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Energy Supply Modelling of a Low-CO_2 Emitting Energy System: Case Study of a Danish Municipality

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Abstract

Many municipalities in Denmark strive to decrease their CO_2 emissions substantially within next 10-15 years, primarily by switching from fossil fuels to solid biomass, wind power and solar power in energy production. However, if these plans were to be realized, Denmark would need to import substantial amounts of biomass to cover the total national demand, hindering the sustainability of this solution.

The municipality of Sønderborg aims to reach zero net CO_2 emissions by 2029. We investigated different scenarios to see how Sønderborg municipality could approach this target in the most energy-efficient and cost-effective way while simultaneously keeping the biomass and waste consumption close to the limits of the locally available residual resources.

We constructed five scenarios representing the state of Sønderborg's energy system in 2029, each scenario emphasizing a different portfolio of energy conversion units. We simulated these scenarios using Sifre, a new mixed-integer linear optimization tool developed by the Danish Transmission Systems Operator, Energinet.dk. We compared the simulation results for the five scenarios based on the total system cost, the total energy system efficiency, the net system CO_2 emissions and the total biomass consumption. Furthermore, we performed a sensitivity analysis of the results.

The results show that scenarios incorporating electrolysis and reversible electrolysis have the lowest total socio-economic system cost and the lowest CO_2 emissions, but the scenario with large share of heat pumps has the highest overall output/input efficiency and the lowest biomass consumption. However, if biomass prices dropped, the scenario with large biomass consumption would have the lowest socio-economic costs.

We conclude that in order to achieve their CO_2 emission goals in the most energy- and cost-effective way, municipalities the size of Sønderborg should compare a wide range of energy system configurations, including a high degree of electrification and a limited biomass use.

Highlights

- Future energy system scenarios development and simulation for Sønderborg, Denmark
- Hourly simulation over a year using the linear optimization tool Sifre
- Lowest cost and CO_2 emissions by using heat pumps, solar heating and electrolysis

Keywords

energy system modelling; renewable energy; Sifre simulation; mixed-integer linear optimization; energy conversion; electrolysis

1 Introduction

Municipal activities play an important role in national and global CO_2-emission reduction efforts. The current Danish government has changed the previous targets of achieving CO_2-free electricity and heat supply by 2035 and transport by 2050. Beside the target of reaching 30% renewables in the final energy consumption in 2020 (according to the EU's climate and energy package from 2008) [1], the policy of the current government is to reduce greenhouse gas (GHG) emissions in 2020 by 20% compared to 2005 in non-quota sectors (transport, agriculture and individual heating). Denmark is close to achieving these goals already now. The targets for 2030 are yet to be stated, but are expected to follow the EU goal of 30% GHG reduction in 2030 in non-quota sectors. The long-term target for 2050 is to become independent from fossil fuels, understood as producing enough renewable energy to supply the total Danish energy consumption on an average annual basis. [2]

Most Danish municipalities have stated some future CO_2 goals. Among the most ambitious ones is Sønderborg, a municipality of about 75,000 residents, located in Denmark on the Southern Jutland peninsula (see Figure 1). Already in 2009 the municipality decided to become CO_2-neutral by 2029. Being a typical middle-sized city in the Danish context, Sønderborg's energy system is small enough to allow a sufficiently detailed system simulation, yet complex enough to represent an urban-scale energy system case.

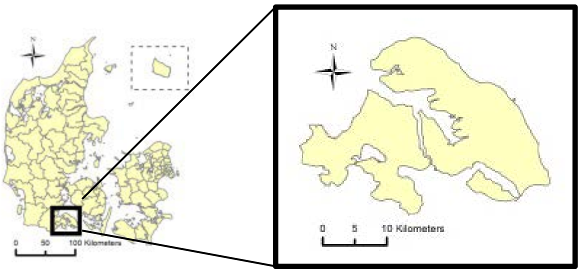

Figure 1 Location of Sønderborg municipality, Denmark.

