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Article

A Novel Method for Analyzing 100% Renewable and Sector-coupled Sub-national Energy Systems–Case Study of Schleswig-Holstein

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Abstract: The energy transition requires integration of different energy carriers, including electricity, heat, and transport sectors. Energy modeling methods and tools are essential to provide a clear insight into the energy transition. However, the methodologies often overlook the details of small-scale energy systems. The study states an innovative approach to facilitate sub-national energy systems with 100% renewable penetration and sectoral integration. An optimization model, OSeEM-SN, is developed under the Oemof framework. The model is validated using the case study of Schleswig-Holstein. The study assumes three scenarios representing 25%, 50%, and 100% of the total available biomass potentials. OSeEM-SN reaches feasible solutions without additional offshore wind investment, indicating that they can be reserved for supplying other states' energy demand. The annual investment cost varies between 1.02 bn – 1.44 bn €/yr for the three scenarios. The electricity generation decreases by 17%, indicating that with high biomass-based combined heat and power plants, the curtailment from other renewable plants can be decreased. Ground source heat pumps dominate the heat mix; however, their installation decreases by 28% as the biomass penetrates fully into the energy mix. The validation confirms OSeEM-SN as a beneficial tool to examine different scenarios for sub-national energy systems.

Keywords: Sector coupling; 100% renewable; Sub-national energy model; Energy transition; Open science.

1. Introduction

To help achieve the 1.5° C targets of the Paris Agreement [1], the European Union (EU) needs a transformation of energy systems based on the smart integration of renewable energy across different sectors. In the European Green Deal, the European Commission stated plans to integrate renewables, energy efficiency, and other sustainable solutions across sectors to achieve decarbonization at minimum cost [2]. The integration of energy systems is often referred to as 'sector coupling' [3]. It indicates the combination of multiple energy sectors, such as electricity, heat, and transport, so that the integrated energy system can achieve the target of overall climate-neutrality.

Decarbonization of heat and transport sectors depends on state-of-the-art techniques such as power-to-heat and power-to-gas. These techniques, used in a sector-coupled network, are expected to increase the energy storage capacity and provide additional flexibility to the energy system. The modeling of multiple energy sectors, especially power, heat, and transport, is becoming popular in the newer energy models. In the past decade, many researchers analyzed the feasibility of integrating other sectors, especially the heat sector, in 100% renewable energy models. These analyses often show that sector coupling decreases the overall system cost; however, the benefits should be further investigated before cross-border transmission in a sector-coupled EU network is implemented.

The North Sea (NS) region can become a pioneer in achieving the European energy transition [4]. The area has enormous offshore wind potential and other renewable sources such as wave energy, ocean thermal energy conversion, carbon capture and storage, etc. Figure 1 shows the spatial implication of the current spatial management options for energy deployment [5].

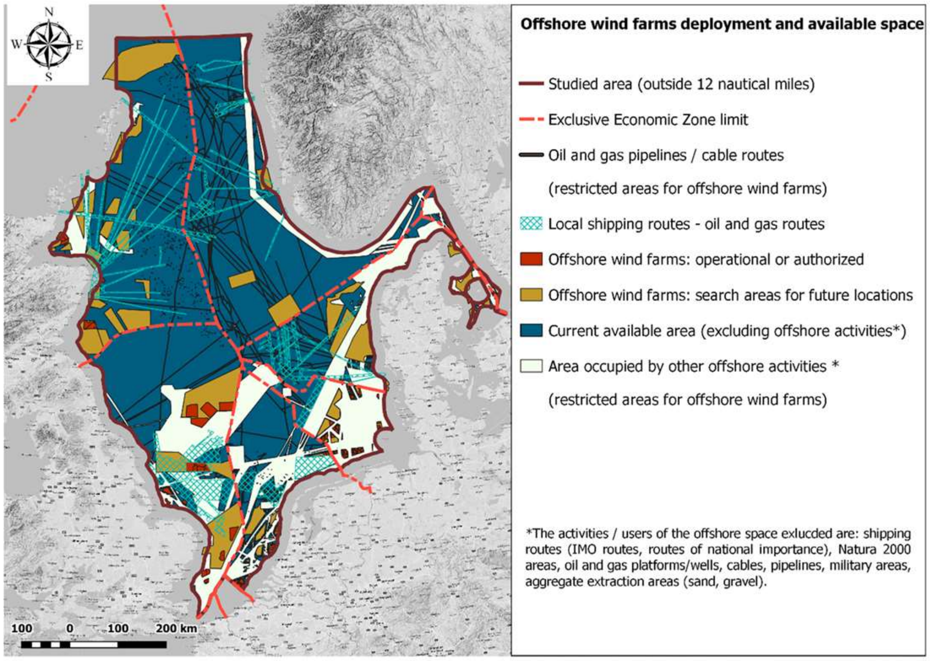

Figure 1. Available offshore space in the NS region excluding existing activities. Source: [5]

It is also possible to strategically transform the region's existing grids and networks to accommodate future sustainable solutions. Altogether, the NS region is in a frontrunner position in the European energy transition. The area can accordingly be seen as a representative region covering the critical challenges for change to a sustainable energy system and the consequences for the incumbent system. Data, models, tools, and possible solutions from the NS region will therefore constitute essential knowledge and methodologies that can be transferred to other areas in transition. The combined use of different modeling tools and concepts to understand and describe different actors' behavior is essential to provide a coherent picture of the necessary transition process of the energy systems over time and for different spatial levels.

Modeling methods and tools play a crucial role in providing insights into the energy transition. However, the modeling methodologies often ignore the details of small energy systems. More aggregated models provide more holistic pictures but cannot absorb the regional specifics and often fail to deliver meaningful results at lower spatial scales, including demand behavior. In general, models need not be necessarily larger and more complex; instead, using model collaboration, different approaches and tools are used in conjunction. Aggregated modeling should have proper parameterization and level of detail to capture the main system aspects and interactions. Similarly, disaggregated models should have proper interlinkages with potential developments and system changes across scales. The linkages between small and large-scale energy systems need to be addressed better. Developing a methodology for building models with provisions to represent small-scale and disaggregated energy systems will enable users to select the details based on the analysis's objective. The study develops a novel method to facilitate disaggregated sub-national energy systems with 100% renewable penetration and sectoral integration. Therefore, the following research question is formulated-

How to develop methodologies for building sub-national models of 100% renewable-based energy systems within the sector-coupled networks?

The Open Energy Modelling Framework (Oemof) is a useful tool for its characteristics such as flexibility, access to collaborative and interdisciplinary modeling, transparency, reliability, open-source, open data approach to enhance understanding of energy systems and accelerate the energy transition [6]. Based on the findings of [7], this study selects Oemof for developing a novel method to answer the research question. The article describes how an hourly optimization model using the framework Oemof is developed and how to use the model to analyze a sub-national energy system. The model is validated using the case study of Schleswig-Holstein (SH) in Germany. Schleswig-Holstein, the northern-most federal state of Germany, is increasingly becoming an energy hub between Germany and the Scandinavian countries due to its geographic location and the ongoing expansion of onshore wind energy.

Section 2 briefly discusses Oemof's usability for developing energy models and presents Germany's Schleswig-Holstein as a potential region to validate the sub-national energy model. Section 3 describes the architecture of the developed model using Oemof. Section 4 describes the application of the model for the case of SH. The input data and the scenarios are presented. Section 5 compares the scenarios and analyzes the results from the SH case study. Section 6 concludes with the final remarks.

2. Literature Review

Modeling methods and tools play a crucial role in providing the insights mentioned above. A broad range of available state-of-the-art energy models portrays a comprehensible picture of the energy transition over different temporal and spatial levels. However, most of these tools are not 'open' or 'free for educational use,' limiting the models' quality, transparency, and credibility. In [7], the author identified 16 'open' tools, which can be used to model 100%-renewable and sector-coupled energy systems in Europe. The proposed list of tools is presented in Table 1-

Table 1. 16 Tools for modeling 100% renewable and sector-coupled energy systems. Adapted from [7].

