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Translating National Energy Vision into Local Scenarios

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ABSTRACT

The energy transition toward a fully decarbonized society requires meaningful actions on a global scale, implemented at the local level. This requires translating a global perspective into local energy planning to implement actions that envisage the local energy system in a broader context. This article aims to translate a fully decarbonized national future scenario shaped by a global perspective to the local level of a Danish municipality. To create an accurate translation of a national scenario, analyzing local potential and constraints is crucial to understand how a specific municipality can become an integral part of a national scenario. To do this, the article outlines four methodological steps for translating and exploring an overarching national scenario in a local context. The article illustrates how a national energy system scenario can inform local energy planning as part of a coherent national energy transition. The article indicates that local energy planning in Denmark can also benefit from this translation to comprehend the national energy transition at the local level, by seeing the local energy planning as part of a more integrated future national decarbonized society.

Keywords

Energy planning and management;
Energy system analyses;
Smart Energy System;
Energy Transition

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1. Introduction

The global shift towards sustainable energy systems is a critical response to the challenges posed by climate change [1]. Nations worldwide are increasingly adopting renewable energy sources (RES) into their energy systems to reduce carbon emissions [2]. In this context, translating national energy strategies into local energy strategies plays a pivotal role in achieving broader sustainability targets. The national commitments rely on local actions that are meaningful at the local level and in their specific geographical context.

In Denmark, known for its ambitious Climate Act [3], the Strategic Energy Planning (SEP) framework has been in place since 2010, aiming to facilitate more comprehensive local energy planning [4]. The framework established methods to collect and analyze data on local energy systems, promoting better alignment and coordination among relevant stakeholders [5,6].

In the Danish context, the SEP framework applies to Danish municipalities at the local level, despite the term “local” having various interpretations within the energy transition discourse [7]. Thus, this article focuses on Danish municipalities at the local level to facilitate local actions in support of a national and global transition.

To achieve an energy transition in Danish municipalities to meet global and national ambitions requires collaborative actions across governance levels [8]. This can be coordinated and outlined through local strategies for the transition, where energy models can be a valuable tool [9].

Energy system models aim to create and investigate various scenarios that explore different pathways for future energy supply and demand [10]. This is observed for multiple scales stretching from a European perspective [11] to national perspectives in Thailand [12], Estonia [13] and Sweden [14], to a sub-national regional

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List of Abbreviations

BAU	*Business-As-Usual*
CHP	*Combined heat and power plant*
DH	*District Heating*
GIS	*Geographical Information System*
HTL	*Hydrothermal Liquefaction*
IDA	*Danish Society of Engineers*
PTX	*Power-to-X*
PV	*Photovoltaic*
RCR 2045	*Randers Climate Response 2045*
RR 2045	*Randers Reference 2045*
RES	*Renewable Energy Sources*
SES	*Smart Energy System*
SEP	*Strategic Energy Planning*
TSO	*Transmission System Operator*
VRE	*Variable Renewable Electricity*

perspective for South West Ireland [15] and the North Denmark Region [16], to the local level for Akita, Japan [17], Aalborg, Denmark [18] and Cuenca and the Galapagos [19].

These studies collectively indicate that energy system modeling is a viable tool for outlining decarbonized societies and exploring various dimensions of the energy transition process. However, energy system modeling can face multiple challenges related to temporal and spatial dimensions, uncertainties, transparency, and integration into broader energy systems, where social dimensions are also crucial [20].

These challenges often vary based on the modeling techniques and the spatial and temporal scales used [21,22]. Additionally, it is crucial to consider the political dimension of models [23]. This is especially relevant for the local implementation of RES, where several dimensions must be coordinated locally [24].

To address some of these challenges at the local level, model coupling can be advantageous, as it enables the model to reflect the local context better. In general, when energy system modelling utilizes local level case studies, these often have varied in modeling approaches, scales of temporal and spatial dimensions, and types of coupling [25]. However, the technical modelling still needs to be linked to practical implementation [26]. Thus, relating local geographical features to energy modeling to explore the model's applicability is important for making the local implementation tangible.

This is observed, for example, in a study for Torino, Italy, where energy modelling and spatial dimensions help to prioritize planning actions and economic resource allocation [27]. As such, the coupling of energy modeling and spatial features can help envision the necessary implementation of RES to achieve a national ambition in a local context. This requires an alignment of the local level with an overarching ambition to reach a fully decarbonized future, which is a complex challenge, as it involves changes across the entire energy system [28]. Additionally, it is often a challenge at the local level to comprehend and translate overarching ambitions into practical local actions [29,30].

To overcome these challenges, the local level requires a consistent and feasible strategy for the national transition that can be effectively translated into the local context. A prerequisite for this national strategy is transparency, which enables actors at the local level to translate it into a local context [31]. Translating this national scenario to a more detailed understanding of the local energy system, where current and future potentials and constraints are considered, moves beyond existing literature, where a coarser knowledge of the local level in Denmark is observed [32].

In a recent publication, Lund et. al. [33] present a transparent, coherent, and feasible strategy for achieving a fully decarbonized Danish society within a global context. The strategy employs a Smart Energy System (SES) approach, where synergies between energy sectors are pivotal. The national strategy is situated within a broader global context, encompassing international shipping and aviation, as well as the sustainable consumption of scarce resources, such as biomass. Thus, this national strategy presents a scenario in which the SES approach achieves a cost-effective, efficient, and 100% renewable energy system through the utilization of synergies across the energy system [34]. As a result, this scenario can serve as an overarching framework that can be translated to the local level to understand how a Danish municipality can envision itself as an integrated part of a broader national transition.

This article aims to translate the overarching national scenario for a fully decarbonized society into a tangible, local scenario that incorporates spatial features. The novelty lies in translation of a national scenario, which is part of a global context, to the local municipal level. Furthermore, a more detailed local energy system analysis of local possibilities is crucial to envisioning the local transition as part of the national scenario's overall transition.

The article addresses the gap between national and local energy planning, highlighting how this challenge can be resolved locally through a scenario that informs local energy planning. As such, the development of a local scenario within a national scenario shaped by a global context guides the local transition to be within the limitations of global boundaries. The analysis uses Randers Municipality as a case study to present a feasible energy system scenario for the future, based on local demands and as an integrated part of a national scenario.

Explorations of how key elements, such as variable renewable electricity (VRE) production and biomass availability, can be identified in the local context to understand the local potential for achieving the scenario. Furthermore, the scenario is discussed as part of an adequate and feasible development toward a fully decarbonized Danish society by 2045.

2. Methodology and scientific approach

To explore how an overarching national energy scenario can be translated into a local energy scenario, the methodological approach from ref [30] is applied and adjusted from a sub-national regional level to a local level perspective. The translation to the local level is combined with model coupling, where spatial features are utilized to analyze the local potential and limitations related to key parameters within the outlined local scenarios. As a result, the methodological approach defines local SEP based on local features and contingent upon an overarching national scenario. In this article, the methodology applied involves the following four steps:

1. **Establish a local energy scenario** to present the existing energy system, typically considering the electricity, heating, industry, and transport sectors.
2. **Aligning the local energy scenario with the overarching national energy scenario** ensures methodological conformity, which necessitates adjustments to local demand and production when rescaling from a national to a local energy scenario.
3. **Creating a future fully decarbonized local energy scenario** based on projections of demands from the aligned local energy scenario and sourcing technologies from the overarching national scenario. Establishing a future business as usual (BAU) scenario is also relevant for comparing the impact of different transition pathways.
4. **Exploring local spatial features** is crucial for evaluating the applicability of the proposed fully decarbonized local energy scenario in a future local context. Doing this more holistically gains a deeper understanding of local potentials and constraints relevant to local SEP processes.

The four methodological steps establish a detailed and local platform for a local transition strategy through a feasible scenario where the local energy system is part of an integrated decarbonized society. This approach enables specific considerations of current and future directions of the local energy planning and modelling, as it has a more detailed understanding, which is outlined as a lack in previous modelling [32].

By creating an integrated threshold for the local transition, it can serve as guidance for the local transition and help to make backcasting [35]. Additionally, the methodological platform enables further investigations into how other strategies or projects can impact the local energy system. Nonetheless, the four steps of the methodology focus on the technical rescaling and translation of energy systems scenarios. However, the socio-technical dimensions of the energy transition are also crucial to consider, as these are vital for implementing a local transition strategy [36]. Exploring local spatial features can enhance this dimension, as it provides insights into local potential and constraints, which are relevant to creating an effective transition strategy.

