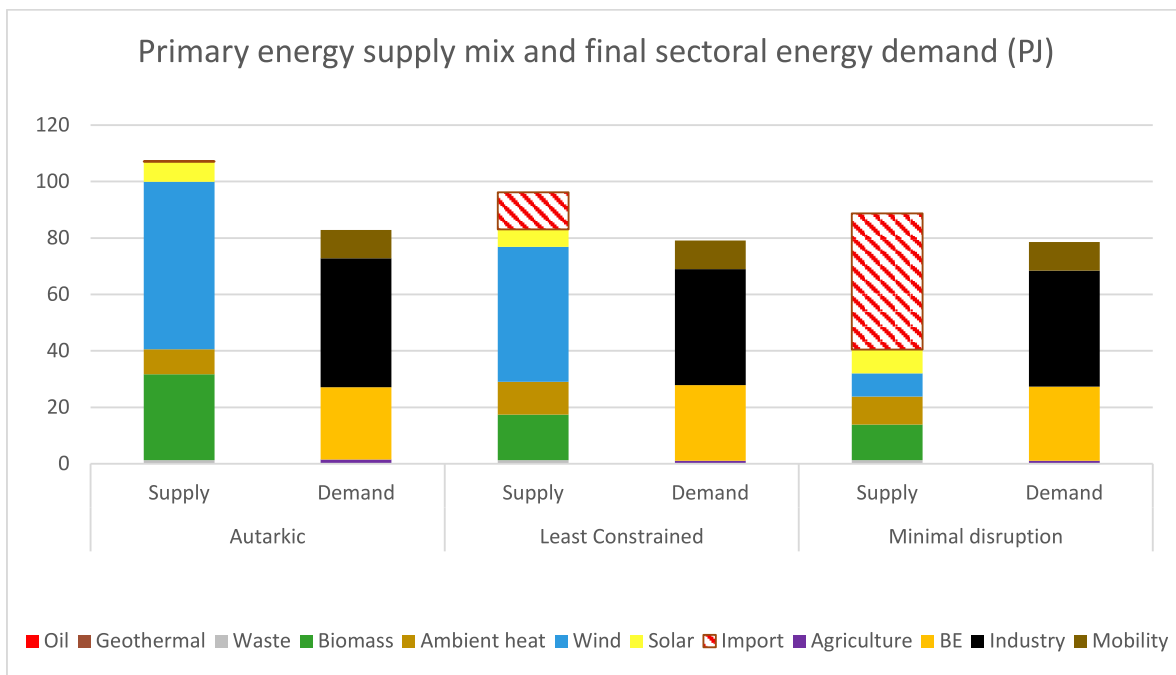


Fig. 5. Primary energy supply and final sectoral demand (data in PJ) for 2050. Import is also included (see dashed bar) to compare the net primary energy supply in the Groningen province and to show transformation losses between primary supply and final demand.

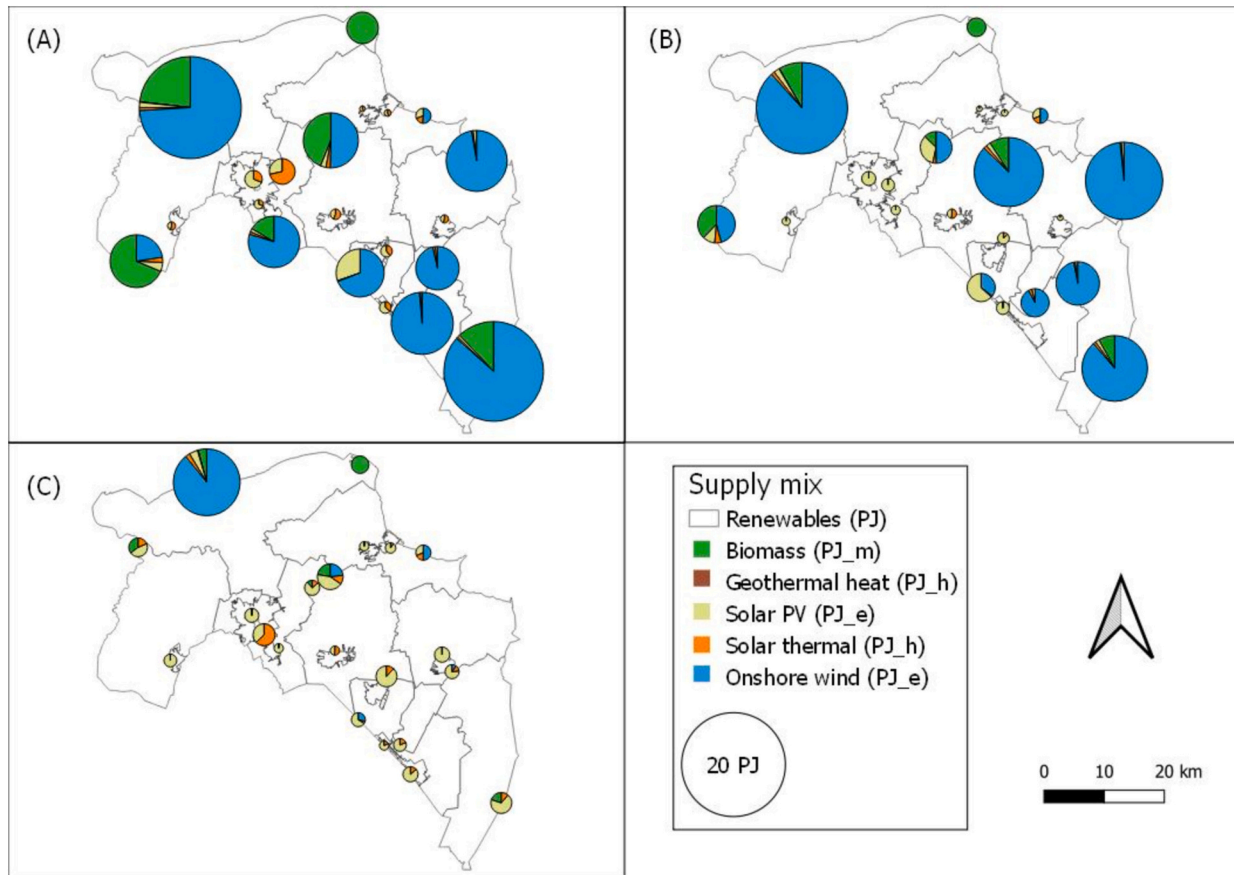


Fig. 6. Comparison between scenarios on renewable energy supply mix in each land-use region and industrial node in the Groningen province. Here, m, h, and e represent multiple, heat, and electricity energy carriers, respectively. The area of a pie represents the energy supply volume in PJ. Regional energy supply mix regional distribution. (A), (B), and (C) represent the autarkic, least-constrained, and minimal-disruption scenarios, respectively.

3.2. Interregional energy flow analyses

3.2.1. Electricity

The net annual flow volumes between different electricity nodes related to HV and MV networks were significantly different between scenarios (Fig. 10). The interregional flows in the autarkic scenario were lower than those of the least-constrained scenario, as the net electricity transmission to the Groningen province was restricted and network capacity was low, with the latter also being the case for the minimal-disruption scenario (Section 2.2.2). Groningen was exporting a net electricity flow of 6.7 PJ or 1.8 TWh in the least-constrained scenario and importing 25.2 PJ in the minimal-disruption scenario. This suggests that, without significant investments in increasing the network capacity, at least in the major HV networks, the province will be dependent on other regions (including the Dutch part of the North Sea) to meet its electricity demands.

Fig. 11 presents the utilization share compared to the maximum available capacity for the HV networks in all scenarios. The available capacity of few connections were fully utilized in the autarkic scenario (Fig. 11(A)), such as the connection between the Het Hogeland (offshore connection) and Groningen municipalities (maximum network capacity of 3.2 GW) and between the Westerwolde municipality and Drenthe province (6.6 GW). The least-constrained scenario (Fig. 11(B)) did not fully utilize most of the connection capacities, and the average capacity utilization was even lower than that of the autarkic scenario. The Netherlands TSO also has plans to expand this network to accommodate a higher inflow of electricity from the North Sea in the future [73,74]. The minimal-disruption scenario (Fig. 11(C)) fully utilized most of the connection capacities and had the highest average capacity utilization

within the scenarios. This indicates that an overall increase in the current HV capacity by 20 % is sensible, and doubling may not be required from a network cost optimization perspective (Section 2.2.2). Another observation is that the HV network might be congested or highly constrained, which might lead to power losses in cities or important industries, as seen in the minimal-disruption scenario, with a capacity near that of Groningen currently [75]. For example, the connection between Het Hogeland (offshore connection) and the city of Groningen is fully utilized in this scenario, which might lead to future network congestion in this city. Congestion is also crucial because supply sources may be underutilized owing to insufficient transmission capacity.

3.2.2. District heating

Fig. 12 shows the DH network infrastructure within the Groningen province for the least-constrained and minimal-disruption scenarios. Multiple locations of heat sources, particularly geothermal and IWH, match with the provincial heat planning report [76]. The autarkic scenario was disregarded because the DH did not influence it. In both scenarios, most cities relied on connections between centralized heat sources on the city outskirts to the city center (via a transmission network), and then to the whole city (via a distribution network). There were no connections from geothermal heat in either scenario, suggesting that geothermal heat extraction and the corresponding heat transmission to the modeled cities were expensive. The utilization potential of heat from geothermal sources was low despite the high available potential within Groningen [77,78] (Fig. 5). The least-constrained scenario included a few additional DH transmission connections from IWH sources (Fig. 12(A)). These connections were missing in the minimal-disruption scenario because industrial connections were restricted in

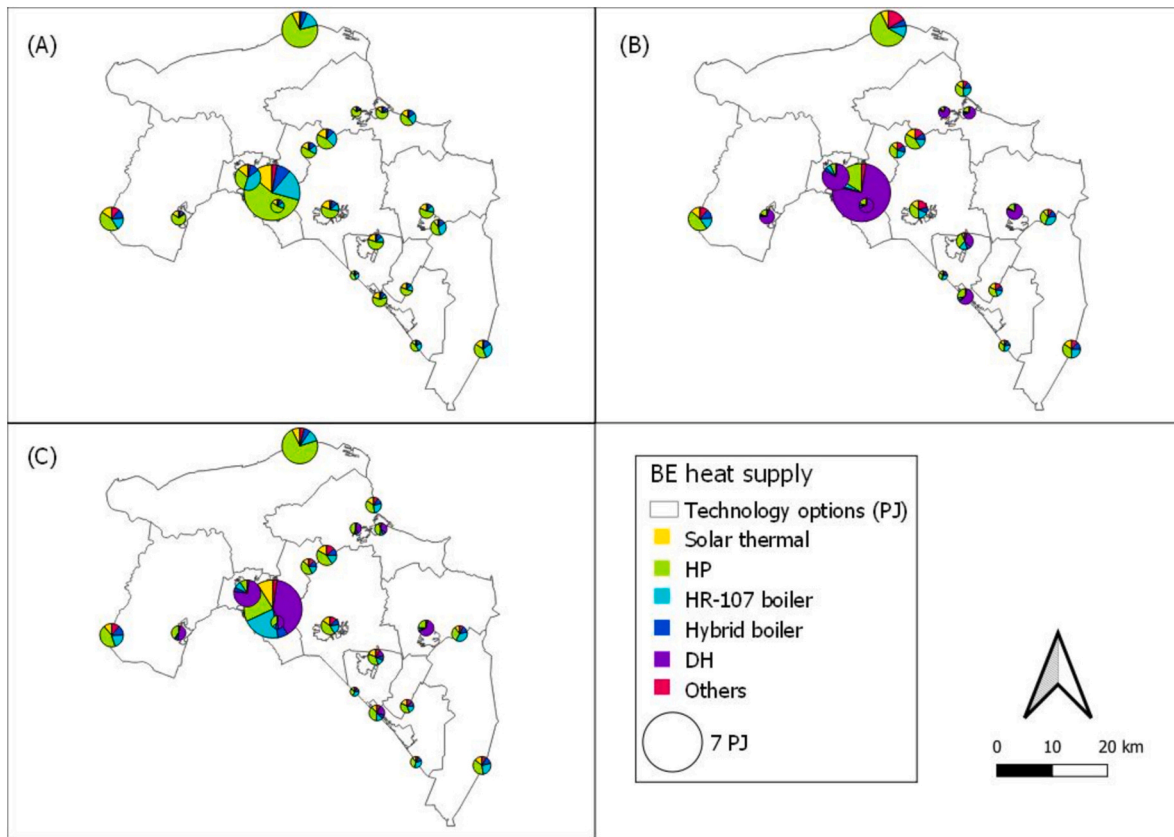


Fig. 7. Heat supply technology options for meeting the BE's heat demand in all of the Groningen province's land-use regions. The area of the pie represents the energy supply volume in PJ. (A), (B), and (C) represent the autarkic, least-constrained, and minimal-disruption scenarios, respectively.

this scenario (Fig. 12(B)). Common centralized DH-related technology options for both scenarios were the compression air source heat pumps and straw biomass-based combined heat and power plants.

Fig. 13 shows the DH supply volumes to the cities and the corresponding penetration percentages. The DH penetration is defined as the percentage of heat demand (in this case, within the BE) met by the DH. The inner city of Groningen had the highest penetration in both scenarios: 81 % for the least-constrained and 75 % for the minimal-disruption scenarios, due to the compact structure and high demand density in the region [15]. The penetration rate varied significantly between cities for both scenarios, with a higher average for the least-constrained scenario (61 %) (Fig. 13(A)) than for the minimal-disruption scenario (38 %) (Fig. 13(B)). Only the Hoogezand-Sappemeer city had no DH connection in either scenario because of the comparatively low heat demand density and large distribution network costs associated with long network routes.