Sl.	Tool	Methodology	Temporal Resolution	Sectoral Coverage	Demand Response
1	Calliope	Linear Programming (LP)	User-defined	-	√
2	DESSTinEE	Simulation	Hourly	-	-
3	Dispa-SET	LP, Mixed-Integer Linear Programming (MILP)	Hourly	√	√
4	ELMOD	LP, MILP	Hourly	√	-
5	ficus	MILP	15 Minutes	√	-
6	LEAP	Simulation and Optimization	Yearly	√	-
7	LUSYM	MILP	15 Minutes, Hourly, Daily, Weekly	-	√
8	MEDEAS	Mixed	Yearly	√	-
9	Oemof	LP, MILP, Partial Equilibrium	User-defined	√	√
10	OSeMOSYS	LP	User-defined	-	√

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11	Power-GAMA	Simulation, LP	Hourly	-	-
12	PyPSA	LP	User-defined	√	√
13	RETScreen	Simulation	Daily, Monthly, Yearly	-	-
14	SIREN	Simulation	Hourly	-	-
15	SWITCH	MILP	Hourly	√	√
16	urbs	LP	User-defined	√	√

The background paper by Hilpert et al. [6] describes how Oemof can facilitate open science in energy system modeling. The article discussed the scientific contribution, concept, architecture, implementation, and usage of Oemof. Figure 2 presents a graphical representation of how to describe an arbitrary energy system using Oemof [6].

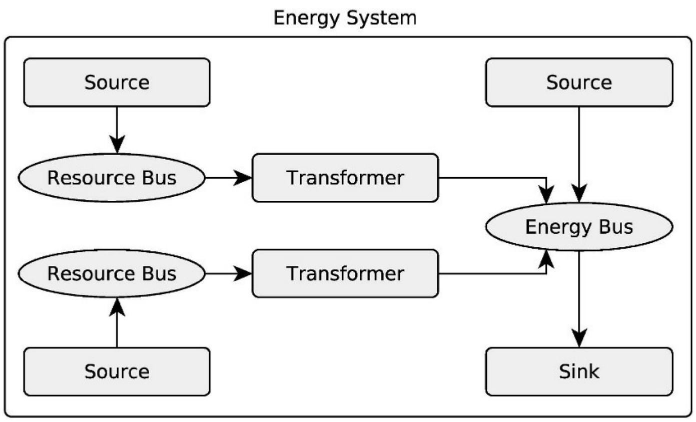

Figure 2. Schematic illustration of an energy system represented as an oemof network. Source: [6].

There are two types of nodes in Oemof- *components*, and *buses*. Every *component* has to be connected with one or more *buses*. The connection between a *component* and a *bus* is the *flow*. The main *components* of Oemof are *Sources*, *Sinks*, and *Transformers*. The *Sources* have only outflows. For example, solar photovoltaics (PV), wind turbines, and biomass commodities are modeled as *Sources*. The *Sinks* only have inflows. Consumer demands such as electricity or heat loads are modeled as *Sinks*. *Transformers* have both inflows and outflows. For example, heat pumps can be modeled as *Transformers*, which receive electricity inflow and convert it to heat outflow. There are also other *components*, such as *ExtractionTurbineCHP*, *GenericCHP*, *Link*, *GenericStorage*, *ElectricalLine*, *GenericCAES*, *SinkDSM*, etc., which are designed in the Oemof Solph package [8].

There are three ways to create an optimization problem based on Oemof-

1. The energy system describes a graph with flows on its edges by combining necessary *components* and *buses;*
2. The basic energy system is adapted by defining additional constraints on top of the aforementioned graph logic; and
3. Custom components are added to a model by subclassing from the core or creating from scratch.

The use cases can be separately or combinedly used in an energy model allowing maximum flexibility. Oemof provides existing functionalities to build energy models for varying scales. Besides, it enables the combination and adaptation of different energy models to create tools with specific research objectives. The readers are suggested to go through [6] for further details on the usefulness, usability, and applications of Oemof.

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For activities and successes in expanding renewable energies, the Schleswig-Holstein achieved first place in the federal state comparison 2019-2020 by the Agentur für Erneuerbare Energien (AEE) [9]. In 2018, electricity generation from renewable energies in SH reached around 150%, which is almost four times Germany's national average of 38%. SH takes a leading position in the expansion of electricity generation from renewable energies. The share of renewable energies in SH was almost 15.8% in the heating sector, slightly above the Germany-wide share of 14.4%. When it comes to the percentage of renewable energies in gross final energy consumption, SH's 36.6% is well above the national average of 16.5%. SH aims to generate at least 37 terawatt-hours of electricity from renewable energies by the year 2025. Figure 3 shows the individual energy sources' shares in the total final energy supply contribution of renewable energies 2018 [10].

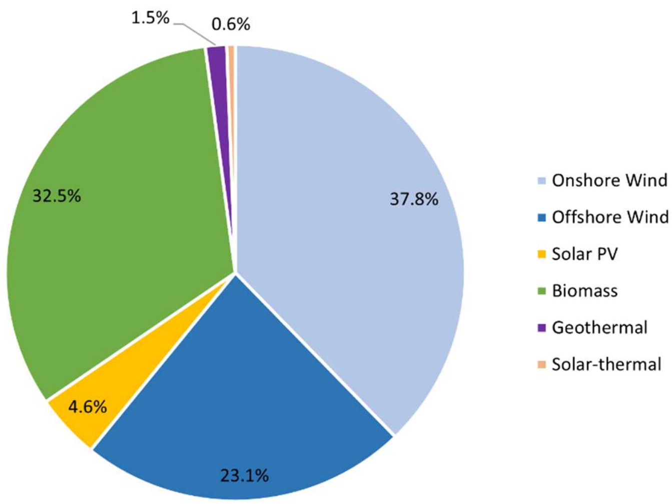

Figure 3. Shares of the renewable sources in the total renewable energy supply in Schleswig-Holstein (2018). Adapted from [10]

Due to its geographical conditions, SH is predestined for the use of wind energy. In SH, wind turbines with a nominal output of around 8.2 GW were installed by the end of 2018, which means that electricity from wind energy makes up the largest proportion of SH's electricity supply from renewable energies. SH considers the expansion of wind energy to increase to at least 25 GW by 2030. Biomass represents one of the largest shares (32.5%) of renewable energies in SH's supply contribution. Wood, energy crops, straw, and biogas can sustainably generate a significant proportion of the energy requirement. SH is well suited for solar systems, as the increased amount of wind between the seas provides natural cooling. The potential of geothermal energy in SH is particularly suitable for space heating and electricity production. Due to the lack of landscape conditions, water traditionally plays a subordinate role as an energy source in Schleswig-Holstein. Since geothermal energy does not depend on the weather or the course of the day, it is ideal for covering the base and medium loads in the heating and electricity markets. The geological subsurface is suitable for storing considerable amounts of energy carriers (e.g., hydrogen, synthetic methane), potential energy, or thermal energy. In theory, porous geological layers and cavities in the subsurface can be used for storage. The latest energy models to analyze the SH energy system should consider the compressed air energy storage capacities in geological formations. Due to the problem-free storage and the diverse and flexible application possibilities, hydrogen is a perfect link in the sector coupling. Hydrogen can make a significant contribution to the decarbonization of these areas of application and comply with the climate policy CO_2 reduction targets by 2050.

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Two points are clear from the literature review. First, Oemof can be used to develop methodologies for building energy models ranging for varying geographical and temporal scopes for highly renewable energy integrated energy systems with interlinked sectors. Second, Schleswig-Holstein is an ideal sub-national region to validate the developed energy model for its prospects in expanding renewable energies across all sectors. Therefore, the study uses Oemof to build an open sector-coupled sub-national energy model and validates it for SH's case.