While most countries have formulated strategies for lowering their CO_2 emissions, regions and municipalities often develop their strategies independently. Thus, ensuring the consistency of the local and the national strategies for CO_2 reduction remains a challenge. In Denmark, most municipalities plan to reduce local emissions by switching from fossil fuels to biomass in heat and electricity generation. However, if these plans were all to be realized, Denmark would need to import substantial amounts of biomass to cover the total national demand. Long-distance transport of biomass, which has a very low energy density compared to fossil fuels, leads to a less efficient and a less sustainable energy supply. It may furthermore be beneficial to prioritize the scarce biomass energy resource for the production of high-grade fuels rather than low-grade thermal energy.

As discussed in [3], the amount of biomass locally sourced in Denmark is limited, thus from a socio-economic perspective its utilization for heat and electricity production is more expensive than using e.g. wind and heat pumps. Since the future transport sector will at least partly require biofuels, biomass and waste (via e.g. thermal gasification) could be used in this sector instead.

Although a municipal strategic energy plan for Sønderborg municipality in 2029 already exists [4], we introduce four alternative scenarios in order to investigate the consequences of implementing novel conversion technologies such as large scale heat pumps, biogas production, thermal gasification, electrolysis, biogas methanation and transport fuel synthesis. The modelling was performed using *Sifre*, a mixed-integer linear optimization tool described further in subsection 2.1.

The objective of this study is to investigate how Sønderborg can become a low-CO_2 emitting municipality in 2029 in an energy efficient and cost-effective way, while also keeping its biomass consumption close to the limits of the locally available residual biomass resources. For this purpose, the results for the five different model scenarios for 2029 were evaluated and compared based on the following indicators: the total system socio-economic costs, the energy system's net CO_2 emissions, the total biomass consumption (relative to the locally available resources) and the total energy conversion efficiency in the system.

Together with increasing role of city-scale climate action, the local focus has been appearing more frequently in the latest energy planning literature. While no peer-reviewed work concentrating on Sønderborg was found, overall energy scenarios and heat supply for a similar sized Danish municipality of Frederikshavn have been analyzed by Østergaard and Lund [5] and Sperling and Möller [6]. Other examples of city scale analysis include energy scenarios of a Hungarian town by Kiss [7] , implementing heat pumps in the municipality of Aalborg by Østergaard [8] and energy policy modelling using MarkAL-TIMES by Comodi et al. [9]. However, none of the aforementioned studies has dealt with modelling biomass conversion and electrolysis in a local perspective, hence the focus of this study.

2 Methodology

2.1 Energy system modelling with *Sifre*

Sifre is a techno-economic energy system modelling tool, developed by the Danish electricity and gas transmission system operator (TSO) Energinet.dk [10]. *Sifre* is a mixed-integer linear optimization tool, which simulates energy flows and energy prices in all sectors of the specified energy system in discrete time steps. A detailed description of the tool and its validation has been published by Energinet.dk [10]. No peer-reviewed work has been yet published based on the results of the *Sifre* tool.

The *Sifre* tool has a modular layout, which allows for a flexible definition of an energy system model with any number of energy conversion units, fuel areas, storages and interconnections. Furthermore, any number of energy input and output streams can be connected to each energy conversion unit. This allows for simultaneous modelling of all sectors of an integrated energy system, i.e. the electricity, heating, gas and transport sectors and their interactions. The modular layout also enables the modelling of energy systems on any scale and geographical level, in particular on a municipal level such as in this work. The tool contains dedicated modules for modelling combined heat and power (CHP) plants, fluctuating renewables, heat pumps, electric vehicles, energy storage and electricity interconnection lines. The tool is, however, not limited to the pre-defined unit types and can in principle be used for modelling any type of energy conversion unit.

The objective of the *Sifre* optimization program is to minimize the total operating expenses of the specified energy system over the simulation period, while fulfilling the specified energy demand during all time steps in the same period. In all simulations performed for this work the simulation period was one year with a time resolution of one hour, resulting in 8760 discrete time steps for a normal year. The *Sifre* tool relies on an external optimization solver for solving the optimization problem; the *Gurobi* solve*r* [11] was used in this work.

Capital expenses are not included in the current version of the *Sifre* tool, but will form part of future model developments. In this work, annualized capital expenses for all new investments in energy conversion and storage units in the system were added to the results post-optimization, based on the installed capacities in each scenario, see subsection 2.4.1. The specific capital costs assumed for each technology are depicted in Table A. 1 in Appendix A.