3.3. Cost analysis

The total system cost of Groningen was 0.4 % and 7 % lower for the autarkic and least-constrained scenarios, respectively, compared with the minimal-disruption scenario (Fig. 14(A)). The import contribution for the autarkic scenario is ~1 B€/year less than that of the minimal-disruption scenario; however, the supply options cost ~0.4 B€/year more. This indicates that the autarkic scenario uses more supply options to achieve regional self-sufficiency. Energy infrastructure is responsible for the maximum share of the total system cost in all scenarios: 49 %, 54 %, and 46 % of the total system cost in the autarkic, least-constrained, and minimal-disruption scenarios, respectively. The import cost is high for the least-constrained and minimal-disruption scenarios because of the high import of NG and hydrogen, along with electricity imports in the minimal-disruption scenario. Considering the components of the

cost, the capital expenditure (CAPEX) is responsible for the maximum share of the total system cost within the Groningen province: 76 %, 75 %, and 75 % of the total system cost for the autarkic, least-constrained, and minimal-disruption scenarios, respectively (Fig. 14(B)).

Within the CAPEX, energy infrastructure made the largest contribution, followed by mobility and the BE sector (Fig. 15). For the BE, the autarkic scenario had the highest CAPEX, followed by the minimal-disruption and least-constrained scenarios. This is explained by extra investment in retrofitting to achieve better insulation and in individual heat sources (the DH infrastructure is non-existent in the autarkic scenario). Energy infrastructure also exhibited high OPEX values for all scenarios. The fuel cost was the highest for mobility in all scenarios, followed by either industry or the BE, depending on the scenario.

Energy infrastructure was further analyzed because of its significant contributions to the total system cost and its contributions to mitigating regional demand-supply mismatches (Fig. 16). Electricity network infrastructure is a key component in both CAPEX and OPEX. The CAPEX for electricity was the highest for the least-constrained scenario (1.8 B€/year), followed by the autarkic (1.77 B€/year) and minimal-disruption (1.6 B€/year) scenarios, because the actual capacity expansion in this scenario was the highest among all. The DH CAPEX was also the highest for the least-constrained scenario, followed by the minimal-disruption scenario, whereas the autarkic scenario had no associated cost. The total CAPEX is the highest for the least-constrained scenario (2.1 B€/year), followed by the autarkic scenario (2 B€/year). This cost structure analysis assists stakeholders in determining where to invest, which systems are cheap and under what conditions, and how the import or export of energy carriers can affect the cost structure. A cost split between HV and MV infrastructures is also possible, even per region [15].

These scenario analyses generate insights that are unachievable through the investigation of a single future scenario, as was the case of the study made by Sahoo et al. [15]. For example, supply options,

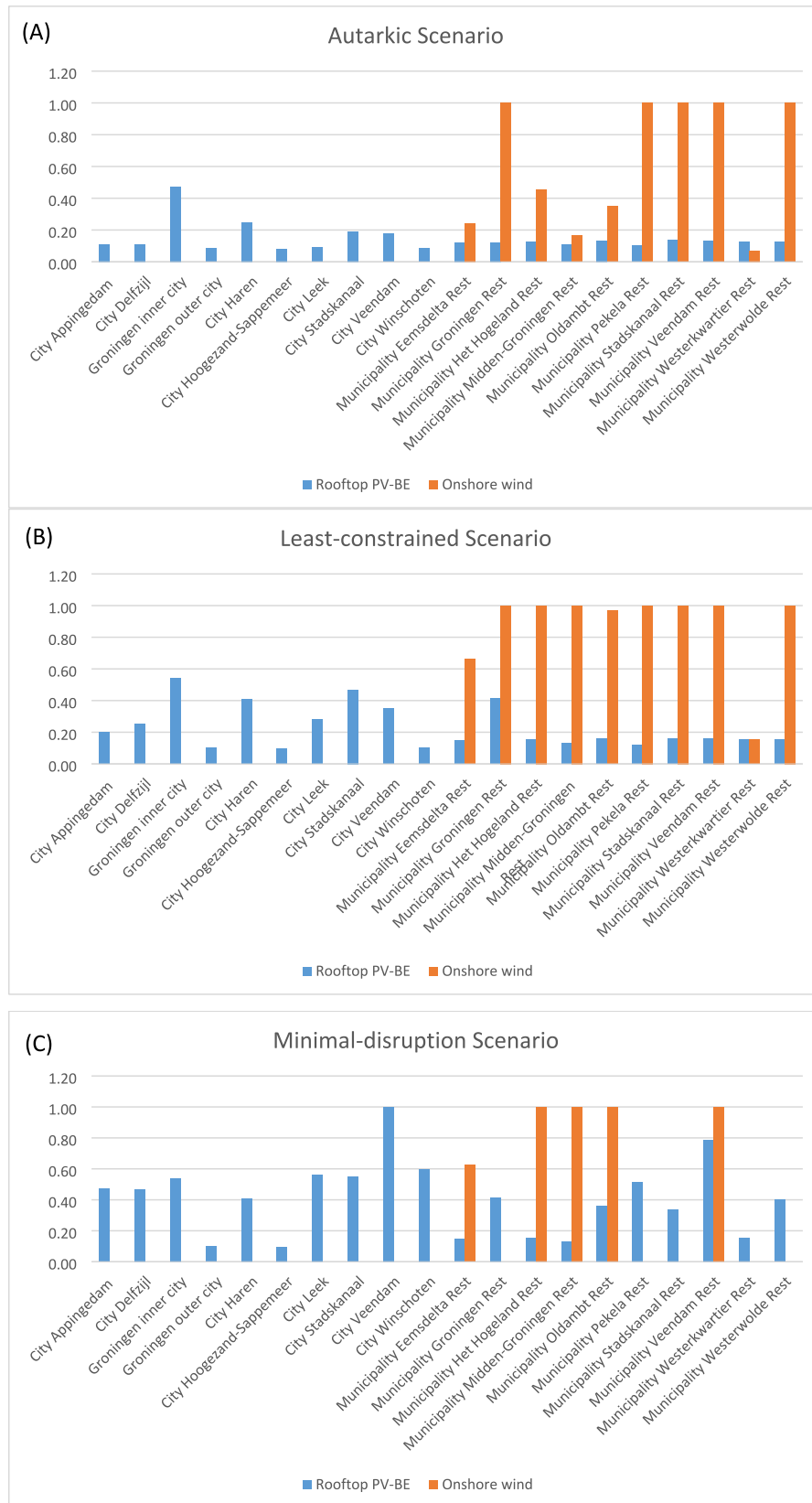


Fig. 8. Maximum capacity potential share used compared to the potential available in each land-use region considered in our study for the Groningen province. Rooftop PVs in the BE and onshore wind farm capacity potentials were considered. (A), (B), and (C) represent the autarkic, least-constrained, and minimal-disruption scenarios, respectively.

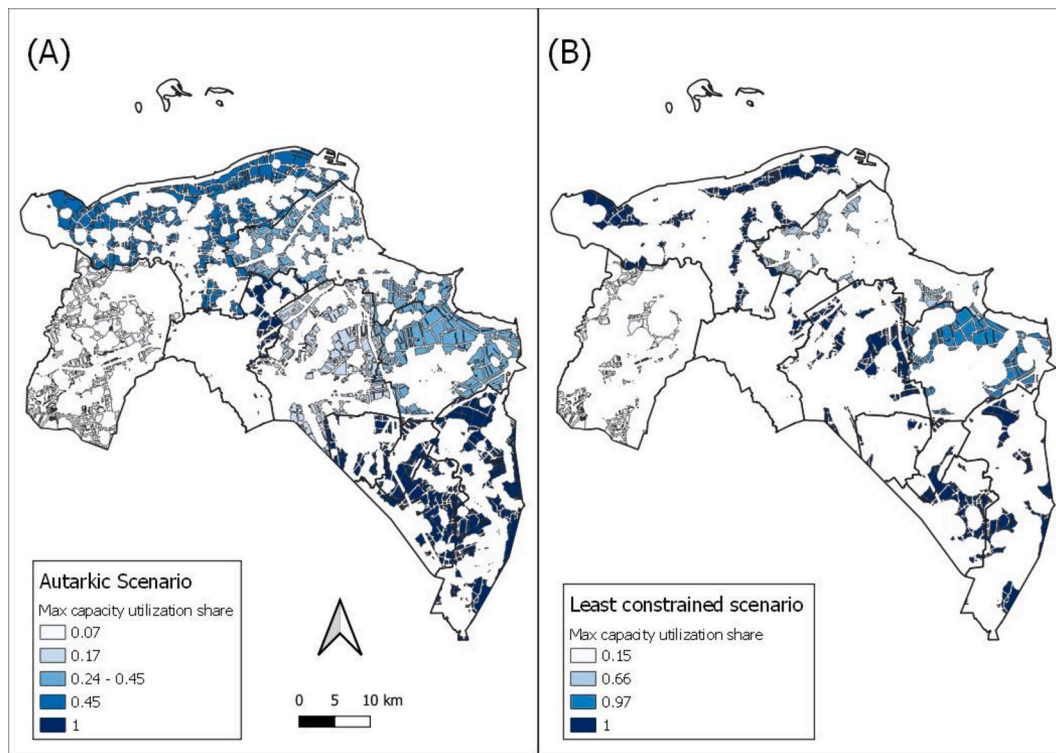


Fig. 9. Analysis of spatial potential related to capacity utilization share for onshore wind farms in each municipality. (A) and (B) represent the autarkic and least-constrained scenarios, respectively. The minimal-disruption scenario is not presented because the overall spatial potential is low and are only present in minimal capacity in a few municipalities.

particularly renewable energies, can be important but depend heavily on different policies regarding space use or infrastructure expansions. The results demonstrate that energy infrastructure, such as DH distribution networks, is highly sensitive to cost changes, exhibiting variable penetration ranges between different cities and scenarios. Finally, it helps identify the key role of the BE and industries in future energy systems in terms of energy demands, investments, and savings options or potentials.

3.4. Sensitivity analysis

Sensitivity analyses were performed. One of the important ambitions of some stakeholders was to analyze the large dependency on onshore wind energy in the autarkic scenario (see Fig. 5), in contradiction with the current political affinity towards solar PV over the societal resistance to onshore wind farms. A sensitivity analysis was performed on the step-wise reduction in the onshore wind farm deployment in the autarkic scenario from 50 % to 90 % – Fig. 17. Here, 90 % represents a case where the spatial distribution of onshore wind farms is similar to the current concentration areas of onshore wind [79]. The onshore wind capacity parameter was accommodated in this sensitivity as it could not be included in any scenario based on their narratives. With a reduction in the capacity potential of the onshore wind energy, the corresponding supply potential also decreased significantly: 6 PJ or 1.7 TWh and 52 PJ reductions for the 50 % and 90 % cases, respectively. However, the supply potential of GBPV energy stalled, even though the capacity potential was available. Rather, a new nuclear power plant in the Eemshaven region (Het Hogeland) assisted in the 75 % and 90 % cases, as the overall electricity supply from renewable energies was low. This

increase in investment cost is mitigated by a decrease in the capacities of renewable energies, leading to a slight overall increase in the total system cost.² Appendix D presents other sensitivity analyses based on stakeholder interactions.

3.5. Stakeholder interaction process findings/observations

The three-hour stakeholder workshop first helped stakeholders understand the capabilities and limitations of the regionalized OPERA modeling tool in more detail. Stakeholders appreciated the strong spatial interface and its linkage with the spatial planning of the tool. This helped them understand the various components of an integrated energy system, as well as interactions between those components, and system behavior under different constraint conditions. We shortlisted three major observations from this workshop: a reflection on policy and strategic policy advice, a detailed impact assessment incorporating capacity investments and other model linkages, and a science-policy interface and enhanced usage of the model (Fig. 18).

First, the tool helped stakeholders better interpret the relationship between spatial and policy constraints and the energy system. Often, stakeholders were either surprised or began to reflect on existing policies and considerations, prompting a more strategic discussion. The strong role of biomass energy (Fig. 5) was unexpected because it has been hardly considered in policies or discussions [61]. Similarly, onshore wind energy was discussed as making a high contribution, whereas current policies do not favor this option. The limited role of GBPV energy also provoked debate because it was not assumed to be less cost-efficient. These illustrations also show how modeling outcomes can influence strategic policy making for future energy systems, considering

² The model optimizes for the entire Netherlands. Therefore, even though the total system cost for the Groningen province in the 50 % case is less than that in the autarkic scenario, the system cost for the Netherlands is higher for this case.

