A regional energy system transition modeling tool for decision support

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Chapter 3 Detailed spatial analysis of renewables' potential and heat: A study of Groningen Province in the northern Netherlands

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Abstract:

Spatially sensitive regional renewables' potentials are greatly influenced by existing land-use claims and related spatial and environmental policies. Similarly, heat particularly related to low-temperature demand applications in the built environment (BE) is highly spatially explicit. This study developed an analytical approach for a detailed spatial analysis of future solar PV, onshore wind, biomass, and geothermal and industrial waste heat potentials at a regional level and applied in the Dutch Province of Groningen. We included spatial policies, various spatial claims, and other land-use constraints in developing renewable scenarios for 2030 and 2050. We simultaneously considered major spatial claims and multiple renewable energy sources. Claims considered are the BE, agriculture, forest, nature, and network and energy infrastructure, with each connected to social, ecological, environmental, technical, economic, and policy-related constraints. Heat demand was further analyzed by creating highly granular demand density maps, comparing them with regional heat supply potential, and identifying the economic feasibility of heat networks. We analyzed the possibilities of combining multiple renewables on the same land. The 2050 renewable scenarios results ranged 2 - 66 PJ for solar PV and 0 - 48 PJ for onshore wind and biomass ranged 3.5-25 PJ for both 2030 and 2050. These large ranges of potentials show the significant impact of spatial constraints and underline the need for understanding how they shape future energy policies. The heat demand density map shows that future heat networks are feasible in large population centers. Our approach is pragmatic and replicable in other regions, subject to data availability.

Keywords: renewable potential, regional level, land-use constraints, scenarios, heat demand, and biomass

3.1 Introduction

Technological advances and reduced costs over the past decade have propelled the deployment of renewable energy sources across the globe. The share of renewables in total energy use in the EU, for example, almost doubled between 2004 and 2018 [169]. During the same period, renewable generation capacity increased nearly 3.5 times in the Netherlands [169]. However, the share of renewables in the Netherlands in terms of gross final energy consumption was only ~9% in 2019, one of the lowest in the EU [169]. While various reasons can be identified, this small share also relates to the high population density and related land demand in the Netherlands. Renewables, such as large-scale solar or wind, have low power densities and require vast amounts of space compared to fossil fuels [15]. Therefore, shifting to renewable energy systems is a key challenge in densely populated countries such as the Netherlands.

Renewables compete with other spatial claims that may be partly or even fully incompatible with renewable energy generation. For example, there exists a full incompatibility between the built environment (BE) and wind farms or large-scale biomass [47]. For example, the same land cannot be used for these energy supply sources and for the BE infrastructure. Similarly, a partial incompatibility exists between the BE and photovoltaics (PV). While large-scale centralized PVs on the ground, i.e. ground-based PV (GBPV), cannot exist within the BE, decentralized PVs in the form of rooftop PV can exist within the BE. Incompatibility is not merely shaped by technical and physical characteristics. Societal considerations and related policies are similarly important. Nature, forests, and other (culturally) valuable landscapes often have protected area status, where renewable deployment is not allowed or at least constrained [18,19]. Societal resistance to changing landscapes and the environmental impact experienced by those near renewable sites also inspire societal debate and spatial policies and choices [18,19,170]. Consequently, finding sufficient, appropriate, and accepted sites for renewable energy generation is a major challenge that is shaped by the spatial policies developed and applied.

There is a multitude of studies that identify the spatial potential for distinct renewable energy deployment, also in the Netherlands [47,171]. Often, such studies consider energy potentials and ambitions based on specific geographical or climatic circumstances. Only few studies explicitly consider spatial potentials for the long term while simultaneously considering alternative land-use functions and societal or policy preferences. Rather, these studies tend to take a more specific focus and apply GIS to analyzing energy potentials considering current technical [53–55], economic [48,56], environmental [49,50], and ecological [51,57] constraints. In addition, only a few studies have focused on social aspects and landscape impacts [49,58]. We attempted to provide a comprehensive understanding of how each or a combination of the above-mentioned constraints can shape the long-term potential for renewable energy deployment in a region. As a result, the understanding of the relationship between renewables deployment, existing landscapes, future developments, and the multiple spatial policies and constraints shaping this relationship remain underdeveloped in policymaking [172].

Most studies analyze the spatial potential of a single renewable resource, such as biomass [47], GBPV [48,49], wind [50,51], or geothermal [52]. We analyzed the spatial potential of each of these resources explicitly in our study. The same land can be simultaneously suitable for multiple resources assisting the use of land for other pressing needs and increasing land productivity. Some studies do consider renewable combinations, amongst which solar and wind combination, for example [53,54], is common. We also could not find any literature providing robust framework considering actual constraints and ambitions related to detailed spatial analysis of a regional energy system. We considered a variety of combinations of these renewables along with discussing the spatial planning involved in the process and changes to the individual energy potential.

This study aims to develop and apply an analytical approach to include spatial policy considerations in identifying long-term spatial potentials for renewable energy sources. The underlying objective is to show how such an approach may assist in comprehensively identifying spatial constraints and their potential adjustments to shape renewable energy potentials. In doing so, we also allowed for the identification of key trade-offs between alternative policy choices. Our approach is based on analyzing the future energy generation potential from various spatially dependent supply sources at a high spatial resolution using geographic information system (GIS)-based tools. The approach simultaneously addresses (a) multiple land uses and related policy constraints, (b) multiple renewable energy sources, and (c) long-term (expected) land-use changes. The approach is meant to be pragmatic, easily replicable in diverse contexts, and modifiable in response to data availability related to in- or exclusion of other land-use constraints. The approach is developed while considering its application in Groningen Province of the Netherlands.

Land uses considered in our approach are the BE, agriculture, nature, network (road, rail, and waterways) infrastructure, and energy infrastructure. While, we simultaneously analyzed social, ecological, environmental, technical, economic, and policy-related constraints. The renewable energy sources we included are solar PV, onshore wind, biomass, and geothermal. All of these are spatially sensitive and are expected to play a major role in the future Dutch energy system [173]. Solar PV includes both rooftop PV (decentralized) and GBPV (centralized), while other forms of decentralized PV, such as façade PV, are less common and are considered beyond the scope of this study. Regarding wind, we included the possibilities of large-scale wind farms. Examples of studies analyzing wind and solar PV potentials at different geographical scales at the municipality [174,175], province, state, or territory [176–178]. Country-specific examples range from the Netherlands [58], Iran [50], US [51], Greece [56], and the UK [179].

Regarding the inclusion of biomass and heat, we added several elements to the analysis not common or existed in previous studies. While (regional) biomass potentials are often studied, also in a Dutch context [180,181], these studies typically overlook future biomass potentials. Including future potentials may be highly relevant, as, for example, forest residues and turf strongly relate to maintaining and developing forest and nature practices [47]. Simultaneously, shifts in agricultural policies and produce are similarly important as these relate to the amount of utilization of agricultural residues. Hence, both aspects were included in our approach, while we also deliberately covered a large variety of biomass types in our analysis, ranging from energy crops to grass refining, which is also not common in the existing literature.

The inclusion of heat demand and supply explicitly in a detailed spatial manner allows for their better integration with other energy carriers in an energy system modeling environment. Regarding the heat supply, we targeted potentials of geothermal heat and industrial waste heat (IWH) potential by considering industries' future final products demand based on [173]. The geothermal potential is considered with above-ground land-use constraints, such as protected areas and the BE, which goes beyond existing studies in the Netherlands [52,59,182] and abroad [183–185] which concentrate on underground structures. We distinctly analyzed heat demand on a provincial level and in doing so, went beyond existing heat-related studies that typically focus on a low geographical scope, such as a municipality, city, or a part of it [61–63]. The heat demand builds on combining a spatial footprint map of the BE with current and future regional demand estimate. This estimate was used to create heat demand density maps for low-temperature application, i.e., the BE, with high granularity (100m

* 100m mesh). This develops our understanding of the economic feasibility of a district heating (DH) network.

Our main research questions, consequently, are:

- *"How can we simultaneously integrate various land-uses and related technical, economic, environmental, ecological, and social constraints in analyzing regional renewable energy potentials, while considering existing policies and future land use activities?"*
- "*How can we analyze existing and project future heat supply from geothermal and IWH and heat demand density from the BE and categorize demand for the study of heat network feasibility?*"

For answering these research questions, we created a framework for detailed spatial analysis of regional renewable energy potentials in a GIS environment by developing scenarios ranging from conservative to progressive in terms of societal and spatially relevant policy constraints. These will allow for the identification of the impact of various policy choices on renewable energy potentials. Within the framework, first we projected various land-use claims and future renewables potentials recognizing various constraints in different scenarios. Then, various renewable land-use combination possibilities were analyzed. The focus was the development of a pragmatic and replicable approach to comprehensively analyze renewable energy potential on a regional level. GIS-based models were used for recognizing various claims and potentials. Finally, heat demand and supply potentials were analyzed. Supply included future waste heat potentials based future production potentials and demand included the BE sector as this heat is highly dispersed. These demand maps were also done by GIS.

Our innovation compared to previous literature are our research is comprehensive because of simultaneous analysis of multiple land uses considering and related technical, economical, ecological, environmental, and policy-related constraints; short- and long-term (expected) changes to various relevant spatial claims; and multiple renewable energy sources allowing for their various feasible spatial combinations. In addition, our study of biomass is exhaustive compared to previous biomass potential-related to literature. An additional innovation is the inclusion of spatially-relevant energy carrier heat by analysis of their demand potential shaped by heat demand densities and supply potential of IWH. The remaining sections include the methodology in Section 3.2, results and analysis in Section 3.3, a discussion of the impact of the chosen method in Section 3.4, and the conclusion and suggestions for future studies in Section 3.5.

3.2 Materials and methods

For applying and testing our approach we chose to study Groningen Province in the Netherlands (Figure 3-1). Groningen is home to almost 600,000 inhabitants and having almost 3000 km^2. This offers a relatively large space potential for renewables by Dutch standards due to a somewhat modest population density (198 inhabitants/km^2). Groningen is well connected with other European countries and the northern offshore part of the North Sea. Groningen Province has high ambitions of becoming 'energy neutral' and a region exporting energy and potentially becoming a key hub in a future hydrogen economy [101–103]. Framed as the 'energy valley of the Netherlands' and fueled by its ambitions and relative abundance of space, Groningen is expected to play a major role in the future Dutch energy system. Nevertheless, Groningen is also subject to a wide range of land uses and related constraints, making it a strong case for testing our approach.

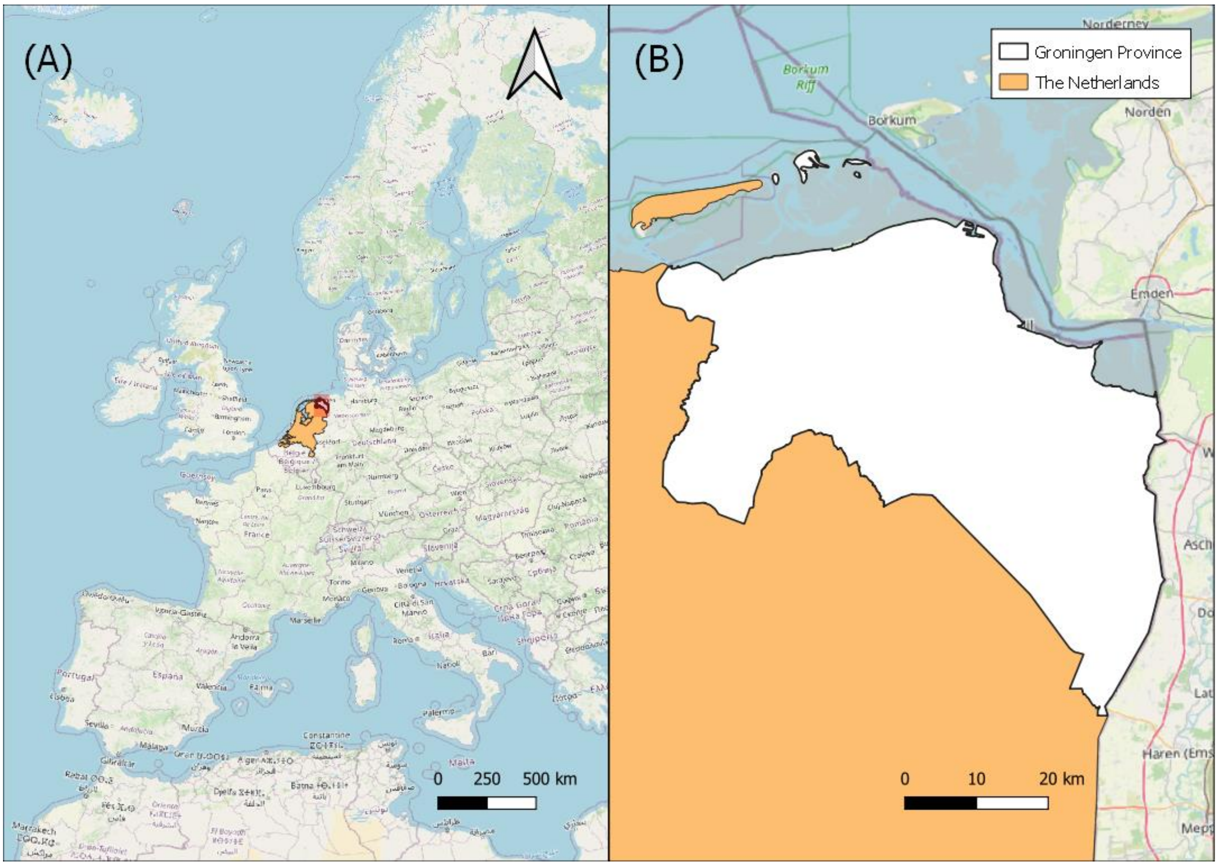

Figure 3-1: (A) The geographic location of the Netherlands at the center of the figure with the red box indicating the analyzed region; and (B) Zoomed-in representation of the study area, Groningen Province.

We quantified renewables' future potentials while simultaneously investigating heat demand in this study. Figure 3-2 presents the flowchart of our research's main stages identifying input and output activities in the methodology. For showing how alternative spatial policy choices may shape renewable energy potential, we created three scenarios representing variations in land-use constraints for the supply sources included. After introducing scenarios (Section 3.2.1), we continue by explaining the GIS data collection (Section 3.2.2), dataset management and processing (Section 3.2.3), and notably address the framework used to estimate renewable potentials for each scenario, including mapped heat demand and supply (Section 3.2.4). The framework operates at three levels: a) identifying future spatial claims for various land-use activities, b) estimating renewables and heat supply potentials considering spatial claims, and c) understanding renewable combination feasibility, given the possibility of multi-use space for different renewables.

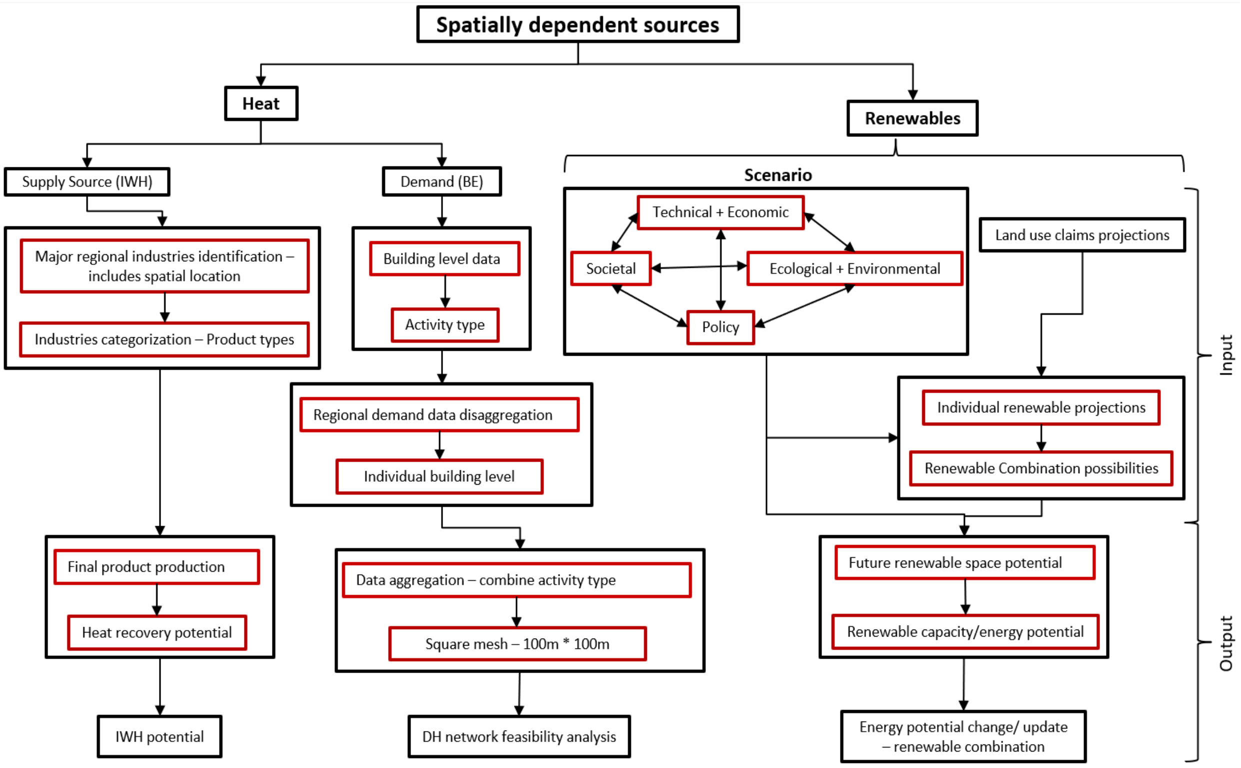

Figure 3-2 Flowchart with our research's main activity stages segregating along with input and output of the methodology

3.2.1 Scenario description

Our scenarios express variations in regulations and societal choices expressed in spatial and environmental policies that influence which areas (a) can or cannot be used for certain renewables, (b) the intensity of using an area for renewables, and (c) buffer zones needed between renewables and other land uses. Therefore, our scenarios are expressions of an interplay between technical, societal, ecological, environmental, and policy-related constraints (see Figure 3-2). Figure 3-3 illustrates how these variations influence renewable energy generation in the different scenarios. Our scenarios target both the medium (2030) and the long-term (2050). We only created and analyzed two scenarios for the mid-term, conservative and progressive, as some restrictions and targets are clear for the next ten years. In the long term, we allowed for more flexibility in interpreting the constraints. Therefore, for 2050, we formulated three scenarios: conservative, progressive, and intermediate. The scenarios target future potential land uses related to renewable energy, with possible impacts of various constraints. The impact of temporal intermittency of renewables and its spatial impact on the future energy system is a part of future research.