The methodological approach emphasizes the overarching national scenario as part of a broader global context, aiming to translate an adequate local energy transition in line with global ambitions. For this article, the Danish Society of Engineers (IDA) scenario for Denmark, the IDA Climate Response 2045 [37] is used as the overarching national scenario. As such, a prerequisite for the sub-national scenarios is coherence with the constraints coming from the inferior level to ensure global cohesion [38].

However, recent political agreements in Denmark suggest a quadrupling of land-based VRE production in Denmark, mainly solar Photovoltaic (Solar PV) and onshore wind turbines [39]. Therefore, it is relevant to reassess the division of VRE in the overarching national

Table 1: Overview of production and capacities of VRE in Denmark in 2020 and estimations for IDA's Climate Response 2045, after methodological amendment to quadrupling of land-based production.

		The Danish Energy System 2020	**IDA Climate Response 2045 original**	**IDA Climate Response 2045 amended**
Estimated VRE Production				
Offshore Wind	[TWh/Year]	10.43	62.87	39.94
Onshore Wind		8.62	16.13	39.06
Solar PV		1.01	12.16	12.16
Total production		**20.06**	**91.16**	**91.16**
Estimated corresponding VRE capacity				
Offshore Wind	[MW]	2,051	14,075	8,900
Onshore Wind		4,232	5,000	12,000
Solar PV		952	10,000	10,000

* Input from 132 MW of wave power in the future national scenario is not included in this table

scenario and adjust it to fit the new political paradigm. This will be beneficial for the local energy scenario, as the political agreement envisions more RES on land, which will impact spatial features in the fourth step of the methodology. A methodological amendment to the composition of VRE in the overarching national scenario is introduced, as presented in Table 21.

The presented amendment in Table 1 alter the national composition of VRE capacities, but the estimated corresponding production is similar. Thus, the amendment does not compromise the constraints from inferior levels to ensure global cohesion.

The political agreement does not specify the distribution between these capacities, but the aim is to produce approximately 50 TWh/year of land-based electricity [40]. Therefore, the amendment to the overarching national scenario maintains the same amount of solar PV capacity, thereby preserving the same ratio between wind and solar energy production. However, the amendment entails a significant shift from offshore wind capacity to onshore wind capacity. As a result, the amended composition of VRE capacities is used in this article to understand the overarching national scenario within the current political framework.

To model these VRE capacities and the rest of the energy system, the primary tool used is the advanced energy system tool EnergyPLAN. The tool is designed to create sustainable energy scenarios that incorporate RES and utilize synergies across the energy sectors to make the system more efficient. The tool enables scenario investigation based on demand and capacity inputs, using an hour-by-hour model of the entire energy system, which encompasses heating, electricity, industry, and transportation. Furthermore, EnergyPLAN is a deterministic simulation tool that helps maintain coherence between the investigated scenarios. [41]

The EnergyPLAN tool, therefore, is relevant to examine energy transition scenarios towards a 100% RES energy system, as part of a fully decarbonized society in the future [42] Moreover, the overarching national scenario also utilizes the EnergyPLAN tool, ensuring consistency between the models as general characteristics and fundamental computational approaches are identical. However, caution remains crucial when using the data as input to the tool.

The EnergyPLAN tool is combined with ArcGIS Pro, a Geographic Information System (GIS) tool that adds a spatial dimension to the scenarios. In this article, ArcGIS Pro is primarily used for mapping RES. The existing wind turbines are shown with specific locations, capacities, and lifetimes. The potential for solar PV systems is estimated by developing a spatial model that utilizes LIDAR data on building elevation to calculate solar radiation for all roofs in the municipality. This model is then further used to estimate solar PV capacity and annual electricity production potential on these roofs.

Finally, the biogas potential from manure, bedding, and straw is estimated. Manure and bedding potentials are calculated based on the Central Livestock Register. A detailed description of the GIS methods can be found in the background documentation [43].

3. Translating an energy scenario

This section aims to establish local energy system scenarios that are integrated into an overarching national energy

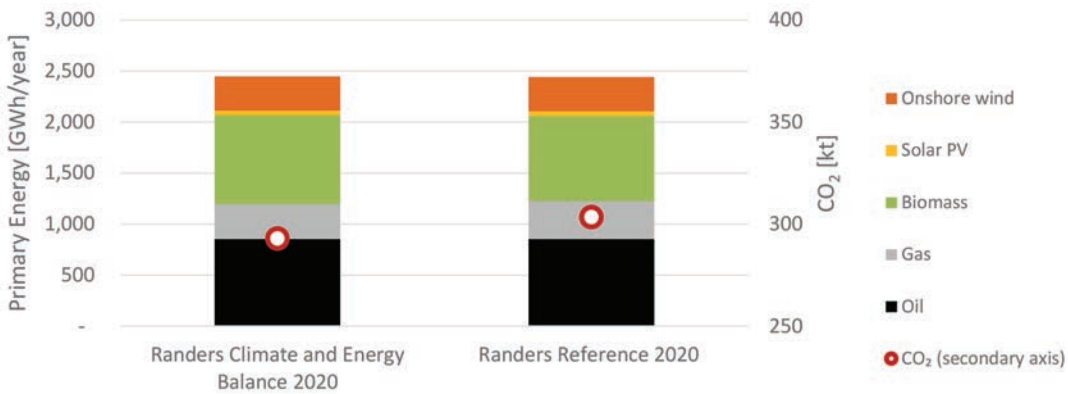

Figure 1: Validation of EnergyPLAN scenario through comparison of fuel balance and CO_2 emission.

scenario. It follows the four steps presented in the methodology. The section elaborates on the fourth step of the method, where model coupling examines the applicability of the proposed energy scenario in a local context, taking into account spatial dimensions. A detailed description of the creation of the scenarios and their results is outlined in the background documentation [43].

3.1 Establish a local energy scenario

Establishing a local energy scenario that reflects the existing energy system is the foundation for the later steps in the methodology. Data is collected and aggregated from multiple sources to establish this scenario, with 2020 serving as the reference year. To identify energy demand and production in Randers Municipality, the climate and energy balance for the municipality is used [44]. Additionally, electricity demand is obtained through the Danish transmission system operator (TSO) to distribute demand among public, private, and industrial uses. Data from the TSO is also utilized to create distribution files for the local production and consumption of electricity [45].

The heat distribution is generated from data provided by the local heat company in Randers, which delivers 90% of the local district heating (DH) [46]. Based on the significant input from this supplier, the same heat profile is assumed to represent all DH grids in the municipality. The DH system's production capacities and efficiencies are determined based on the energy producer count [47]. Similarly, the capacity for onshore wind turbines is determined through the national data register for wind turbines [48]. The capacity and production from solar PV are determined through data from the Danish TSO [49,50].

The mentioned data are used to establish a reference energy system for Randers Municipality in 2020, employing the EnergyPLAN modelling tool presented in Section 2.

The EnergyPLAN reference scenario is developed as an endogenous model that balances local heat and electricity demand through a technical simulation strategy that minimizes fuel use in the system. As a result, when excess electricity is available, the selected simulation strategy aims to lower production at the combined heat and power plant (CHP) through electrical heat pumps and boilers [51].

The same simulation strategy is used for additional local scenarios. The reference scenario is validated against the primary energy consumption from the climate and energy balance, which deviates less than 1%, as well as the corresponding CO_2 emissions, which deviate by 3.5%. This can be observed in Figure 1.

3.2 Aligning the local energy scenario

A key aspect of creating an integrated energy scenario for a local municipality is contextualizing and aligning the local scenario within a broader, overarching scenario. In this article, the scenarios for Randers Municipality aim to be integrated as part of a national transition towards a fully decarbonized society.

The overarching national scenario presents a strategy for Denmark to become a fully decarbonized society within a broader international context [33,37]. The scenario also accounts for Denmark's share of international shipping and aviation, only consumes a sustainable amount of biomass, and outlines that Denmark will also deliver flexibility and reserve capacity in the European electricity grid [33]. Therefore, methodological

Table 2: Randers' share of the Danish population in 2020 [52] and projection for 2045 [53] and land area share[54].