The output of the *Sifre* tool is a table detailing the values of all model variables for each time step of the simulation. The output from each run of the 2029 scenarios in this work consisted of 996 time series with 8760 time steps each. Original routines for post-processing and analyzing all *Sifre* model outputs of this work were implemented using the programming languages *Matlab* and *Python*.

2.2 Models of the energy system of Sønderborg municipality

2.2.1 Time frame

Models of Sønderborg municipality's energy system for the years 2014 and 2029 were implemented in *Sifre*. The year 2029 was chosen because the municipality has an official goal of becoming CO_2 neutral by then. Five scenarios for the year 2029, described in detail in subsection 2.3., were investigated. Subsections 2.2.2 - 2.2.8 describe all energy conversion pathways that are included in the 2029 scenarios. The structure of Sønderborg's energy system in 2014 was modelled and analyzed in order to compare the results of this modelling scenario with historical data and thereby calibrate the model. A schematic layout of the model for 2029 is shown in subsection 2.3.1. A corresponding schematic for the 2014 calibration scenario can be found in the Supplementary material.

2.2.2 Hydrogen production and fuel cell operation

Hydrogen can be produced via electrolysis of water molecules into hydrogen and oxygen. In the model, only solid oxide electrolysis cells (SOEC) are assumed, as their expected efficiency and costs are projected to be superior to those of alkaline electrolyzers by the year 2029 [12–15]. Heat is also considered an input for decreasing the required electricity input, as this process takes place at 650-

800°C. By reversing the electrolysis process, electricity and heat (and water) can be produced. In the model this can be achieved using a solid oxide fuel cell (SOFC). It is assumed that the electrolyzer and the fuel cell are the same device; a reversible solid oxide cell that can alternate between operating in SOEC and SOFC mode [13]. The device is expected to run more often in electrolysis mode than in fuel cell mode, and is thus technically optimized for electrolysis operation. When operated in fuel cell mode, the maximum power output of the device is assumed to be 25% of the maximum electrolysis power input. This difference between fuel cell and electrolysis mode is due to the different power densities in the solid oxide cells, depending on their operating mode: current density and voltage are each halved when running in fuel cell mode as compared to electrolysis mode. The energy inputs, outputs and efficiency that are assumed for the electrolysis and fuel cell processes are listed in Table A. 2. No electrolysis or fuel cell capacity is included in the 2014 scenario.

The hydrogen produced in the model is utilized as an input for the fuel cells and for upgrading of biogas to synthetic natural gas (SNG) and reformation of syngas to methanol rather than an end-user fuel, since, following the municipal expectations, transport fuel mix is kept the same as now. The addition of hydrogen in these processes allows for a more energy efficient utilization of the energy obtained from the scarce residual biomass resources [16].

2.2.3 Biogas production and upgrade

In the model, biogas can be produced using manure, straw and electricity. For the biomass inputs, we assume a wet matter mass input composition of 81% mixed animal manure and 19% straw [17]. Assuming a dry matter content of 6.2% and 53% for manure and straw, respectively, this corresponds to 32.7% of the total energy inputs originating from manure and 65.6% from straw. The remaining 1.7% of the energy inputs is supplied in the form of electricity. The process yields a digestate as a byproduct, which could potentially be sold as fertilizer, but this use is disregarded in the model.

In Sifre, biogas can either be used directly in (modified) gas boilers or be upgraded to natural gas quality. The biogas is assumed to be upgraded by the addition of hydrogen in a process called methanation, where CO_2 present in biogas reacts with H_2 to form CH_4 (and water). In this manner the energy harnessed from the manure and straw is utilized more efficiently as compared to upgrading the biogas by filtering out the CO_2 [16]. The upgraded biogas gas is treated identically to natural gas of fossil origin in the model and is assumed to be injected to the local gas distribution network in Sønderborg municipality. The energy inputs, outputs and the efficiency of the biogas production and upgrading processes are listed in Table A. 2. No biogas production or upgrade capacity is included in the 2014 scenario.