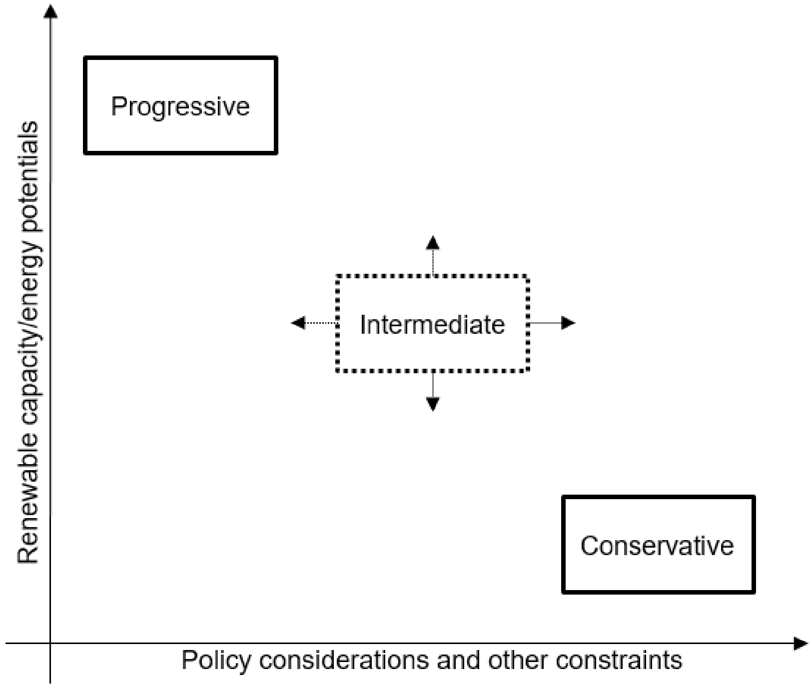

Figure 3-3: Illustration of the positioning of scenarios in terms of renewable potentials and policy and other constraints explicitly considered for the target years 2030 and 2050. For 2030, only conservative and progressive scenarios were considered, while for 2050, we analyzed all three scenarios.

The conservative scenario strictly follows existing policies regarding constraints on renewable deployment to limit the impact of this activity on the environment, ecology, society, and existing landscapes. When policies are unclear, we were cautious about changing or adding activities in an area and considered higher estimates for buffer zones. The conservative scenario considers social aspects as crucial, such as the "not in my backyard" (NIMBY) phenomenon, and quantified social aspects according to existing restrictions or literature.

The progressive scenario maximizes renewable space potential by including only undisputed constraints or exclusion zones as reflected in (inter)national restrictions. Hence, exclusion zones and buffer distances are as low as possible and considerations regarding esthetics, societal resistance, or landscape identity are not considered 'crucial.' Combining renewables with alternative land uses is also strongly endorsed, when possible, for example, GBPV in agriculture and refining livestock grass.

Finally, the intermediate scenario seeks the middle ground between progressive and conservative scenarios. Some policies are straightforward and can be translated to yes or no, including inclusion or non-inclusion of constraint layers. Otherwise, we assumed a medium position between the conservative and progressive scenarios. The buffer spaces were adjusted accordingly. Section 3.2.4.2 provides details on the operationalization of these scenarios.

3.2.2 Data collection

Data were collected mainly from open sources. The common open sources are the National Georegister [186], ThermoGIS [99], and the Global Wind Atlas [187]. The National Georegister is a public platform for accessing geo datasets from the Dutch government. Similarly, ThermoGIS is a web-based service developed by the Netherlands Organization for Applied Scientific Research (TNO) to support the government and companies in developing geothermal energy in the Netherlands. Related to energy infrastructure, the national electricity transmission system operator, TenneT, provides online data on high-voltage (HV) electricity transmission lines [160], and the national energy network operator, Gasunie, provides data on natural gas (NG) transmission lines [188]. Data on medium voltage (MV) and low voltage (LV) electricity transmission lines were provided by the regional network operator ENEXIS [189]. The Dutch Central Bureau of Statistics (CBS) [149,152] contains historical spatial statistics, such as land use for different existing activities and livestock. Open data may not be as easily available in other regions as in the Netherlands, also affecting the replicability of our approach. Nevertheless, even when data may be (much) less available, open-source data does allow our approach to be used, albeit possibly with less detail. For example, universal data may be derived from open street maps, DIVA-GIS, Natural Earth Data, and OpenGeoPortal. Within the European context, open data sources are European Environment Agency, Eurostat, and INSPIRE. Hence, despite limitations on good data quality with high spatial resolution, we also note that application of our systematic methodological steps remains valid, at least to a large degree possible.

3.2.3 Managing and processing datasets

The management of the GIS datasets included adjustment of data layers to achieve a common coordinate reference system EPSG:28992 – Amersfoort/RD New. Each data layer was processed to include the geographical scope of Groningen Province, and different resolution maps were used for different purposes. We mostly used vector data and sometimes raster data as inputs. Vector data are represented as points, lines, or polygons, discrete attributes within a mapped region, whereas rasters are represented as pixels, that is, continuous. We switched to raster data whenever relationships were established between layers or maps. The modeling details are presented in Appendix 2.3.

3.2.4 Modeling framework

Our modeling framework is intended for detailed spatial analysis, without considering cost optimization. It is suitable for modelers intending to combine the outputs of spatial analysis of renewables and other highly spatially dependent demand and supply sources in an energy system modeling environment. Figure 3-4 presents the modeling framework used to identify the energy potentials of the included renewables. First, we investigated spatial claims by considering important land-use activities, both existing and future projections (Section 3.2.4.1). These claims acted as inputs for the renewable potential analyses (Section 3.2.4.2). Finally, we examined the renewable combinations to understand the overall potential (Section 3.2.4.3).

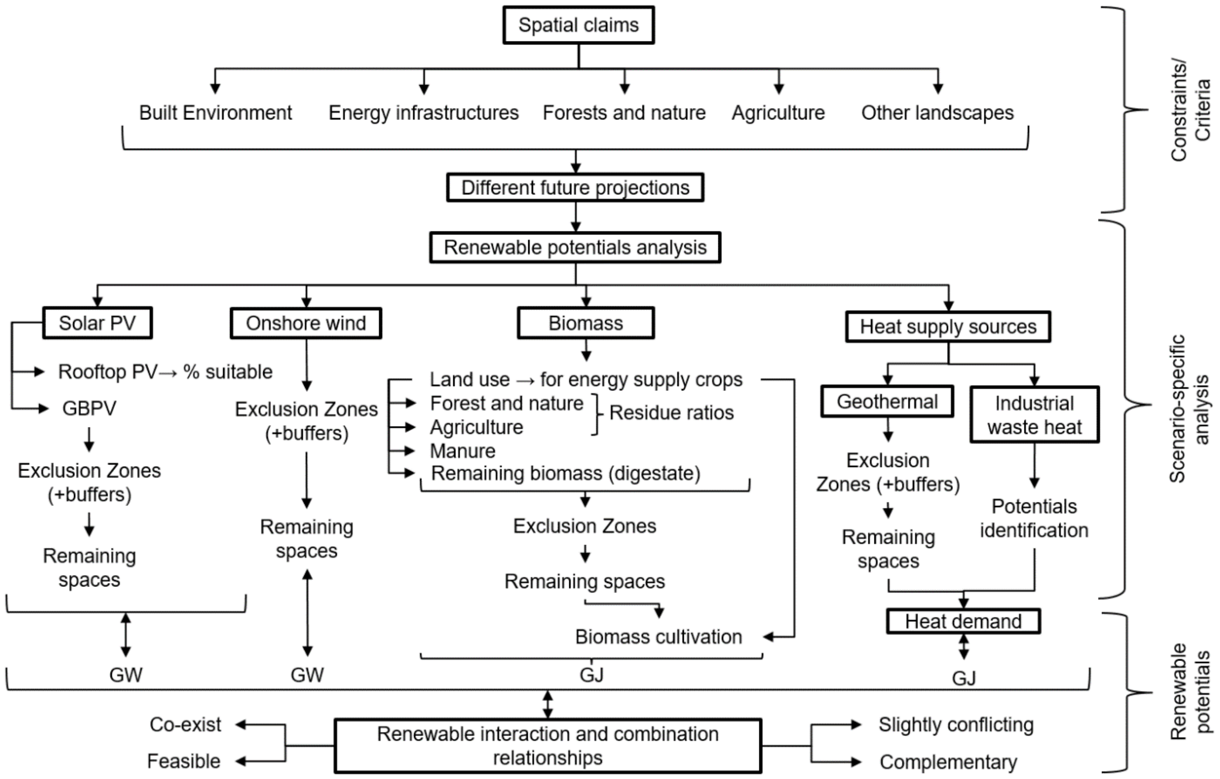

Figure 3-4: The modeling framework for identifying the capacity and energy potentials of renewables. Heat supply sources are linked to heat demand. GBPV = Ground-based PV, GW = Gigawatt, and GJ = Giga Joule.

3.2.4.1 Spatial claims

Our approach starts by identifying exiting land uses, related spatial and environmental regulations, and future land use projections, which can be based on GIS data, national statistics, and a range of national and regional policy reports. For the case of Groningen, we mostly used the regional policy documents, the Groningen Environmental Vision 2016-2020 (GEV) [18] and the Groningen Ordinance 2016 (GO) [19], to identify both existing restrictions and plans and projections of different land-use changes. The Groningen Nature Management Plan 2021 [190] identifies the province's future development and management of nature reserves and landscape features. Following these policies, we selected BE, energy infrastructure, forest and nature reserves, agriculture, and other landscapes as important land-use claims to consider. Table 3-1 describes these claims in detail, including their expected future land-use changes. Appendix 2.1 further explains these claims as constraints or criteria layers, mentions spatial resolutions of the corresponding GIS maps, and provides maps references. Appendix 2.2 presents the current and short-term land use graphically.

Table 3-1 Major spatial claims considered for analysis and their detailed description

Spatial claim name	**A detailed description of the claim**
BE	The BE includes buildings for housing, services, retail and catering, business, public and socio-cultural activities, urban green spaces, and water and infrastructure [18]. For future projections, we considered the growth of the BE to be the same as the historical trend [152].
Energy and network infrastructures	This category includes roads, railways, waterways, electricity transmission lines, and NG lines. We expect NG lines to remain relevant in the future because they are most likely to be retrofitted for hydrogen [191]. These infrastructures are important because they act as technical constraints for the deployment of renewables, mostly with buffer zones around them. In the future, most of this infrastructure will grow. The short-term expansion of this infrastructure is documented in policy and, hence, part of our analysis. We translated the future long-term expansion into additional buffer spaces around the existing infrastructure.
Forest and nature	Forests and nature reserves are protected areas, constrained from additional activity under existing

Spatial claim name	A detailed description of the claim
reserve	conditions [18,19]. Within forests, we only considered prospective forest development zones within which there is room for forest development and new timber cultivation [18,19], thus relevant from a biomass production perspective and constrained from wind and solar deployment. The Dutch Nature Network Netherlands (NNN) incorporates protected nature sites, including the Natura 2000 area. We assumed their projected growth to be similar to the historical trend [152].
Agriculture	Agriculture is divided into livestock and crop cultivation activities. Depending on the policies, agricultural spaces can harvest biomass from agricultural residues or energy crops. Agricultural lands are simultaneously suitable for most renewables, as they are generally not limited to GBPV or wind turbines. We restricted the maximum percentages of land used for renewables depending on the scenarios (detailed explanation in section 3.2.4.2.
Other landscapes and protected areas	National landscapes, national parks, groundwater protection areas, and silent areas were added as additional land uses. Groundwater protection areas limit the use of underground construction related to wind farms and geothermal heat extraction. Silent areas and adjoining buffer zones are restricted to wind farms owing to the associated noise. We do not change the scope of these areas in the future.

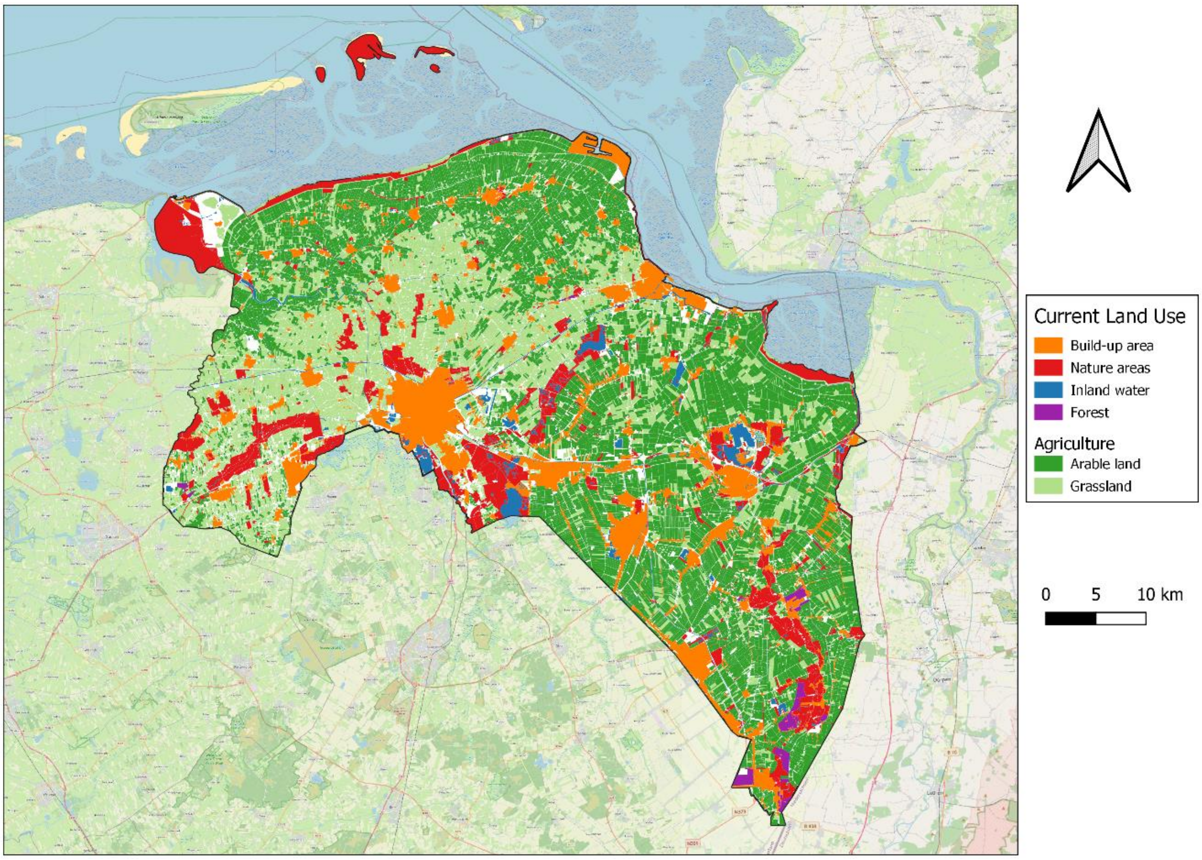

Figure 3-5: Current land use of major spatial claims in Groningen Province.