Population	**Year**	**2020**	**2045**
Denmark	[People]	5.823.000	6.263.444
Randers	[People]	97.805	111.509
Randers' population share	[%]	**1,68%**	**1,78%**
Land area			
Denmark	[km^2]	42.951	
Randers	[km^2]	748	
Randers' land area share	[%]	**1,74%**	

adjustments are required to align and integrate the Randers reference 2020 scenario with the overarching national scenario.

To do this in a pragmatic and transparent manner, the municipality's current and projected population share, along with its geographical land area, is relevant for assessment. In Table 2 the current and projected population of Randers Municipality is shown along with the land area.

To make a methodological adjustment of the energy demand, the population share is used, as it relates to the current energy demand [52,53]. The projected population and land area are presented in Table 2 is mainly relevant for the third step where future capacities are allocated. The land area is relevant for the development of future scenarios as it relies on the introduction of new RES and available biomass from the land area within the municipality.

The link between the local energy scenario and the land area is explored in the fourth step of the methodology. However, from Table 2, it is observed that Randers Municipality constitutes approximately 1.7% of Denmark's area and population today and in the future. Thus, Randers Municipality is an average municipality in terms of demographics and land area. As a result, the established local scenario is allocated a share that is not actually within the municipality's boundaries. This concerns the capacity of offshore wind turbines and cooling demand. Apart from these two examples, no new demand or technologies are introduced to the scenario. However, additional adjustments to existing demands are introduced.

The transport demand is adjusted to include international shipping and aviation by using a population share of the national numbers. The heat demand is adjusted according to the Danish heat atlas [55] utilizing data from Heat Plan Denmark 2021 [56]. Using the Danish heat atlas enables the quantification of heat savings and district heating expansions in local areas, which is relevant in creating future scenarios.

Adjusting the Randers Reference 2020 to align with the overarching national scenario is crucial to ensure methodological consistency, which is essential for the later development of a fully decarbonized local scenario. However, the adjustment amends the fuel balance and CO_2 emission in the Randers Reference 2020 system. This creates a new scenario named Randers Base Model 2020. The impact of methodological adjustments can be observed in Figure 2.

Figure 2 shows how the adjustments transition the Randers Reference 2020 into the Randers Base Model 2020. The differences between the scenarios primarily relate to the introduction of international shipping and aviation, leading to increased oil consumption. Similarly, an increase in gas consumption and a decrease in biomass consumption are observed, which correspond to the adjustments made for heating demand through the Danish heating atlas. Moreover, the allocation of offshore wind capacity is noticeable in the overall fuel balance. A more detailed and comprehensive overview of the Randers Base Model 2020 scenario is outlined as a Sankey diagram in Figure 3.

3.3 Create a future local energy scenario

After applying methodological adjustments to Randers Reference 2020, the resulting Randers Base Model 2020 serves as the foundation for creating future local energy scenarios. To translate the pathway from an overarching fully decarbonized national scenario into a local scenario, future capacities are allocated to the local context.

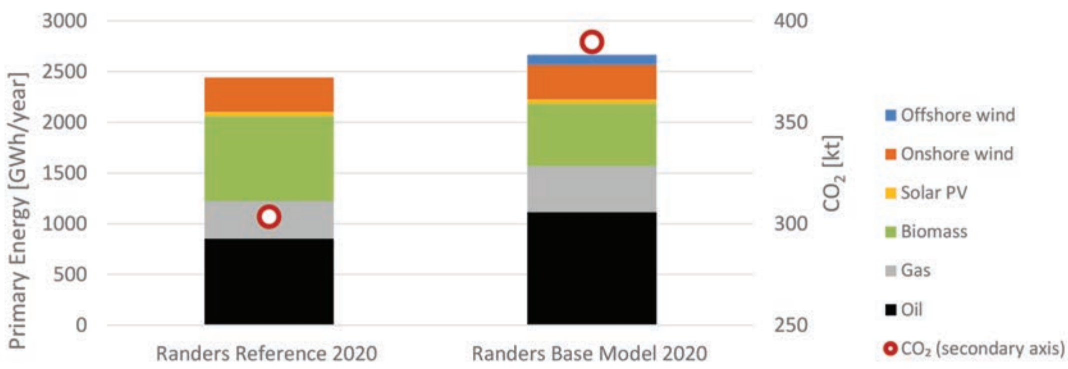

Figure 2: Overview of the fuel balance and CO_2 emission before and after the methodological adjustment.

However, future local energy demands are projected from the base model scenario according to the national transition pathway. Therefore, it is crucial to assess how the new developments in the national pathway align with the local context.

Based on this, the scenario *Randers Climate Response 2045 (RCR 2045)* is developed. The capacities from the overarching national scenario are sourced according to the projected population share outlined in Table 2 to cover the projected local demands.

A key assumption that is translated from the overarching national scenario into the *RCR 2045* scenario is the significant energy savings and efficiency improvements applied to the local demand. As part of the development of the *RCR 2045*, an assessment of local potential and constraints is relevant, for example, related to the introduction of excess heat into the local DH systems. In this regard, the existing plans for the expansion of DH systems and the potential future integration of excess heat are practical [46,57,58].

Based on a similar assessment of available information inputs for the energy system, it is concluded that, for example, waste incineration is not expected to be relevant within Randers Municipality in the future.

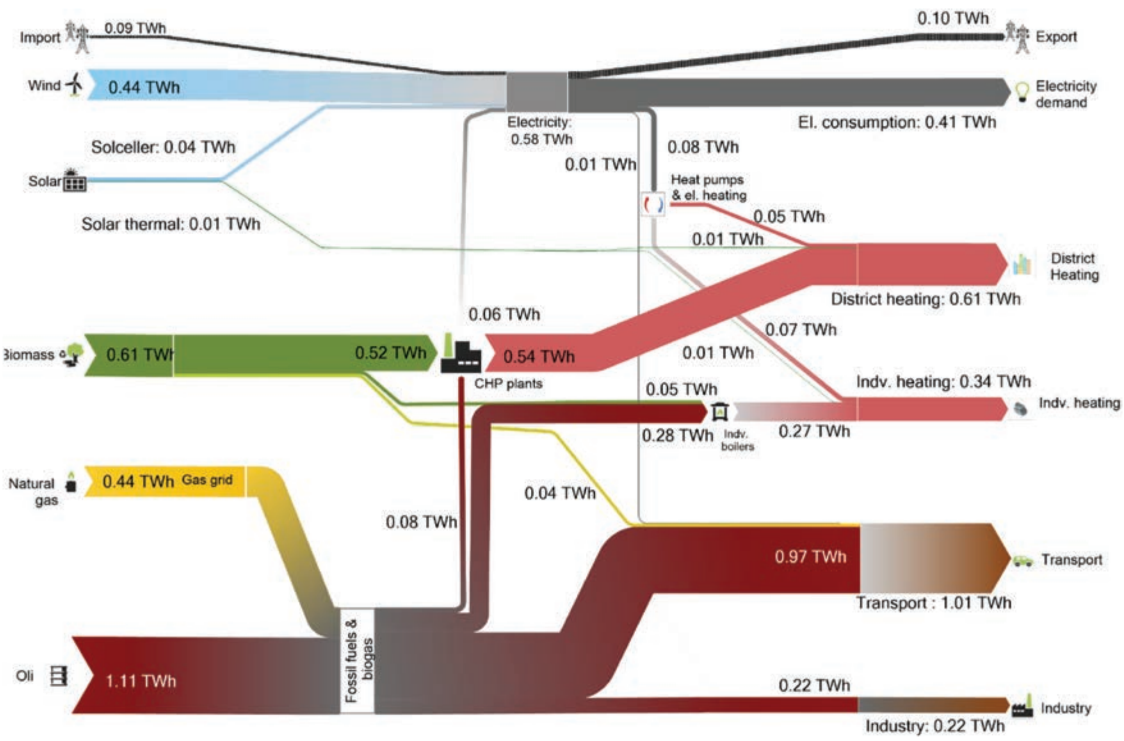

Figure 3: Randers Base Model 2020 Sankey Diagram. Created with inspiration from ref. [37].

However, the biogenic waste input to, e.g., biogas through increased municipal waste sorting [59] is assumed to be available for future biogas production in the local energy system.