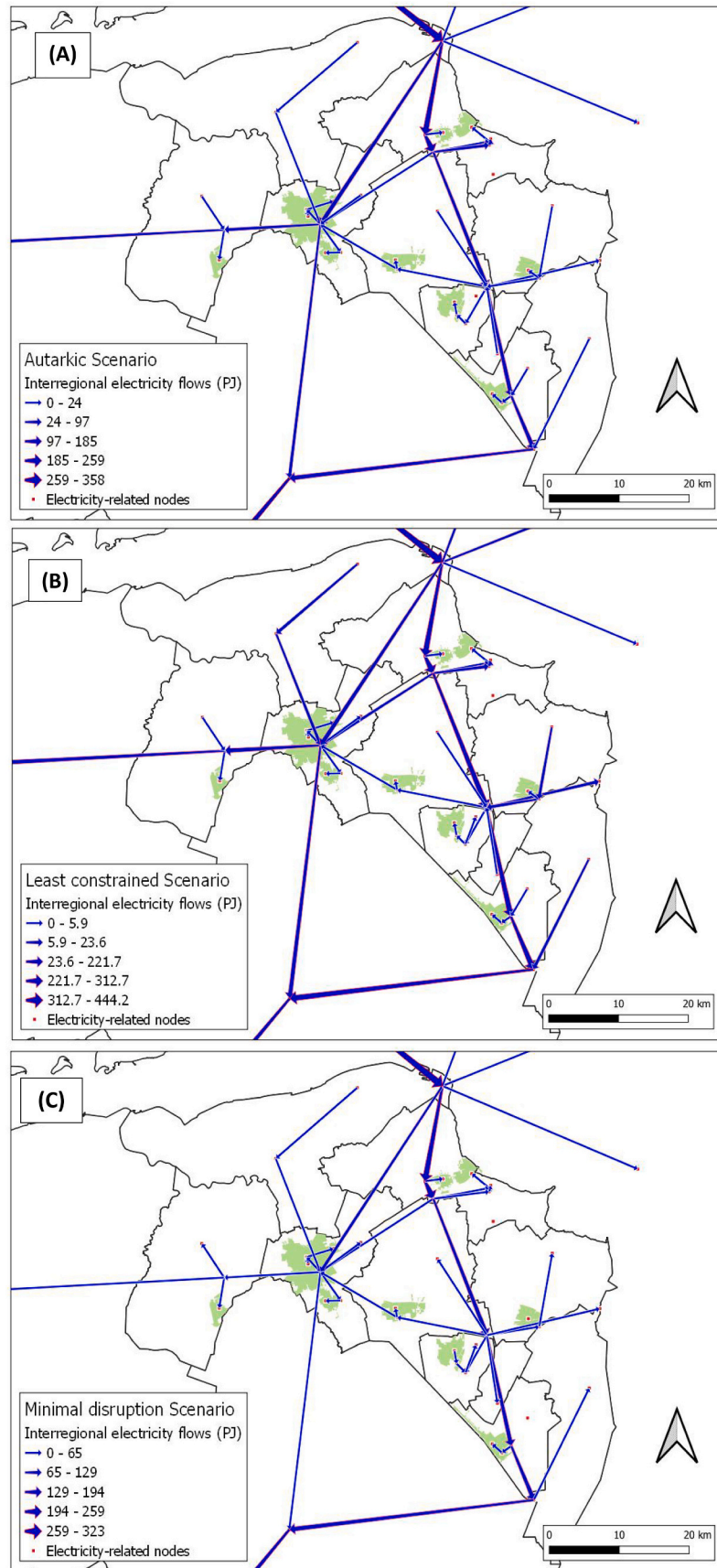


Fig. 10. Interregional net annual electricity flows obtained from the optimization modeling results for the HV and MV networks with the arrow width representing the net annual flow volumes in PJ, and the arrow directions representing the net flow directions. (A), (B), and (C) represent the autarkic, least-constrained, and minimal-disruption scenarios, respectively.

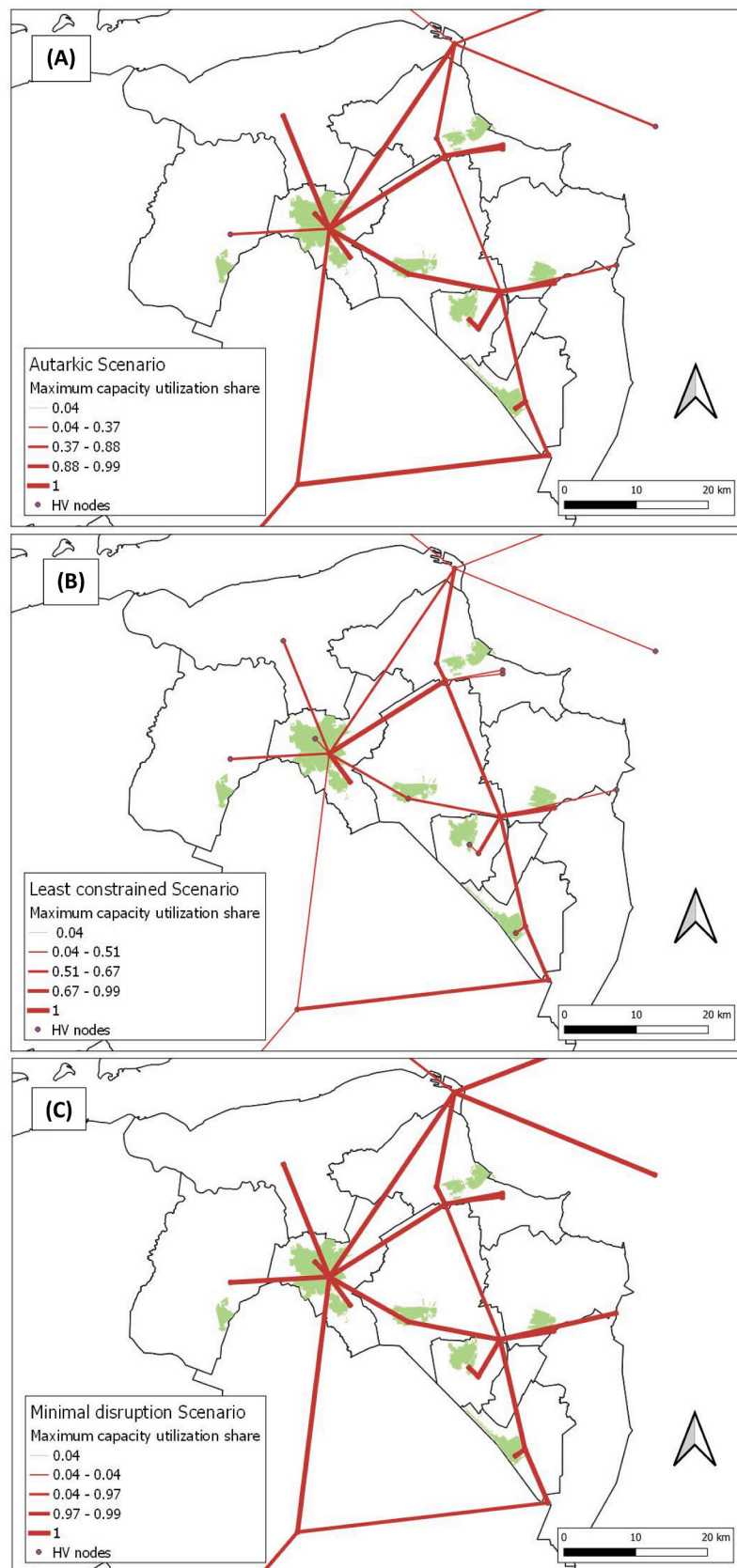


Fig. 11. Utilization share of the maximum capacity of the HV network in 2050 for the Groningen province. The thickness of the line represents the share of the maximum HV network capacity utilized. (A), (B), and (C) represent the autarkic, least-constrained, and minimal-disruption scenarios, respectively.

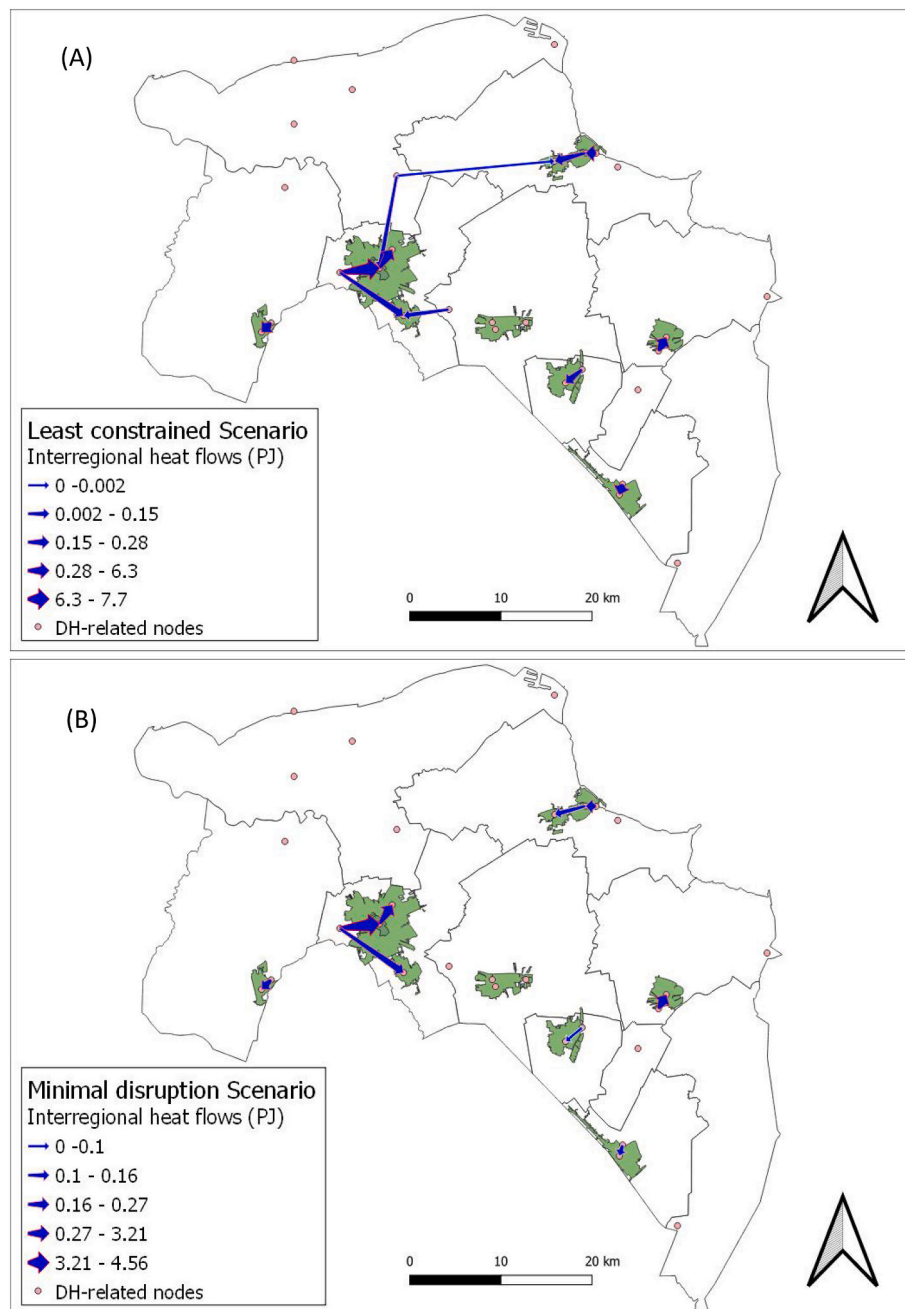


Fig. 12. Net annual heat flows in the DH network within the Groningen province. The thickness of the arrow represents the annual net flow volumes in PJ, and the direction represents the net flow direction. (A) and (B) represent the least-constrained and minimal-disruption scenarios, respectively.

that the current emphasis is mainly on solar PV as a supply option through various policies and subsidy schemes [80].

The stark contrast between the current spatial plans and the efforts needed to push policies to meet the regional and national targets also led stakeholders to reflect on more pragmatic policies. To exemplify, current provincial reports [9,10] and the majority of stakeholders support small turbines (with a hub height of <15 m). Although this has benefits, the stakeholders were surprised by its modest contributions. In addition, these turbines require immense space, a factor that has not been adequately discussed. Another practical example discussed was that of Hoogezand-Sappemeer, which is planning a DH network, although this is the only city where the model saw no DH penetration (see Section 3.2). Finally, in contrast to regional short-term land-use plans [79], our analysis showed a low onshore wind energy potential for the Eemshaven region and a high potential for Het Hogeland (see Section 3.1), which

also surprised stakeholders. Notably, the role of electricity network infrastructure on spatial distribution and regional wind energy potential was not fully understood by stakeholders. Its investigation was only possible through an integrated analysis such as ours. From these examples, stakeholders confirmed that our spatial interface could assist them in evaluating the effectiveness of various policies and instruments related to land-use planning and regional and local energy-related policies.