3. Model Architecture

3.1. Elements and Objective Function

The study develops a unique hourly optimization tool using a hybrid approach. The technological capacities are exogenously set, and the investment capacities are endogenously resolved. Technical limits set the boundary of the system so that the solutions are realistic. The sub-national model, 'Open Sector-coupled Energy Model for Sub-national Energy Systems (OSeEM-SN)', is created using Oemof Tabular [11]. Figure 4 illustrates the OSeEM-SN energy model.

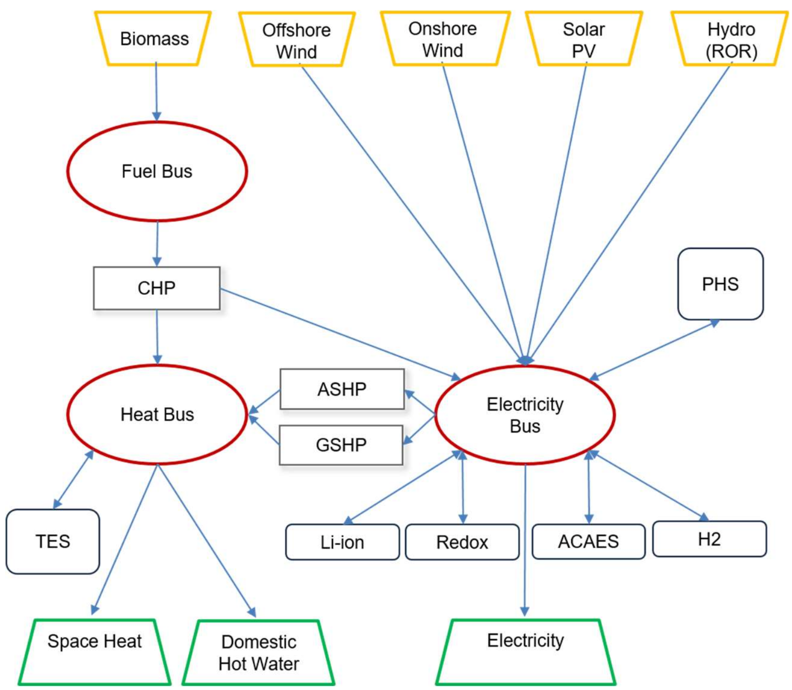

Figure 4. Simplified block diagram of the OSeEM-SN model

The model presents SH as a self-sufficient energy system, where the demands are met using its renewable resources. In the real case, other energy systems are connected with the SH system; for example, the neighboring region's electricity bus will be connected with SH's electricity bus using a transmission line (transshipment approach), which uses the Oemof class *Link*. For visualizing such energy systems, the readers are suggested to look into [12] where the author connected two energy systems using *Link*. The model also does not consider industrial process heating because of limited data availability and model complexity of high-temperature technologies. The *nodes* (i.e., *components* and *buses*) of the OSeEM-SN model according to the Oemof Classes are presented in Table 2.

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Table 2. List of all components and buses of the OSeEM-SN model

Oemof Class	Nodes	Remarks
Bus	Electric Bus	Represents grid or network without losses.
	Heat Bus	
	Fuel Bus	
Sink	Electricity	Represents the electricity and building heat demands in the energy system.
	Space Heat	
	Domestic Hot Water (DHW)	
Source	Offshore Wind	Represents the volatile generators of the energy system.
	Onshore Wind	
	Solar PV	
	Hydro Run-of-the-river (ROR)	
	Biomass	Represents the biomass commodities which are fed into the CHP plants.
ExtractionTurbineCHP	Combined Heat and Power (CHP)	Represents the heat generators of the energy system. The OSeEM-SN model uses extraction turbines and uses only biomass as the fuel.
Transformer	Air Source Heat Pump (ASHP)	Complements CHP for meeting heating demands.
	Ground Source Heat Pump (GSHP)	
GenericStorage	Li-ion (Li-ion)	Represents batteries.
	Vanadium Redox Flow (Redox)	
	Adiabatic Compressed Air Energy Storage (ACAES)	Simplified model as Generic Storage. Presents electricity storage.
	Hydrogen (H_2)	
	Pumped Hydro Storage (PHS)	Storage units with constant inflow and possible spillage. The storage capacity is not expandable.
	Thermal Energy Storage (TES)	Simplified model as Generic Storage. Presents heat storage in sensible hot water tanks.

The OSeEM-SN model follows the formulation described by Hilpert [13]. The model limits the volatile generators, biomass commodities, and storage capacities by putting maximum limits. However, the limit for using heat pumps depends on the electricity availability. OSeEM-SN uses a perfect foresight approach, indicating the weather and

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renewable data are provided in advance. Detailed mathematical formulations for the OSeEM-SN model follow the modeling equations presented by Maruf [12]. The model optimizes the operating and investment costs of all the volatile generators, CHP, heat pumps, and storages. The endogenous variables are presented using x and the exogenous parameters are presented using c as listed in Table 3.

Table 3. Variables and parameters for cost optimization of OSeEM-SN

Variables/Parameters	Description	Technology
x_v^{flow}	Flow of volatile generator unit v	Offshore Wind
$x_v^{capacity}$	Capacity of volatile generator unit v	Onshore Wind Solar PV
$c_v^{marginal\_cost}$	Marginal cost[1] of volatile generator unit v [12]	Hydro ROR
$c_v^{capacity\_cost}$	Capacity cost[2] of volatile generator unit v [12]	
x_{chp}^{flow}	Flow of CHP unit chp	CHP
$x_{chp}^{capacity}$	Capacity of CHP unit chp	
$c_{chp}^{marginal\_cost}$	Marginal cost of CHP unit chp	
$c_{chp}^{capacity\_cost}$	Capacity cost of CHP unit chp	
x_h^{flow}	Flow of heat pump unit h	ASHP GSHP
$x_h^{capacity}$	Capacity of heat pump unit h	
$c_h^{marginal\_cost}$	Marginal cost of heat pump unit h	
$c_h^{capacity\_cost}$	Capacity cost of heat pump unit h	
x_s^{flow}	Flow of storage unit s	Li-ion
$x_s^{capacity}$	Capacity (power) of storage unit s	Redox ACAES
$x_s^{storage\_capacity}$	Storage capacity (energy) of storage unit s	H_2 PHS (No Investment)
$c_s^{marginal\_cost}$	Marginal cost of storage unit s	TES
$c_s^{capacity\_cost}$	Capacity cost (power) of storage unit s	
$c_s^{storage\_capacity\_cost}$	Storage capacity cost (energy) of storage unit s	

[1] The marginal costs are calculated based on variable operation and maintenance costs, carrier costs, and the efficiency.
[2] The capacity costs are calculated based on fixed operation and maintenance costs, and the annuity.