Moreover, the amended VRE capacities in the overarching national scenario presented in Table 1 result in the future local energy scenario having 158 MW of the national offshore wind turbine capacity allocated, and sourcing 216 MW of onshore wind turbine capacity, together with 178 MW of solar PV capacity, to the local context. The local energy scenario that defines the *RCR 2045* scenario is presented as a Sankey diagram in Figure 4. A more detailed description of all methodological choices and the local scenario can be found in the background documentation [43].

To contextualize the future *RCR 2045* scenario, a future reference scenario representing BAU scenario development is also created. In the *Randers Reference 2045 (RR 2045)*, the local energy system transitions according to existing political agreements in the reference year. This scenario is used as a future baseline to understand how an adaptation of a fully decarbonized society impacts.

Since the *RR 2045* scenario serves only as a comparison point, it follows the transition pathway outlined in the overarching national reference scenario. This results in, for example, that the transport demand is assumed not to have supplementary fuel input from Hydrothermal Liquefaction (HTL) and pyrolysis processes, which are instead covered by more electricity in road transport and fossil fuel input for aviation. To illustrate how the two different pathways in the *RCR 2045* and the *RR 2045* scenarios transition the local energy system, a comparison of fuel balance and CO_2 emission is presented in Figure 5

In Figure 5, it is observed that the *RCR 2045* scenario has lower energy consumption than the other two scenarios. In the *RR 2045* scenario, a significant amount of fossil fuels is still consumed in the transportation sector, and natural gas remains a part of the energy system. In the *RCR 2045* scenario, primary energy consumption is primarily sourced from RES, including onshore and offshore wind turbines, solar PV, which are used directly or converted into heat or electrofuels. The category "*other renewables*" in the *RCR 2045* scenario encompasses solar and geothermal energy sources for heating purposes.

The biomass in the *RCR* 2045 scenario is consumed in the biogas, HTL, and pyrolysis sectors to produce liquid and gaseous fuels. The production from these capacities exceeds the local demand, resulting in the export of biogas and biofuel. The gas consumption in the *RCR 2045* scenario is 0.19 TWh/year and 0.25 TWh/year of biofuel. In Figure 5, this is only observed as an

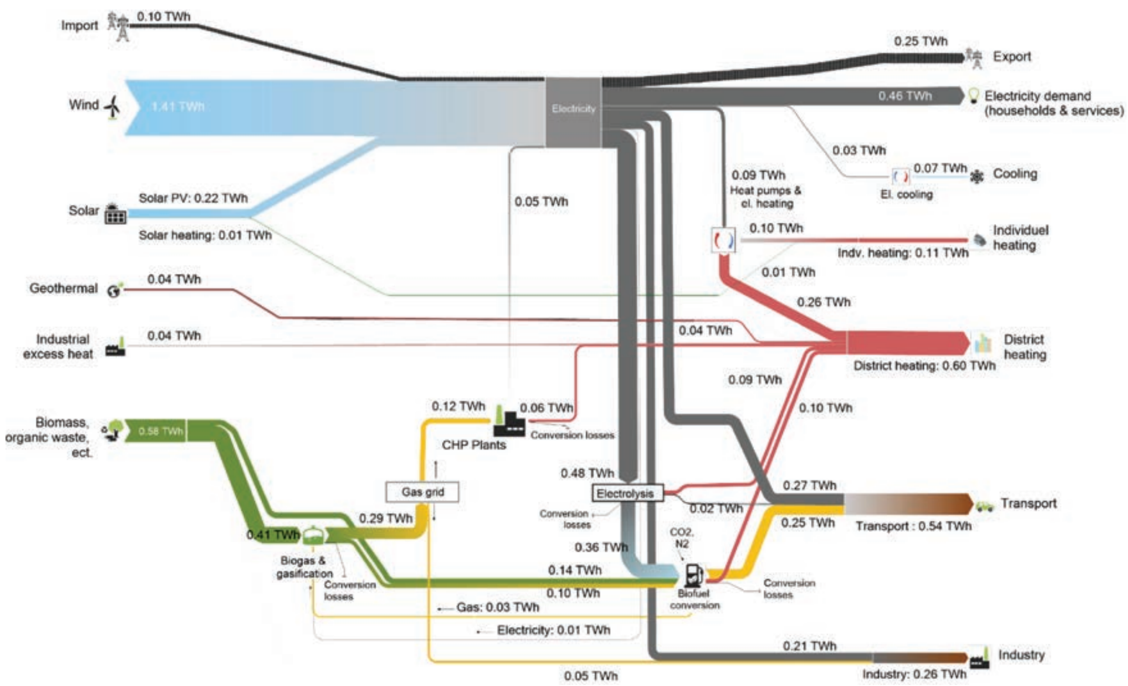

Figure 4: Randers Climate Response 2045 Sankey Diagram. Created with inspiration from ref. [37].

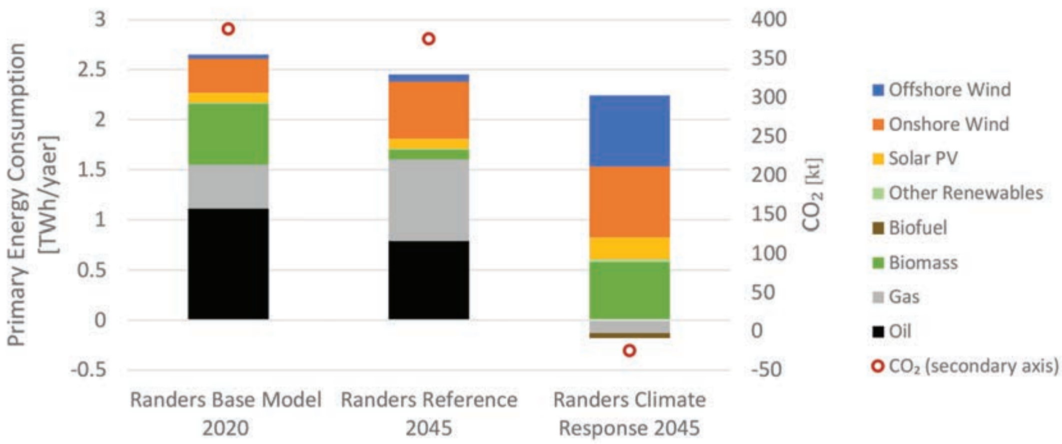

Figure 5: Comparison of the fuel balance between the scenarios Randers base model 2020, Randers reference 2045, and Randers climate response 2045.

export, since the figure shows the yearly fuel balance. Similarly, VRE is utilized in electrolysis to produce 0.36 TWh/year of hydrogen, which is used directly or in combination with CO_2 to create electrofuels that meet or exceed local transport demand.

Based on this methodology, the foundation for further explorations of the local energy system transition as part of a national energy system is established. For example, a more detailed examination of the storage in the local energy system can be conducted, as this plays a pivotal role throughout the energy transition [60]. Additionally, the energy transition, which eventually can be achieved by implementing Randers Climate Response 2045, relies on local actions. However, local coordination and balance in energy planning can impact how these actions outlining the energy transition can be implemented locally [24,61]. As such, local implementation challenges concerning local opposition to onshore wind turbine projects or repowering projects, together with large-scale PV installation, can occur due to a lack of landscape democracy [62].

In this perspective, an exploration of local spatial features related to need and possible VRE capacities in the future, together with an understanding of future local biomass resources for the energy system, is relevant.

3.4 Exploring local spatial features

The *RCR 2045* scenario emphasizes the importance of the local allocation of area for VRE and the strategic utilization of biomass resources to achieve both local and national sustainable energy objectives. To explore how this applies to the local context, a study is conducted to assess how local spatial features align with the demands in the RCR 2045 scenario.

3.4.1 Wind and solar PV energy

The implementation of VRE sources in RCR 2045 depends on local energy planning and political ambition in Randers Municipality. As such, the outlined composition of VRE in the RCR 2045 can be impacted by the local context. This can be explored through additional scenarios to the RCR 2045 scenario, where different VRE capacities cover the same total production to ensure global coherence. As such, three additional scenarios of the RCR 2045 are created to explore the total substitution of offshore wind electricity by either pure solar PV, pure onshore wind, or a mix following the same ratio as the distribution of onshore technology in the IDA Climate Response 2045 (IDA distribution) as presented in Table 1. These scenarios are presented in Figure 6.