2.2.4 Syngas production and reformation to methanol

The model includes thermal gasification of solid biomass and waste for the production of synthesis gas (syngas). Syngas is a gas mixture that primarily consists of hydrogen and carbon monoxide and can be reformed to various gaseous and liquid fuels by well-known chemical processes. Syngas is not used as an end-product in the model, but is assumed to be reformed to methanol for use as a transport fuel. The methanol produced in the model is assumed to partly replace the diesel and gasoline demand in Sønderborg municipality. In principle, the methanol could be further reformed to dimethyl ether (DME), but the choice of methanol rather than DME as an electrofuel does not influence the results of the current model. Some authors do, however, argue that methanol may be more suitable as an electrofuel than DME [18,19]. The energy inputs, output and efficiencies of the gasification and reformation processes are listed in Table A. 2. No syngas production or reformation capacity is included in the 2014 scenario.

2.2.5 Individual heating production

Approximately 428 GWh, corresponding to 53% of the final heat demand in Sønderborg municipality, was supplied by individual heating in 2014. Individual heating refers to the heat supply in buildings that are not connected to a district heating network. Five types of individual heating supply are considered in the model; their energy inputs and efficiencies are listed in Table A. 3. In the model, individual heat pumps are assumed to generate three units of heat for each unit of electricity they consume, i.e. they operate with a coefficient of performance (COP) equal to 3.0.

2.2.6 District heating production

Sønderborg municipality has an extensive district heating system, which is actually composed of five separate district heating networks. In the current model the district heating system is treated as one fully interconnected network. The assumed installed capacities of the heat production units in the model are furthermore aggregated values for all five district heating networks. Approximately 383 GWh, corresponding to 47% of the end-user heat demand in the municipality, was supplied in the form of district heating in 2014. To satisfy this district heating demand, a total of 504 GWh heat were generated, as transmission losses in the district heating network amount to around 24%. The energy inputs, outputs and efficiencies of all district heating production units were taken from statistics obtained from the Danish Energy Agency [20].

Nine types of heat production units for district heating are considered in the model; their energy inputs, outputs and efficiencies are listed in Table A. 4. Sønderborg municipality has several combined heat and power (CHP) plants. The largest is located in the city of Sønderborg and consists of a waste incineration part and a gas turbine part. In this work, these two parts of the power plant are modelled as two distinct units. The remaining CHP plants are smaller gas turbine units. In addition to the CHP plants, several boilers running on natural gas, biomass and electricity exist in the municipality. No biogas boilers were present in the municipality's energy system in 2014, but such boilers are included in some of the 2029 scenarios.

The utility-scale heat pumps are assumed to operate with a coefficient of performance (COP) equal to 3.0. The production of the solar heating plants in the model was defined using a time series with an hourly resolution as an input, assumed to be identical to the historical production of the Broager solar heating facility in Sønderborg municipality in 2014. The production data for this solar heating plant is available in hourly resolution at [21]. One of the district heating production plants in Sønderborg municipality is a geothermal power plant, which is connected to an absorption heat pump and supplemented by a biomass boiler. The geothermal facility supplies water at 42°C. This power plant setup was not modelled with great precision in this work, but based on ref. [20] it is assumed that the geothermal part delivers 38% of its total energy inputs while the biomass part is assumed to deliver the remaining energy inputs.

2.2.7 Electricity production and import/export

Electricity was generated within Sønderborg municipality in the year 2014 using its waste incineration CHP plant, natural gas CHP plants, onshore wind turbines and photovoltaics. Furthermore, the municipality is connected to the Western-Danish electricity grid (DK1) with an effective transmission capacity of 270 MW [4]. Sønderborg municipality was a net importer of electricity in 2014; only 16.3% of its total electricity consumption was generated within the municipal borders in 2014.

The installed renewable electricity generation capacity in Sønderborg municipality in 2014 was 14.6 MW onshore wind turbines and 1.48 MW photovoltaics [22]. The renewable electricity generation profile was defined in the form of time series with an hourly resolution. For the 2014 scenario, we used historical time series for wind and photovoltaic production in Southern Denmark. For the 2029 scenarios, modelled time series for wind and photovoltaic generation were used. These time series were all supplied by Energinet.dk.