Table 3-2 Area-wise distribution (in 100 km²) of land-use activities (current, 2030, 2050) in Groningen

Land-use type		Area (km²) (*100)		
		Current	**2030**	**2050**
Buildup area		2.76	2.88	3.12
Nature area		2.44	2.68	3.21
Inland water		0.69	0.69	0.69
Forest		0.14	0.15	0.18
Agriculture	Grassland	5.94	5.70	5.32
	Arable land	9.26	9.12	8.69

Land-use type	Area (km²) (*100)		
	Current	**2030**	**2050**
Total	21.23	21.22	21.21

In Groningen, as in many other regions, there are overlaps mainly between agriculture, forests, and natural areas. We considered the following priority order for projecting future land-use claims: BE>Nature>Forest>Agriculture. We prioritized the BE because the current and future expected need for additional housing, notably around existing urban areas, cannot be compromised. The BE represents hard claims [47], and we assumed that adjoining agricultural land would be used for this purpose. We further assumed that land use for the BE, nature, and forest claimed in a year cannot be claimed again for other activities in the subsequent years. Between forest and nature, nature is allocated first as the growth and maintenance of natural areas are a priority for national and provincial governments [18,19]. In addition, this clear allocation and categorization help to project their future growth properly. Figure 3-5 represents the current land use of major spatial claims in Groningen Province. Table 3-2 presents an area-wise distribution of current and future land-use, i.e. 2030 and 2050, activities. The inland water spread is assumed to be constant from now until 2050. Table 3-3 discusses these activities, allocation methods, assumptions, and GIS methods in detail, along with suitable references.

Table 3-3 Detailed discussion of methods related to future allocation of major activities, including assumptions and the stepwise method followed for modeling purposes

Activity	Assumption and allocation methods (Why and how done)	Stepwise methods for modeling (What was done)
BE	- The BE assumes priority compared to other spatial claims because land claims associated with population growth cannot be compromised with other claims, i.e. hard claim [47]. - Growth rate is considered from CBS regional land-use statistics of 15 years (2000-2015), i.e. 120 ha/yr [152], starting from 2020 till 2050. This is also in line with the range considered in [47] at the national level. Industries are considered a part of overall BE growth. - Growth of the BE is only possible in agricultural land and not in other spatial claim regions of previous periods, mainly nature and forests. - For a particular future period (2020-2030 or 2030-2050), the BE is first allocated, followed by nature and forest in the same order.	- For 2030, since CBS statistics [152] show an increase in the buildup area being concentrated in Groningen city due to high population growth rate, we created a buffer around this city, i.e. uniform growth around the city, to accommodate entire growth from 2020-2030 in this region. We limited this growth to Groningen municipality to have uniform policy regulation associated with infrastructure development. The BE growth takes place along all types of vegetation plots, for example including fallow land and other agricultural usages. For other regions, land dedicated to the BE remains the same as the current distribution. (N.B.: Groningen city is a part of Groningen municipality) - For 2050, we assumed that other cities with moderate current growth will also start growing after 2030 at the same rate as Groningen city. This included Delfzijl city in Delfzijl municipality and all urban areas/buildup areas in the Het Hogeland municipality, including Eemshaven, as the expansion of economic activities is expected in these regions. We selected these regions as they have either high growth or growth rate of buildup area (mostly >10%) between 2000 and 2015 as per CBS [152]. - The added regions are merged with BE from the previous period. - We excluded areas occupied by nature and forest from the previous period. For example, we excluded current nature and forest areas for considering the growth of the BE in 2030.
Nature	- Nature growth rate of 0.45%/yr considered from CBS [152]. - Growth cannot happen in the area occupied by the BE for the same year and forest for the previous period. - Most of the inland water bodies are a part of nature areas. They are not	- For both 2030 and 2050, a buffer area is created around all nature spaces from the previous periods (current or 2030) assuming spaces surrounding existing nature areas are more suitable and feasible for new nature areas. Therefore, the growth is assumed to be uniform surrounding the existing areas. - We removed areas occupied by the BE (same period) and forest (previous period)

Activity	Assumption and allocation methods (Why and how done)	Stepwise methods for modeling (What was done)
	considered for growth, and we excluded these areas from nature area calculations.	- Nature growth takes place along all types of vegetation plots. - Similar to the BE, the additional regions are merged with existing regions from the previous period. - For land allocation calculation purposes, we excluded inland water bodies.
Forest	- Growth rate is the same as for nature areas - Growth cannot happen in areas occupied by the BE and nature areas for the same period	- The method is similar to that of nature areas, the only difference being that both the BE and nature areas are removed from the same period.
Agriculture	- land available under different vegetation types, such as arable land and grassland, for a period is dependent upon the BE, nature, and forest areas of the same period. - Agriculture received the lowest priority compared to other activities as self-sufficiency in food is not a priority for our regional analysis, especially when compared to other activities described in this table (see section 3.2.4.2.3 for detailed discussion).	- Land uses help replicate related to the growth of the BE, nature, and forest areas for the same period are deducted to obtain future agricultural land under different vegetation types. - Change in agriculture land use affecting biomass-related activity is reflected in section 3.2.4.2.3.

Figure 3-6 presents the nature area modeling for 2030 with the help of the model builder feature in ArcMap as an illustrative example. A buffer was applied to the current nature area – also see Table 3-3. The buffer included the current nature area and an additional area surrounding the current area corresponding to the buffer length. Since the nature area expansion will take place only in the current agricultural land, this land overlapping the buffer nature area is clipped and merged with the current nature area. From this area, the BE 2030 and the current forest is removed to obtain nature area 2030. Appendix 2.3 further details modeling of other spatial claims for different years to along with the explanation of various logics used in creating those models. Overall, models created by the model builder allowed us to only provide input layers without having to save intermediate layers. This is specifically helpful in our case where buffer distances are not known beforehand and a numerous iterations are involved to obtain the appropriate buffer lengths. This is necessary in regional contexts where the pressure on the land is enormous for various spatial activities. In addition, a large number of intermediate steps are sometimes involved to determine various spatial claims and having models beforehand helps in this direction.

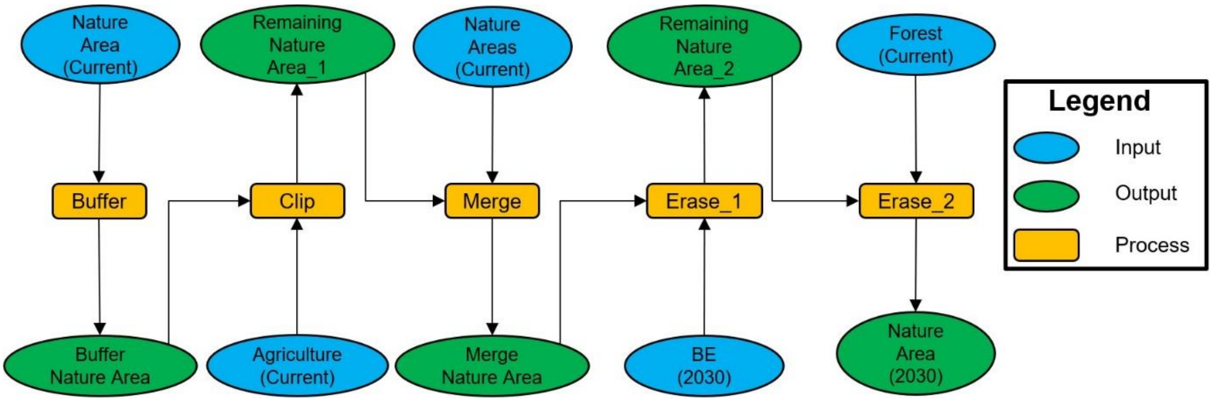

Figure 3-6: Modeling of the nature area for 2030 in the model builder of GIS.

3.2.4.2 Spatial potentials

After projecting spatial claims of important land-use activities, we investigated the space potentials of solar PV (Section 3.2.4.2.1), onshore wind (Section 3.2.4.2.2), biomass (Section 3.2.4.2.3), and heat supply sources (Section 3.2.4.2.4). We here describe the steps taken in our case of Groningen province, to illustrate the key steps and choices which may help replicate our regional projections in other studies. The first step is identifying important spatial claims and key constraints, which may be based on policy considerations or societal preferences. In this regard, we can confidently say that constraint for one renewable might act as a feasible criterion for another. Second, future expansion or changes of these claims or constraints should be carefully considered. And third, one must identify buffer distances which might be based on safety, technical, or societal considerations. These spaces are usually determined by literature, with similar research, and policy documents. Mostly, we identified and segregated exclusion zones through constraint layers (and included buffer) before identifying renewable space potential. We followed a Boolean logic, where if an exclusion zone is considered for a scenario, the corresponding region is not suitable as a potential renewable region – marked by '✓' in various renewable allocation tables. Renewables' feasible space potential are dependent upon the scenario which contains relevant constraints considerations including buffers – also see Figure 3-7. This model is generic and can be adapted to different situations, subject to data availability related to various land-use types and constraint conditions. Additionally, Appendix 2.3 presents simplistic generic model representation in GIS for renewable potential and the actual models used in the paper. In addition, the Appendix further explains the logic used in the creation of those models. The actual models are used to identify various regional renewables potential for different selective scenario and years.

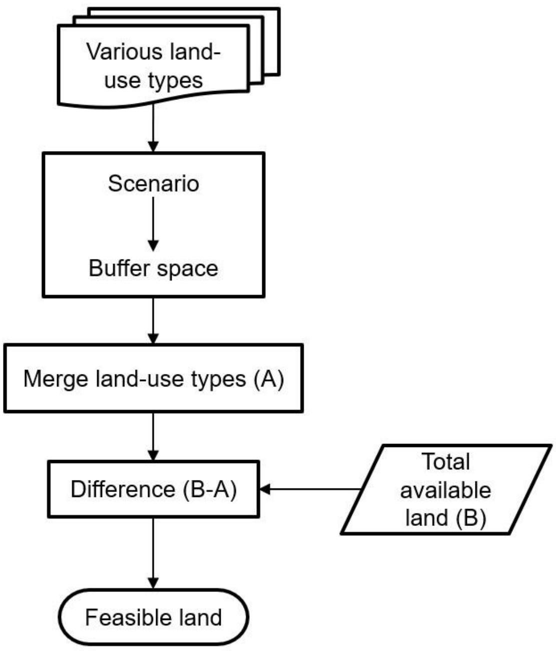

Figure 3-7 Mathematical model for identifying feasible land for renewables in the future

3.2.4.2.1 Solar PV

For rooftop PV and GBPV, we chose different approaches. Rooftop space utilization depends on suitable rooftop spaces. In our case of Groningen, we first considered an annual building growth rate of 1% from now until 2050 based on construction and demolition differences from CBS [192]. Although currently less than 5% (2019 data) of the total BE rooftop space in Groningen space is utilized for PV [119,193], recent years have shown a rapid increase. DNV-GL [194] and Holland Solar

[195] studies indicate that suitable rooftop surfaces are just above 60% in the Netherlands. Similarly, Bódis *et al.* [196] suggest 49 %–64% of EU roofs are suitable for PV. Based on this, we considered 60% of the rooftop spaces to be suitable for PV installation in the progressive scenario. We assume that no more than roughly 80% of rooftop space can be utilized due to constraints such as visual impact, grid issues, and lack of incentives, leading to utilization of 50% (≈80%*60%) of the projected rooftop space for PV in our progressive scenario – see Table 3-4. For the conservative scenario, we assumed a modest doubling of the current utilization, amounting to 10% utilization of rooftop space in 2050, with 8% in 2030. The intermediate scenario assumed a 30% rooftop space utilization.

The GBPV space potential depends on factors such as competing land-use claims, regulations, existing landscapes and infrastructures, and societal preferences. We followed different methods for various scenario operationalization of the GBPV. The conservative scenario considers zero space potential, where existing controversy over GBPV will result in municipal zoning plans to prohibit their development [19]. We excluded existing and permitted GBPV, as no current GIS data could be used for existing spatial locations of GBPV, while there are no definitive indications for planned GBPV locations in policy documents[3].

For the intermediate and progressive scenarios, we first identified spatial land-use claims of the BE (along with buffers), forest and nature reserves, national landscapes, and networks and energy infrastructure (along with buffers) as exclusion zones (Table 3-4). The BE is excluded as a techno-economic constraint where no large-scale GBPV can be constructed [197–203], while buffer spaces surrounding the BE are also exclusion zones due to social constraints such as visual impact and NIMBY issues. We considered different buffer spaces for different scenarios, with the intermediate scenario providing more buffer distance (1,000 m [48]) than the progressive scenario (500 m [204]). Forests and nature reserves are considered ecological and environmental constraints, similar to [201,203], and based on regulations in [18,19], and national landscapes as social and planning constraints [18,19,197,201,203], and hence considered as exclusion zones in both scenarios.

It is impossible to construct solar farms near network and energy infrastructures due to safety issues [201]. We estimated buffer distances for these constraints based on their density, growth expectation, and the vulnerability of the spaces surrounding these constraints. These are considered 'hard' constraints; therefore, we applied them similarly to both scenarios. We explicitly considered roads [197–203,205], railways [199,203], waterways [197,199,202,203,205], HV- electricity lines [197–199,201,202,205], and NG lines within this category. The buffer distances for roads and electricity transmission lines increased from 2030 towards 2050 to account for the increased network density and electricity transmission capacity, respectively. More buffer spaces are required for provincial or regional roads, as they are expected to widen to account for increasing traffic [152]. While different buffer spaces are needed for roads with different sizes and intensities, we chose an average distance for efficiency reasons.

The power density of solar PV is related to converting space potential to capacity potential, which we subsequently analyzed (Figure 3-8). Different PV power densities are considered in different studies [167,175,201,206]. We adapted future power densities provided in [207], accounting for the expected technology development.

[3] There are also uncertainties regarding additional GBPV installation due to opposition to changes in the landscape. Also, there is a lack of GIS data on planned GBPV locations. For example, the National Georegister [186] indicates planned solar parks on a distributed space of 14 km^2 in Groningen province, however, we could not find any other spatial policy-related document supporting this claim.

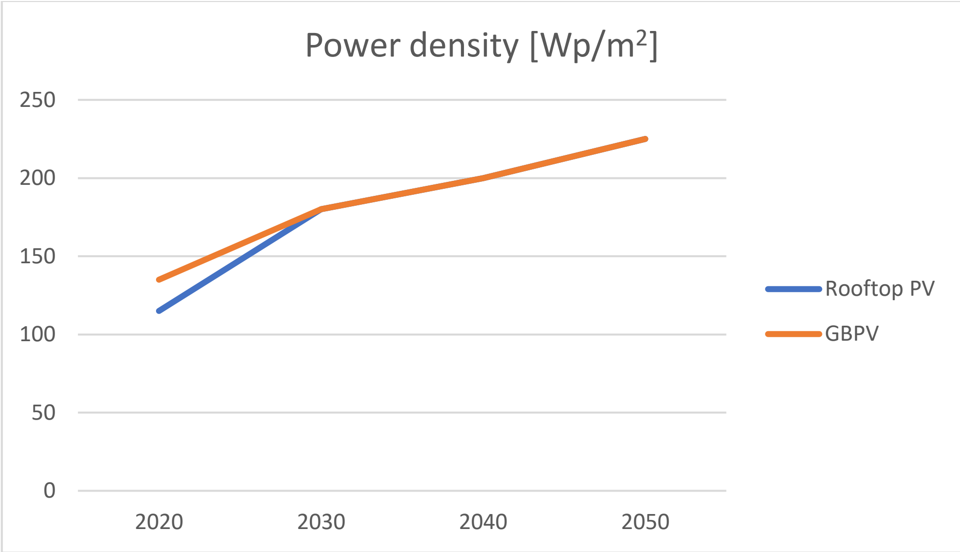

Figure 3-8: Future development of rooftop and ground-based PV power density to 2050.

Table 3-4 Summary of space allocation for rooftop PV for targeted future years considering various scenarios. In addition, constraints are considered related to GBPV site selection and information on constraint types for different scenarios. Suitable references are made to appropriate literature, wherever possible

Solar PV type	Constraint type	2030[a]		2050[a]		
		Conservative	Progressive	Conservative	Progressive	Intermediate
Rooftop PV	-	8% of the projected rooftop space (based on [119,192,193] and own assumptions)	50% of the projected rooftop space	10% of the projected rooftop space (based on [119,192,193] and own assumptions)	50% of the projected rooftop space (based on [194–196] and own assumptions)	30% of the projected rooftop space (own assumptions)
GBPV						
Exclusion layers or constraints considered for GBPV analysis[b]						
Built environment [197–203]	Technical and economical constraint, but buffer space is a social constraint [203]	no GBPV [19]	✓ (+500) [204]	no GBPV [19]	✓ (+500) [204]	✓ (+1000) [48]
Forest and nature reserve [18,19,201,203]	Ecological, environmental		✓		✓	✓
National Landscape [18,19,197,201,203]	Social, planning		✓		✓	✓
Network and energy infrastructures[c] [201]						
Roads [197–203,205]	technical	no GBPV [19]	✓ (+30)	no GBPV [19]	✓ (+50)	✓ (+50)
Railways [199,203]	technical		✓ (+100)		✓ (+100)	✓ (+100)
Waterways [197,199,202,203,205]	technical		✓ (+30)		✓ (+30)	✓ (+30)
HV- electricity transmission lines [197–199,201,202,205]	technical		✓ (+200)		✓ (+250)	✓ (+250)
NG lines	technical		✓ (+100)		✓ (+100)	✓ (+100)

[a] '✓' represents the inclusion of a constraint layer or an exclusion zone for GBPV, i.e., corresponding space is considered not suitable for GBPV.
[b] Numbers within () represent buffer distances in m.
[c] Buffer spaces related to network and energy infrastructure are based on own estimates.