Figure 6 shows how changes to the VRE capacities in the *RCR 2045* scenario impact the local electricity balance. From the figure, it is observed that without offshore wind capacity, the overall electricity exchange increases. This is related to the capacity factor of the technologies and production profile, resulting in an increased import. Similarly, exports increase due to excess VRE production that is not absorbed in the local energy scenario. This results in an increase in the annual electricity exchange in the scenarios. The additional scenarios outlined in Figure 6 also represent changes to the land-based VRE, which subsequently impact the local context. Exploring the spatial features related to

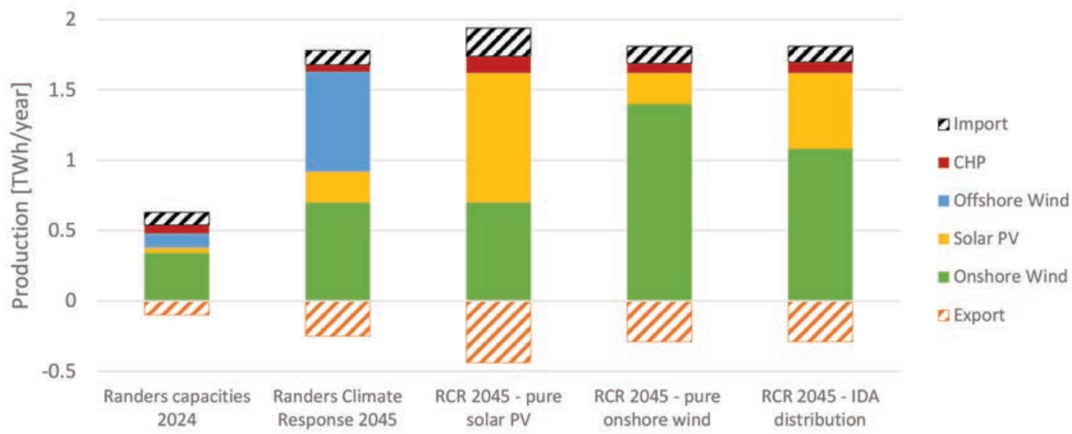

Figure 6: Overview of electricity production in existing and new scenarios to explore how local capacities can substitute for offshore wind electricity generation.

the scenarios can help estimate the land area requirements for each scenario.

In Denmark, several regulations are in place to protect neighbors from the negative impact of wind turbines, which depend on the height of the turbine [63]. The same is in place for ground-mounted utility-scale solar PV [64]. Thus, the cost, technical area requirements, and type of wind turbine or solar PV impact the land area requirements. To explore this, technical assumptions on feasible wind turbines and solar PV [65] are used to estimate the land area requirements related to each scenario. For solar PV, this also concerns the placement of larger capacities on the rooftops of commercial or residential buildings, which will not require a large land area [66].

Analyzing the local solar PV potential at rooftops in the municipality using updated local data as described in Section 2 can help explore the future need for utility-scale solar PV, depending on the scenario. To achieve this, it is assumed that existing rooftop and utility-scale solar PV systems will remain in place in the future. Moreover, capacities are updated to account for the recent years of development. Based on this, the solar PV potential at large buildings (exceeding 1000 m^2) is estimated to be 320 MW [43]. Assuming this rooftop potential is utilized, and capacity exceeding this potential is implemented as utility-scale solar PV, the technical area requirement for the different scenarios can be estimated as presented in Figure 7.

In Figure 7, it is observed that the technical land area requirements for VRE production depend on the technology deployed. Moreover, the land area requirement is approximately the same between already installed capacities and the *RCR 2045* scenario and the RCR 2045 – pure onshore wind scenario. Additionally, it is noted that substituting offshore wind production exclusively with solar PV exceeds the rooftop potential at large buildings. However, if the IDA distribution is applied, a complete

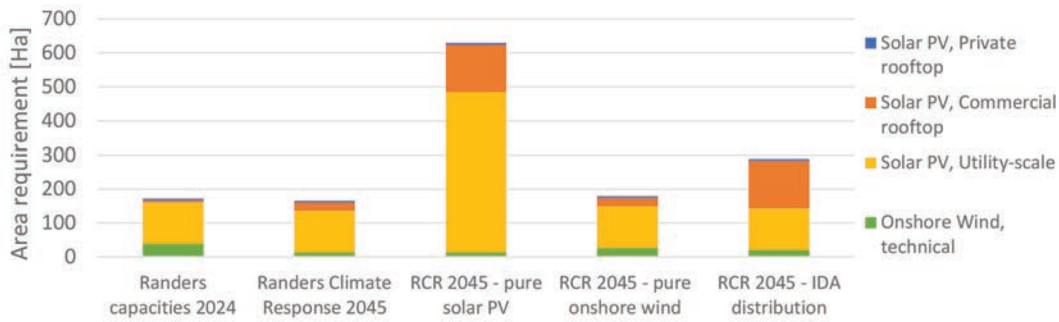

Figure 7: Overview of the estimated technical area requirement for VRE production without offshore wind power.

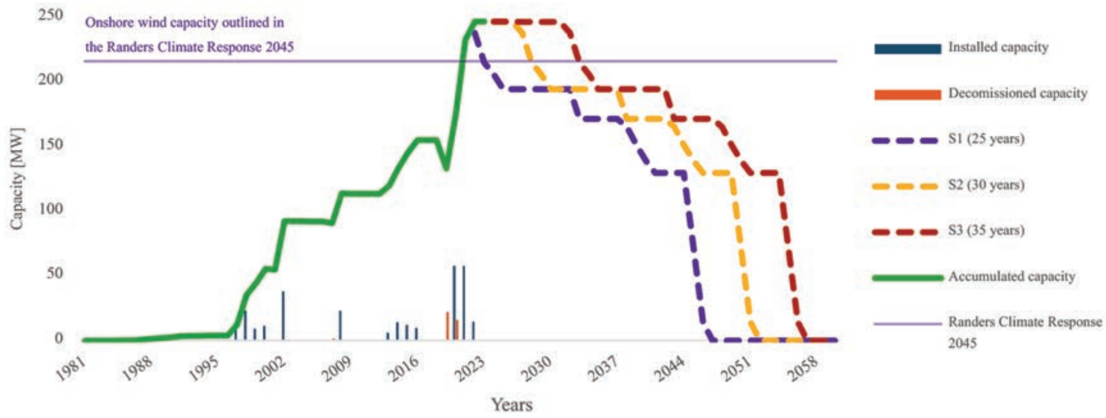

Figure 8: Existing and projected onshore wind capacity in Randers Municipality with different expected lifetimes.

utilization of the solar PV potential at large rooftops and an additional 90 MW in onshore wind turbine capacity can cover the offshore wind power. Therefore, it is relevant to project the lifetime of the existing onshore wind capacity in Randers Municipality to comprehend the temporal dimension related to these capacities. This is outlined in Figure 8 with different technical lifetimes of 25 (S1), 30 (S2), and 35 (S3) for the existing wind turbine capacities.

According to the projection of onshore wind turbine capacity in Figure 8 Randers Municipality currently has more capacity than outlined in *RCR 2045*. However, a continued effort to plan for new capacities is required to keep this level. Focusing on the re-establishment (repowering) of onshore wind turbines could be a key element in ensuring future capacity in the local energy system. Moreover, repowering can potentially be implemented more easily in the local community, as the question is not about introducing capacities in new areas, but rather about maintaining the existing areas' production. As such, repowering can be used to elevate local ownership and generate income for the local community through the legal framework in place [67].

However, early dialogue and an adequate participation process with owners, local communities, and other relevant stakeholders remain crucial to ensure social acceptance [36]. Assuming a technical lifetime of 30 years for existing wind turbines, spatial features can be coupled to determine in which decade various clusters of wind turbines will become relevant for repowering. This is presented in Figure 9.

Based on Figure 9 it can be observed that multiple clusters of small-capacity wind turbines scattered throughout Randers Municipality can be repowered. This knowledge can be utilized in the local energy planning to engage with these communities and encompass the capacity outlined in *RCR 2045* in existing areas with wind turbines.