2.2.8 Fossil fuel and natural gas import

As in reality, all natural gas, gasoline, diesel and heating oil is imported in the 2014 model scenario. Sønderborg municipality is connected to the national gas transmission grid. It is assumed that the time profile of the supply of natural gas can be fully regulated based on the demand. The natural gas is used for CHP plants and boilers and for industrial processes. In the 2029 scenarios it is assumed that a part of the transport sector runs on natural gas. Diesel and gasoline are consumed by the transport sector only and heating oil is used for individual heating. The import of fossil fuels is not assumed to follow any specific time profile, as these fuels can easily and cost-effectively be stored in large quantities.

2.3 Scenario definitions

2.3.1 Description of scenarios

Table 1 displays the energy scenarios we constructed: calibration scenario (labelled 0) representing simulation of the year 2014 and five scenarios A-E representing alternative options for the state of Sønderborg municipality's energy system in 2029.

Table 1 Modelled scenarios and their descriptions.

Year	Scenario symbol	Scenario name	Description
2014	0	Model calibration	Simulation of Sønderborg's energy system in 2014 for comparison with historical data.
2029	A	Municipal plan	Future scenario according to the current strategic energy plan of Sønderborg municipality [4,23].
2029	B	Biomass	Future low fossil-fuel scenario where biomass replaces fossil fuels, without any significant electrification (e.g. no utility-scale heat pumps).
2029	C	Electrification	Future low fossil-fuel scenario with a focus on electrification, where biomass consumption is kept close to the locally available limits.
2029	D	Electrolysis	Same as the Electrification scenario, with the addition of gasification and solid oxide electrolysis for a more energy-efficient biomass utilization. All biogas upgrade is done via biogas methanation (the addition of hydrogen) instead of CO_2 removal.
2029	E	Reversible electrolysis	Same as the Electrolysis scenario, with the addition of reversible solid oxide cells for electrolysis and fuel cell operation.

Each of the scenarios A-E represents a different development of Sønderborg's energy system until 2029. Scenario A seeks to emulate the current strategic energy plan of Sønderborg municipality [4]. Scenario B represents a "Biomass" scenario in which fossil fuels have mostly been replaced by units that combust biomass. Scenario C represents an "Electrification" scenario in which fossil fuels have mostly been replaced by electricity consuming units, such as heat pumps. Scenario D ("Electrolysis") is an extension of scenario C, with the addition of hydrogen production from electrolysis and syngas production from biomass gasification. Scenario E ("Reversible electrolysis") is an extension of scenario D, with the assumption that the electrolyzers are also able to operate in fuel cell mode. Another difference is that natural gas boilers are only used in the current system and in scenario A, are replaced by biogas in scenarios B, C and D and not used at all in scenario E. Note that scenario A, which represents the municipality's plans, can be viewed as a compromise between scenarios B and C.

Figure 2 is a schematic representation of 2029 scenarios, depicting the energy sources, conversion units, transmission lines and energy services and their interconnections. A similar figure for the year 2014 is attached in the Supplementary material.