Most agricultural fields are, in principle, suitable for the GBPV. Competition with agricultural production and opposition to landscape land changes, however, can severely limit the fraction that will be utilized. For the Dutch case, Folkerts *et al.* [207] suggest that 1.5% of agricultural land could be covered with PV in 2050. In addition, the national energy system modeling scenarios ADAPT and TRANSFORM consider the future growth of renewables as inputs [208]. TRANSFORM is progressive compared to ADAPT concerning renewable deployment (Figure 3-9) and suggests that up to almost 40 GW of GBPV might be deployed, while 12,500 km^2 of agricultural land may be available by 2050 in the Netherlands based on the projection of CBS data [152]. From the power density estimate (Figure 3-8), we calculated the percentage of agricultural land cover for GBPV as 0.18-0.2% and 1.1-1.4% in 2030 and 2050, respectively, by combining the ADAPT and TRANSFORM scenarios. We considered 0.2% and 1.3% of the feasible agricultural land to be covered with GBPV in the 2030 and 2050 progressive scenarios, respectively. For the 2050 intermediate case, 0.8% of the feasible land was assumed to be covered with GBPV.

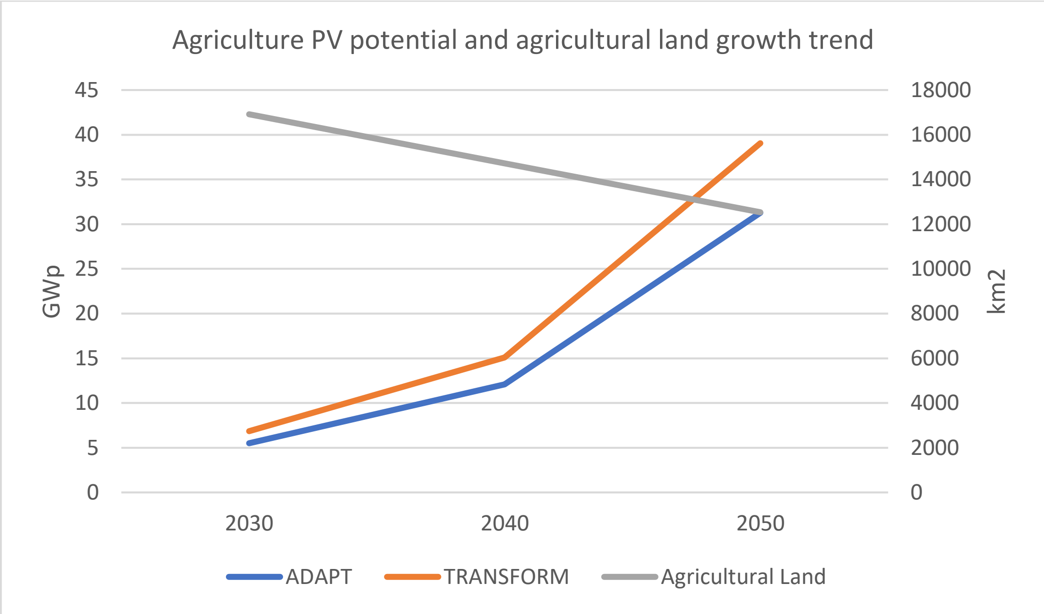

Figure 3-9: Primary Y-axis: Potential of GBPV (values in GWp) in agriculture in ADAPT and TRANSFORM national energy system scenarios; Secondary Y-axis: Future development of agricultural land (values in km²) at the national level based on the historical trend of 15 years, i.e., 2000-2015.

3.2.4.2.2 Onshore wind

As the onshore wind is highly contested in the Netherlands, no further expansion is considered in the conservative scenario. For the remaining scenarios, onshore wind is possible. We incorporated all GBPV constraint layers, that is, the BE (with buffers) [50,51,56,209–212], forest and nature reserve [18,19,50,209,212], national landscapes [18,19,50,56,212], and network and energy infrastructure [50,51,56,209–212] (Table 3-5). Additionally, we considered MV and LV transmission networks, along with buffers, as these networks can cause safety and security issues similar to HV lines. Wind farm visibility issues are far greater than GBPV, along with noise issues representing social constraints. Therefore, we considered greater buffer distances to the BE of 1,000 m [56] and 2,000 m [50,51,179] in the progressive and intermediate scenarios, respectively, from the BE. We included three additional exclusion zones: groundwater protection areas, silent areas (with buffers), and airports (with buffers).

Groundwater protection areas and prohibition of underground digging [18] currently act as planning constraints for wind turbine construction. However, the 2050 progressive scenario neglects this constraint to push for more space potential for wind farms. Silent areas can be considered an ecological and environmental constraint [18,19]. As noise is an important issue associated with wind turbines, these areas should be distant, where noise from wind turbines should be minimal. Therefore, we analyzed the noise propagation and distance relationship in detail using the following equations based on [51]:

$$L_o = L_s - 10\log_{10} 2\pi R^2 - \alpha R \tag{7}$$

where

$$R^2 = H^2 + D^2 \tag{8}$$

L_O (variable) and L_S (parameter) are the sound power or pressure levels at a source and an observer or listener, respectively. H (parameter) is the height of the tower or hub. α (a fixed parameter) corresponds to atmospheric absorption with a value of 0.005 dB/m. D (parameter) is the observer's distance from the tower. A Vestas V100 turbine with a hub height of 100 m and sound power at the source of 105 dB propagates a sound level of 21 dB at a distance of 2,000 m, the buffer distance for the intermediate scenario, which is well within the socially acceptable sound limit for silent areas of <30 dB in the Netherlands [213].

Airports and associated buffer areas are unsuitable for wind farms for air transport safety reasons [50,210,212], a technical constraint. We considered a buffer distance of 3,000 m [56,210,212] for the intermediate scenario, while for the progressive scenario we push it to 1,500 m. HV lines have a buffer distance of 250 m, similar to [50], for 2050. We calculated the capacity potential based on a power density of 10 MW/km^2 [167]. Combinations with other renewables and land-use activities can affect the final space potential (Section 3.2.4.3).

Table 3-5 The selection of constraints includes names and types related to wind farm site selection for different scenarios. The conservative scenario in both 2030 and 2050 are not represented, as additional onshore wind turbine installations are not allowed in these years. Suitable references are made to appropriate literature and policy documents related to the selection of constraint layers and setting values for buffer distances

Constraint name	Constraint type	2030[a]	2050[a]	
		Progressive	Progressive	Intermediate
Built environment [50,51,56,209–212]	Technical, economical, buffer space is a social constraint	✓ (+1000) [56]	✓ (+1000) [56]	✓ (+2000) [50,51,179]
Forest and nature reserves [18,19,50,209,212]	Ecological, environmental	✓	✓	✓
National landscapes [18,19,50,56,212]	Social, planning	✓	✓	✓
Groundwater protection area [18]	planning	✓	×	✓
Silent area [18,19]	ecological, environmental, buffer space is a social constraint	✓ (+1000) (calculation based on [51])	✓ (+1000) [51]	✓ (+2000) [51]
Airport [50,210,212]	technical	✓ (+1500)	✓ (+1500)	✓ (+3000) [212]
Network and energy infrastructures[b]				
Roads [50,51,56,209–212]	technical	✓ (+30)	✓ (+50)	✓ (+50)
Railways [50]	technical	✓ (+100)	✓ (+100)	✓ (+100)
Waterways [209,210]	technical	✓ (+30)	✓ (+30)	✓ (+30)
Electricity transmission lines (HV, MV, and LV)	technical	✓ (+200 – HV, 50 – MV and LV)	✓ (+250 – HV, 100 – MV and LV)	✓ (+250 – HV, 100 – MV and LV)

Constraint name	Constraint type	2030[a]	2050[a]	
		Progressive	Progressive	Intermediate
[50,211,212]				
NG lines	technical	✓ (+100)	✓ (+100)	✓ (+100)

[a] ✗ represents non-inclusion of a constraint layer for analysis and ✓ represents inclusion. Numbers within brackets represent buffer distances in m. Numbers within () represent buffer distances in m.
[b] Buffer distances considered for network and energy infrastructures are based on own estimates.

3.2.4.2.3 Biomass

Land use and related biomass production from now to 2050 are highly uncertain and strongly depend on policy choices and market developments [47]. When it comes to biomass, our approach calls for a close engagement with relevant national literature to identify regionally available biomass, suitable vegetation types, and pragmatic yield projections. Our approach also depends on translating national and regional discussions on the development of nature and agriculture into possible scenarios. Ongoing Dutch political debates regarding changes in various agricultural aspects, such as the reduction of livestock populations or restrictions on straw use for energy production purposes, combined with land-use changes related to crop cultivation and nature and forest regions, can shift energy production choices in different directions due to differences in yield and energy content (see Table 3-6). In the future, if policy leans towards ecological and environmental ambitions, natural areas and forests will increase. Hence, energy production from agricultural land (e.g. residues such as straw and energy crops) and livestock (e.g., manure) may drop, while forest residues (e.g., thinning) and nature residues (e.g., reed and turf) may increase. Similarly, as the Netherlands faces a general concern regarding livestock-related emissions and land use, their populations might decrease, leading to reduced manure production. Relevant vegetation types to include for Groningen in our analysis of biomass potential are arable land, grassland, nature, forests, and fallow land. Fallow land is almost negligible compared to other land-use types. Internationally also, agricultural residues, forest residues, energy crops, and animal manure are important biomass categories [214]. Data on various biomass types at a high geographical resolution within the European context can be found in the ENSPRESO database [215].

Table 3-6 Different vegetation types that can be a source of energy production in Groningen. We included the yield and energy content of different biomass types and related comments based on Faaij et al. [47]. *Additional references are related to analyses of specific biomass production types*

Vegetation type (biomass type)	Yield potential (odt/(ha.yr)	Energy content (GJ/ton) (LHV)	Comments and additional references
Energy crops (Miscanthus, willow)	11-16, miscanthus - 13 [180,181], willow – 10 [216,217]	18	An increase in yield related to crop production leads to more land availability for energy crops. In the context of the Netherlands, studies [47,180,181,216,217] considered miscanthus and willow as potential energy crops. The yield range of energy crops is associated with two components: change of productivity of energy crops over time and differences in low and high yield land. For analysis purposes, we considered a fixed potential of 12 odt/ha.
Agriculture residues (straw)	3.7	16	Agricultural residues are used as fertilizer (due to organic content) or fodder for animals. Only straw can be a source of energy production. Part of straw is retained in the soil; therefore, the yield potential is low. Another reason for considering low yield is, based on recent policy discussions, we realized that straw produced from agriculture cannot be fully utilized for energy production purposes as straw will be used for maintaining soil organic content leading to a reduction in straw availability.
Forest residues - thinning	2	18	Harvestable wood can yield high-quality wood which is suitable for timber. Residues, such as thinning, can become a good source of energy production if a forest is well managed. Since only a part of the forest is utilized for additional energy production purposes, the yield is low.

Vegetation type (biomass type)	Yield potential (odt/(ha.yr)	Energy content (GJ/ton) (LHV)	Comments and additional references
Nature (turf, reed)	1.4 – 4.5	16	Turf has a lower yield (1.4) compared to reed (4.5). Turf is largely composted, and reed is partly used for thatch application. Therefore, these components are not fully available for energy production resulting in low overall yield. For our calculation purposes, we considered an average yield value of 3 odt/ha.
Infrastructure (verge grass)	5.1	20	Verges of roads and edges of waterways that are mowed regularly are called verge grasses and can be a source of energy production. Due to a low production density, verge grass has a low yield.
Grass refining	8 (arable land), 12 (grassland) N.B.: Here dry matter (DM) is considered instead of odt as the grass is used for bio-refining instead of energy production purposes.	20	For arable land, we considered that grass is grown in between crop growing seasons, i.e. catch crop [218,219]. Grass can grow in March/April and the first cut can happen in May/June and its season can end in September/October [220]. We plan to achieve 2 cuts with a high yield potential of 4 t DM/ha/cut/yr [221]. Crops such as potatoes can be grown till March [222]. In grassland, we propose to have perennial grass (ryegrass) or clover or a combination for higher yield and the activity will be carried out over the year [218]. N can be added to improve yield [218]. For this, we propose 5 cuts. 1st and 2nd cut will have higher productivity similar to arable land. 3rd to 5th cut will have a low yield of 3 t DM/ha/cut/yr [221]. From DM, 30% can be removed as proteins, such as whey, phosphate, or amino acids for livestock or industrial applications [220,222–224]. In addition, wet matter (from fresh grass) can be suitably bio-refined for different applications, including soil fertilization [223]. The additional advantage is, for example, soy can be produced which can reduce dependency on its import [222].

Agricultural land is associated with two biomass-related activities: energy crops and agricultural residues. Since agricultural land is shrinking in Groningen [152], our conservative scenario assumes there is no additional land available for energy crop production [214]. The progressive scenario assumes additional land becomes available for energy crops as less land is used for food production due to advanced techniques and more fertilizers. Faaij *et al.* [47] considered 5%–12% of agricultural land available for energy crops in 2050 in the Netherlands. Similarly, Van der Hilst *et al.* [180] suggested 6.1%-10.2% of arable land and 8.6% of grassland availability for energy crops in 2030 in the north of the Netherlands (comprising three provinces, including Groningen). For our progressive scenario, we identified 10% of arable land and grassland for energy crops.

Additionally, Hoogwijk *et al.* [214] suggested using 57%–76% of fallow land for energy crop production. They did not consider full fallow land utilization to avoid deforestation, policy, and society-related issues. We considered a high percentage (76%) of fallow land use for energy crop production in our progressive scenario.

Londo *et al.* [216,217] considered willow as a cost-effective energy crop option in the Netherlands. Van der Hilst *et al.* [180,181] considered Miscanthus an economically and environmentally effective energy crop in the northern Netherlands. Additionally, Faaij *et al.* [47] maintained that miscanthus and willow are potential energy crops for the Netherlands. Therefore, we suggest these energy crops on additional arable and fallow land in Groningen. Different studies have provided different yields of miscanthus and willow (Table 3-6). We considered a fixed value of 12 oven-dry tons (odt)/(ha.yr).

Extracting biomass from agricultural residues, such as straw, is possible if demands related to providing animal fodder and maintaining soil fertility are already fulfilled. We assumed that agricultural residues from 90% (energy crops take the remaining 10%) of the projected arable land are available for biomass in the progressive scenario, and no residue availability in the conservative scenario (Table 3-7). We considered a low yield, as straw can partly be retained in the soil or used as fodder (Table 3-6). In addition, with recent political discussions, we realize that straw use for biomass purposes might decrease. Therefore, in the conservative scenario, we assumed no straw use for energy production.

Considering non-agricultural land activities, we assumed 100% forest land availability for biomass purposes in the progressive scenario by allowing small-scale intervention and fully compensating damage [19], resulting in a low yield of 2 odt/(ha.yr). Similarly, with proper management, each natural land could become available for energy production in the progressive scenario, leading to a low yield of 3 odt/(ha.yr).

Manure production potential is less dependent upon land-use changes but rather changes in the livestock population resulting from policy regulations. We based animal growth projections on the latest Dutch Climate Agreement and Energy Outlook (KEV) 2020 database [225], which considers ongoing discussions in the Netherlands that the current livestock population is too high and may be restricted in the future. We considered two manure types: liquid (from cattle and pigs) and solid (chickens). In the Netherlands, liquid manure is mainly used for biogas production through digestion because of its low energy density. Solid manure is used for combustion purposes. To calculate the biogas production potential, we used Eq. 9:

$$\mathrm{Q}(r) = \sum_{lt} CF * LP(r, lt) * AM(r, lt) \qquad 9$$

where indices *r* and *lt* are the region and livestock type, respectively. Q (variable), *CF* (fixed value), *LP* (parameter), and *AM* (parameter) are biogas production, the manure to biogas conversion factor, the livestock population, and the amount of manure, respectively. For both cattle and pigs, we considered a production potential of 0.53 GJ biogas/ton manure based on the Netherlands Environmental Assessment Agency (PBL) study [226]. This value is similar to the volumetric yield of methane (responsible for biogas production) considered in [227,228]. For solid manure, we considered an energy potential of 10.4 GJ/ton manure, adapted from [226]. In the progressive scenario, we considered a total manure production potential of 12.5% [214] as the rest is utilized as fertilizer for increasing soil organic content.

For the remaining biomass, we considered grass refining and verge grasses near road infrastructure. Grass can be grown between potato and sugar beet crop growing seasons (arable land) once every 3 or 4 years to reduce crop disease burdens [229] and nitrate leaching [218]. Two cuts can be made to increase the yield (see Table 3-6 for details). In grasslands, perennial grass and clover can be grown annually, and more cuts (5-7) can be performed. In the progressive scenario, 50% of the arable land can be used for grass refining, similar to the land dedicated to sugar beet and potato production in Groningen [149,230] (see Table 3-7). Similarly, 50% of grassland grasses were used for refining in the progressive scenario. The remaining land was left for livestock grazing. The outcomes of bio-refining processes, such as proteins, soy, whey, and phosphate, can be directly fed to livestock in a targeted manner and used for industrial applications. Only fibers, which account for nearly 30% of the dry matter (DM) [220,222–224], are considered for biomass production.