The objective function of OSeEM-SN is created from all instantiated objects which use all operating costs and investment costs arguments:

$$min: \sum_{v,t} \overbrace{x_v^{flow}(t) \cdot c_v^{marginal\_cost}}^{operating\_cost\ Volatile\ Generator} + \sum_{v} \overbrace{x_v^{capacity} \cdot c_v^{capacity\_cost}}^{investment\_cost\ Volatile\ Generator} + \sum_{chp,t} \overbrace{x_{chp}^{flow}(t) \cdot c_{chp}^{marginal\_cost}}^{operating\_cost\ CHP} + \sum_{chp} \overbrace{x_{chp}^{capacity} \cdot c_{chp}^{capacity\_cost}}^{investment\ cost\_CHP} + \sum_{h,t} \overbrace{x_h^{flow}(t) \cdot c_h^{marginal\_cost}}^{operating\_cost\ Heat\ Pump} + \sum_{h} \overbrace{x_h^{capacity} \cdot c_h^{capacity\_cost}}^{investment\_cost\ Heat\ Pump} + \sum_{s,t} \overbrace{x_s^{flow}(t) \cdot c_s^{marginal\_cost}}^{operating\_cost\ Storage} + \sum_{s} \overbrace{x_s^{capacity} \cdot c_s^{capacity\_cost} + x_s^{storage\_capacity} \cdot c_s^{storage\_capacity\_cost}}^{investment\_cost\ Storage} \quad (1)$$

3.2. Development Methodology

OSeEM-SN considers the existing capacities of the volatile generators and PHS. The model also assumes that the current biomass and biogas capacities are converted to CHPs. The maximum potentials of the resources limit the investment capacities of additional volatile generators and CHPs. The storage capacities are expandable to their utmost limits, except PHS, where no further capacity expansion is possible. Heat pump expansion depends upon the availability of power from renewable electricity resources. The model also uses cost and demand data as inputs of the model. After investment and dispatch optimization, the model outputs such as investment capacities can be obtained. Details of the model input and output are presented in Figure 5.

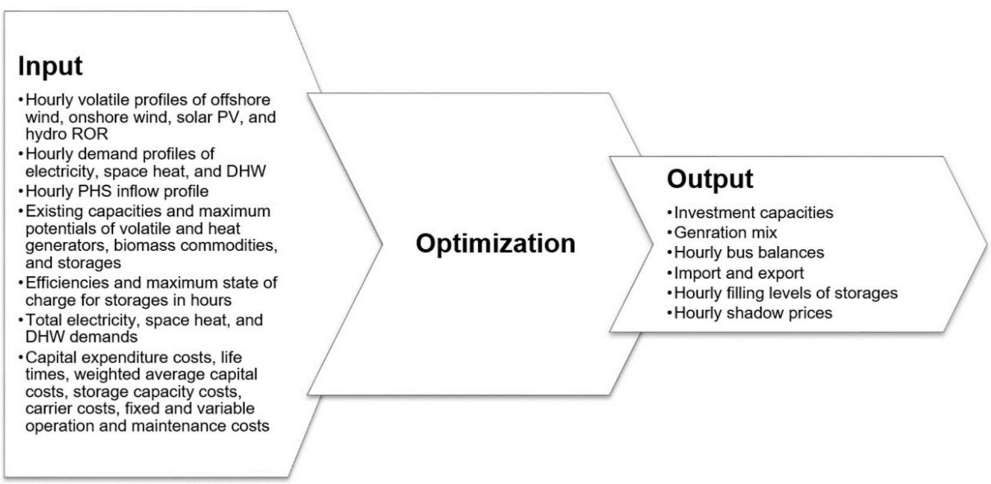

Figure 5. OSeEM-SN Input and Output

The OSeEM-SN model is developed using a Python Script, Oemof Solph, Oemof Tabular, and tabular *.csv* data files. The development methodology steps for OSeEM-SN are stated below.

1. Importing necessary data packages (Python Script)
2. Setting up the input datapath (Python Script)
3. Setting up the result directory (Python Script)

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4. Reading input data (Python Script)
5. Creating the energy system (Oemof Solph)
6. Creating the buses (Oemof Solph)
7. Adding buses to the energy system (Oemof Solph)
8. Adding components to the energy system (Oemof Tabular)
9. Reading demand data (Oemof Tabular)
10. Creating the Model (Oemof Solph)
11. Solve the optimization problem (Oemof Solph)
12. Post-processing of results (Oemof Tabular)
13. Writing results (Oemof Tabular)
14. Plotting results (Oemof Tabular)

Data preparation is an essential step of the model development process, where the data are normalized and scaled for use as the input of OSeEM-SN. For different scenarios, the input data are varied in the data handling stage.

4. Model Validation: Case of Schleswig-Holstein

4.1. Hourly Renewable Profiles and Demand Data

The OSeEM-SN model is validated using historical data for a full year. According to [14], data from 2011 are used for analyzing 2050 scenarios, except for hydro data which uses 2016 data. Table 4 shows the hourly input data sources used for validating the OSeEM-SN model.

Table 4. Hourly input data sources for the OSeEM-SN model

Data	Source	Remarks
Wind profiles Solar PV profiles	Renewables Ninja project [15]	Based on the MERRA-2 dataset.
Hydro ROR inflow PHS scaled inflow	Dispa-SET project [16]	-
Electricity demand	OPSD project [17]	Based on the ENTSO-e statistical database [18].
Space heat demand	OPSD project [17]	Based on the When2Heat dataset [19]

The onshore wind profile is obtained from the MERRA-2, current fleet dataset for the NUTS-2 region (SH: DEF0). The offshore wind profile represents the offshore profile of Germany based on the MERRA-2 database. The solar PV profile is also obtained for SH (NUTS2, DEF0). The hydro ROR and PHS scaled inflows are obtained from Dispa-SET's 2016 data. The Inflows are defined as the contribution of exogenous sources to the level (or state of charge) or the reservoir. Scaled inflows are normalized values of the inflow concerning the nominal power of the storage unit. The PHS inflows are scaled down to match SH's inflow profile (in MWh). Germany's demand data (electricity, space heat, DHW) are downscaled based on population to represent SH's hourly demand profiles. The wind, solar, and hydro normalized profiles do not change in the scenarios and can be visualized as shown in Figure 6.

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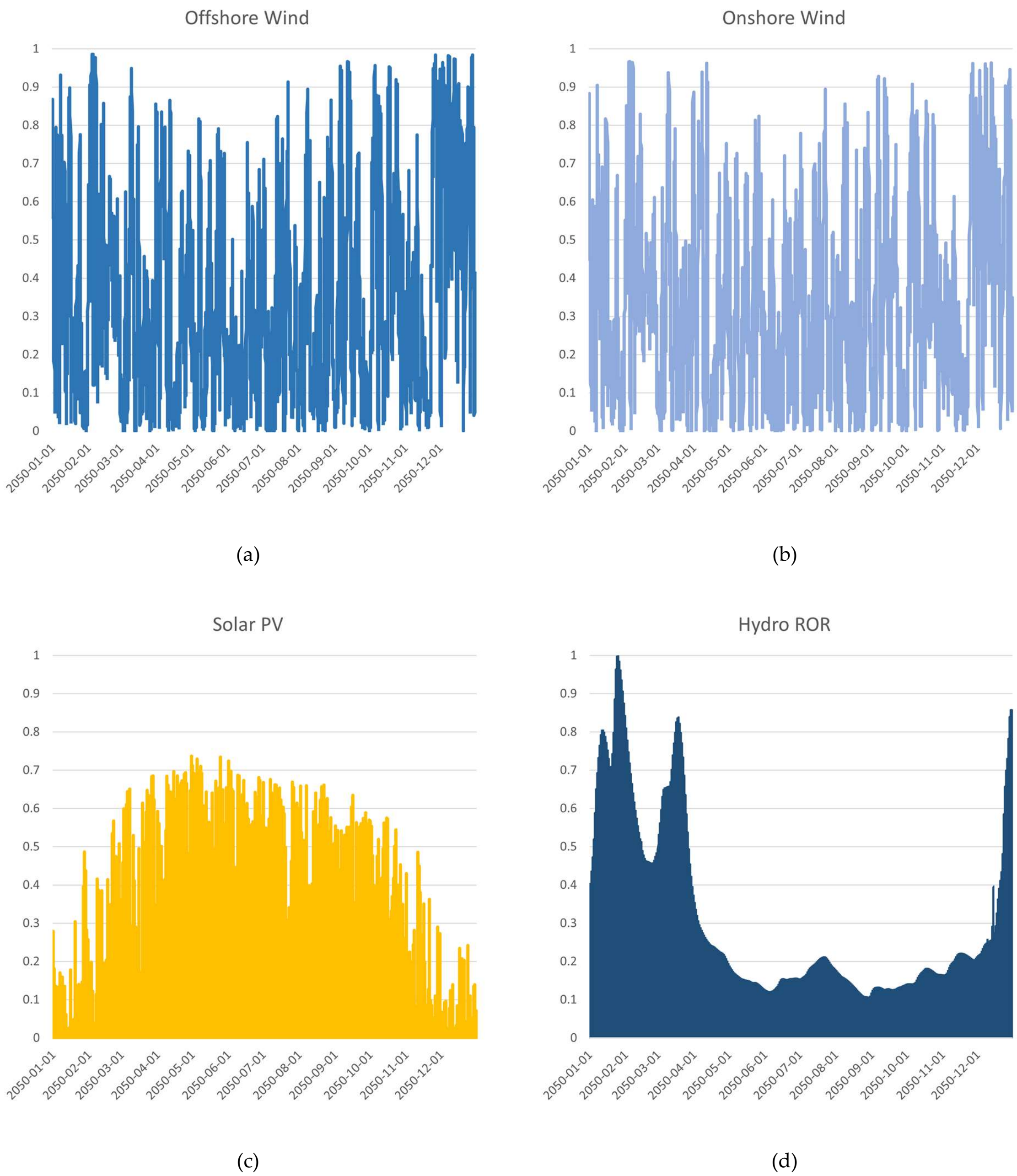