3.4.2 Biomass availability

A key component of the national scenario is for Denmark to utilize only its national share of sustainable biomass resources. This must align with the ambitious transformation of the Danish land area, which is solidified as part of recent political agreements [68,69]. The political agreements offer concrete solutions to the climate and nature challenges faced, and they call for a significant shift in land use in Denmark. The political ambition aligns well with the principle from the overarching IDA Climate Response 2045. Nonetheless, the political agreement impacts the *RCR 2045*, as it depends on access to various local biomass resources.

This calls for a strategic use of the available biomass resources. The RCR 2045 scenario introduces new biomass conversion technologies that must be established to cover future demand. These technologies are expected to enable a more efficient and local use of biomass, thereby helping to reduce overall Danish biomass consumption. The RCR 2045 scenario utilises biomass input in the form of manure, straw, organic waste and wood in the energy system, making it relevant to investigate if this amount of resources is available locally. A detailed overview of the biomass consumption in the *RCR 2045* scenario is presented in Table 3

A central element of the scenario is the more efficient utilization of straw, which can be used in biogas plants and thermal gasification processes. Therefore, the future straw potential in Randers Municipality is important for

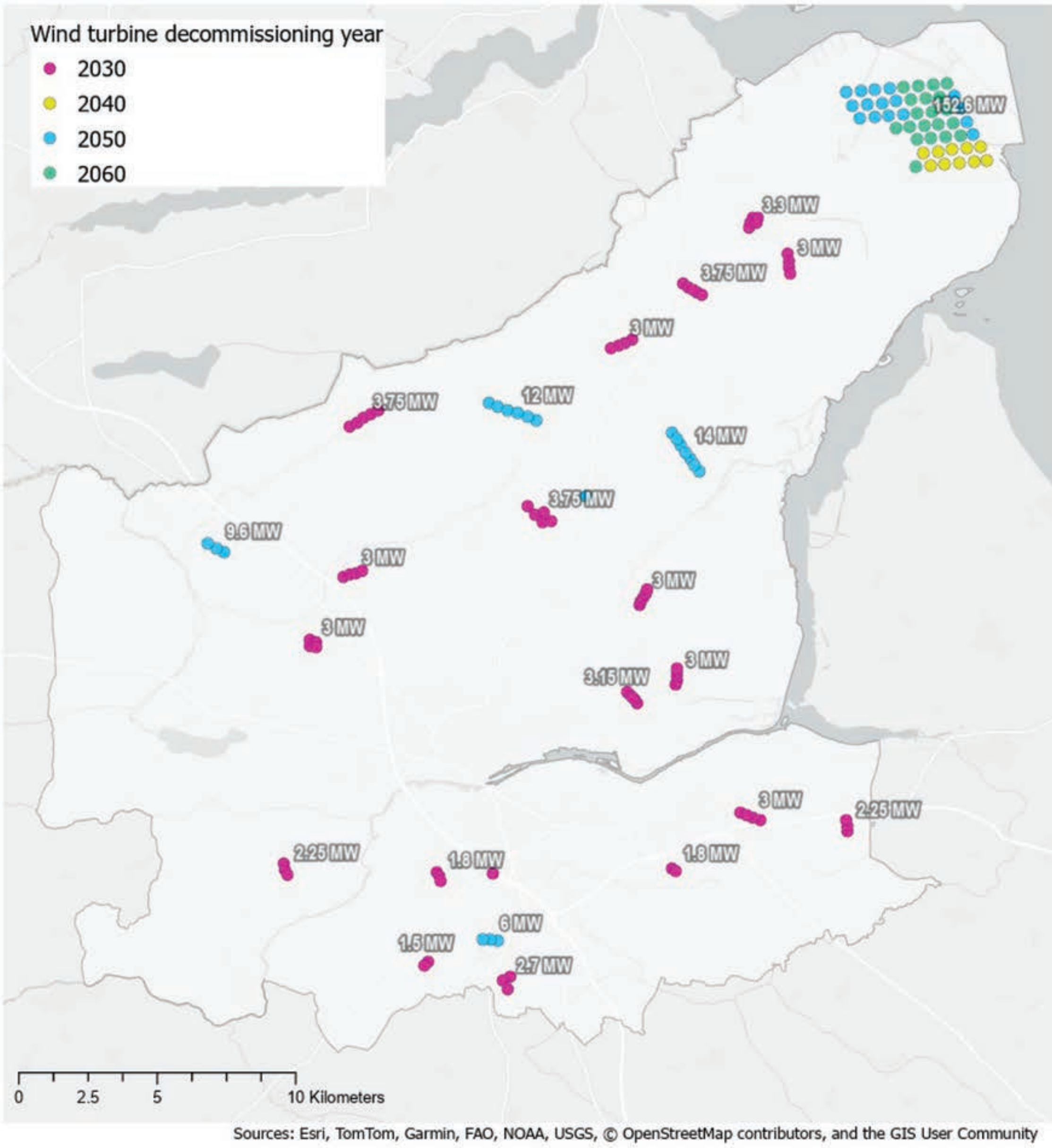

Figure 9: Decommissioning year for wind turbines, assuming a lifespan of 30 years. Capacity [MW] represents the total capacity of wind turbines within a specific grouping.

Table 3: Biomass consumption in the Randers Climate Response 2045 scenario.

[GWh/year]	Manure	Straw	Organic waste	Wood
Biogas plant	145	98	66	-
Industry	-	-	-	0.53
Thermal gasification	-	50	-	74
HTL	-	-	-	74
Pyrolyses	-	49	-	49
SUM	**145**	**197**	**66**	**198**

both the local and national energy transition. Several factors, e.g., crop and soil type, impact the local straw potential. Subsequently, the political agreement framing the conversion of agricultural land areas into wetlands will impact this potential. The methodology behind the estimation of the straw potential is further explained in the documentation [43].

Based on this estimation and potential future conversion of land use according to the political agreement, a map of the future straw potential in Randers Municipality can be generated, as presented in Figure 10.

Figure 10 categorizes the future straw potential post-2030, considering the remaining agricultural fields with straw potential after land areas beneficial for conversion into nature projects, such as wetlands and forests, have been transformed. It should be noted that the conversion of land areas is not based on concrete proposals but constitutes a theoretical potential based on national and local ambitions and screenings [70]. Afforestation is designated for the desired land areas in the municipality by 2030 and 2050 [71], while wetland areas are fields with an organic carbon content above 6% [72]. When the data behind the map in Figure 10 are aggregated, the local straw potential is summarized as presented in Table 4.

Based on Table 4, it is observed that if all areas designated for afforestation and wetlands are implemented,