We calculated the buffer space surrounding roads for verge grasses and excluded them from other renewable analyses. We assumed a utilization percentage of 40% in the progressive scenario to account for wastage during the removal process and unfavorable economics for complete grass removal. Other biomass such as organic wastes or municipal solid wastes, which hardly affect land-use patterns or spatial claims and are spatially independent, are not part of our analysis but may be included in the future.

Table 3-7 Summary of space allocation for different biomass types for targeted years considering various scenarios

Biomass category	Biomass type	2030		2050		
		Conservative	Progressive	Conservative	Progressive	Intermediate
Agricultural land (includes arable land, grassland, and fallow land)	Energy crops (miscanthus [47,180,181], willow [47,216,217])	57% fallow land [214]	10% arable land [47,180], 10% grassland [47,180], and 76% fallow land [214] (projections used)	57% fallow land [214]	10% arable land [47,180], 10% grassland [47,180], and 76% fallow land [214]	4% arable land and 66% fallow land
	Agricultural residues (straw)	No production	90% of the projected arable land. Projections based on other spatial claims related to BE and forest, for example. The remaining is associated with land usage related to energy crops.	No production	90% of the projected arable land	50% of the projected arable land
Forest	Wood (thinning)	25% of the projected space utilization. The projection is based on historical trend.	100% of the projected space utilization	25% of the projected space utilization	100% of the projected space utilization	50% of the projected space utilization
Nature reserve (includes NNN and other natural areas, excludes water bodies)	Turf and reed	25% of the projected space utilization. The projection is based on historical trend.	100% of the projected space utilization	25% of the projected space utilization	100% of the projected space utilization	50% of the projected space utilization
Manure	Livestock farming (solid manure, liquid manure)	No production	12.5% utilization of the projected total manure potentials [214]	No production	12.5% utilization of the projected total manure potentials [214]	No production
		Production potential for all future cases: Liquid manure = 0.53 GJ (biogas)/ton manure, based on PBL study [226], Solid manure = 10.4 GJ/ton manure, adapted from the same study [226]. Liquid manure is mainly considered from cattle and pigs and solid manure from chicken livestock. The animal growth projection is considered from KEV 2020 database [225].				
Remaining biomass	Grass verges (along with network infrastructure, mainly roads)	20% utilization of roadside buffer space	40% utilization	20% utilization	40% utilization	30% utilization
		Buffer distances of 30 m and 50 m are considered for 2030 and 2050, respectively, which we excluded in other renewable analyses – see Table 3-4 and Table 3-5. In addition, the width of the road itself is assumed to be 60% of the buffer space.				

	Grass refining	20% utilization of projected arable land cover	50% arable land utilization based on 2000-2020 historical statistics of land dedicated to sugar beet and potato production in Groningen [149,230]. Additionally, 50% of grassland is dedicated to grass refining along with meeting livestock feed demand.	20% utilization	50% each of arable land and grassland utilization	30% each of arable land and grassland utilization

3.2.4.2.4 Heat supply sources and demand

Depending on the regional climate, studying heat may or may not be considered a priority to include in an analysis of regional energy potentials. In the case of Groningen, heat is a major factor especially in low-temperature applications of the BE. As such, we chose to explicitly include it in our analysis. Depending on the region, different heat sources may be available, ranging from geothermal, solar thermal to industrial waste heat (IWH). For Groningen, IWH is included due to an abundance of industries with expected heat recovery potential in the future, while also geothermal heat is included as it has a high potential for future exploration [59]. Solar thermal may be an option but is not employed on a serious scale in the Netherlands. Owing to the high transmission losses, heat-demanding regions constrain the heat supply potential. Hence, in our approach, we analyze both heat supply and demand explicitly to combine this, along with other energy carriers, considering spatial restrictions to their interactions in an overall energy system modeling environment.

Geothermal heat

In the Dutch case, few policies discuss constraints or guidelines for identifying suitable geothermal sites and supply limitations. The literature is also not clear regarding above-ground constraints or criteria. As such, considering the replicability of our approach, geothermal is a strong example of how we may still come to realistic assumptions in the face of limited policies.

Several spatial claims are possible or even evident constraints for geothermal wells. These include the BE, forest and nature reserves, national landscapes and parks, and groundwater protection areas, which we include as exclusion regions (Table 3-8). The 2050 progressive scenario does not consider some of these constraints, such as national landscapes and groundwater protection areas[4], as the intrusion of a geothermal well may be considered acceptable in such a scenario. To calculate geothermal potential, we utilized a 3D web-based information system called ThermoGIS [155], developed by TNO, for the Netherlands. Here, we would like to point out that our geothermal study is an advanced study of underground geothermal potential study by TNO. This may not be the case for other regional analyses related to geothermal heat where more rough estimates may have to be made. Nevertheless, the steps described below can provide important inputs into how to come to fair estimates even with less detailed data.

Important for identifying geothermal potential is the difference between potential recoverable heat, technical potential, and economic potential, which for our analysis were available on regional maps

[4] The maps we used for our analysis considered potentials excluding vulnerable regions, such as NG extraction regions which coincide with earthquake-prone regions in Groningen. Therefore, earthquake regions are not explicitly constrained in geothermal analysis.

and could be combined (Figure 3-10). Potential recoverable heat represents heat that can be extracted from a reservoir without economic and technical limitations, expressed in GJ/m^2 [60]. The technical potential is the amount of heat that can be suitably extracted without economic limitations, considering aspects such as flow rate, transmissivity, permeability, and temperature [155]. Two parameters are optimized in the technical potential map: the well distance and pump pressure. Regular replenishment is not guaranteed; rather, the well distance is optimized such that after 50 years, the difference between production and return water temperature is 90% of the original temperature difference. The economic potential map uses a discounted flow model to calculate the unit technical cost considering the doublet depth as the input parameter [155]. Since both technical and economic potential maps are qualitative, we combined these maps with the potential recoverable heat map and filtered out regions with low technical and economic potential. It is important to recognize that the overview layers show the cumulative potentials of different aquifer layers available in a location, whereas a drilling permit is generally granted to or applied for one of these layers. Additionally, the potential recoverable heat can have a higher value than the technical potential, leading to an overestimation of the geothermal potential. Finally, we might underestimate the potential as geothermal wells built outside exclusion zones might still (partially) tap into aquifers in exclusion zones when considering excluded areas. Since potential recoverable heat is highly disperse, we only considered grids (1 km * 1 km) which have a minimum threshold of 0.6 PJ/km^2 in our overall regional geothermal heat potential calculation.

Table 3-8 Constraints considered related to installations for geothermal heat supply and information on constraint type for different scenarios

Constraint	Constraint type	2030[a]		2050[a]		
		Conservative	Progressive	Conservative	Progressive	Intermediate
Built environment	Technical, economical (projections used)	✓	✓	✓	✓	✓
Forest and nature reserves	Ecological, environmental (projections used)	✓	✓	✓	✓	✓
National landscapes	Social, planning	✓	✓	✓	×	✓
National Park	Ecological, environmental	✓	×	✓	×	✓
Groundwater protection area	planning	✓	×	✓	×	×

[a] × represents non-inclusion of constraint layer and ✓ represents inclusion.

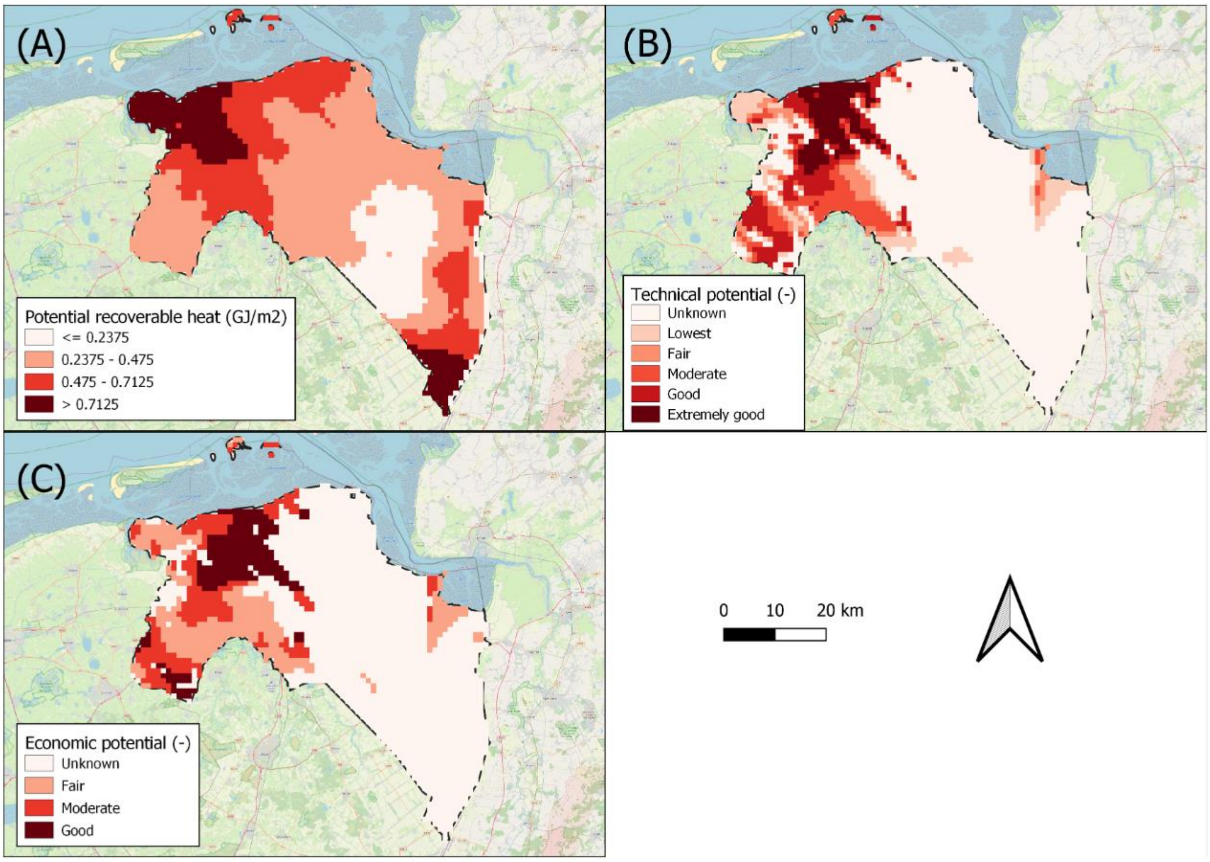

Figure 3-10: (A), (B), and (C) represent the potential recoverable heat in GJ/m2, technical potential, and economic potential, respectively. The figures were adapted from ThermoGIS.nl [99]*. The spatial resolution was 1 km × 1 km* [155].

Industrial waste heat

The first step for calculating IWH potential was identifying major energy-consuming industries as these industries have a high chance of a strong IWH potential. For such industries, often national data is available on production volume or emissions. For Groningen, these are industries such as primary aluminum and chloro-alkali production (Table 3-9). The second step considered industries or industrial subsectors where no data or literature is readily available on their heat recovery potential. We chose to categorize these industries into subsectors, based on a broader group of the NACE Rev. 2 classification [231], for which recovery potential is available from various sources. For example, methanol was placed under the chemical category (code number 20) to identify the IWH potentials. Third, for these industries, we considered the final main product and corresponding energy demand growth projections from our previous work [173] and MIDDEN reports [95]. MIDDEN was a joint initiative by the Dutch PBL and TNO and aimed to provide detailed insights, related to current production volumes, energy demands, and supply sources, of every major industrial subsector in the Netherlands. The future production volumes are based on the projections used in the Dutch KEV [147], SAVE model database [232], and our previous work [173]. Fourth, based on energy consumption information and literature information of heat recovery potential share, we calculated IWH potential for the current and future situations. Fifth, significant energy demand reductions may follow energy efficiency improvements and product and process-related energy consumption changes. Hence, we cautiously determined IWH potentials for each industrial subsector. Finally, it is important to note that replicability may be severely constrained by data availability on production volume or corresponding energy demand. If so, it may be suitable to work with the bandwidths of expected potential based on data on similar industries in other regions such as the Netherlands where data is available.

Table 3-9 Overview of the major industrial subsectors in Groningen and current energy consumption and proportion of heat recovery potential. Additionally, we describe industrial product types and production volumes in these subsectors and comments related to calculating recovery potential heat potential calculations. Potentials (including ranges) are investigated from literature reviews

Industry type/subsector	Description	Energy consumption[a]	Heat recovery potential	Comments/Remarks
Aluminum (Base metal)	Even though a lot of aluminum-related products are produced in the Netherlands, we were interested in primary aluminum which is only manufactured in Groningen. Aldel company in Delfzijl industrial cluster in Groningen produces nearly 30 kilotons (kt) of this product annually (2017 data), but has an allowance to produce 180 kt annually.	15.21 MWh_e/tonne liquid primary aluminum	5-10% of the input energy [233]	Exhaust gases are released at a temperature of 100^{0}C. According to [233], 15% of the final energy input is lost in the exhaust gas, of which 5-10% can be reutilized. As such, heat recovery potential is low when electricity is used as input.
Chloro-alkali (chemical)	Only Nouryon Delfzijl is a major chloro-alkali production plant in Groningen with a production capacity of 120 kt (2017 data) chlorine per year. The energy sources for this industry are a biomass power station, gas-fired CHP, and a waste incineration plant with approximately equal shares of each.	0.93 PJ_e + 0.23 PJ_h	10% of the fuel input [234]	To calculate fuel input, we identified the efficiency of supply sources. We considered an efficiency of 30% for gas-fired power plants [235] and 90% overall efficiency of CHP [236]. Since incineration plants utilize waste, we did consider any additional recovery potential.
Dairy products (Food and beverage)	There is only one production plant of Friesland Campina company in Bedum, Groningen, responsible for the manufacture of Cheese and Whey powder with a production capacity of 87 kt and 53 kt, respectively, per year.	0.66 PJ of fuel input energy from NG boilers	25% of the energy input [234]	We assumed an NG boiler efficiency of 85% to calculate energy input
Methanol (Chemical)	We only analyzed bio-methanol production as Groningen only produces this product through BioMCN company. The current capacity is 900 kt (2019 data based on 2017 estimate) considering two lines of operation in BioMCN.	21 PJ as net energy input	8.8% [231,237], 25% [231,238], and 7% [239] of energy demand	To identify methanol recovery potential, we used generic chemical and chemical product category (20) of NACE rev. 2 (see Appendix A of [231])
Salt (Chemical)	There are two salt production plants in Groningen, AkzoNobel Delfzijl and Nedmag Veendam, with a total production capacity of nearly 2.8 Mt.	1.6 PJ_h/Mt		
Paper and board (Paper and paper products)	Although different types of paper and board are produced in the Netherlands, we concentrated on Groningen, where the solid board is only manufactured through five production locations by Eska B.V. and Solidus Solutions Board B.V. companies. Since we do not have information on the production capacity of individual plants, rather overall product types, we calculated the production volume based on the employee distribution. The overall production capacity is 58.4 kt (2015 data) of the final product.	0.8 PJ (heat demand excluding supply from CHP)	9.1% [231,237], 25% [231,238], and 7.4% [239] of the energy demand	The energy consumption calculations did not consider CHP, similar to [240], as this energy is already supplied in an energy-efficient manner.

Industry type/subsector	Description	Energy consumption[a]	Heat recovery potential	Comments/Remarks
Potato processing (Food and beverage)	Potato products are subdivided into two broad product types: frozen/chilled and potato flakes/dried. These different products have different energy inputs due to different processes. Groningen only produces dried potato products by a company called Aviko Rixona in Warffum. This plant produces 30 kt of finished products (2017 data).	6.95 GJ_h/tonne dried potato product	10.8% [231,237], 10% [231,238], and 6.4% [239] of the energy demand	We considered the generic food products (10) and beverages (11) of NACE rev. 2 [231]. Additionally, energy input is only heat demand as electricity demand is low. In addition, as electricity is difficult to be recovered, it is not produced on-site, similar to [233].
Sugar (Food and beverage)	Out of two production plants in the Netherlands, one is in Groningen named Suiker Unie in Vierverlaten. Since individual plant capacity data is not available, we allocated annual production based on CO_2 emission. The capacity is 0.47 Mt (2016 data).	2.8 PJ_h/Mt		

[a] Subscripts ‘e’ and ‘h’ denote electricity and heat, respectively.