Figure 6. Normalized input profiles of volatile generators of OSeEM-SN model (a) offshore wind (b) onshore wind (c) solar PV (d) hydro ROR

Figure 7 shows the normalized demand profiles of SH in 2050. The total electricity demand for SH in 2050, based on the representative year, is 18.6 TWh_{el}. Total space heat demand is 18.6 TWh_{th}, and the DHW demand is 4 TWh_{th}. The amount of available biomass is calculated from the Hotmaps project [20]. The study assumes that the existing biomass and biogas power plants are converted to CHP plants by 2050. CHP's electrical and thermal efficiencies are assumed 45%, and the condensing efficiency is assumed 50%. The COP of ASHP and GSHP are assumed 2.3 and 3.9 [21].

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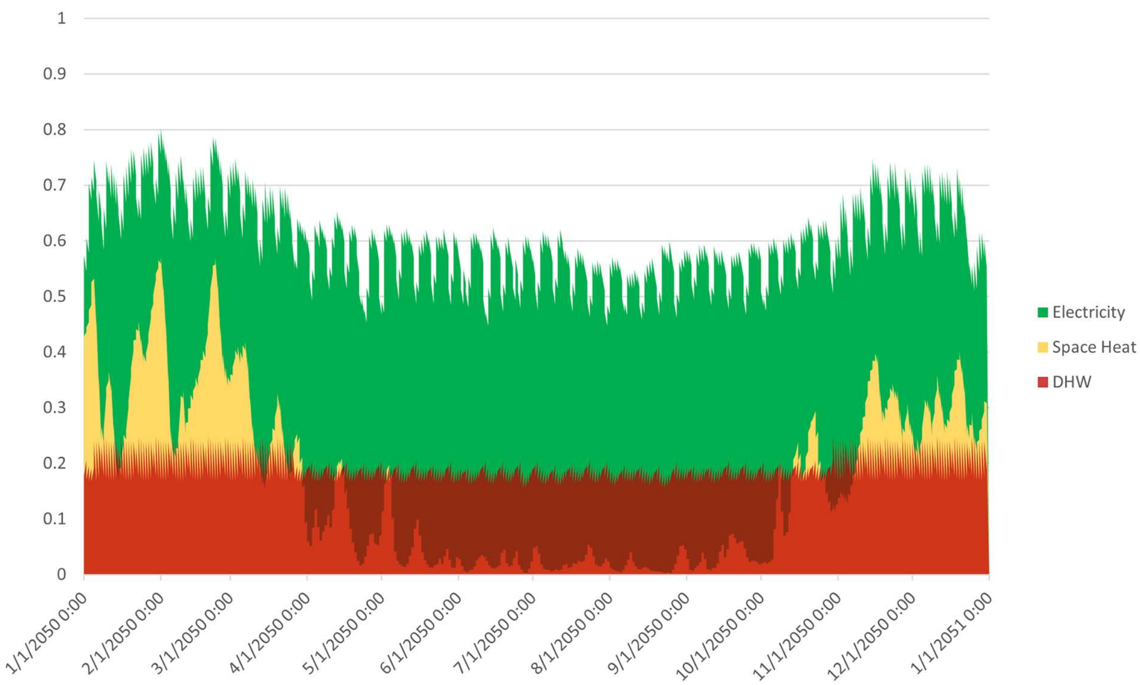

Figure 7. Normalized demand profiles of SH in 2050

4.2. Capacity and Available Potential

The existing capacities and available potentials for the volatile generators and the storage investments are taken from different sources, namely Hotmaps project [20], ANGUS II project [21], Deutsche WindGuard [22], AEE [23], LIMES-EU project [24], as listed in Table 5. The available potentials are calculated from the maximum potentials and the existing capacities. The Li-ion, Redox, and H_2 potentials are assumed to be 5% of Germany's available potentials, as stated in the project databases. The ACAES potential is assumed to be 50% of Germany's total potential because of its availability in only Northern Germany.

Table 5. Capacity and available potential for volatile generators and storage in SH in 2050

Technology	Existing Capacity	Available Potential
Onshore Wind [GW_{el}]	7 [22]	1.9 [23]
Offshore Wind [GW_{el}]	1.7 [22]	25.2[1] [24]
Solar PV [GW_{el}]	1.6 [23]	6.7 [23]
Hydro ROR [MW_{el}]	2 [23]	4 [23]
Biomass & Biogas	1 GWh [23]	21.8 PJ [20]
Li-ion [MW_{el}]	-	782.5 [21]
Redox [MW_{el}]	-	46.5 [21]

H_2 [MW_{el}]	-	505 [21]
ACAES [MW_{el}]	-	1715.5 [21]
PHS [MW_{el}]	120 [25]	-
TES [MW_{th}]	-	1000[2]

[1]The maximum offshore wind potential according to the LIMES-EU project is 83.6 GW_{el}. The available potential of SH assumes the equal distribution of remaining capacities in the three Northern states of Germany.

[2] Own assumption

4.3. Cost Data

Table 6 presents the cost data taken from various resources as described in [12].

Table 6. Cost data for OSeEM-SN Model [12].

Technology	Onshore Wind	Offshore Wind	PV	ROR	Biomass	Li-ion	H_2	Redox	PHS	ASHP	GSHP	ACAES	TES
Capex (€/kW)	1075	2093	425	3000	1951	35	1000	600	2000	1050	1400	750	0
Lifetime (Years)	25	25	25	50	30	20	22.5	25	50	20	20	30	20
WACC	0.025	0.048	0.021	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
VOM Cost (€/MWh)	0	0	0	0	11.3	1	1	1	0	0	0	1	0
FOM Cost (€/kWh)	35	80	25	60	100	10	10	10	20	36.75	49	10	0.38
Storage Capacity Cost (€/kWh)	-	-	-	-	-	187	0.2	70	-	-	-	40	38
Carrier Cost (€/MWh)	-	-	-	-	34.89	-	-	-	-	-	-	-	-

4.4. Other Input Data

The loss rates are 1% for PHS, and 1.4% for TES [21]. Hydro ROR efficiency is 90% [21]. The roundtrip efficiencies are 92%, 80%, 46%, 75%, 73% and 81% for Li-ion, Redox, H_2, PHS, ACAES, and TES [21]. The maximum state of charge capacity in terms of hours at full output capacities are 6.5 hours, 3.3 hours, 168 hours, 8 hours, 7 hours, and 72 hours

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for Li-ion, Redox, H_2, PHS, ACAES, and TES [21]. Land limitation for onshore wind is 4 MW/km², and offshore wind is 6 MW/km² [24]. The solar PV installations consider the protection of nature reserves and restricted zones.