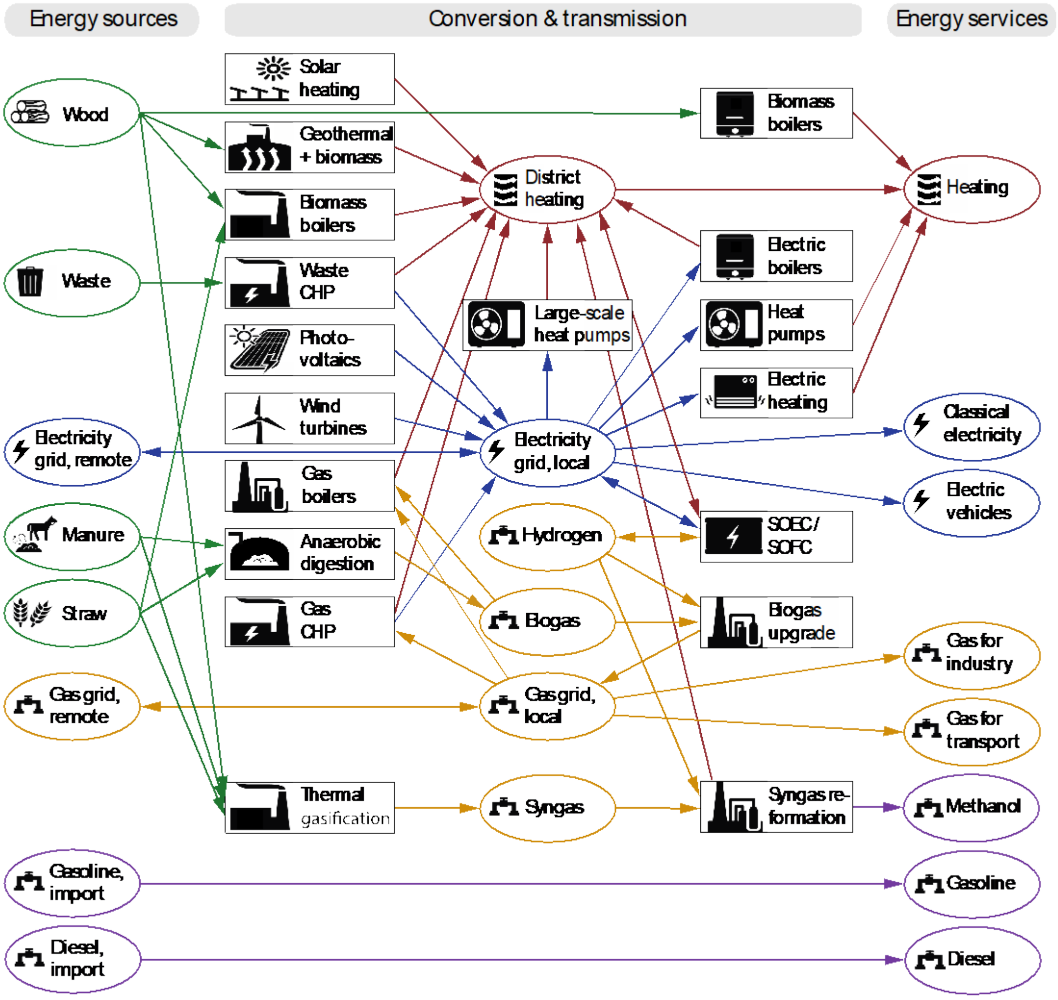

Figure 2 A schematic representation of the model of Sønderborg municipality's energy system showing the components and energy flows of the model for the 2029 scenarios. Energy sources and imports to the municipality's energy system are shown on the left hand side of the flow chart and energy services (demand) in the municipality is shown on the right hand side. Rectangular fields denote energy conversion units and

elliptical fields denote energy carriers and distribution networks. For simplification, the schematic excludes the energy storage facilities of the model.

2.3.2 Locally available residual biomass resources

The locally available residual biomass resources in Sønderborg municipality are listed in Table A. 5. In scenarios C-E, the available biomass in the model was constrained based on the availability for 2029 in the table. In scenarios 0 and A, the biomass consumption was not constrained. No data was found regarding the availability of waste for incineration purposes. In 2014, the waste was supplied from both local and imported municipal waste, and it is assumed in all scenarios that the import of waste can be regulated to match the demand.

2.3.3 Demand for energy services

The demand for energy services in the 2014 model scenario was based on historical data [4,20,22]. The demand in scenario A was based on Sønderborg's strategic energy plan [4]. The demand values in scenarios B-E were decided upon by the authors as a part of developing the scenarios, using scenario A and the general scenario descriptions from subsection 2.3.1 as guidelines. Table 2 shows the applied energy demand for each energy service type across all scenarios. The model optimizes against the demand for these energy services on an hourly basis according to the hourly distribution for each type.

Table 2 The annual demand for each type of energy service in the model.