Heat demand analysis

In our approach, we specifically analyzed heat demand related to low-temperature application, i.e., the BE, which is highly spatially explicit. Industries are point sources and therefore do not require a spatial analysis of the heat demand density. We did not consider a specific scenario for analyzing heat demand. Rather, from now until 2050, we considered a uniform reduction in heat demand by 0.2%/year based on the optimized aggregate BE heat demand obtained for Groningen Province in [173]. We disaggregated provincial heat demand towards a building level by using the following equation, similar to [241]:

$$q\ (bl, bt, r, s) = \frac{A\ (bl, bt, r, s)}{\sum_{bl} A(bl, bt, r, s)} * Q(bt, r, s), \tag{10}$$

where indices *bl*, *bt*, and *r* represent the building level, building type, and region or municipality, respectively. The building types considered were residential and service buildings. *Q* (parameter) and *q* (variable) are the heat demands at the municipality and building levels, respectively. *A* (parameter) represents the spatial footprint or gross floor area of the building (m^2). To calculate heat demand density, we created grids or square mesh of 100 m in GIS. We aggregated building level data to grid level. To achieve this, we first merged buildings level maps of residential and service buildings. Then, we joined this merged map with grid maps using a summary function to obtain aggregated heat values on a grid level, thus also aggregating building types in this process, i.e. $\sum_{bt} q$. We used current building-level spatial footprints for future heat demand density analyses as we considered changing spatial footprints beyond our scope of the study. We categorized the grids into different heat demand classes based on [241] to analyze the feasibility of a DH network.

3.2.4.3 Renewable combinations and land-use considerations

Some renewables can simultaneously exist in the same space, allowing for more potential to be unlocked. In our approach, we considered several conflicting and complementary relationships and translated these into changes in the individual renewable potential. Table 3-10 summarizes these combinations. If renewables' combination possibilities exist in any of the scenarios, we recalculated renewable potentials accordingly.

GBPV and biomass

This combination is termed as 'agrivoltaic' or 'agriphotovoltaic.' Few recent studies exist on this combination. Examples of biomass types are wheat [242], lettuce [20,21], maize [243], and potato, winter wheat, celeriac, and clover grass [244]. For this combination, instead of constructing GBPV on the ground, some vertical spaces (4-5 m) should be left for crop growth [21,242]. As both GBPV and biomass compete for solar radiation, more panel height ensures more homogeneous daily irradiation at ground level [242] but has higher construction costs. The land equivalent ratio (LER) is used to describe the performance or yield of combined production compared to separate cases (see Eq. 11 (adapted from [242,244])

$$LER = \frac{Yield_{PV}(dual)}{Yield_{PV}(singular)} + \frac{Yield_{biomass}(dual)}{Yield_{biomass}(singular)} \tag{11}$$

where *Yield*, *singular*, and *dual* represent output; single energy production, either GBPV or biomass; and the production of both GBPV and biomass; respectively. If LER >1, then combined crop energy production is more than separate production [21,242,243]. The LER ranges reported in previous studies are 1.32 - 1.64 [242], >1 - <1.75 [21], and 1.28 - 2.02 [243]. We considered an LER value of 1.5, with a biomass yield of 50% less than biomass production alone. This suggests that combining biomass and GBPV is beneficial in terms of energy potential per unit of land compared to either production alone. We did not apply a higher LER value than these studies because they researched an experimental rather than a mass scale. In addition, we considered willow or miscanthus (both have <4 m height) as biomass, which are not considered in any of these studies, leading to uncertainties regarding biomass productivity. In addition, increasing vertical space increases investment costs in GBPV, which we have not considered.

Wind and geothermal

This combination can also co-exist. Wind turbine construction needs to create shallow trenches and cablings underground. Geothermal requires deep underground arrangements, depending upon the aquifer depth, for producer and injector piping [59]. After wind turbine construction, many above-ground free spaces are available [245], which can be utilized for geothermal-related heat exchangers, injection pumps, and connecting pipes [59]. Thus, wind and geothermal can simultaneously occupy the same space without reducing either the capacity of wind farms or the energy potential of geothermal heat.

GBPV and wind

This combination results in the highest power density among all renewables considered pairwise [245], thus sharing a complementary relationship. Energy-producing companies should prefer this arrangement because of the similar network infrastructure and concentrated power production. With proper planning, wind turbines can be installed between adjacent rows of the GBPV, and cables and other network infrastructures can be laid without capacity reduction of either of them.

GBPV, wind, biomass, and geothermal

This combination is also feasible because of the simultaneous presence of complementary and conflicting relationships. We kept the power density of wind and energy potential of geothermal the same as their singular cases. To reduce the pressure on the land-use planning aspect of constructing and maintaining installations related to four renewable resources, we slightly reduced the power density of GBPV by 10%, allowing more gaps between solar panels. This reduction also allows a wider gap between solar panel rows, which can be helpful for various activities, such as maintenance of equipment and infrastructure related to geothermal, wind, and GBPV. More gaps between the GBPV rows would also allow a better yield of biomass. As we found no detailed studies on the effect of wind farms on biomass yield, the biomass yield was reduced by 50% in line with the agrivoltaic case.

Table 3-10 Summary of a few important renewable combinations explicitly considered in our study. We presented the relationships between renewables in these combinations, energy potential changes associated with land-use changes, and explanations related to energy potential changes and relationships within renewable combinations

Renewable combinations	Relationship	Capacity or energy potential changes	Explanations for relationship and energy potential changes
GBPV and biomass	Slightly conflicting	GBPV capacity remains the same, biomass energy potential reduced to half	The relationship can be conflicting as both compete for the same solar radiation [242]. Studies suggest different ranges related to outputs from this combination [21,242,243]. For our study, we considered that GBPV power density remains unchanged leading to a reduction of biomass energy potential by half.

Renewable combinations	Relationship	Capacity or energy potential changes	Explanations for relationship and energy potential changes
Wind and geothermal	Co-exist	No changes in wind power density or geothermal energy potential	As the presence of one does not affect the potential of the other, this combination can co-exist. This applies to both underground and above ground. For geothermal, we must make sure that extraction takes place in the same aquifer to achieve similar energy potential.
GBPV and wind	complementary	No changes in either power densities	This relationship can be complementary from energy companies perspective. There is no evidence in spatial analysis-related literature on GBPV and wind, for example [53,245,246], related to a reduction in power densities when both renewables are considered simultaneously.
GBPV, wind, biomass, and geothermal	feasible	Wind power density and geothermal energy potentials remain the same, GBPV potential reduced by 10%, biomass potential reduced by 50%	This relationship is also considered feasible due to a combination of complementary and conflicting relationships. In the combination, GBPV power density is reduced marginally, i.e. 10%, to reduce pressure on land-use and planning aspects of constructing and maintaining four renewable resources. We reduced biomass yield by 50% to account for shade and changes in solar irradiation effect due to GBPV. In addition, wind turbine effect on crop growth is unknown.

3.3 Results

In this section, we analyze results related to the space potentials of renewables and heat demand distribution in Groningen on a detailed geographical scale (Section 3.3.1). Section 3.3.2 analyzes renewable combinations. Reflections on whether our approach delivers on identifying key policy considerations follow in section 3.4.

3.3.1 Analyses of renewable potentials and heat

The subsections are in the following order: solar PV (Section 3.3.1.1), onshore wind (Section 3.3.1.2), biomass (Section 3.3.1.3), and heat supply and demand (Section 3.3.1.4).

3.3.1.1 Solar PV

For rooftop PV (Table 3-11), the increase in capacity potentials between the 2030 and 2050 progressive scenarios is attributed to more buildings, leading to more rooftop space, and higher power density in 2050. Another provincial study [173] targets a rooftop PV capacity of 3 GW for Groningen in 2050. Our capacity potential in the progressive scenario is comparable, suggesting that a renewable-intensive system with high rooftop PV penetration is appropriate for meeting future emission targets. A CE Delft regional report [167] considering a 0.2-1.2 GW range for its different scenarios in 2050 is lower than our range of 0.7-3.7 GW.

Table 3-11 Rooftop PV space potential (in km^2) and capacity potential (in GW) for different future scenarios

Year	Scenario	Rooftop space projection (km^2)	Space utilization (km^2)	Capacity potential (GW)
2030	Conservative	28	2.24	0.4
	Progressive	28	14	2.5
2050	Conservative	33	3.3	0.7

Year	Scenario	Rooftop space projection (km²)	Space utilization (km²)	Capacity potential (GW)
	Progressive	33	16.5	3.7
	Intermediate	33	9.9	2.2

Figure 3-11 and Table 3-12 present the GBPV space potential in agricultural and non-agricultural land for future scenarios. The difference in the BE buffer distance between the 2050 progressive and intermediate is singularly responsible for the large difference in land-use potential (720 km^2 compared to 350 km^2). This finding suggests the massive impact of a single constraint on societal preference can have on the future GBPV potential. The feasible space potential for the 2030 progressive scenario is 13% higher than that of the 2050 progressive scenario. However, the capacity potential is comparable because of the higher power density and more agricultural land allocation in 2050.

Other studies [165] and [247] target a 2050 GBPV capacity of 7.4 GW for Groningen and 34 GW for the Netherlands, respectively, which aligns with the potential achieved in our intermediate scenario. This finding suggests that our power density and land-use considerations are viable. Van der Niet *et al.* [167] targeted 0.7-3.8 GW for Groningen Province in 2050, which is lower than our range of 0-17 GW. For comparison with other renewables, we calculated the energy supply in the PJ (Table 3-15). For this, hourly solar irradiation for the whole of the Netherlands was averaged out, and full load hours (FLH) of rooftop PV and GBPV were explicitly calculated based on the OPERA Dutch energy system model [1].

A detailed analysis shows that non-agricultural land is mainly located on the edges of crop plots and intermittent spaces between different landscapes. These are often relatively small and potentially less attractive for GBPV. Approximately 20% of all available non-agricultural land contains land of smaller (< 1 km^2) isolated plots. With effective planning, a combination of agricultural and nearby (small plots of) non-agricultural land for GBPV can be supported.

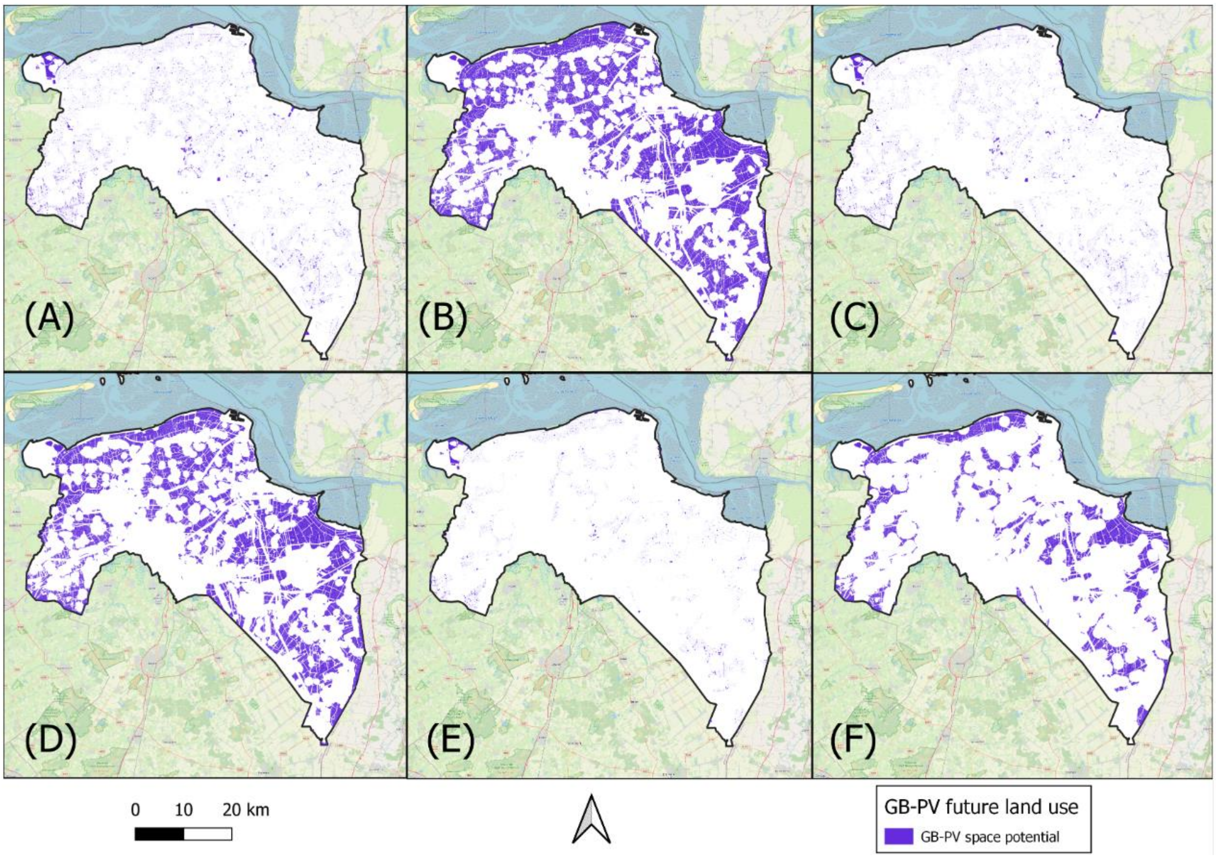

Figure 3-11: The space potential for GBPV on non-agricultural and agricultural land in future years and scenarios. (A), (C), (E) represent non-agricultural land suitable for GBPV, whereas (B), (D), and (F) represent agricultural land. (A) and (B) represent the 2030 progressive scenario, (C) and (D) represent the 2050 progressive scenario, and (E) and (F) represent the 2050 intermediate scenario.

Table 3-12 Land-use potential (in km²) and capacity potential (in GW) for GBPV in future scenarios

Scenario	Feasible agricultural land (km²)	Non-Agricultural land (km²)	Capacity potential (GW)[a]
Progressive 2030	746	78	= (746*0.2%+78) km2*0.18 GW/km² = 14.3
Progressive 2050	658	65	= (658*0.013+65)*0.225 = 16.6
Intermediate 2050	320	31	= (320*0.008+31)*0.225 = 7.6

[a] To calculate capacity potential, we used the percentage of agricultural land use (arable land and grassland combined), i.e., actual agricultural land allocation, and power densities (in GW/km2) for different scenarios, refer to section 3.2.4.2.1 for details.

3.3.1.2 Onshore wind

Figure 3-12 and Table 3-13 show a significant space potential difference (10.5 times) between the 2050 progressive and intermediate scenarios, mainly due to buffer spaces associated with the BE, airports, and silent areas. This difference emphasizes the significant effect of spatial policies on future renewable potential. A decrease in space potential between 2030 and 2050 is mainly due to increased land use associated with the BE and nature. Our estimated potential in the 2050 progressive scenario is largely similar to [165] and [247] targeting 2.24 GW (Groningen) and 10 GW (the Netherlands), respectively, to meet future electricity demand and climate targets simultaneously. Similarly, a regional study on Groningen aiming at 0.6-1.7 GW in 2050 [167] is within our range of–0-2.6 GW. We used hourly wind speed at a hub height of 100 m for Groningen to convert capacity to energy potential, following a power velocity curve of a Vestas V100-1.8 wind turbine, based on [1]. We considered FLH corresponding to a standard single row of five turbines, resulting in a 48 PJ energy potential for the 2050 progressive scenario (Table 3-15).

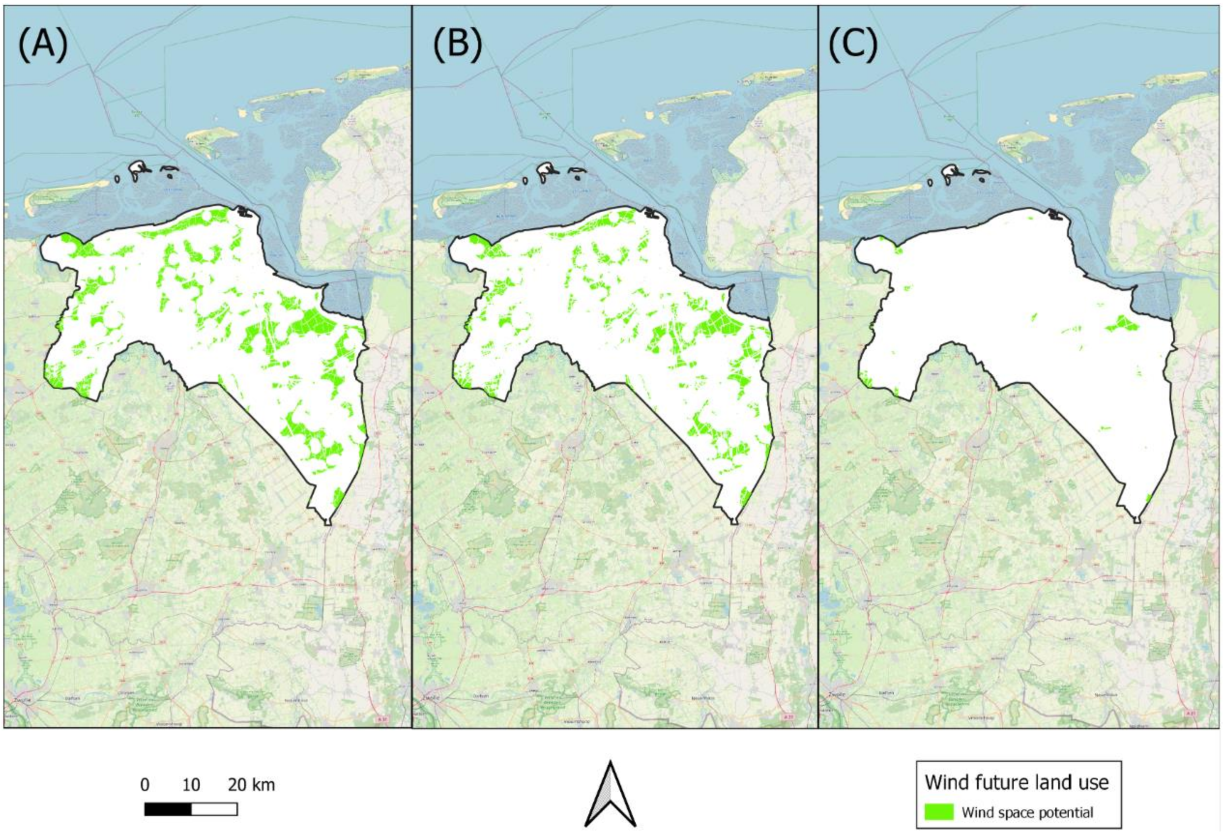

Figure 3-12: The space potential for onshore wind. (A), (B) and (C) represent the 2030 progressive, 2050 progressive, and 2050 Intermediate scenarios.