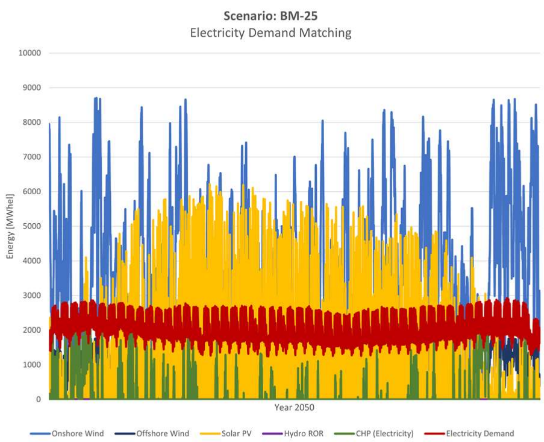
4.5. Scenarios

The study assumes three scenarios for validating the OSeEM-SN model for Schleswig-Holstein- BM-25, BM-50, and BM-100. The scenarios represent 25%, 50%, and 100% of the total available biomass potentials, respectively. The study aims to investigate how the results change upon varying one parameter of the model. However, the model does not account for all the parametric variations for the input data; rather, it focuses on the model's usability to create different scenarios and examine different possible pathways.

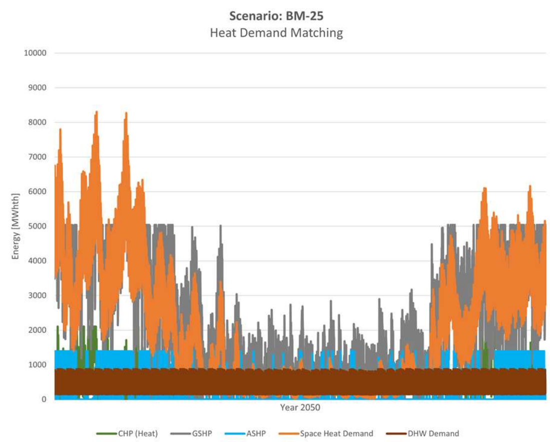
5. Discussion

5.1. Supply-Demand Matching

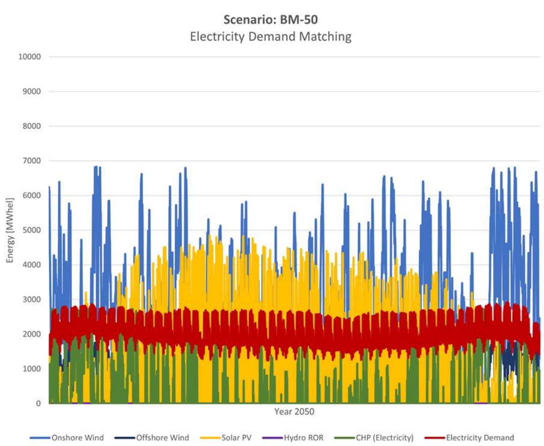
The OSeEM-SN model reached feasible solutions for all three scenario assumptions. Figure 8 shows the supply-demand matching of electricity and heat demands for the three different scenarios over the year 2050.



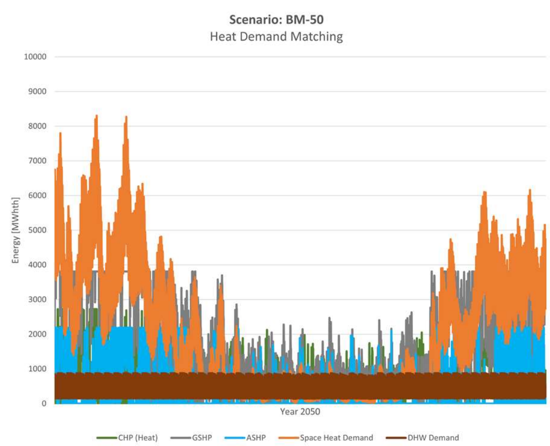
(a)



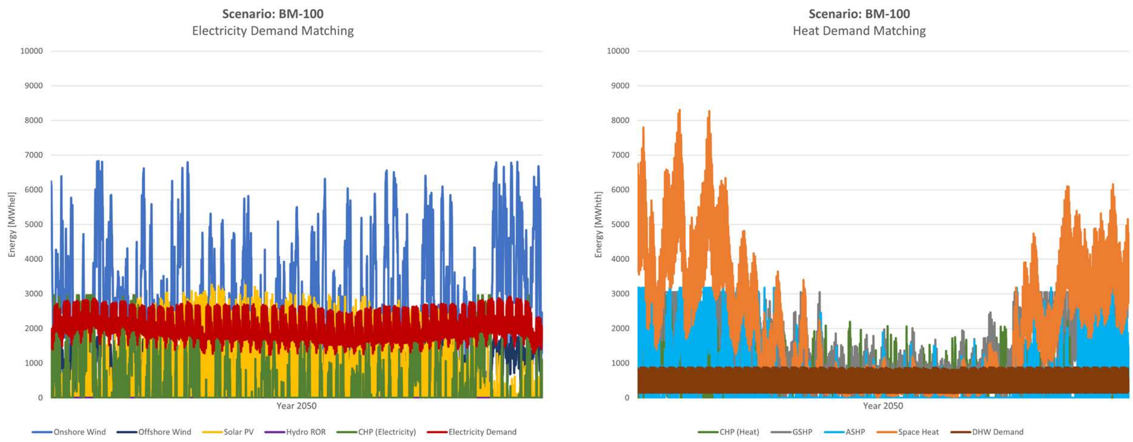
(b)



(c)



(d)



(e) (f)

Figure 8. Supply-demand matching for the three scenarios over the year 2050 (a) BM-25 electricity demand matching (b) BM-25 heat demand matching (c) BM-50 electricity demand matching (d) BM-50 heat demand matching (e) BM-100 electricity demand matching (f) BM-100 heat demand matching.

The energy generation from onshore wind in BM-25 is 26.6 TWh_{el}, which drops to 20.9 TWh_{el} in BM-50 and BM-100 scenarios. Similarly, solar PV generation drops from 8.7 TWh_{el} in the BM-25 scenario to 6.8 TWh_{el} in the BM-50 scenario and 4.6 TWh_{el} in the BM-100 scenario. Offshore wind generation remains the same, 5.5 TWh_{el}, in all three scenarios. The CHP generation for electricity and heat increases with increasing biomass availability in the scenarios, from 1.5 TWh in the BM-25 to 3 TWh in the BM-50 scenario and 3.8 TWh in the BM-100 scenario. In contrast, heat pump (GSHP and ASHP) generation reduce from 21.5 TWh_{th} in BM-25 to 18.9 TWh_{th} in the BM-100 scenario. Therefore, it is obvious from the scenarios that- with increasing biomass penetration in the energy mix, the CHP plant capacities are expanded, increasing electricity and heat generation. This, in turn, reduces the expansion of other power plants and heat pumps to meet the demands.

5.2. Scenario Comparison

5.2.1. Capacity Expansion

According to the optimization from OSeEM-SN, the required investment of different technologies can be obtained. Table 7 compares the required investments on top of the existing capacities of Table 5 for the three scenarios.

Table 7. Comparison of capacity expansion for three scenarios.