Energy service	**Demand in each scenario (GWh/year)**					
	0	**A**	**B**	**C**	**D**	**E**
District heating	383	445	445	445	445	445
Individual biomass heating	39	26	187	26	0.0	0.0
Individual gas heating	199	74	0.0	0.0	0.0	0.0
Individual oil heating	116	68	0.0	0.0	0.0	0.0
Individual electric heating	53	305	305	305	305	305
Individual heat pumps (heat prod.)	21	40	21	182	208	208
Electricity (classical)	440	305	305	305	305	305
Electricity (transport)	0.1	19	19	34	34	34
Natural gas (industry)	279	279	279	279	279	279
Natural gas (transport)	0.0	30	30	0.0	0.0	0.0
Gasoline (transport)	230	155	155	155	115	115
Diesel (transport)	270	300	300	300	260	260
Methanol (transport)	0.0	0.0	0.0	0.0	80	80
Total energy demand	**2030.1**	**1782**	**1782**	**1767**	**1767**	**1767**

Each type of end-user energy demand is defined by two parameters in the model; a scalar value for the annual energy demand and a time series containing the demand profile for each hour of the year. The demand value time series were normalized such that the sum over one year (8760 hours) equals one. For a given type of energy demand, the energy demand for each hour of the year is thus found by multiplying the annual energy demand for that type by the corresponding normalized time series.

The district heating demand is assumed to remain constant in scenarios A-E. The assumed increase in district heating demand compared to the 2014 scenario is due to an anticipated conversion of some areas in the municipality from individual heating to district heating. Individual gas and oil heating is assumed to be significantly reduced in scenario A compared to the 2014 scenario. In scenarios B-E it is assumed that no gas and oil are used for individual heating. The individual heating demand is primarily assumed to be supplied by biomass boilers in scenario B and by heat pumps in scenario C-E. Time series for the heat demand profile were based on measured data on 53 single-family houses in Sønderborg, obtained from Sønderborg Fjernvarme (Sønderborg municipality's district heating company). The same heat demand profile was assumed for district heating and individual heating.

The term *classical electricity demand* is used for all electricity demand except heat pumps, electric vehicles and electrolysis. The classical electricity demand is assumed to be lower in 2029 than in 2014, as anticipated in Sønderborg municipality's strategic energy plan. The classical electricity consumption is the same in scenarios A-E. In scenarios A and B the electricity demand due to electric vehicles is assumed to follow the projection from Sønderborg's strategic energy plan. Electricity demand for heat pumps is not a direct input parameter in the model, as it is dictated by the end-user heat demand from individual and large-scale heat pumps. Time series for Danish classical and electric vehicle electricity demand were obtained from the Danish TSO, Energinet.dk. Classical electricity demand time series for 2014 were based on measured data while time series for 2029 were based on simulations by Energinet.dk. Demand response is not considered in this study.

The end-user demand for natural gas in the model is divided into industry gas demand and transport gas demand. The industry gas demand value and profiles were obtained from the Danish gas TSO, Energinet.dk. The industry gas consumption is assumed to remain unchanged from 2014 to 2029. Some natural gas consumption for transport is assumed in scenarios A and B, but none in the other scenarios. The increase in electric vehicle energy demand in scenarios C-E compared to scenarios A and B is based on the assumption that the natural gas vehicles in scenarios A and B are running on electricity (with a double efficiency compared to gas vehicles) in scenario C-E.

The total demand for liquid transport fuels is expected to decrease from 2014 to 2029, due to an increased energy efficiency of the vehicles. The total liquid transport fuel is the same in scenarios A-E. In scenarios D and E, methanol (produced by biomass gasification and syngas reforming) is assumed to replace some of the gasoline and diesel demand. The liquid transport fuel demand is assumed to have a constant demand profile because these fuels can easily be stored to match possible fluctuations in supply and demand.

2.3.4 Installed energy conversion capacities

The installed capacities for the energy conversion units in the 2014 model scenario were based on historical data [4,20,22]. The assumed capacities for scenario A were based on Sønderborg's strategic energy plan [4,22]. The capacities for each conversion unit across all scenarios can be seen in Table 3. The installed capacities in scenarios B-E were derived using scenario A and the general scenario descriptions from subsection 2.3.1 as guidelines. Furthermore, the energy conversion capacity values were chosen subject to the constraint that the demand for end-user energy services described in subsection 2.3.3 should be fulfilled for all time steps.

Table 3 Total installed capacities for each type of conversion unit in the model, for all scenarios.