Stakeholders requested additional studies while comparing their original assumptions with the model outputs. The first was to assess the impact of higher wind and biomass energy prices on the deployment of other options, particularly GBPV energy. Similarly, they questioned what would happen with possible changes in energy-intensive activities, owing to the closure or addition of industries. For this purpose, we performed additional sensitivity analyses of the autarkic scenario owing

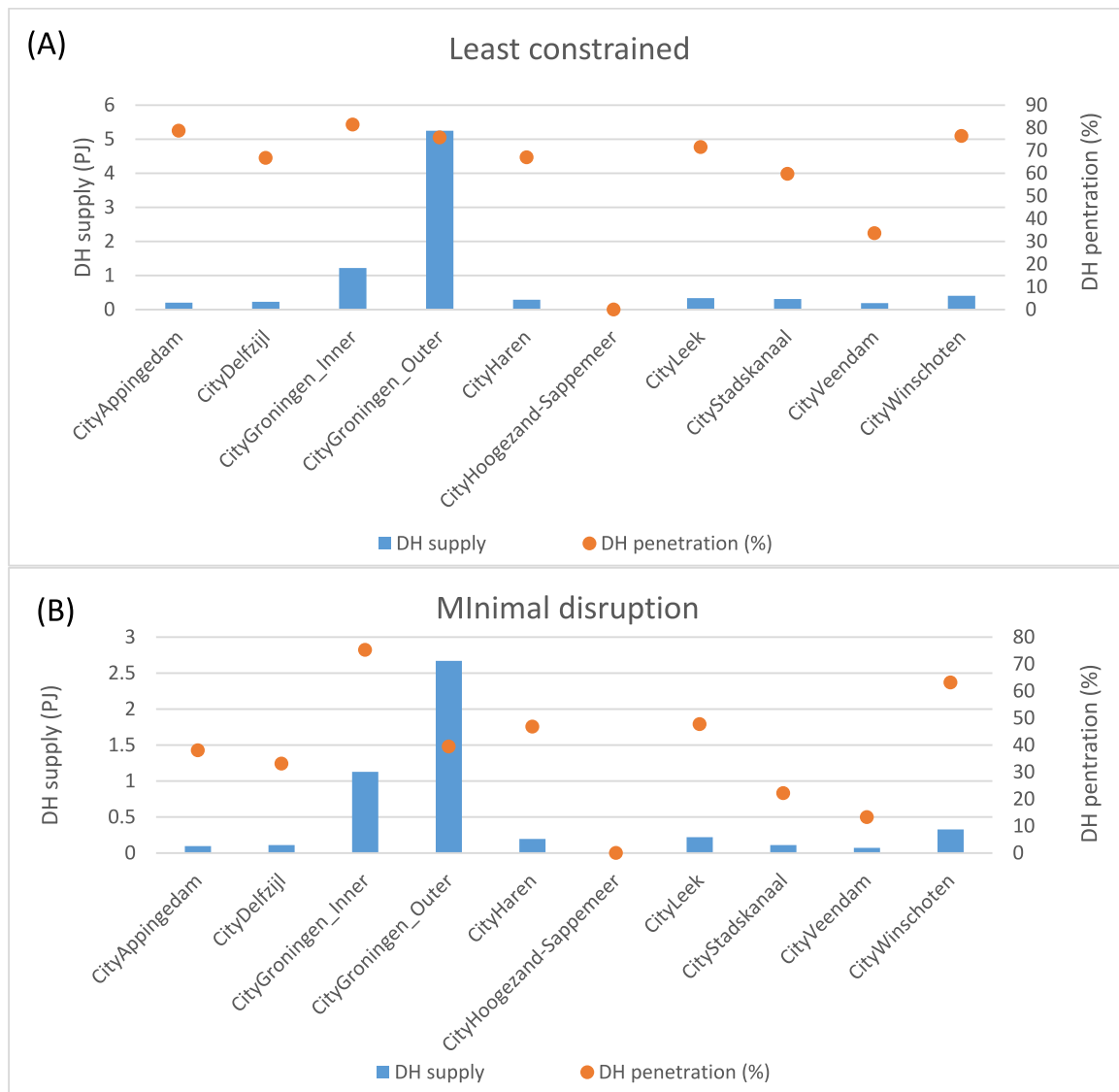


Fig. 13. DH supply (data in PJ) and DH penetration (data in %) in primary and secondary vertical axes, respectively, for cities included in our study within the Groningen province. (A) and (B) are the least-constrained and minimal-disruption scenarios, respectively.

to its large capacity range for supply options. The results showed that even if the costs of the abovementioned supply options increased by 80 %, the biomass energy contribution actually increased slightly and then became stable (see Fig. D-1 in Appendix D). In this sensitivity analysis, the contribution of onshore wind energy decreased rapidly when the price of the corresponding technology option increased. Conversely, the contribution from solar PV increased slightly. When industrial activities increased from -50 % of their projected capacity to $+100$ %, the supply of onshore wind energy increased rapidly; the biomass energy contribution increased slightly, and then became stable at the maximum contribution; and the solar PV contribution increased slightly (Fig. D-2 in Appendix D). These additional analyses show the capacity of our tool in assisting policymakers and other stakeholders in better determining the optimal use of alternative resources. Notably, the enhanced role of biomass energy, the variable role of wind energy, and GBPV energy being suboptimal even when wind and biomass energies were constrained are strong examples of previously held misconceptions.

The second main observation was the urge of stakeholders to better understand the costs of the energy system in the face of societal resistance. Stakeholders initially accepted that the system would be more expensive if less socially contested options were selected (notably, GBPV

energy). Nevertheless, after seeing the added costs of said choice, they discussed whether capturing possible savings due to increasing the use of onshore wind and biomass energies could help create societal support by distributing such savings to communities [81–83]. This may alter the discussions on future energy options to determine how financial redistribution may make these renewable energies more socially accepted. For example, onshore wind farm capacity utilization was 3.3 GW in the least-constrained scenario, compared with 0.7 GW in the minimal-disruption scenario (Fig. 5), leading to an overall system cost reduction of 440 M€/year (Fig. 14). Harnessing these savings may compensate people living nearby who would have to bear noise impacts and visual intrusions, thus constituting a societal trade-off. Trade-offs are also related to the system configuration in the scenarios. For example, the minimal-disruption scenario limited landscape changes but largely depended on energy imports, which could become system bottlenecks in the future.

Elaborating on the impact assessment aspect and focusing on investment, the stakeholders were interested in a detailed breakdown of costs and benefits in financial, social, and ecological aspects. Based on the existing capacity of the tool, it is possible to provide more details, showing the outcomes of the model in categories ranging from demand

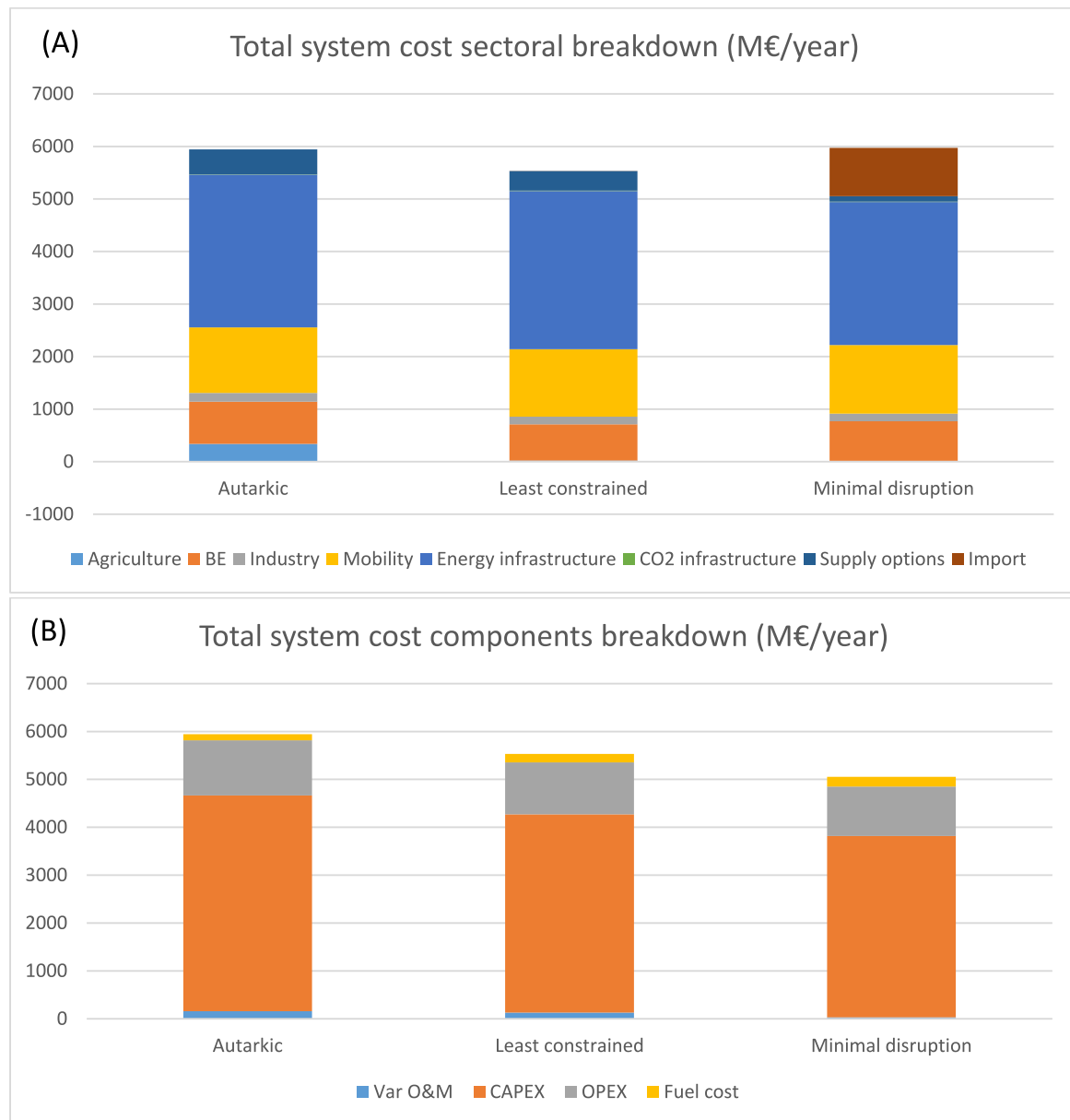


Fig. 14. Total system cost breakdown for different scenarios within the Groningen province (data in M€/year). (A) presents breakdown into sectors, infrastructure, supply options, and import. (B) presents breakdown into cost components, namely variable O&M, CAPEX, OPEX, and fuel costs (includes biomass). Storage (including electricity) is a part of supply options.

to infrastructure. For example, related to the BE, the model can segregate the investment in building stocks among building types, energy infrastructure, and centralized and individual heat supply options (Appendix Table D1 in Appendix D). Similarly, the model can calculate the cost of individual energy infrastructures and thus suggest the future costs borne by different infrastructure companies (DH, HV, or MV). Alternatively, provincial or municipal governments may bear these costs in coordination with energy infrastructure companies. However, the tool does not identify who should bear the individual costs or what choices or preferences individuals have. Similarly, it cannot determine the ecological and social impacts of the supply-side infrastructure. Nevertheless, the tool provides the possibility of linking to other specialized regional models. Examples include linking to activities such as job creation via a macroeconomic model [84]; understanding the impacts of land-use changes associated with expanding energy-demanding sectors and supply options, particularly renewable energies [85]; analyzing landscape, nature, and biodiversity [86]; and

better understanding the impact of stakeholders by linking with a regionalized simulation or agent-based model [87]. In addition, the structure of the model allows for easy connections to other geographical scopes, such as the local or pan-European level.

The final main observation was that stakeholders had difficulties in fully grasping the modeling scope, capabilities, limitations, and understanding and interpreting some of its results (Fig. 18). An extensive survey and a three-hour workshop can promote the collaboration between the model, energy experts, and wider policy and societal communities. While much ground was covered, stakeholders expressed the need to better understand the model, its assumptions, and what its outcomes meant. They expressed a desire to actively interact with the model, implying that they could alter assumptions and constraints to see its impacts. An explicit example is a calculator-like application or a visual-based interface of our model, similar to the EU greenhouse gas calculator [88] or the energy transition tool of the Netherlands [89]. In this regard, we recommend that the model has a basis for connecting or

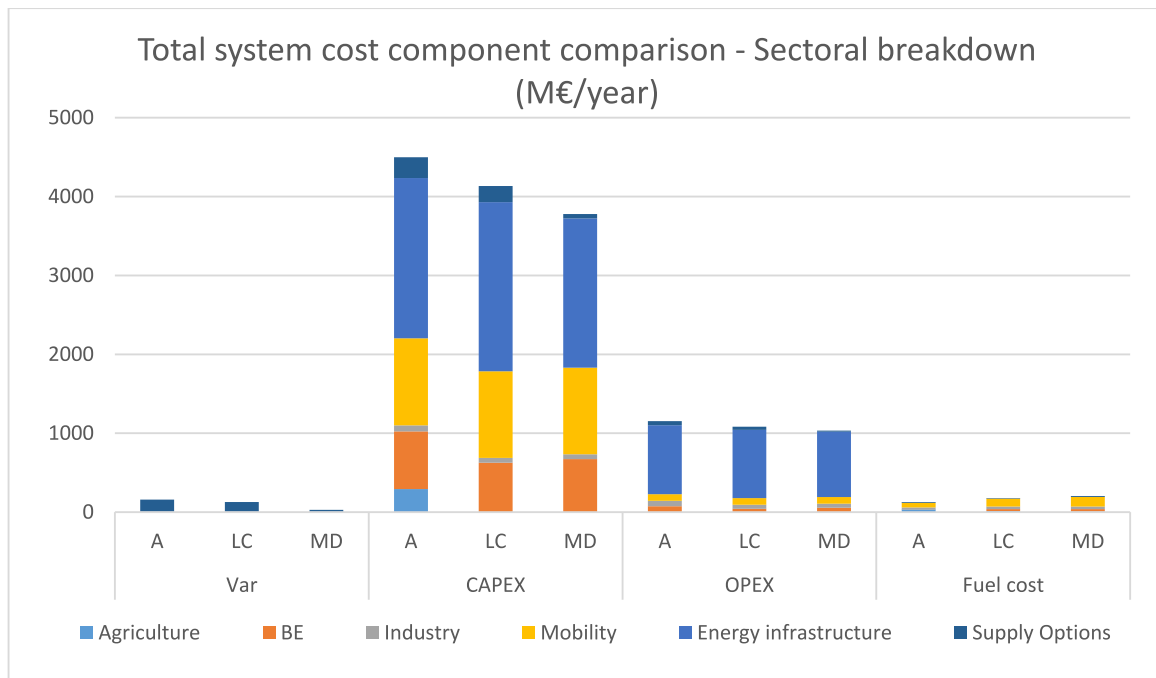


Fig. 15. Total system cost component comparison between scenarios with breakdown into sectors, infrastructure, and supply options (data in M€/year). A, LC, and MD represent autarkic, least-constrained, and minimal-disruption scenarios, respectively.