Table 3-13 Land-use potential (in km^2) and capacity potential (in GW) for onshore wind in future scenarios

Scenario	Land-use potential (km^2)	Capacity potential (GW)
Progressive 2030	330	= 330 km2*10 MW/km2 = 3.3 GW
Progressive 2050	260	2.6
Intermediate 2050	25	0.25

3.3.1.3 Biomass

Significant energy potential differences exist between different biomass sources, particularly for the progressive scenario in 2030 and 2050 (Table 3-14). Agricultural residues, energy crops, and grass refining were responsible for the high potential in this scenario. Grass refining may contribute >50% of the total biomass energy production. Differences between scenarios follow policy choices, societal preferences, and the utilization of agricultural residues and grass growth for refining and crop cultivation. The conservative scenario emphasizing the maintenance of soil organic matter does not produce energy from straw, whereas the corresponding energy production is ~5 PJ in the progressive scenario.

A national report [248] showed very high biomass content related to agriculture (545 PJ) and forest and nature (40 PJ) in 2030 for the Netherlands. These values seem higher when we consider that Groningen occupies ~9% of the Netherlands. The reason for this difference in biomass potential compared to our findings is that they considered the entire agricultural land, along with a high yield potential (16 odt/ha) for biomass production. Our forests and nature reserves biomass calculations seem low because the corresponding land uses are significantly lower, 2%–3% in Groningen compared with the Netherlands [53], and a strong overlap exists between these areas in Groningen. Another national study [247] calculated Dutch biomass production at 150 PJ and 250 PJ in 2030 and 2050, respectively, without detailing the sources. Our analysis shows a range of 3.5-25 PJ (including biogas) in Groningen for 2030 and 2050, which is comparable to these values.

A Groningen-based study [249] indicated a potential biogas production of 15 PJ/year. A related national RVO study [250] considered manure, organic waste, agricultural residues, sea algae, energy crops, and sewage waste as biogas sources. Based on [251–254], we calculated a maximum biogas production of 10.2 PJ by secondary conversion of energy crops, agricultural residues, verge grass, and grass refining. We can also obtain an extra 1.3 PJ of biogas from sewage sludge and organic waste [165] (see Table 3-15). Additionally, sea algae were not included in our analysis. Similarly, [167] indicated a 3 PJ biogas supply from locally available biomass for both 2030 and 2050 in all of its scenarios, without detailing the biomass sources.

Table 3-14 Biomass energy potential (in PJ) for different future scenarios and biomass types. Input data are based on Table 3-2, 3-6, and 3-7

Biomass	2030		2050		
	Conservative	Progressive	Conservative	Progressive	Intermediate
Energy crops	0.01	3.22	0.01	3.04	0.76
Agricultural residues	-	4.86	-	4.63	2.57
Forest	0.01	0.06	0.02	0.07	0.03
Nature	0.32	1.29	0.39	1.55	0.77
Manure (liquid) (PJ_biogas)	-	0.16	-	0.16	-
Manure (solid)	-	0.09	-	0.09	-
Verge grass	0.30	0.60	0.45	0.90	0.68
Grass refining	2.92	14.14	2.78	13.32	7.99

The electricity demand for Groningen Province is estimated to be 120 PJ for 2050, excluding 620 PJ demand for hydrogen production in large-scale industrial electrolyzers [173]. The cumulative electricity supply from solar and onshore wind is 114 PJ, while 24 PJ of biomass can be partly utilized for electricity (Table 3-15). Therefore, if the progressive renewables approach is not followed, the province will continue to import electricity in the future without considering offshore wind potential as part of the Groningen potential.

3.3.1.4 Heat supply and demand

The authors first discuss the heat supply (Section 3.3.1.4.1), followed by the analysis of the heat demand (3.3.1.4.2).

3.3.1.4.1 Heat Supply

Geothermal

Slight potential differences exist between the 2030 conservative and progressive scenarios (Table 3-15 and Figure 3-13) due to restrictions related to groundwater protection areas and national parks in the conservative case. Geothermal potential slightly decreases in 2050 compared with 2030 is mainly due to an increase in the BE. Overall, the potential is much higher than the current supply. For Groningen, most of the heat should come from the Upper Rotliegend aquifer, which is part of the Permian stratigraphic unit [52,60,99]. Our results are higher than 20 PJ for 2050 noted in [165] mainly because we considered potential recoverable heat from the aggregate of all layers, instead of the technical potential of only the Rotliegend aquifer.

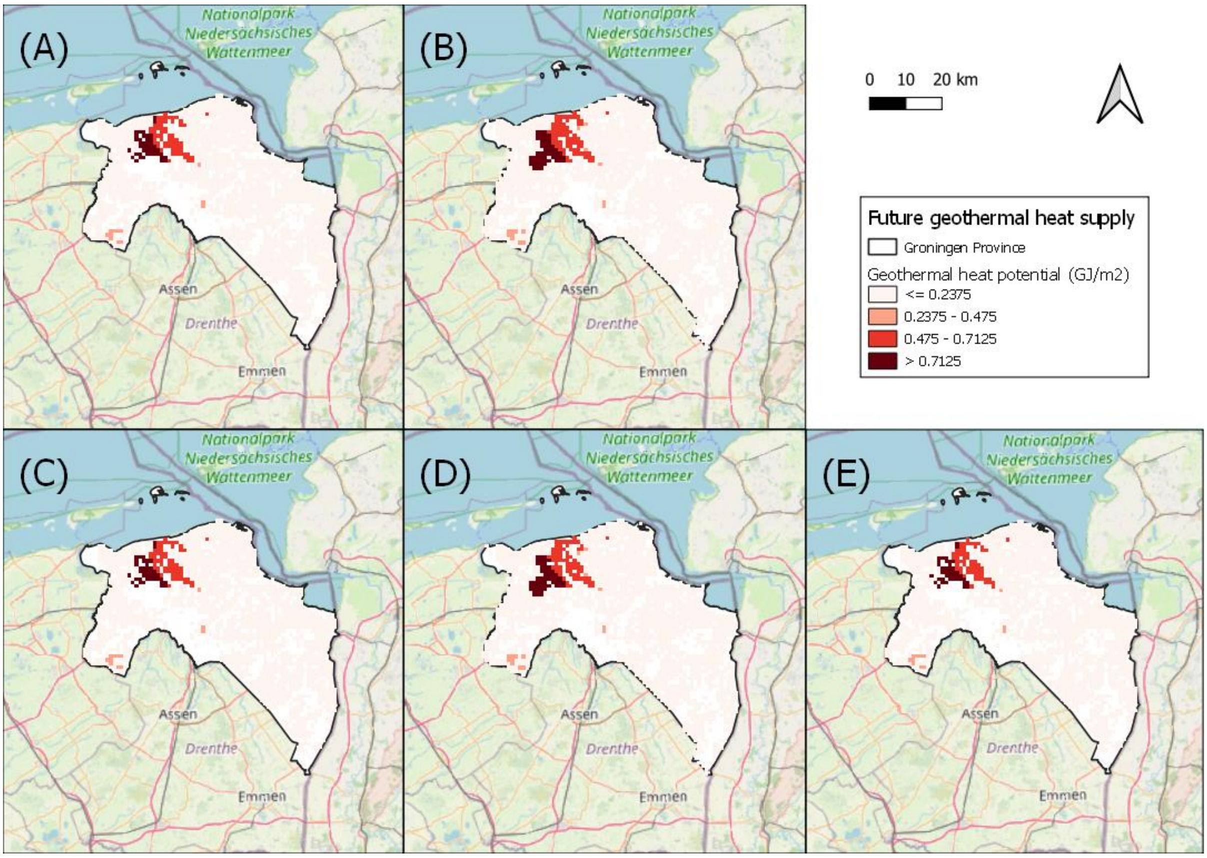

Figure 3-13: Future geothermal space and energy potential. Energy is represented as potentially recoverable heat (GJ/m²). (A) and (B) are 2030 conservative and progressive scenarios, respectively. (C), (D) and (E) are 2050 conservative, progressive, and intermediate scenarios, respectively.

Table 3-15 Energy supply potential (in PJ) for future scenarios and comparison with current supply statistics. Current (2016 data) statistics are based on the literature

Renewables[a]	2030		2050			Current
	Conservative	Progressive	Conservative	Progressive	Intermediate	Supply [102,249]
Solar (rooftop+GBPV) – in PJ_e	1.21	54.64	2.22	65.85	31.68	0.14
Wind – in PJ_e	0	60.77	0	47.88	4.60	3.8
Biomass[b] – in PJ_{bm}	3.57	24.26	3.64	23.59	12.81	5.9
Biomass[c] – in PJ_{bg}	-	1.5	-	1.5	-	
Geothermal – in PJ_h	35	44	33	33	43	0.1

[a] Subscript e, bm, bg, and h denote electricity, primary biomass, biogas, and heat, respectively. Primary biomass can be converted to other secondary forms depending upon applications.

[b] If we perform secondary conversion of biomass to biogas based on literature [251–254], we obtain a maximum biogas potential of 11 PJ from energy crops, agricultural residues, verge grass, and grass refining.

[c] We have added an estimate for future potential from organic waste and sewage sludge based on [173]. For 2030, there was no data; however, since we do not expect major changes to the organic component, we considered this to be the same as 2050.

Industrial waste heat

We identified Groningen industries with a positive IWH supply potential (Figure 3-14). Table 3-16 presents the present and future final product production volumes and their IWH potentials. The production volume and energy demand estimates were based on [95,147,232]. Our analysis shows that methanol and salt have higher IWH potentials compared with other industries. This potential is dependent upon future demand and production of final products and production methods. Since the literature provides only generic energy savings and IWH potentials, case-by-case analysis of energy supply sources and production methods is required for properly identifying heat potentials. The IWH potential range is 2.225-9.585 PJ and 2.337-10.178 PJ in 2030 and 2050, respectively.

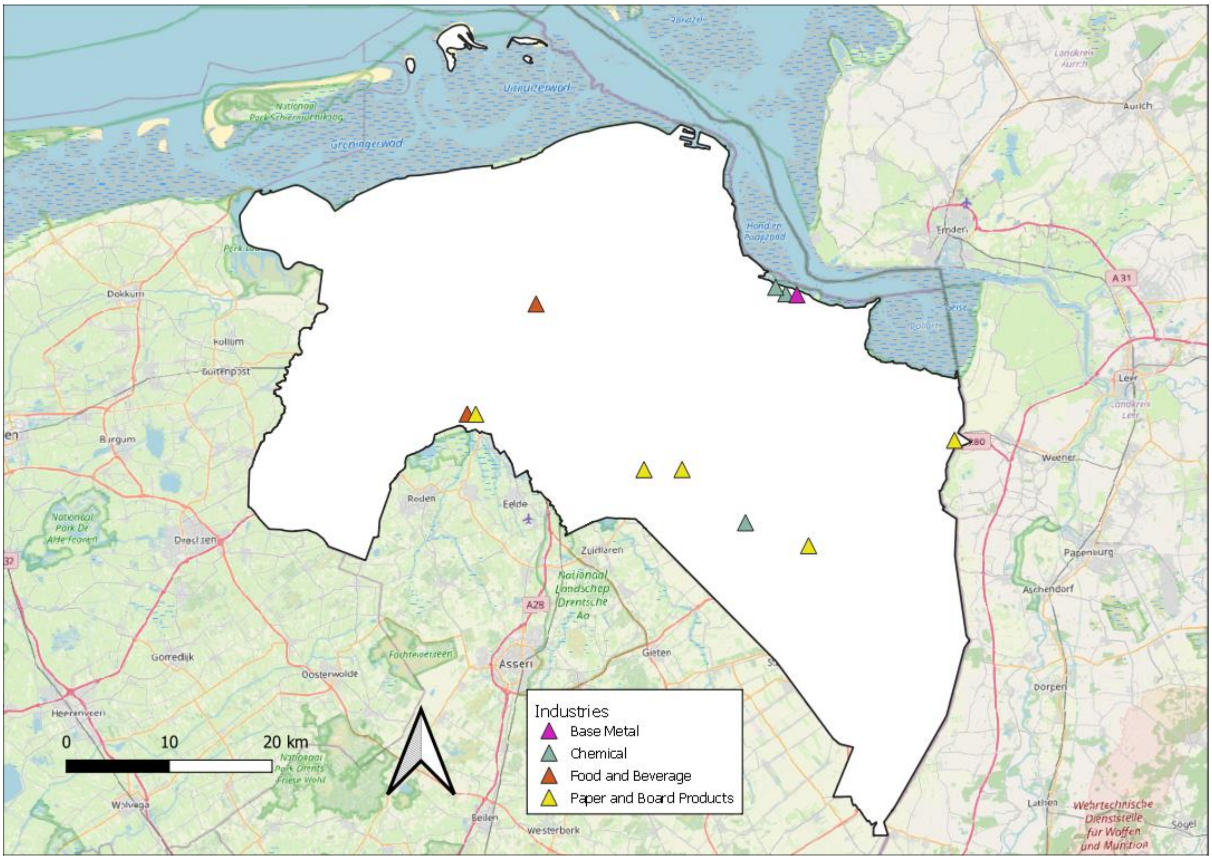

Figure 3-14: Identification of major industries in Groningen Province as potential sources of IWH in the future.

Table 3-16 Final production volume (in Mt_final Product) of different major industries in Groningen Province. Future estimates are based on projections from [95,147,173]. *Estimates of IWH potentials (in PJ) were made based on* [95,173]. *IWH potential ranges are due to ranges of energy demand and savings potentials*

Industry	Production (Mt_final Product)			IWH potentials (PJ)		
	Current	2030	2050	Current	2030	2050
Liquid Aluminum	0.08	0.11	0.138	0.22-0.44	0.26-0.73	0.25-0.91
Chloro-alkali	0.12	0.122	0.126	0.1-0.12	0.09-0.15	0.1-0.15
Dairy	0.14	0.15	0.18	0.03-0.34	0.25-0.6	0.3-0.7
Methanol	0.9	0.92	0.95	1.47-5.25	1.5-5.4	1.55-5.55
Salt	2.8	2.85	2.97	0.36-1.3	0.05-2.31	0.05-2.41
Paper Board	0.06	0.065	0.074	0.06-0.2	0.06-0.22	0.07-0.25
Potato processing	0.03	0.033	0.038	0.013-0.022	0.015-0.025	0.017-0.028
Sugar	0.47	0.51	0.6	0.084-0.142	0-0.15	0-0.18

3.3.1.4.2 Heat demand

Figure 3-15 presents heat demand density maps for Groningen Province using spatial footprints of existing buildings (2016 data). We zoomed into Groot-Groningen (Groningen city and Haren) due to its high concentration of residential and service buildings with high density.

A heat demand density >3,000 GJ/ha corresponds to a 'very dense' concentration [241] and is highly suitable for DH networks, followed by 'dense' concentrations of 1,200-3,000 GJ/ha. Our analysis shows that the current 2,130 ha of densely concentrated areas will drop to 1,762 ha by 2050. Areas with dense concentrations will be reduced from 9,160 ha to 8,441 ha by 2050, reducing the need for heat supply sources and the profitability of DH networks. However, because our calculations show modest geothermal and IWH potentials (Table 3-17), we expect these heat sources to be fully utilized as the distances between supply and demand sources are not large, albeit considering losses. Geothermal can mostly supply heat to larger villages in Het Hogeland municipality, the Eemshaven industrial region, and Groningen city (Figure 3-13). IWH can supply heat to the Delfzijl, Appingedam, and Eemshaven industries and surrounding residential areas (Figure 3-14). A heat demand-supply overview showed that demand always exceeded supply, and there was no need for long transmission Figure 3-13, 3-14, and 3-15).