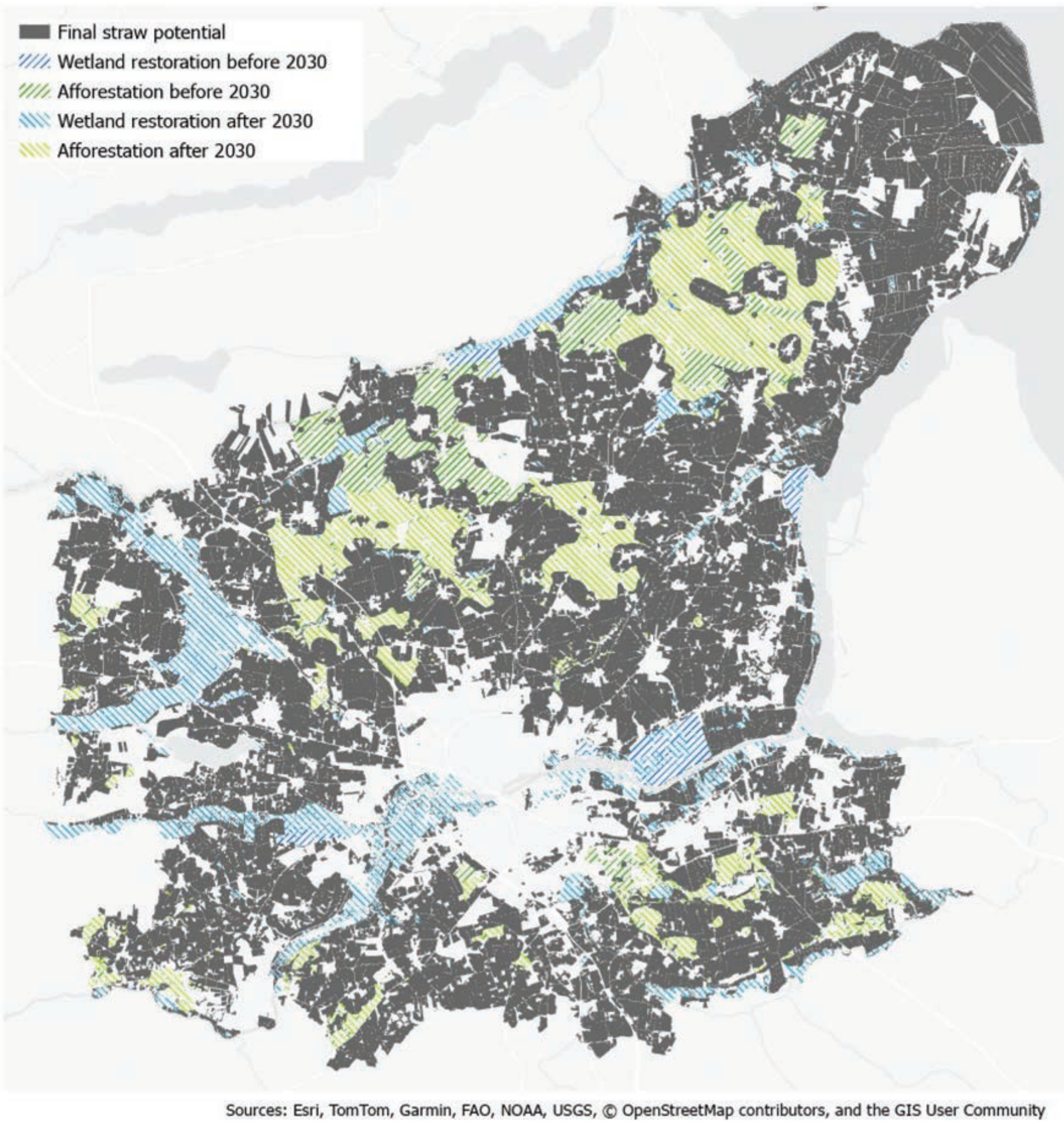

Figure 10: Map of areas allocated for wetlands and afforestation before and after 2030 to estimate future straw potential.

Table 4: Straw potential before and after the implementation of nature projects. This assessment does not take into account current usage.

	Hectar	Dry matter, ton	GJ/year	GWh/year
Current straw potential (prior nature projects)	55,260	122,849	1,092,966	303.6
Wetlands before 2030	826	1,799	6.007	4.4
Afforestation before 2030	2,584	5,845	52,000	14.4
Wetland after 2030	4,630	4,890	43,504	12.1
Afforestation after 2030	6,286	14,138	125,786	34.9
Future straw potential (post nature projects)	**40,935**	**96,177**	**855,668**	**237.7**

this will reduce the straw potential in the municipality by approximately 22%. The *RCR 2045* utilizes 197 GWh/year of straw, indicating that the future local straw potential can meet local demands. However, it should be noted that some of the straw is already used for other purposes. According to Statistics Denmark, the national distribution in 2023 was as follows: 27% was used for heating, 11% for feedstock, 19% for bedding, and 42% was left on the fields [73]. If this 42% unharvested straw is assumed to be used in RCR 2045, a total of 130 GWh/year is available within the municipality.

Another aspect of this area conversion is that afforestation could potentially increase the wood chip potential. In existing forests, the local potential for firewood and wood chips is estimated to be 90 GWh/year, with an additional estimated potential of 90 GWh/year from new forests, resulting in a total potential of 180 GWh/year in the future [43]. In this context, it is worth noting that, in practice, it will take several years for a new forest to reach its full potential, as it needs to attain a specific size.

A limitation in this regard is that if a new forest is designated to have biodiversity objectives, it may reduce the potential for utilizing the biomass. Additionally, the biogas potential from cattle and pigs is estimated and mapped based on data from the Central Livestock Register [74] where standard figures for biogas production depend on herd size and the type of stable. The result is shown in Figure 11, and a description of the method is provided in the documentation [43].

The numbers outlining Figure 11 estimates the biogas potential for Randers Municipality from cattle and pig manure to be 67 GWh/year and 22 GWh/year from bedding. The overarching national scenario utilizes the Energy Crop Analysis [75], where an additional input for biogas production originates from source-separated organic and green waste. Based on Randers Municipality's population share, a total organic and green municipal waste input of 66 GWh/year is estimated. Table 5 compares the biomass resources used in the *RCR 2045* scenario with the local availability of mapped biomass.

Table 5 shows a lack of manure and wood in the future, while there is an excess of straw. As such, the mapping indicates a minor lack of local biomass availability for the outlined *RCR 2045* energy scenario in the future. In this perspective, an adequate utilization can be important for Denmark to reduce its dependence on imported biomass or gas in the future. Therefore, energy planners at the local level need to understand the importance of biomass in the future energy system and help to raise awareness of future implications related to landscape changes and adequate utilization of the resources. As a result, energy planning towards a decarbonized society needs to be coordinated locally as part of input from other sectors and arenas [24].

Integrating spatial features for biomass availability, particularly straw and manure, in conjunction with local wind resources, can identify areas of potential synergy relevant to the future energy system. These synergy areas can be significant, as clustering specific types of facilities can be beneficial for producing biogas and electrofuels, which are essential for the future energy system.

Within these areas, further studies are required to investigate how excess heat from these processes can be utilized in existing or new district heating (DH) systems and vice versa. Moreover, knowledge concerning the repowering of existing wind turbines, as presented in Figure 9, is also relevant to consider. However, mapping the potential based on postal codes is the initial step towards a more concrete local discussion on how these synergies can be leveraged as part of the future energy system. These potentials are outlined in Figure 12.