Technology	**Scenario-wise Investments**		
	BM-25	**BM-50**	**BM-100**
Onshore Wind [GW_{el}]	1.9	0	0
Offshore Wind [GW_{el}]	0	0	0
Solar PV [GW_{el}]	6.7	4.9	2.7
Hydro ROR [MW_{el}]	4	4	4

CHP [GW]	1	1.6	1.9
GSHP [GW_{th}]	5	3.8	3
ASHP [GW_{th}]	1.3	2.1	3.1
Li-ion [MW_{el}]	782.5	782.5	782.5
Redox [MW_{el}]	46.5	46.5	46.5
H_2 [MW_{el}]	397	0	0
ACAES [MW_{el}]	357.1	357.1	357.1
TES [MW_{th}]	1000	460.2	0

The results show no need for additional investment in offshore wind plants to meet SH's energy demand. As a result, the offshore capacities can be reserved for supplying other states' energy demand, especially those in Southern Germany. CHP investment rises because of the higher availability of biomass over the three scenarios and the high overall efficiency due to the combined production of electricity and heat. This impacts the investment in onshore wind and solar PV capacities and reduces investments in volatile generators. GSHP investment also decreases with increasing CHPs; however, ASHP investment increases to complement the heating demand. For storage, Li-ion, Redox, and ACAES are used to their maximum investment capacities for all three scenarios. Hydrogen storage is used only in the BM-25 scenario, indicating its use only in low biomass availability cases. The need for TES storage decreases over the scenarios with more biomass availability. Therefore, with limited biomass, it is possible to meet the heat demand with a heat storage option.

5.2.2. Investment Cost

The study calculates the annual investment cost (AIV) by multiplying the Annuity with the model's optimized capacity, as shown by (2). The Annuity calculation is shown in (3) which considers the capital expenditure (Capex), weighted average cost of capital (WACC), and the lifetime (n). The total investment cost (TIV) is obtained by multiplying the Capex and the model's optimized capacity, as shown by (4). In the case of storage, the investment cost considers both power and energy costs.

$$c^{AIV} = c^{Annuity} \cdot c^{optimized\_capacity} \quad (2)$$

$$c^{Annuity} = c^{Capex} \cdot \frac{(c^{WACC} \cdot (1 + c^{WACC})^{n}}{((1 + c^{WACC})^{n} - 1)} \quad (3)$$

$$c^{TIV} = c^{Capex} \cdot c^{optimized\_capacity} \quad (4)$$

Figure 9 compares the volatile generators' investment cost, i.e., wind, solar PV, and hydro ROR plants. We see that the total investment cost for the volatile generators in SH decreases by 76% (4.9 bn € vs. 1.1 bn €) over the scenarios. The annual investment cost decreases from 262.7 mn €/yr to 61.5 mn €/yr with the increasing biomass availability.

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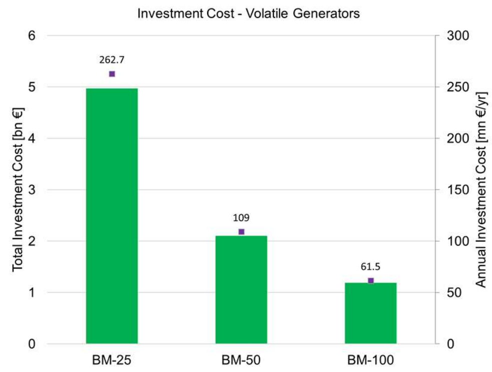

Figure 9. Comparison of volatile generator investments in SH

Figure 10 compares the investment cost of CHP plants and heat pumps (GSHP and ASHP). Overall, the total investment cost increases by 7% (10.6 bn € vs. 11.3 bn €) over the scenarios. The annual investment cost increases from 819.2 mn €/yr in the BM-25 scenario to 853.7 mn €/yr in the BM-100 scenario.

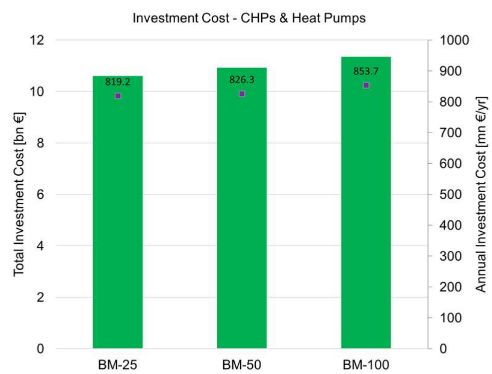

Figure 10. Comparison of CHP and heat pump investments in SH

Figure 11 compares the storages' investment cost, i.e., Li-ion, Redox, H_2, ACAES, and TES. The total investment cost for the storages in SH decreases by 69% (4.5 bn € vs. 1.3 bn €) over the scenarios. The annual investment cost decreases from 357.6 mn €/yr in the BM-25 scenario to 105.1 mn €/yr in the BM-100 scenario.

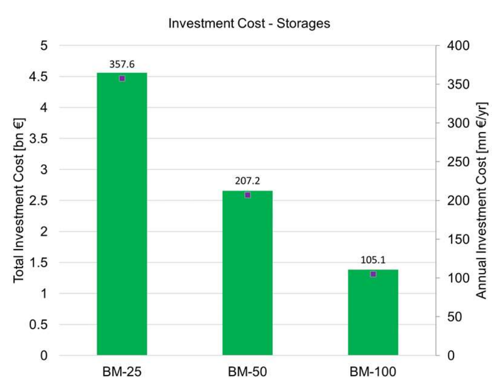

Figure 11. Comparison of storage investments in SH

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The total investment in volatile generators, CHPs, and storages is 20.1 bn € in the BM-25 scenario. The investment decreases by 22% in the BM-50 scenario (15.6 bn €) and 30% in the BM-100 scenario (13.9 bn €). The annual investment cost decreases accordingly, from 1.44 bn €/yr in the BM-25 scenario to 1.02 bn €/yr in the BM-100 scenario. Figure 12 illustrates the total investments for different scenarios from OSeEM-SN optimization results.

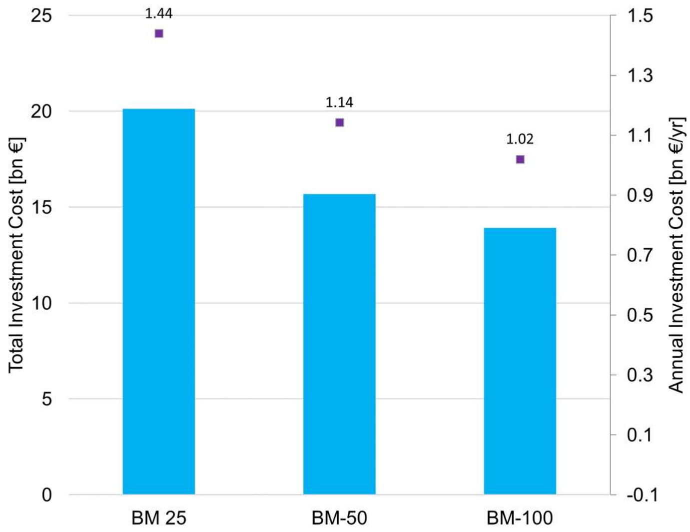

Figure 12. Comparison of total investments (volatile generators, CHPs, and storages) in SH

5.2.3. Energy Mix

Figure 13 compares the energy mix results of the OSeEM-SN model. Figure 13 (a) compares the electricity generation from the combined (i.e., existing, and new) capacities. The onshore wind generation dominates the energy mix because of high wind availability in SH. The onshore wind electricity generation varies between 20.9 TWh_{el} and 26.6 TWh_{el} for the three scenarios. The model does not suggest installing new offshore capacities because of two reasons- (i) the cost of offshore is higher, and (ii) the demand is already met using other resources. However, this is only valid for SH's sub-national case, where plenty of renewable resources are available. The scenario will be different for a larger case with a lack of adequate renewable resources. The offshore electricity generation from the existing capacities is the same for the three scenarios, 5.5 TWh_{el}. The hydro ROR electricity generation also remains the same, 0.016 TWh_{el} for all three scenarios. Solar PV-based electricity varies from 8.7 TWh_{el} in the BM-25 scenario to 4.6 TWh_{el} in the BM-100 scenario. Overall, the electricity generation decreases by 17% (42.4 TWh_{el} vs. 34.9 TWh_{el}) from the BM-25 scenario to the BM-100 scenario. Therefore, with high biomass-based CHPs in the energy mix, the curtailment from other variable renewable energy plants can be decreased. Figure 13 (b) compares the heat generation from the combined CHP capacities and new heat pump capacities. GSHPs dominate the heat mix; however, the installation of GSHP decreases as the biomass penetrates more into the energy mix. From BM-25 to BM-100 scenario, while the CHP-based heat generation increases by 154% (1.51 TWh_{th} vs. 3.84 TWh_{th}), the GSHP installation decreases by 28% (19.8 TWh_{th} vs. 14.1 TWh_{th}). However, the demand is also complemented by ASHPs, which increase from 1.69 TWh_{th} in the BM-25 scenario to 4.79 TWh_{th} in the BM-100 scenario.