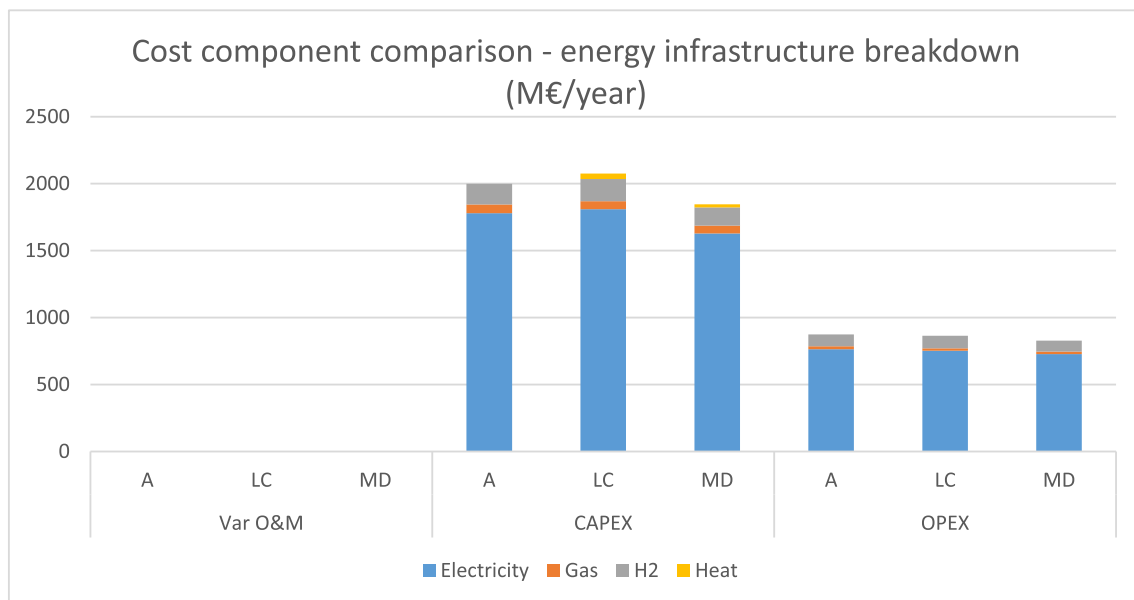


Fig. 16. Cost components comparison for energy infrastructure between scenarios (data in M€/year). A, LC, and MD represent the autarkic, least-constrained, and minimal-disruption scenarios, respectively.

linking to such an interface. Alternatively, a simplified energy model would allow for direct interaction through a visual interface but would reduce the modeling capacities and the quality of its results.

4. Discussion

Involving stakeholders in developing scenarios and discussing modeling results showcased the importance of including their inputs in a regionalized energy model for analyzing future energy transitions and related spatial policies. Stakeholders realized how an integrated energy system model that considers the interactions between supply, demand,

and infrastructure works, along with its limitations. They also understood that the tool could assist them in making informed choices regarding future energy system-related investments, land-use planning, and setting climate policy targets. From the perspective of a modeler, we understood the strong potential for improving or modulating the capabilities of the tool to better cater to the requirements of various stakeholders, while respecting limitations.

The workshop and related interactions provided informed policy choices and trade-offs and reflected future regional (spatial) targets. For example, we showed that current regional renewable energy deployment plans underestimate the difficulty of achieving the 95 % emission

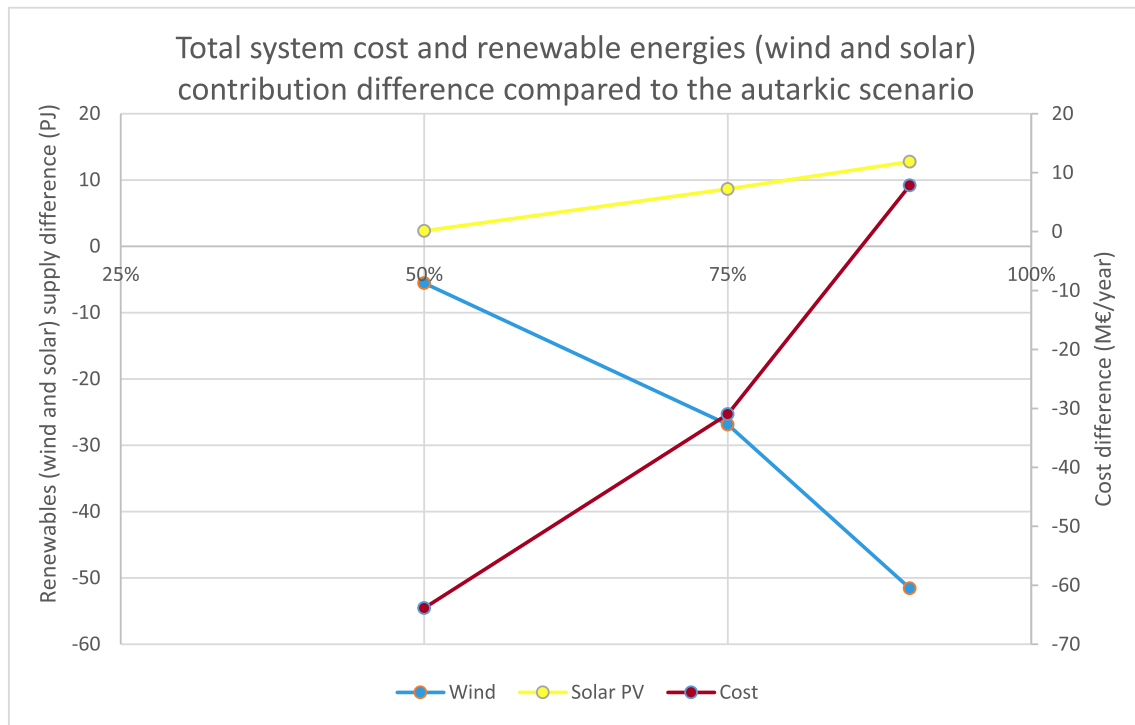


Fig. 17. Renewable energies (wind and solar) supply and total system cost difference compared to the autarkic scenario with data on the primary and secondary vertical axes, respectively, with units in PJ and M€/year, respectively. Percentages in the x-axis represent the percentage reduction of the onshore wind farm capacity compared to the wind farm capacity of the Groningen province for the autarkic scenario.

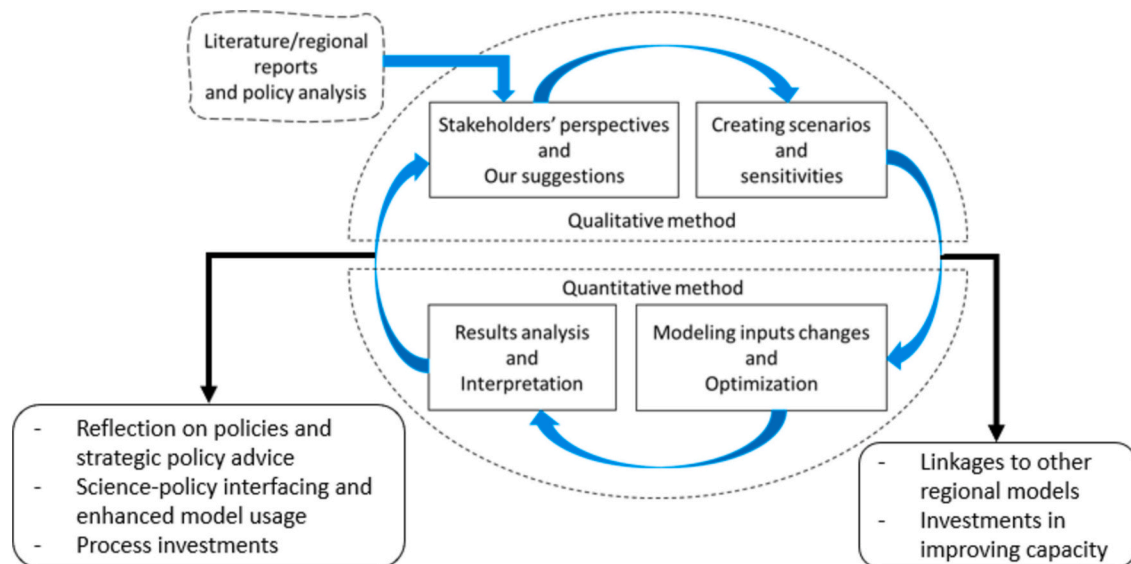


Fig. 18. Review and update of the conceptual map (Fig. 1) based on the stakeholders' interaction process during the workshop.

reduction target by 2050, especially if regional self-sufficiency is pursued. The workshop discussion indicated that current policies to promote solar PVs are influenced by a lack of awareness and popular public opinion rather than objective information. In addition, our research showed that plans for allocating regional renewable resources highly underplay the linkages between the spatial distribution of regional demand and supply and constraints associated with related infrastructure. For example, the Eemsdelta municipality has been allocated the highest capacity of 400 MW of the total provincial allocation of 855 MW of onshore wind energy by 2030 [79,90], which was also reflected in the minimal-disruption scenario. However, the share of onshore wind

energy utilization is quite low for this municipality compared to others within the province where future allocations are planned. Stakeholders also seem to underestimate the importance of infrastructure related to linking the future increasing demands with sustainable supply options, the time needed to plan and execute such projects, and the necessary (spatial) planning and investment required. Our research provides an opportunity to review government spatial plans and stakeholder expectations related to the future growth of renewable energies.

The modeling outcomes allowed for enhanced discussions on the societal acceptability of alternative pathways for achieving carbon neutrality and, specifically, on certain supply options. Identifying the

different costs associated, especially with allowing more or less wind energy deployment, sparked a debate. Notably, stakeholders doubted their current focus on pushing solar PVs to avoid the spatial and societal impacts of onshore wind farms. Solar PVs were discussed more critically, and serious considerations were given to opportunities to capture and redistribute some of the budget to onshore wind energy implementation, especially in the context of social acceptance. While this remained a general and open conversation, it illustrates how the model can help spawn alternative arguments.

As reflected in our workshop, expanding onshore wind energy is considered a limited opportunity in the Netherlands owing to the expected landscape impacts, with most being planned to be pushed offshore. Theoretically, the North Sea can allow for a major export of wind energy, as shown by our minimal-disruption scenario. However, the overall system may become highly constrained, particularly if the expansion of the corresponding HV network is not planned simultaneously. This also emphasizes the need to simultaneously analyze infrastructure growth, increase in demand, and implementation of renewable energy projects, respecting spatial constraints.

The inclusion of stakeholders proved highly valuable and highlighted the importance of enhancing the policy-science interface. Scientific research benefits from policy considerations, and vice versa. Energy transition research requires large financial investments and has clear spatial and societal implications, which requires a strong knowledge base for informed decision-making. A spatially detailed and integrated model can be an important knowledge base, benefiting from linking it to various regional models such as macroeconomics, society, environment, and land-use impacts to produce a sophisticated regionalized decision-supporting toolkit. Similarly, investing in collaboration between modelers and policymakers is pivotal. Multiple knowledge-sharing sessions and regular interactions with the stakeholders are needed because a three-hour workshop session was insufficient. This iteration, along with iterations via interactions with other regionalized tools, can significantly improve the robustness and flexibility of our tool. These process investments can assist stakeholders in making well-informed choices related to energy policies, creating science-based policies, and expediting decision-making and the implementation of energy system-related planning. This can reduce costs and effort compared to implementing uninformed choices.

5. Conclusion and policy implications

Regional energy system analysis is often neglected in the context of integrated energy system modeling, specifically when considering interactions with stakeholders. This study tested and validated a previously developed regional modeling framework named OPERA, considering the interactions with regional stakeholders, with an analysis of the Groningen province located in the northern Netherlands. Their diverse inputs and perspectives on future energy systems were obtained via a questionnaire, creating three future regional scenarios as modeling inputs: autarkic, least-constrained, and minimal disruption. Stakeholders included regional and local policymakers, industrial experts, environmental and nature specialists, and energy infrastructure experts. They were subsequently included in a workshop to discuss the model's capabilities and limitations, the scenario results, and sensitivity analyses. A novelty of our research is the simultaneous analysis of regional land use and spatial planning, climate targets, and national and regional policy effectiveness. We highlight the following conclusions from the study:

- Stakeholder interactions confirmed that our modeling framework is capable of functioning as a decision-supporting tool, which was the objective of this study. A key novelty is the simultaneous analysis of the varied ranges of future primary energy supply and mixes, demand-supply mismatches, spatial allocation of resources, the role of energy infrastructure, and system cost. The vast range of symbiosis

between energy-demanding sectors, constraints associated with energy flows, and gaps between renewable energy potentials and utilization cannot be adequately analyzed otherwise.