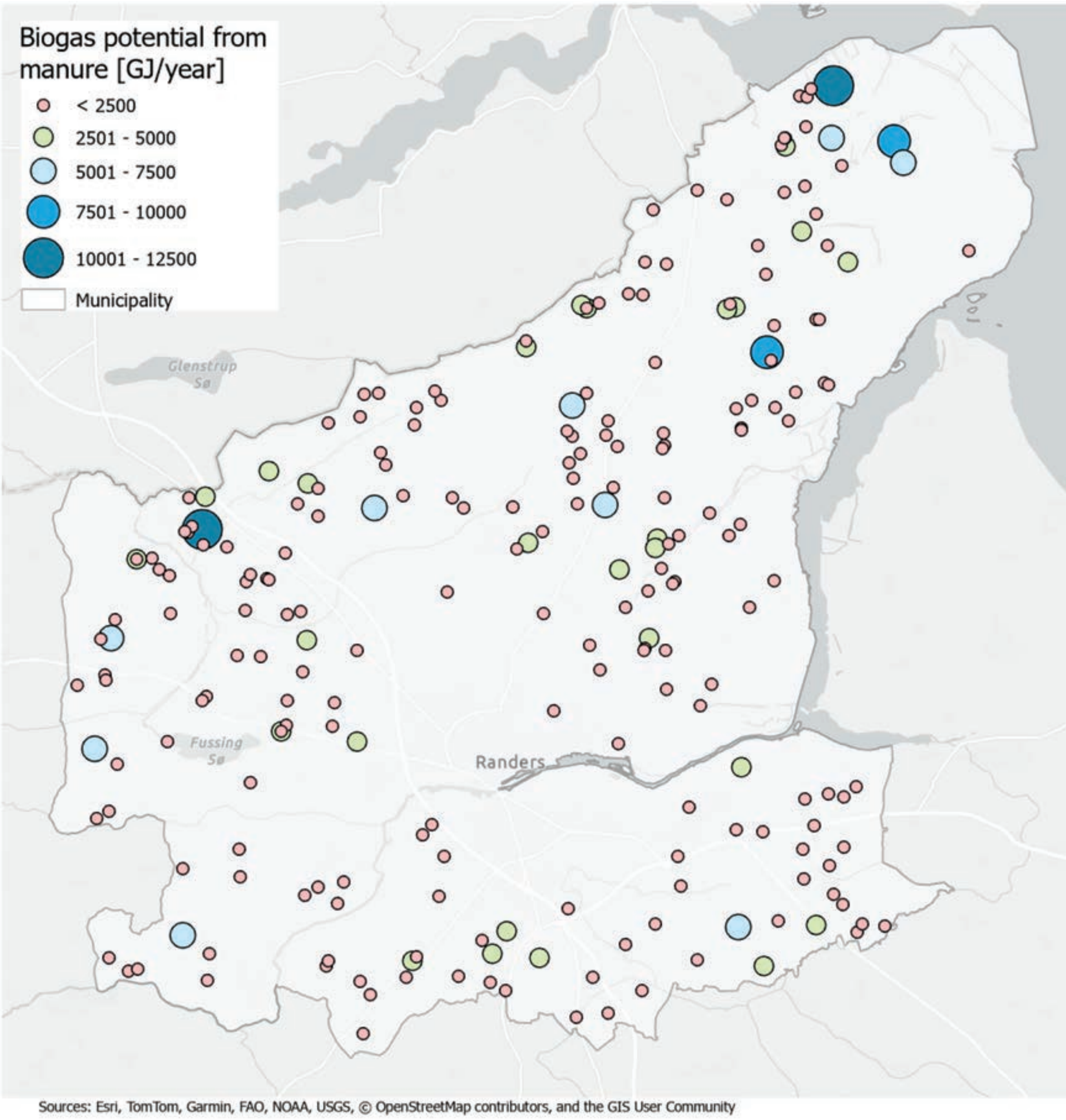

Figure 11: Map of the biogas potential from manure distributed by farm.

Table 5: Comparison of biomass consumption in Randers Climate Response 2045 and availability based on mapping of current and future biomass resources within the municipality.

GWh/year	Manure	Straw	Organic waste	Wood	Sum
Randers Climate Response 2045, demand	150	200	70	200	620
Current mapped potential	90	300	70	90	550
Difference from Randers Climate Response 2045 demand	-60	100	0	-110	-70
Future mapped potential	90	240	70	170	570
Difference from Randers Climate Response 2045 demand	-60	40	0	-30	-50

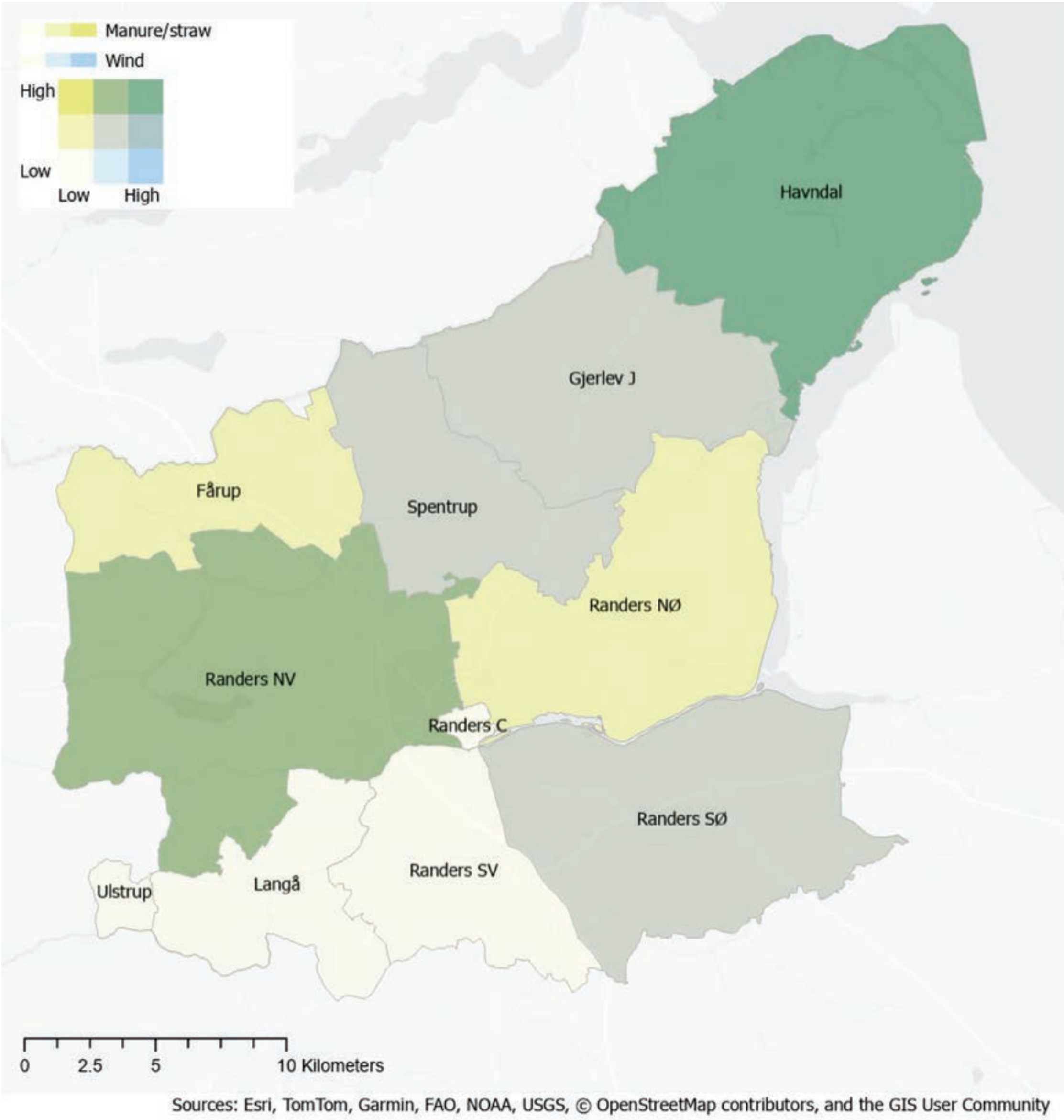

Figure 12: Map of manure/straw and wind resource potential divided by postal codes within Randers Municipality.

These inputs can enable a more detailed and holistic energy planning approach, where synergy areas can be analyzed more in depth, with special attention to how the local energy system and storage systems can be integrated with these areas to create local value.

4. Conclusion

In this article, a fully decarbonized Danish scenario serves as the overarching framework for rescaling and translating a similar transition to Randers Municipality. By adhering to the methodological steps outlined, the scenarios are developed to ensure conformity between the local and national scenarios. Exploring the future potential of wind and solar energy, along with the availability of biomass, offers valuable insights into the local context relevant for energy planning. Incorporating the latest political agreements ensures relevance and a solid foundation for local energy planning.

The developed Randers Climate Response 2045 presents a feasible scenario for the energy transition in Randers Municipality, which aligns with the global ambition. The scenario, combined with an exploration of local potential, creates a potential maneuver room for local energy planners to achieve the essential elements of the outlined transition. Coupling energy system analysis, translated and transferred through the presented method, with spatial features, facilitates a more tangible understanding of local development within the broader context of global transition. However, local debates may arise regarding the appropriate allocation of variable renewable energy within Randers Municipality which can result in local implementation challenges.

Increasing the amount of VRE capacity could benefit the national grid and attract energy-intensive industries, fostering local value creation through synergies with other energy sectors. On the other hand, decreasing the amount of VRE capacity puts the overall national transition at risk. Nonetheless, the future need for VRE in the RCR 2045 scenario is nearly present in the existing energy system. The analysis indicates an estimated shortage of local biomass to meet future demand. This suggests a need for a more strategic utilization of the biomass in the future to ensure an efficient consumption of local biomass.

The overarching national scenario prioritizes a strategic resource use of local biomass but does not restrict cross-border biomass trade, which is necessary to realize the RCR 2045 scenario. However, without a greater emphasis on biomass utilization, reducing Denmark's reliance on imported biomass can be difficult, making the Danish energy system more vulnerable to a global energy crisis.

In conclusion, the translation of an overarching national scenario, which is part of a broader global context, can help a municipality understand its role in the energy transition. However, it is also important to be aware that the choice of overarching national energy scenario and the translation methodology only represent one of many possible futures. Furthermore, applying the outlined methodology implies an enhanced alignment and coordination of a national energy transition, which requires sufficient resources and skills across different planning levels and a more holistic, iterative and adaptive energy planning approach. Nevertheless, applying the methodology can help to leverage local energy planning from solely focusing on individual local transitions to focusing on a coherent national energy transition, where municipalities see themselves as an integrated part of a fully decarbonized society and create a platform for local energy planning and actions.

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