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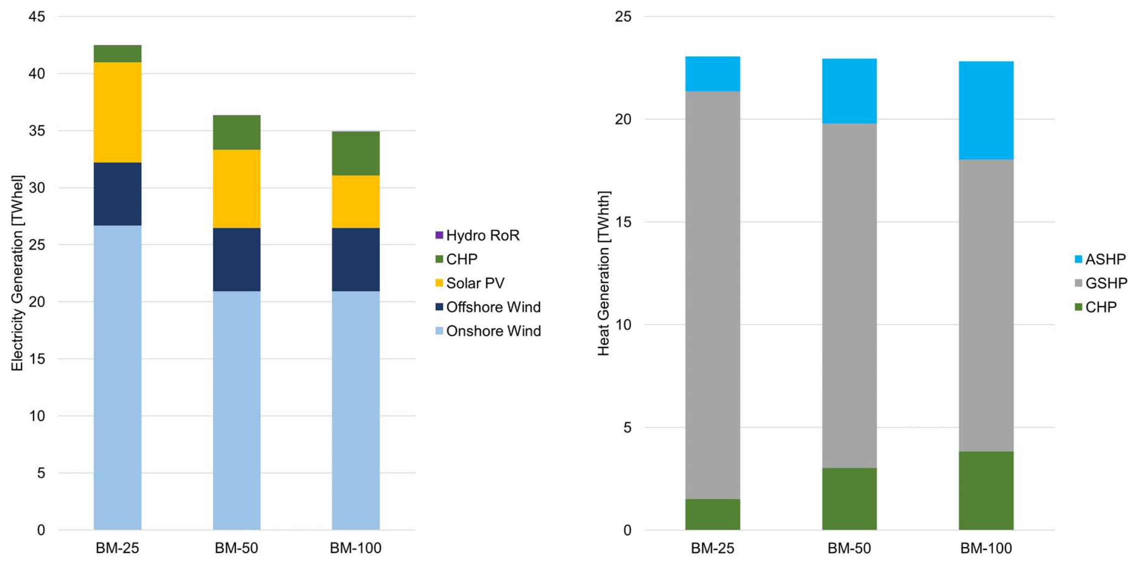

(a) (b)

Figure 13. Energy mix for different scenarios in SH (a) electricity mix (b) heat mix

The analysis based on OSeEM-SN model results is summarized below-

1. SH has adequate renewable resources to meet its electricity and building heat demands.
2. The onshore wind dominates electricity generation.
3. Electric heat pumps, mainly GSHPs, dominate heat generation.
4. The batteries offer short-term storage solutions for electricity storage.
5. ACAES, H_2, and TES are promising storage solutions, especially when renewable energy availability is limited.
6. Power-to-heat devices, such as GSHP and ASHP, stand out as prominent heating options besides traditional CHPs.
7. TES plays an important role in integrating the power and heat sectors.
8. Increasing biomass in the system impacts other technologies' investment costs and can reduce the overall system cost.
9. The optimization reached feasible solutions without utilizing the full potential of many resources. Therefore, the high amount of available potential, especially offshore wind resources, emerges as a promising alternative for powering up other parts of the country, especially Germany's high energy-consuming industrial southern states.

5.3. Limitations of the Study

The model is in its early stage of development, and therefore the analysis conducted in this study is subject to certain limitations. Since the results highly depend on the inclusion of different technologies and demands, the results may change based on the newer version of the model with more components and demands. This will also broaden the scope of the model to use it for different geographical contexts. The current version of the OSeEM-SN model does not consider-

1. Geothermal, ocean and wave energy, concentrated solar power plants, etc.;
2. Industrial process heating demands;
3. Transmission line modeling;
4. Latent and thermo-chemical heat storages as TES options;
5. Interconnection with neighboring regions;

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6. Modeling of electric vehicles, coupling of the transport sector, and provision of vehicle-to-grid charging;
7. Renewable heating options, such as using solar thermal collectors; and
8. Demand response management.

Nevertheless, as a continuous development of the model, future versions will gradually include different technologies, demands, and other components into the model.

6. Conclusion

This study's main objective is to develop methodologies for building sub-national models of 100% renewable and sector-coupled energy systems. The model used Oemof Tabular to develop a state-of-the-art tool, to analyze sub-national energy systems. The model consists of the basic renewable resources and storage options to meet the electricity and building heat demands. Oemof Solph's functionalities are used for the core part of the model. Simple Python scripts and tabular data files allow the user to change the model's input details and analyze energy systems for different scenarios.

The study validates the model for Schleswig-Holstein's energy system analysis. The OSeEM-SN model optimized three different scenarios for different available biomass potentials. The model could reach feasible solutions for all three scenarios, indicating the feasibility of a 100% renewable and power-building heat coupled energy system for Schleswig-Holstein. Analysis of the results shows that, with increasing biomass availability, volatile generator investment decreases. The increasing amount of biomass-based CHP plants impacts both the electricity and heat generation mix.

The study also identifies the current limitations of the model. Since the model is based on Oemof, the model's upgradation is possible using different functionalities under the Oemof framework. The model has been validated with SH's case study, and the results have been analyzed in detail in the study. Therefore, the OSeEM-SN model is presented as a beneficial tool to create different scenarios and examine different possible pathways for sub-national energy systems of similar contexts.

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Data Availability Statement: Data, source codes, and results of the model is available in the following Github repository [26]: https://github.com/znes/OSeEM-SN.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

List of Abbreviations

Abbreviation	Elaboration
ACAES	Adiabatic Compressed Air Energy Storage
AEE	Agentur für Erneuerbare Energien (Agency for Renewable Energies)
AIV	Annual investment cost

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ASHP	Air source heat pump
bn	Billion
Capex	Capital expenditure
CHP	Combined heat and power
CO_2	Carbon dioxide
DHW	Domestic hot water
el	Electrical
EU	European Union
FOM	Fixed operation and maintenance
GSHP	Ground source heat pump
GW	Gigawatt
GWh	Gigawatt-hours
H_2	Hydrogen
hr	Hour
kW	Kilowatt
kWh	Kilowatt-hours
Li-ion	Lithium-ion
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
mn	Million
MW	Megawatt
MWh	Megawatt-hours
Oemof	Open Energy Modelling Framework
NS	North Sea
OSeEM-SN	Open Sector-coupled Energy Model for Sub-national Energy Systems
PHS	Pumped hydro storage
PV	Photovoltaic
Redox	Vanadium Redox Flow
ROR	Run-of-the-river

SH	Schleswig-Holstein
th	Thermal
TIV	Total investment cost
TW	Terawatt
TES	Thermal energy storage
TWh	Terawatt-hours
VOM	Variable operation and maintenance
WACC	Weighted average capital cost

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