- The workshop provided an opportunity to reflect on stakeholders' perspectives and current policies on different aspects of future energy systems, which is unique to this study. Currently, ground-based PV (GBPV) energy has been significantly promoted by regional policies; however, our results and sensitivity analyses determined that this option was less cost-effective than assumed. To illustrate this, the utilization potential of GBPV energy was only 0.37 GW in the autarkic scenario based on optimization, compared to the availability potential of 22 GW based on land use. Similarly, stakeholders became aware of the regional potential of utilizing biomass energy, which is a less favorable supply option under current regional policies. To further illustrate, in the autarkic scenario, the biomass energy utilization potential was 31 PJ out of the total 33 PJ available. Thus, some results made stakeholders aware of the diverse solutions for mitigating environmental impacts. The novelty is the simultaneous analysis of spatial and energy planning and policies, land use claims, and their impact on integrated energy systems.
- The interaction process opened discussions on the trade-offs, complementarity, and impacts associated with the different choices of stakeholders. For example, if landscape protection was prioritized (minimal-disruption scenario), the total system cost (5972 M€/year) and dependency on regions outside of Groningen (net import 48 PJ/year) were high, whereas, in the autarkic scenario, this cost (5943 M€/year) and dependency (net import 0.1 PJ/year) were low. On the other hand, the land use and related spatial impacts were less for the minimal-disruption scenario (for example, 47 km² of land was dedicated to onshore wind farms) compared with the autarkic scenario (272 km²). These results provoked discussions on social acceptance, economic burden sharing, regional self-sufficiency targets, and emission-reduction and renewable energy production targets. Such detailed input and feedback from stakeholders are lacking in the current literature.
- Our research highlights the importance of the science-policy interface. An attempt was made to bridge this gap by pushing and enhancing modeling capabilities. Still, further process investments are required to link the model with other regionalized models, improve its user interface and the communication of results, and conduct research-backed, informed decision-making for regional policy planning and spatial policies.

The method is universal and applicable to other regions. This study provides a major step towards bridging the knowledge gap between a regional decision-supporting tool for energy systems and stakeholder expectations regarding the applicability of such a tool. Our diversified results and the stakeholder interaction process confirm that such an iterative process is necessary for having a richer and more informed discussion of regional policies and spatial planning.

CRedit authorship contribution statement

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

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 will be made available on request.

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Appendix A. Detailed description of the regionalized OPERA model

Regionalization, relies firstly on representing the Groningen province through multiple region and nodes, each of which represents a spatial unit. Specifically, larger population centers ($>10,000$ inhabitants) and the remaining part of each municipality within the Groningen province are represented as land-use regions, while large industries or industrial clusters are represented as nodes, implying that if a municipality hosts one or more of these, there are multiple nodes per municipality (with the non-industrial and non-urban areas being ‘municipality rest’). In addition, geothermal doublets linked to economically viable use of geothermal are also added as nodes in the model. Finally, other regions are also represented as explicit regions in the model, being the two adjacent provinces of Friesland and Drenthe, the rest of the Netherlands, the Northern part of the Dutch North Sea and the rest of the Dutch North Sea and, finally, nodes representing countries abroad connected to the Groningen province via electricity infrastructure.

Each of these spatial units can have their own distinct energy demand profile for energy demand related to various energy carriers, such as heat and electricity, and the potential for energy generation, such as the onshore wind or ground-based photovoltaics (GBPv) energies, depending upon their usage or applicability. Demand is based on current energy use and future projections, for example heat demand in the BE. Similarly, industrial energy demand can depend upon technological advances, changes in processes, and efficiency measures. Potential for energy generation is based on both technological potentials while considering technological improvements (learning curves) and the spatial claims exerted currently and in the future by other land uses, including projected changes in the land-uses, such as the BE, agriculture, nature, and road and rail infrastructure, along with considering the impacts of land use and spatial planning-related policy constraints (Fig. A-1).

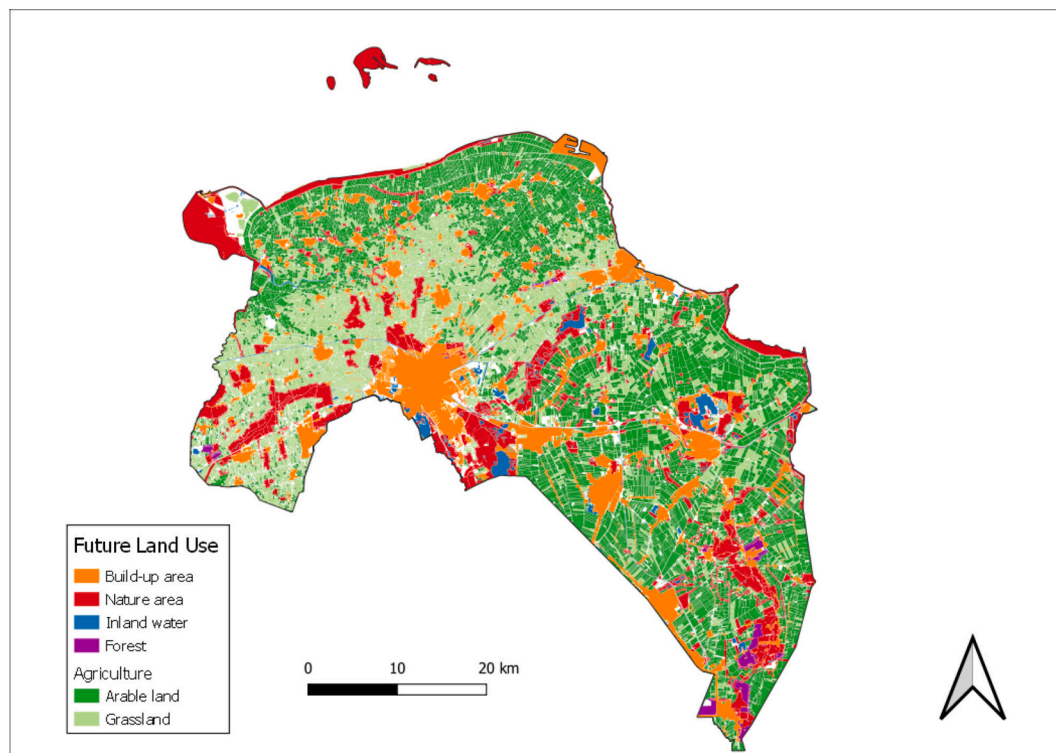


Fig. A-1. Future land use (2050) considering major spatial claims for the Groningen province [3].

Energy infrastructure, particularly related to electricity and heat are also represented. For electricity infrastructure, the model has a complete spatial representation of the HV network and a good representation of the MV network with its connection to cities and the rest of each municipality. For heat infrastructure, our previous work included the development of a detailed representation of district heating (DH), which is used to provide heat to low temperature heat demand in the BE. The model has a pan-provincial DH network supply heat to large population centers within the Groningen province along with interconnections to industries for the supply of IWH – Fig. A-2.

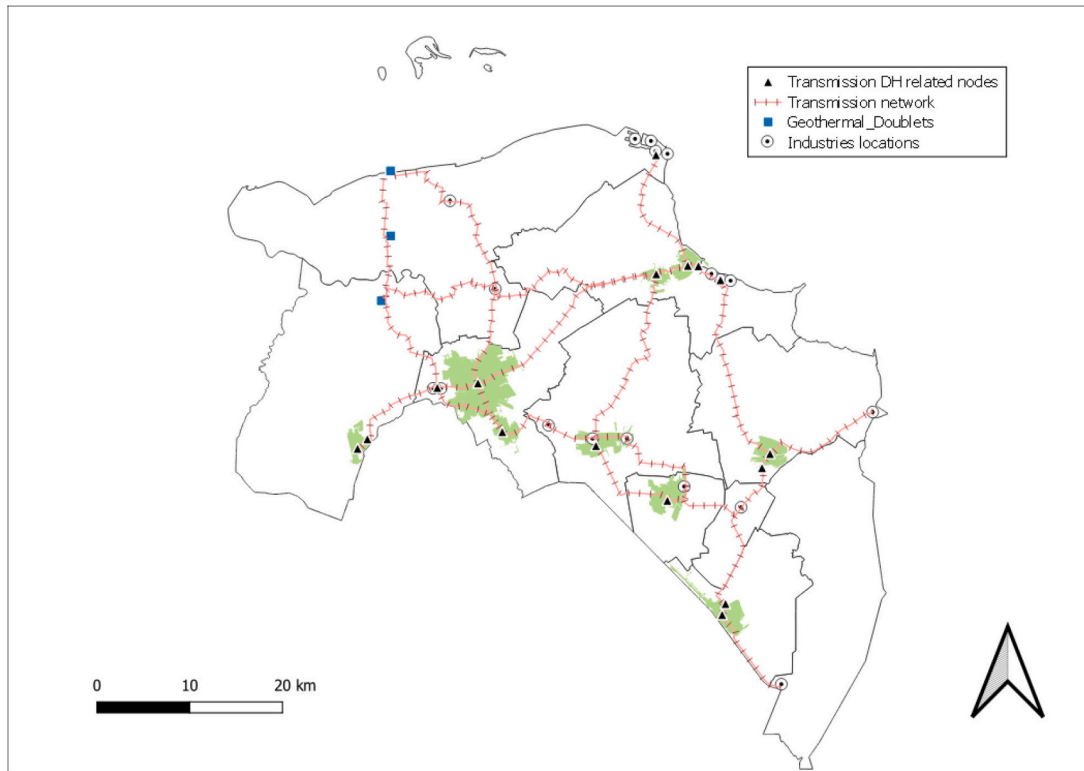


Fig. A-2. DH network in the regionalized OPERA model at a pan provincial level considering interconnections with industries and geothermal doublets [15].

The regionalized model has spatially-detailed inputs related to renewable energy supply options such as solar, wind, biomass, and geothermal energies. Hydroelectricity is not included because of its limited potential in the Netherlands. Regional renewables capacity limits can be imposed within the model. Network characteristics (cost and losses per unit distance) and capacity limits (particularly for electricity) can be adjusted in a highly detailed spatial manner. Energy demanding sectors, particularly the BE and industries, are highly spatially explicit. The model uses input data related to spatial distribution of various building types and energy label allocated to each distinct land use region – refer [58] for detail on these categorizations. Industries inputs are main product production volumes, corresponding energy demands, alternative technology options or processes, and their corresponding costs and technical characteristics. Limits can be imposed on the sectoral emissions levels.

The model performs optimization at the national level with a focus on total system cost minimization. Despite targeting optimization on a national level, the model is explicit in considering what this implies regionally. In addition, the model can impose additional regional targets. The modeling outputs for each land-use region includes renewable capacity utilized and energy produced from a variety of supply options, while considering available potentials and thus spatial constraints. Sectoral final energy demands on a highly spatially-detailed regional level is also an output from the model. Therefore, the model can perform energy balances and supply energy mixes at a regional level. The model can show utilized network capacity at a nodal level and interregional energy flows. The model can predict efficiency improvements associated with the BE, along with building energy label changes and corresponding investments. The model can additionally estimate DH penetration at the city level. Since the model only considers cost optimization, this implies that stakeholder demands for, e.g., a more socially just or ecologically friendly optimization are not part of the optimization. Such demands can only be represented as specific spatial claims that can constrain energy generation, for example. Similarly, the role of flexibility in both energy supply and demand is not sufficiently addressed on a regional level.

Appendix B. Survey questions

Key parameters were identified for stakeholders to reflect upon from diverse topics related to energy-demanding sectors, supply options, and infrastructure. The questions were based on a review of relevant literature and (spatial) policy reports on the regional energy system (Fig. 3). Spatial policies are in a Dutch context mostly developed on a provincial and municipal level, while energy policies are mostly a national task with an increasing role for a collaborative process based on provincial and local partners [91]. The policy documents included existing policies of the Groningen province [9,10], its municipalities, and the national level targeting municipalities and provinces [92].

1. What percentage of the agricultural land in the Groningen province do you think can be used for the construction of land-based solar parks in 2050?

(Explanation: agricultural land refers to both arable farming and livestock farming. Most agricultural land is in principle suitable for ground-based solar parks. The basic principle here is that no more food production can take place. Partly because of this, there is a clear limit to the amount of agricultural land that can be used.)

(N.B.: National studies generally indicate roughly 1.1–1.4 % (e.g. [93–95]). That is precisely why an assessment by relevant interest groups and policy-makers is necessary.)

Options:

- 0
- 0.5
- 1
- 1.3
- 2
- 2.5
- 5
- 10
- I do not feel comfortable to answer this
- Others

2. What share of the existing roof surface in the Groningen province do you think can be used for sun on roofs?

(Explanation: this concerns all roof space (companies, offices and sheds). Of these, about 40 % is known to be virtually unsuitable due to an unfavourable orientation to the sun. A part is also difficult because of building constructions, monumental protection or shade.)

Options:

- 8
- 20
- 50
- 60
- I do not feel comfortable to answer this
- Others

3. How much extra onshore wind farms will the Groningen province have in 2050? (in addition to the already promised 855.5 MW).

(Explanation: 855.5 MW of onshore wind farms has currently been pledged. This question concerns the addition of onshore wind farms up to 2050. In the case of 'large' turbines (roughly >150 m), onshore wind energy is, according to our model, the cheapest form of renewable energy generation in the Netherlands for the time being. This question relates to wind from such 'large' windmills.)

(N.B.: the Groningen province as a whole is approximately 2400 km² of land. In this question we assume roughly 10 MW of capacity per km². The current wind farms occupy less than 3 % of the provincial land use)

Options:

- No extra wind farms on land
- 10 km² (<0.5 % territory province)
- 25 km² (1 %)
- 50 km² (2 %)
- 100 km² (4 %)
- 250 km² (10 %)
- 500 km² (24 %)
- I do not feel comfortable to answer this
- Others

4. What distance should we maintain between windmills and the built environment?

(Explanation: a major criterion is noise nuisance. The height of the turbine is of great importance. We roughly assume 'large' wind turbines with a turbine height of 100–140 m (3–6 MW). This means that it is usually possible to achieve noise standards from about 500 m away. Different rules are used in different countries, from roughly 4× the turbine height (400–600 m) to 10× the height of the entire mill (1500–2500 m).)

Options:

- 500 m
- 1000 m
- 1500 m
- 2000 m
- 3000 m
- I do not feel comfortable to answer this
- Others

5. What distance should we maintain between windmills and quiet areas?

(Explanation: this concerns areas where extra silence is pursued because of nature (lower standards for noise). Existing examples are the Lauwersmeer, the Waddenzee, and parts around the Schildmeer.)