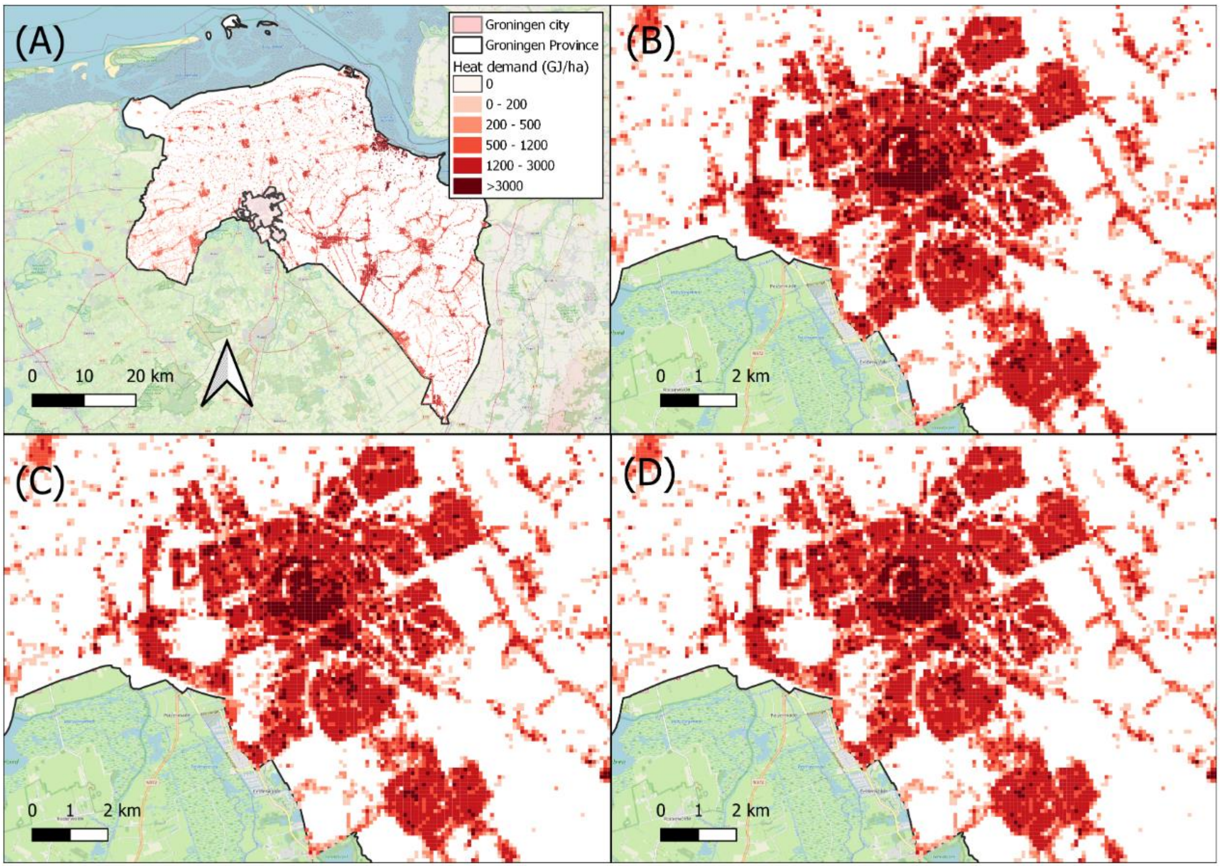

*Figure 3-15: Heat demand density maps for the built environment, i.e., households and services. Resolution of 100*100 m², i.e., 1 ha, was used for mapping purposes. Spatial footprints of current buildings (2016 data) were used for this map. (A) represents current heat demand data obtained from* [255]. *(A) also marks Groningen city along with Haren, i.e., Groot Groningen, which is zoomed-in in the subsequent representations. (B), (C) and (D) represent the current (2016 data), 2030, and 2050 heat demand density. Heat demand in the future is uniformly reduced over the entire built environment within the province. Heat demand density categorization is in GJ/ha and is based on* [241].

Table 3-17 Heat demand and supply comparison for 2030 and 2050 in Groningen Province. The future demand is based on [173]. *On the supply side, a combination of ranges from industrial waste heat and geothermal heat is used*

Heat (PJ)	2030	2050
Demand	39.56	37.55
Supply (IWH and geothermal)	4.9-12.8	4.8-13.2

The detailed spatial analysis of heat demand in the BE shows heat is highly dispersed. Proper planning can be done so that heat supply sources are located near to demand as creating a DH network is cost intensive. In addition, DH can face competition with individual heat sources which may be influenced by policies on subsidizing either DH or individual devices such as heat pumps.

3.3.2 Scenario potentials for renewable combinations

This section considers the 2050 progressive and intermediate scenarios, as their renewable combinations are interesting from a future land-use perspective (see Figure 3-16). In particular, we investigated the combination of energy crops with GBPV on agricultural land due to their slightly conflicting relationships. There are abundant spaces for growing energy crops on land unsuitable for GBPV. To illustrate, 53.2 km^2 and 86.9 km^2 of grassland and arable land, respectively, are 10% of the total space potential for energy crops grown in the progressive scenario. Excluding suitable GBPV space, we still obtain a feasible space of 307 km^2 and 438 km^2 of grassland and arable land, respectively. We calculated that 9 km^2 is suitable for both GBPV (considering agricultural land-use restrictions) and energy crops when overlapping the GBPV space potential and agricultural land in the progressive scenario. Even though this combination increases the overall land potential and reduces the spatial footprint of individual activity, it may not seem urgent or necessary in the current context as biomass potential is reduced, but most likely will be required in the future to create space for a new activity (or activities that we have not considered in our analysis) or accommodate the rapid expansion of an existing activity. Similarly, 430 km^2 and 653 km^2 of grassland and arable land, respectively, are suitable for energy crops and not feasible for GBPV in the 2050 intermediate scenario.

In the progressive scenario, 74 km^2 of GBPV suitable land in the progressive scenario can be overlapped with 260 km^2 of land suitable for wind (Figure 3-16), making the space ideal for power developers. Similarly, 34 km^2 and 25 km^2 of GBPV and wind, respectively, can be synchronized in the same location in the intermediate scenario; however, much higher coordination is required because the space potentials of both renewables are low. There is a modest overlap between geothermal and wind in the progressive scenario, and as such, they share a co-existing relationship. If this is implemented, then effective planning and synchronization are required, and biomass and GBPV potentials are reduced by 50% and 10%, respectively.

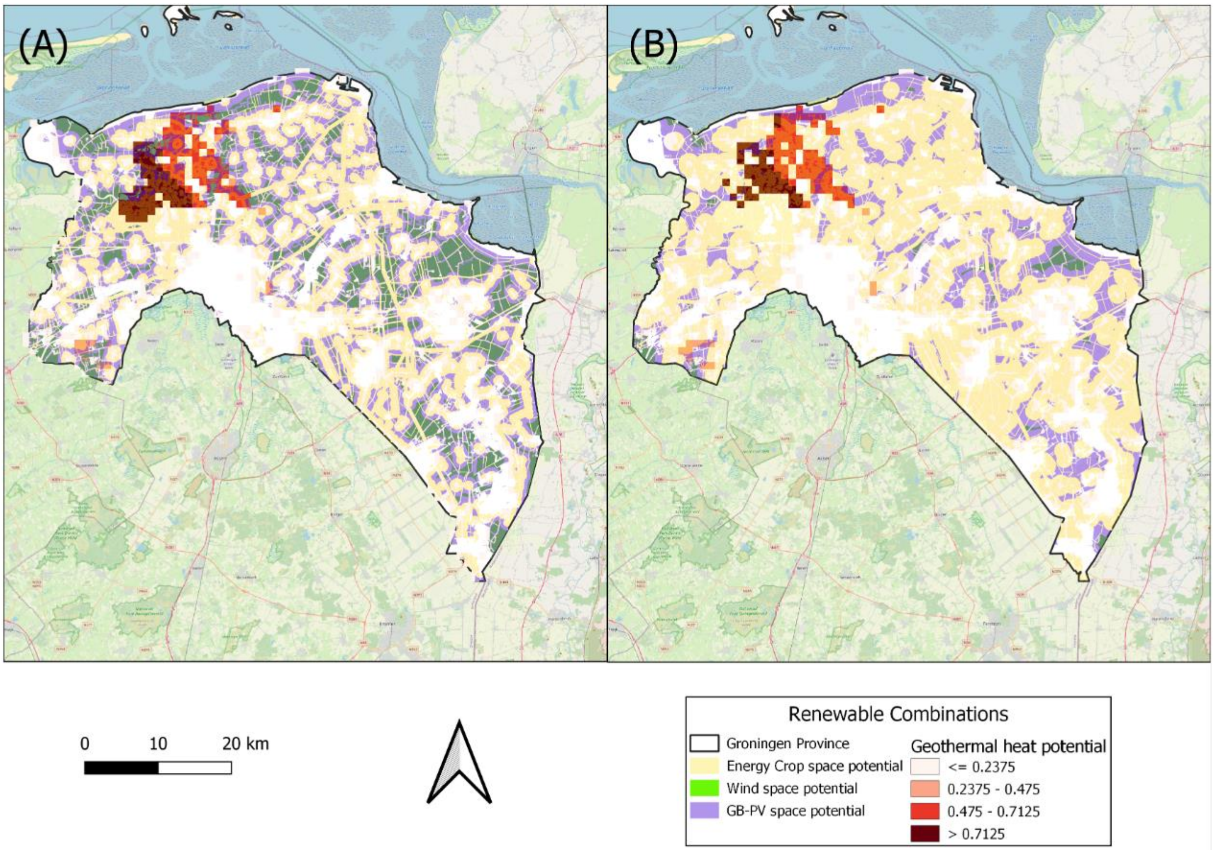

Figure 3-16: Renewable combination analyses for 2050. (A) and (B) represent progressive and intermediate scenarios, respectively. For geothermal, the potential is in GJ/m². Energy crop space potential represents feasible agricultural land space unsuitable for GBPV as biomass and GBPV share a slightly conflicting relationship.

3.4 Discussion

Methodologically, we made a variety of assumptions worth discussing for their potential implications. To identify the future space potential of renewables, we projected land-use activities related to the BE, nature, and forest based on historical statistics. For this allocation, we uniformly increased the space surrounding the existing activities subject to restrictions. This may not always hold, as various activities' growth is dependent on future land use-related policies, stakeholder interactions, and societal perspectives. The BE growth or change is also dependent on macroeconomic factors, such as job availability and income levels, which are dynamic and difficult to predict. In addition, the impact of a new activity on existing land use can depend on land pricing and policy interactions between local, municipal, and provincial levels, which are difficult to include in our analysis. Considering protected areas, nature and forests have many overlaps and are difficult to demarcate. Nature and forest growth might not occur simultaneously as historical statistics suggest, as other activities could be prioritized. In addition, some municipalities might take the initiative to introduce forests and natural uses into new areas. Overall, this can affect the space potential of renewables and their distribution pattern. Similarly, the future development of energy and network infrastructures is highly uncertain.

In the future, hydrogen networks could be retrofitted with existing NG pipelines or create new networks, while some NG networks may become redundant. In addition, the relative distance of certain energy/network infrastructures can determine the suitability of renewables installation. For example, GBPV and onshore wind farms are economically more attractive when placed closer to major networks or energy infrastructures. Rather than performing only feasibility analysis as we did, additional site suitability analyses would thus help to determine the relative desirability of different locations.

There is also scope to include societal perspectives related to landscape changes. Most of the exclusion layers we considered were based on policy measures and other studies. People might strongly oppose changes to open landscapes related to the installation of renewable infrastructure, particularly those related to wind turbines. For example, turbines with a 100 m hub height can cause serious opposition due to visual intrusion, particularly in a country as flat as the Netherlands. Current policy documents suggest preferences for 3-5 turbine installations in a single line with a hub height of ≤ 15 m [18,19] to reduce the visual impact as much as possible. This policy can significantly reduce the capacity potential obtained in our analysis. To properly understand the societal perspective, relevant stakeholders' interactions and viewpoints are required. This can assist us in properly modeling the spatial distribution of renewables and understanding their true potential.

The heat demand density for low-temperature applications is affected by the spatial spread of the BE. It is difficult to predict the future BE spatial footprint. We used footprints of existing buildings to calculate the future demand density distribution, which can be affected by policy choices such as insulation and renovation requirements. We projected future demands based on optimization results from previous studies [173]. Nevertheless, efficiency gains and altered consumption patterns may explicitly affect heat demand density and the economic feasibility of a DH network.

The scenario results show that the range of capacity or energy potentials decreases from 2030 towards 2050 for GBPV, wind, and biomass, mainly due to an increase in claims related to other hard constraints, such as the BE or forest. However, this decrease is uncertain as land use associated with any or each of these claims may change or technology innovation may not occur. In addition, we found that lands feasible for GBPV are also suitable for wind in the scenario, which are mostly agricultural fields. If renewable installations take place in these locations, a lot of planning and coordination between various is required. If not planned or coordinated properly, it might act as a limitation in some regional contexts.

A final and crucial issue is the potential replicability of our approach. One of the major challenges is easy access to high quality data. While we at several moments in Section 3.2 also indicate how limits to data availability may affect the chosen approach, we acknowledge that the Dutch context provided us with relatively abundant and high-quality data. If such data is available, the steps presented in our approach are not only replicable but also present the kind of considerations and arguments analysts can take when considering how existing land uses, policies and social preferences may shape renewable energy potential in the region analyzed. If data availability and quality pose limitations, some strategies may allow our approach to be modified to remain useful in other regional contexts. For one, our approach does show which kind of data should ideally be available for performing a detailed spatial analysis. Secondly, increasingly there are open data sources available for many regions of the world that may help extract data on energy and network infrastructures and protected areas with reliable quality (see Section 3.2.2). Thirdly, several pragmatic strategies can be employed. A lack of available policy regulations or guidelines may, for example, be mitigated by conducting interviews with policy and market experts. A lack of data on biomass potentials may, for example, be mitigated by translating data of regions with comparable geographical and climatic context to the region of analysis. As less and lower quality (estimated) data may have clear impacts on the quality of the results, it may also be sensible to work with bandwidths to partly account for uncertainties. Either way, while data limitations do influence using our approach, they do not prevent its use in another context, nor do they undermine the steps and arguments presented in the approach. Hence, replicability may be constrained or will require additional work, but remains valid even when access to high quality data is limited.

3.5 Conclusions and future work

Our analytical approach aimed to integrate various land-uses and related technical, economic, environmental, ecological, and social constraints in analyzing future regional renewable energy potentials with high spatial detail. Additionally, heat demand analysis on a low-temperature level related to the built environment (BE) was targeted as they are also highly spatially explicit. While doing so, we attempted to link heat demand and supply potentials. Our practical application in Groningen Province was intended to identify whether our approach would deliver relevant results. Our results were convincing in showing that including spatial policy considerations is a crucial addition to energy potential studies. We formulated scenarios for 2030 and 2050 to identify the impacts of various constraints and investigated solar photovoltaics, onshore wind, biomass, and geothermal energy sources. Heat supply additionally included industrial waste heat. The findings firstly showed the significant impact spatial land-use constraints have on energy potentials as the 2050 scenarios results ranged 2 - 66 PJ for solar PV and 0 - 48 PJ for onshore wind and biomass ranged 3.5-25 PJ for both 2030 and 2050. Results further indicated that major heat supply sources can be suitably linked to large population centers and heat networks within these centers can be economically feasible. The results are quite revealing as it shows that Groningen Province can comfortably meet the provincial share of the national medium-(2030) and long-term (2050) targets only in the progressive scenario, suggesting rapid changes in policies towards supporting renewables installation. Therefore, our approach did allow us to add spatial detail and context to the results from other studies.

We additionally concluded that our analytical approach could provide a comprehensive understanding needed for developing realistic energy policies or the consideration of how spatial and environmental policy changes may be sensible in the face of energy ambitions. While in other regions other spatial claims choices may be warranted, we explicitly included future claims related to the BE, agriculture, nature, network and energy infrastructure. Our comprehensiveness is based on the simultaneous explicit analysis of multiple energy sources, allowing for land-use combination possibilities for these sources (e.g., biomass and GBPV). These combinations even lead to higher potential in some cases compared to individual sources, which is particularly helpful in contexts where land availability is limited. Regarding energy potentials, we specifically added detail by developing a clear method for systematically increasing or optimizing various biomass potentials, which could act as a guideline for planners to formulate policy on.

Apart from the obvious application of our approach in other regions, we see several other key pathways for future research. For one, we will incorporate these results, particularly related to explicit renewables and their interaction, into an energy system modeling environment, where we plan to establish an appropriate spatial resolution suitable for the proper analysis of regional energy systems, particularly related to electricity and heat balancing. Our analysis will involve creating appropriate infrastructures for these energy carriers. This will involve creating electricity networks at different voltage levels. Secondly, we will add detail to our analysis on heat supply, demand, and infrastructure. We will focus on the BE-related heat infrastructure, and include distances related to waste heat applicability in these systems. Finally, we also plan to consider different stakeholder viewpoints to complete our modeling framework on a regional scale.

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Supplementary material

Supplementary material related to this study can be found in Mendeley data (DOI: 10.17632/stjdyxdybg.1).