Options:

- 500 m
- 1000 m

- 1500 m
- 2000 m
- 3000 m
- I do not feel comfortable to answer this
- Others

6. How many small windmills will there be in the Groningen province in 2050?

(Explanation: this concerns windmills with a height of less than 15 m. Currently, there are more than 100 small windmills in the province, usually on a farmyard.)

Options:

- 200
- 500
- 1000
- 2000
- 5000
- 10,000
- I do not feel comfortable to answer this
- Others

7. How will we deal with the energy generated from offshore wind farms in the Groningen province in 2050? (multiple options possible)

Options:

- It is transported to land via cables as electricity
- It is transported to land as hydrogen via gas pipelines
- Mostly via cables, transport less than hydrogen to land
- Mostly like hydrogen, less transported to land via cables
- Both are an option, let the energy model determine the choice
- I don't feel comfortable to answer this

8. What percentage of the agricultural land in the Groningen province do you think can be used for energy crops in 2050?

(Explanation: agricultural land refers to both arable farming and livestock farming. This concerns agricultural land that is primarily used for the production of energy crops, such as miscanthus and willow in Groningen, for example. As a result, food production no longer takes place.)

Options:

- 0 %
- 5 %
- 10 %
- 20 %
- 30 %
- I do not feel comfortable to answer this
- Others

9. How much (regional produced) manure do you think may be available for energy generation in the Groningen province in 2050?

(Explanation: manure production is closely related to developments in the livestock. This concerns both liquid (mainly pigs and cows) and solid (mainly chickens). Of course, a part is intended for the fertilization of agricultural land. Another part is used for biogas and biofuel.)

Options:

- A percentage of manure will still be available for energy generation
- Manure is no longer available for energy generation
- I do not feel comfortable to answer this
- Others

10. If available (question 9), what proportion of the (regional produced) manure do you think will be available for energy generation in the Groningen province in 2050?

Options:

- 5
- 10
- 20
- 40

- 60
- 80
- I do not feel comfortable to answer this
- Others

11. Will the Groningen province use biomass energy extracted from protected forests and nature reserves in 2050?

(Explanation: this is based on good management of nature that can lead to biomass, such as reed, wood, greenery, etc. This leads to a low biomass yield per hectare, which is also included in our model as such.)

Options:

- Yes
- No
- I do not feel comfortable to answer this

12. If 'yes' (question 11), what percentage of the protected forests and nature reserves in the Groningen province will biomass energy be extracted in 2050?

Option:

- 0
- 25
- 50
- 100
- I do not feel comfortable to answer this
- Others

13. Can agricultural residues in the Groningen province be used for energy generation in 2050?

(Explanation: this concerns material that remains after harvesting. This can partly be used as food for livestock, to improve the soil and – possibly – to generate energy. When used for energy, we take into account a research-supported (relatively limited) yield per hectare.)

Options:

- Yes, they can be (partly) used for energy generation
- No, it is better to use them for other purposes
- I do not feel comfortable to answer this
- Others

14. If so (question 13), what percentage of agricultural residues in the Groningen province in 2050 will be used for energy generation?

Options:

- 10
- 30
- 60
- 90
- I do not feel comfortable to answer this
- Others

15. Which part of the agricultural land can also be used for growing grass – in addition to (livestock) food production - for energy generation in the Groningen province in 2050?

(Explanation: this concerns agricultural land as well as arable land and livestock. Energy can be (partly) extracted from grass, in addition to other products (including proteins). On grassland, we assume 5 harvests per year, whereby we only use part for energy (there must be enough for the cattle first). On arable land, we assume 2 harvests per year, because it is only possible to grow grass after the harvest and before the new growing season.)

Options:

- None (0 %)
- 10 %
- 30 %
- 60 %
- 90 %
- I do not feel comfortable to answer this
- Others

16. Will natural gas continue to play a role in the future energy system of 2050, for example, for some industry and for heating in certain parts of the built environment?

(Explanation: this does not concern biogas (including methane).)

Options:

- Yes, we import that entirely from outside the Province
- Yes, that comes for a (considerable) part from the Province itself
- No
- I do not feel comfortable to answer this

17. With regard to the capture, transport and storage of CO₂ (CCTS), what options do you see for 2050 in the Groningen province? (several options possible)

(Explanation: it is likely that there will still be CO₂ emissions in 2050, partly because some industrial processes are difficult to change. This would be possible even without the consumption of natural gas. Although these processes do not take place in Groningen, this is the case in the Netherlands. It may also be desirable or even necessary to store CO₂ during the combustion of biomass and to achieve negative emissions. Finally, techniques for so-called direct air capture, in which CO₂ is extracted directly from the air, are emerging and may also be attractive in the future.

Our energy system model shows that it is cost-effective to invest in CCTS and that the Groningen province is an attractive location to do this due to its energy infrastructure and landfall (including Norway, Denmark and offshore wind farms).)

Options:

- Investments are made in CCTS infrastructure, but only for the capture of CO₂ from point sources and in relation to emissions in Groningen itself.
- Investments are made in CCTS infrastructure, both for point sources and from the air (direct air capture), but only for emissions from the Groningen province.
- Investments are made in CCTS infrastructure, both for point sources and from the air (direct air capture), whereby Groningen can also serve as a location to compensate for national emissions.
- There is no investment in CCTS infrastructure in Groningen.
- I do not feel comfortable to answer this.

18. Is CO₂ storage allowed in the Groningen subsurface?

Options:

- No
- Yes, but not in the Groningen field
- Yes, the Groningen field is also an option
- I don't feel able to answer this

19. Can CO₂ also be stored in the Groningen subsurface from other parts of the country?

Options:

- Yes
- No
- I do not feel comfortable to answer this

20. On what scale do you expect heat networks in the built environment in the Groningen province in 2050?

(Explanation: our model can handle both localized small networks and a complete province-wide network. Cities here refer to centres with more than 10,000 inhabitants.)

Options:

- Only small networks in cities at the level of a neighbourhood to possibly a district
- Networking at the multi-district / city district level
- City-wide networks (>50 % of city), provincial network
- I do not feel comfortable to answer this
- Others

21. What percentage of the built environment in the Groningen province do you expect to be heated by a heat network in 2050?

(Explanation: this concerns the percentage of the total demand for heat from the built environment in the Groningen province (excluding industry, including homes and offices). The other part is heated by other techniques such as heat pumps, biogas, or, possibly, hydrogen. Please note: we assume an increase in the energy efficiency of buildings, which will lead to a decrease in total demand. That is why this question concerns the percentage of the (remaining) demand.)

Options:

- 10
- 20
- 30
- 50
- I do not feel comfortable to answer this
- Others

22. Heat networks can use the following sources in 2050: (several options possible)

Options:

- Electric boiler
- Electric heat pump
- Combined heat and power plants
- Solar thermal
- Biomass boiler
- Hydrogen boiler
- Aqua-thermal
- Residual heat from industries and companies
- I do not feel comfortable to answer this
- Others

23. What do you think is the role of hydrogen for heating the built environment in the Groningen province in 2050?

Options:

- We don't use hydrogen for that
- Only via central combustion and heat networks
- Only via adding to (bio)gas in the guest network
- Only via the residual heat from electrolysis and heat networks
- Via the gas network to individual houses
- A combination of options 2 to 5
- I do not feel comfortable to answer this
- Others

24. Is geothermal energy permitted as a part of the energy system in the Groningen province in 2050?

(Explanation: geothermal energy is possible in Groningen, although this is not economically viable in the entire province. It is important to recognize that in the current 'earthquake area' the economic extractability is low and our model therefore does not include this area. Concerns about earthquakes can of course reduce the desirability of (especially deep) geothermal energy)

Options

- Yes
- No
- I do not feel comfortable to answer this

25. If yes, we use this geothermal for

Options:

- Heat and electricity production
- Heat only
- I do not feel comfortable to answer this

26. In 2050, will we use residual heat from industry and companies (e.g., data centers) in the Groningen province?

(Explanation: this concerns heat that the industry itself can no longer use)

Options:

- Yes, especially or only for residual heat that is located near the built environment (<5 kms)
- Yes, with a robust network to which various sources are connected and which transports heat through a (large part) of the province
- Yes, but on what scale I dare not estimate
- No
- I do not feel comfortable to answer this

27. How do we deal with the risk of overproduction due to sun on roofs?

Options:

- The overproduction is mainly absorbed by the electricity grid
- The overproduction is mainly absorbed at home level in storage
- The overproduction is mainly stored at the district/district/city level
- The overproduction is partly absorbed by the grid and partly by storage
- I don't feel comfortable to answer this
- Others

28. Will the capacity of the MV grid in the urban environment in the Groningen province increase in 2050?

(Explanation: this concerns centres with >10,000 inhabitants)

Options:

- No, it stays the same
- Yes, 1.5 times more than now
- Yes, 2 times more than now
- Yes, 3 times more than now
- Yes, more than 3 times more than now
- I do not feel comfortable to answer this

29. Will the capacity of the MV grid in the rural environment in the Groningen province increase in 2050? Explanation: This concerns all areas outside the cities (cores with >10,000 inhabitants)

Options:

- No, it stays the same
- Yes, 1.5 times more than now
- Yes, 2 times more than now
- Yes, 3 times more than now
- Yes, more than 3 times more than now
- I do not feel comfortable to answer this

30. Will the capacity of the HV grid in the Groningen province increase in 2050?

(Explanation: in the ENTSOE database in which projected expansions are given, there is no planned expansion until 2045)

Options:

- No, it stays the same
- Yes, 1.2 times more than now
- Yes, 1.5 times more than now
- Yes, 2 times more than now
- Yes, more than 2 times more than now
- I do not feel comfortable to answer this

31. How do you see the role of the Groningen province in the transport (transmission) of electricity and hydrogen in 2050?

Options:

- Limited, it's mainly about being self-sufficient with limited imports and exports
- Serious quantities of electricity and hydrogen are transported via Groningen, partly due to imports from the North Sea and exports to the rest of the country
- I do not feel comfortable to answer this
- Others

32. What is your view on the use of existing energy infrastructure for the energy system in Groningen in 2050?

(Explanation: Infrastructure refers to the physical installations and connections needed to generate, store, convert, and facilitate transport. These include gas pipelines, pipes for hydrogen, cables for electricity, installations for heating buildings, installations for energy conversion (e.g. hydrogen), heat networks, geothermal wells, etc.)

Options:

- We are going to make almost full use of existing infrastructure by adapting it and supplementing it with what is not yet there
- We will only partly use existing infrastructure as adaptation has too many limitations; a part will therefore become redundant and a lot will be new
- We will only make very limited use of existing infrastructure as adaptation has too many limitations; much will become redundant and most of it will be new

- In addition to existing cables for the electricity system, we will only partly use existing infrastructure because adaptation has too many limitations; a part will therefore become redundant and a lot will be new
- In addition to existing cables for the electricity system, we will only make very limited use of existing infrastructure because adaptation has too many limitations; much will become redundant and most of it will be new

33. What do you expect to be the result of the energy transition in 2050, specifically for the Groningen province? (several options possible)

(Explanation: the energy transition will affect many socio-economic processes. We ask you to estimate what you expect.)

Options:

- Circular economy leads to lower demand for industrial production
- Biobased working and construction means that agriculture produces products for industry (and can therefore only be used for energy generation to a limited extent)
- Citizens generate a significant part (>50 %) of their energy themselves, with or without the help of cooperative/collective organizations
- Car ownership will at least halve (the rise of car sharing), which could create large hubs for parked shared cars that can also act as an energy buffer
- For a large part (>70 %) of the housing stock before 1990, we are going for 2050 to replace
- A significant part (>50 %) of the existing (heavy) industry will no longer be located in the Groningen province
- Partly as a result of national policy, nuclear energy (nuclear power plant) in the Groningen province to be established
- Hydrogen leads to the arrival of a cluster of (new) industry
- Others

34. How do we in the Groningen province deal with the need for buffering and storage of energy, conversion (e.g. hydrogen) and capture/storage of greenhouse gases in relation to the total energy production and consumption of our province in 2050?

(Explanation: in addition to the generation of energy and the pursuit of energy efficiency, the buffering of energy (daily to seasonal storage), conversion (e.g., hydrogen) and the capture/storage of greenhouse gases (mostly CO₂) are also part of achieving an energy-neutral energy system. This can be done both within and outside the Province. The question is to what extent these activities should be solved wholly or partly within the Province itself or whether this takes place elsewhere.)

Options:

- Buffering and storage, conversion and capture/storage of greenhouse gases take place entirely or largely within the province
- Buffering and storage, conversion and capture/storage of greenhouse gases partly (25–75 %) take place within the province
- Buffering and storage, conversion and capture/storage of greenhouse gases do not or hardly take place within the province
- Groningen takes a leading role in buffering and storage, conversion and capture/storage of greenhouse gases and therefore does more than it needs itself (participates for other regions)
- Buffering and storage and conversion largely or completely in Groningen, capture/storage partly (30–70 %)
- Buffering and storage and conversion largely or completely in Groningen, capture/storage hardly or not at all
- Groningen takes a leading role in buffering and storage and conversion and therefore does more than it needs itself (participates in other regions); but capture/save only its own part (100 %)

35. How do you see the role of the Groningen province in generating energy in 2050?

Options:

- CO₂ neutral (e.g. 95 %) for the Province in accordance with current targets
- Less than CO₂ neutral, the current goals are too ambitious
- Slightly more than CO₂ neutral, the Province has to do a little more to achieve CO₂ neutrality at national level (e.g. 10–20 % extra)
- Significantly more than CO₂ neutral, the Province has to do a lot more to achieve CO₂ neutrality at national level (e.g. 50 % extra)
- Others

36. Which of the following principles do you prioritize when it comes to achieving the ambitions (e.g. 95 % CO₂ neutral) regarding energy transition in the Groningen province until 2050?

Options:

- Lowest possible costs; we want to achieve our ambitions as cheaply as possible
- Sustainability; we accept that the costs are sometimes higher because a sustainable future is not always the cheapest
- Support base; above all, we want a socially acceptable and feasible energy system, even if this sometimes comes at the expense of price and sustainability

37. Are there other themes or aspects related to the energy transition that we should take into account when calculating the energy system in 2050?

Appendix C. Detailed scenario description

The detailed scenario description is presented in [Appendix Table C1](#).

Appendix Table C1

Detailed description of the autarkic, least constrained, and minimal-disruption scenarios.

Topic	Detailed	Autarkic	Least constrained	Minimal disruption
Objective		The idea is to solve the problem within the province, i.e. regional self-sufficiency. Therefore, the region does not lean on the North Sea. No fossil fuels are used. Therefore, the emphasis is on having a high regional renewable contribution. Efforts are made to achieve high efficiency. The aim is to achieve sustainability, even if costs are sometimes higher.	We allow imports from other regions and the North Sea without restriction and utilization in the province. Additional constraints as little as possible are included, i.e., maximum optimization or utilization of resources, leading to a low total system cost at the national level. This means that no additional constraints are imposed on the regional level.	There is a minimum intervention with the environment. Emphasis is on protecting the landscape. Therefore, renewables onshore energy production is limited and rather pushed to offshore. Existing infrastructure is utilized to the maximum so that minimum additional land is required for new infrastructure, i.e., investment in infrastructure is less. The aim is to achieve a socially acceptable and feasible energy system, even if this sometimes comes at the expense of price and sustainability.
Space	Solar	- 5 % of the projected agricultural land to be used for GBPV - 60 % of the share of the projected rooftop space of the BE to be dedicated to PVs	- 1.3 % of the projected agricultural land to be used for GBPV - 50 % of the share of the projected rooftop space	- No additional space allocated for GBPV, than what has been allocated in the recent short-term targets within the policy documents. For this, we considered 275 MW capacity (target for 2025 as per the Beleidskader zonneparken 2021 2025 report [68]). - 50 % of the share of the projected rooftop space of the BE to be dedicated for PVs
	Wind	- 500 m buffer distance from the BE - 500 m buffer distance from the silent areas	- 1000 m buffer distance from the BE - 1000 m buffer distance from the silent areas	- No additional space allocated for GBPV, than what has been allocated in the recent short-term targets within the policy documents. We stick to the near-term target of 855.5 MW for 2050 for the Groningen province.
	Biomass	- 30 % of the agricultural land is dedicated for energy crops - 60 % manure utilized for energy purposes - 100 % forest and nature reserve utilized for energy - 60 % agricultural residues to be used for energy - 40 % grass refining used for energy production purpose	- 10 % of the agricultural land for energy crops - 40 % manure utilization - 50 % forest and nature reserve - 30 % agricultural residues - 10 % grass	- 5 % of the agricultural land will be used for energy crops - 10 % manure utilization - 25 % forest and nature reserve - 10 % agricultural residues - 0 % grass
Energy Infrastructure	Electricity	We add enough capacity so that most of the network connections run below the maximum capacity at most of the times - HV capacity is increased by 1.2 times The network allows electricity produced from offshore and import from abroad to pass through the province, without utilizing within the region. Electricity produced within the region is utilized within the region. For this, net import and export of electricity is restricted for the Groningen province.	We add high capacity range so as to allow an easy movement of renewable energy within the region - HV capacity is increased by 2 times	Emphasis is on utilizing as much as the existing infrastructure as adding infrastructure would require additional space from the existing landscape. - HV capacity was slightly increased (1.01 times) compared to the current capacity
	Heat	Pan provincial heat network with connections to geothermal doublets and industries (for residual heat). This is used to meet heat demand of the BE in major population centers within the province	Pan provincial heat network with connections to geothermal doublets and industries (for residual heat). This is used to meet heat demand of the BE in major population centers within the province	Only active connection of DH network from city outskirts. This involves transmission network connection to city center and distribution network connection through the city.
	Hydrogen	The network allows hydrogen produced from offshore and import from abroad to pass through the province, without utilizing within the region. Hydrogen produced within the		

(continued on next page)

Appendix Table C1 (continued)

Topic	Detailed	Autarkic	Least constrained	Minimal disruption
	NG	region from industries is utilized within the region. Hydrogen stored in salt caverns can be transported to other regions. Net import and export of hydrogen is restricted for the Groningen province. NG import through Groningen is allowed and extraction from Groningen gas fields is restricted. Net import and export of NG is restricted for the Groningen province. Therefore, upgraded biogas (in NG network) produced in Groningen will be used in activities requiring NG use, such as methanol production or technology options in various sectors such as the BE.	NG import through Groningen is allowed and extraction from Groningen gas fields is restricted. There is no restriction on the use of imported NG in the Groningen province.	NG import through Groningen is allowed and extraction from Groningen gas fields is restricted. There is no restriction on the use of imported NG in the Groningen province.
Other infrastructure	CO ₂	Local production and use or underground storage of CO ₂ after capture from point sources, such as industrial nodes. Direct air capture (DAC) option capacity is also restricted.	Local production and use or underground storage of CO ₂ after capture from point sources, such as industrial nodes. Direct air capture (DAC) option capacity is also restricted.	Local production and use or underground storage of CO ₂ after capture from point sources, such as industrial nodes. Direct air capture (DAC) option capacity is also restricted.
Technology options and other sectoral constraints	Industries	Hydrogen electrolyzer capacity of 20 MW which is planned to be installed in Delfzijl in the short-term (Groningen seaports report) will be installed. The purpose of this electrolyzer is only to meet hydrogen demand of the province.		
Targets	Emission reduction	Regional emission reduction more than the national emission reduction target, i.e., regional target is 100 % and the national target is 95 % for greenhouse gas, as the province plans to do more compared to the national targets.	Only follows national greenhouse gas emission reduction target of 95 %	Regional greenhouse gas emission reduction target 95 % along with the national target of 95 % reduction
Supply options	Woody biomass	Woody biomass produced within Groningen is utilized in Groningen. Imported woody biomass will be only allowed to pass through the province.		
	Wood chips biomass	Biomass produced within Groningen will only be utilized within Groningen. No biomass is exported. Therefore, unused wood chips can be used as woody biomass within the province.		
	Geothermal	Geothermal is allowed for heat production purposes		Geothermal will not be used due to earthquake tendency in the Groningen province

Appendix D. Extra analysis

We tested whether regional PV penetration increased in renewable energy supply mix if social cost³ were imposed on the above-mentioned renewables (Fig. D-1). As expected, the contribution from sun increased slowly (+7 PJ in the 80 % case) and the contribution from onshore wind energy decreased (−13 PJ in the 80 % case) with an increase in costs associated with onshore wind and biomass energies. The biomass energy contribution increased compared to the autarkic scenario because there was still some potential for some biomass energy utilization,⁴ which became stable afterwards as this potential was already fully utilized. This suggests that biomass remains a cheap renewable supply option and utilized fully even when its price is almost doubled. The total system cost for the Groningen province increased with increasing renewable supply cost as anticipated, with 80 % case showing 90 M€/year cost increase compared to the autarkic scenario.

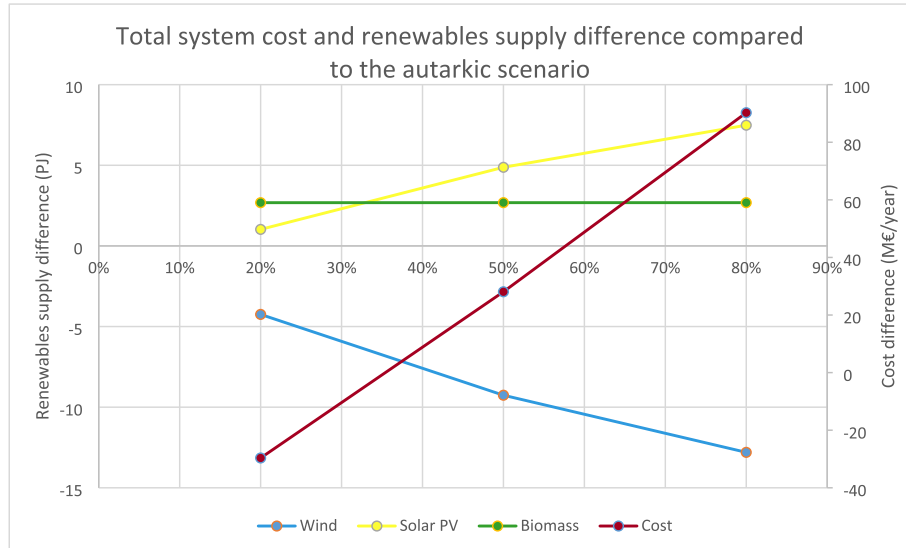


Fig. D-1. Renewable energies (wind, solar, and biomass) supply difference and total system cost difference compared to the autarkic scenario data in the primary vertical axis and the secondary vertical axis, respectively, with units PJ and M€/year, respectively. Percentages in the x-axis represent the percentage increase in the social cost of both onshore wind and biomass energies simultaneously compared to the autarkic scenario. Thus 0 % represents the autarkic scenario.

Another sensitivity analysis was performed on the future production capacity (main product volume) of industries in the Groningen province as stakeholders were concerned regarding the uncertainties associated with their future production volumes – see Fig. D-2. With an increase in main product demand there is an increase in the supply of renewables, particularly onshore wind energy whose supply potential increased by 30 PJ for the 100 % increase case. Similarly, the final energy demand also increase for the industry sector within Groningen. All of this leads to a significant increase of cost with an increase of 482 M€/year for the 100 % case.

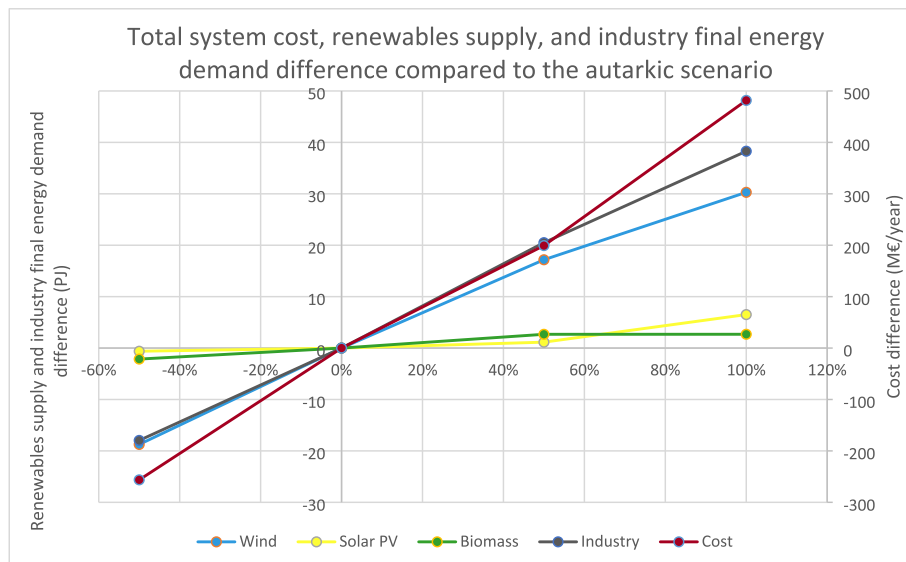


Fig. D-2. Renewable energies (wind, solar, and biomass) supply and industry final energy demand difference in the primary vertical axis with unit as PJ and total system cost difference in the secondary vertical axis with unit as M€/year, compared to the autarkic scenario. Percentages in the x-axis represent the percentage

³ We increased the price of technology option for onshore wind energy. Similarly, the cost of energy carriers were increased for biomasses having spatial impacts, land use impacts, or politically debatable biomasses namely straw, local wood chips, grass refining, and energy crops.

⁴ This concerns biomass types that are balanced at the national level and no distinction is made at the regional level

change in the demand of the final main product of the industries in the Groningen province compared to the autarkic scenario. Thus, 0 % represents the autarkic scenario.

The stakeholders were interested in understanding the investment responsibility related to different sectors and actors. The model in the current state can already identify some of these responsibilities. Appendix Table D1 provides an illustration for the BE, where the total costs of the households and services sectors have been segregated, along with including costs associated with the DH network responsible for meeting the heat demand of the corresponding sector. The households sector (within the BE) has been further segregated into rental and owner-occupied homes to make further classification regarding who will bear what cost. Since DH is responsible for supplying heat to both households and the services sector in cities, no further classification is made for this energy infrastructure. Clearly, there are major differences between scenarios regarding different cost components. For example, the autarkic scenario targeting self-sufficiency has the highest total cost (803 M€), followed by the minimal-disruption scenario (778 M€). However, the DH costs for the corresponding scenarios are 0 and 24 M€, respectively.

Appendix Table D1

Total system costs associated with the built environment (prices in M€/year).

Built environment	Autarkic	Least constrained	Minimal disruption
Rental homes*	287	273	290
Owner occupied homes	192	182	194
Services	324	235	271
DH	0	42	24
Total	803	733	778

* household dwellings classification into rental and owner occupied homes was based on the current classification share (2022) of the corresponding homes with data obtained from Central Statistics Bureau of the Netherlands [96].

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