Conversion unit	**Product**	**Installed capacity (MW)**					
		0	**A**	**B**	**C**	**D**	**E**
Natural gas boilers	District heating	160.1	50.0	0.0	0.0	0.0	0.0
Biogas boilers	District heating	0.0	0.0	50.0	10.0	10.0	10.0
CHP (natural gas)	District heating Electricity	64.8 71.4	64.8 71.4	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0
CHP (waste)	District heating Electricity	20.0 4.5	20.0 4.5	20.0 4.5	20.0 4.5	20.0 4.5	20.0 4.5
Geothermal + absorption heat pump	District heating	43.0	43.0	43.0	10.0	0.0	0.0
Biomass boilers	District heating	17.4	25.6	140.4	25.6	25.6	25.6
Electric boilers	District heating	8.0	8.0	8.0	8.0	8.0	8.0
Heat pump (utility-scale)	District heating	0.0	50.0	0.0	187.8	195.3	203.4
Solar heating	District heating	26.1	194.9	194.9	194.9	194.9	194.9
Biomass boilers	Individual heating	17.1	11.4	57.4	11.4	0.0	0.0
Electric heating	Individual heating	25.7	17.1	17.1	17.1	17.1	17.1
Natural gas heaters	Individual heating	57.1	21.2	0.0	0.0	0.0	0.0
Oil heaters	Individual heating	32.8	19.4	0.0	0.0	0.0	0.0
Heat pumps	Individual heating	6.0	11.4	6.0	52.0	63.4	63.4
Photovoltaics	Electricity	14.8	40.0	40.0	40.0	40.0	40.0
Wind turbines (onshore)	Electricity	14.6	30.0	30.0	30.0	30.0	30.0
Wind turbines (coastal-near)	Electricity	0.0	120.0	100.0	140.0	150.0	150.0
Solid oxide electrolyzer cells (SOEC)	Hydrogen District heating	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	20.0 0.4	40.0 0.8
Solid oxide fuel cells (SOFC)	Electricity District heating	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	10.0 1.5
Anaerobic digestion	Biogas	0.0	10.0	10.0	10.0	10.0	10.0
Biogas CO_2 removal	Natural gas	0.0	10.0	10.0	10.0	0.0	0.0
Biogas methanation	Natural gas	0.0	0.0	0.0	0.0	16.0	16.0
Gasifiers	Syngas	0.0	0.0	0.0	0.0	12.0	12.0
Syngas reformation	Methanol	0.0	0.0	0.0	0.0	10.0	10.0

In scenarios A-E, the total DH production capacity remains constant at 456.3 MW and the total individual heating production capacity remains constant at 80.5 MW, although the composition of this capacity varies across the scenarios. In scenario B, biomass fueled heat production is emphasized, but in scenario C-E, electricity-based heat production is emphasized. The installed capacities for solar heating, photovoltaics and onshore wind turbines equal those assumed in Sønderborg's strategic energy plan. Due to land use considerations, we have assumed that further expansion of this production capacity is not possible, and the installed solar heating, photovoltaics and onshore wind capacity therefore remain constant throughout scenarios A-E. An expansion of coastal-near wind turbines beyond the strategic energy plan is, however, assumed in scenarios C-E, to partially compensate for the increased total electricity demand in these scenarios.

The pathway of biogas production and upgrade to natural gas quality through CO_2 removal is not present in the 2014 scenario but is introduced in scenarios A-C. In scenarios D and E, all biogas upgrade is assumed to take place by biogas methanation (the addition of hydrogen) instead of CO_2 removal. The pathway of syngas production from biomass and hydrogen, along with reformation of the resulting syngas to methanol, is only present in scenarios D and E. Hydrogen production is thus only needed in scenarios D and E, and no SOEC production capacity is thus assumed for any of the other scenarios. Finally, the option of operating the solid oxide cells in fuel cell mode is only present in scenario E.

2.4 Economic data and assumptions

2.4.1 Capital and operating expenses and economies of scale

As mentioned in section 2.1, the currently available version of *Sifre* does not calculate capital expenses and only takes operating expenses into account. Annualized capital expenses were therefore added to the model results after the optimization.

The capital expenses for an energy conversion power capacity *P* of type *i* can be written as:

$$C_i = c_i * P_i$$

where c_i denotes the specific capital expenses (capital expenses per conversion power capacity). The energy conversion capacity in the model can be divided in two categories; investments performed in 2014 or earlier and investments performed after the year 2014. The latter category will be referred to as *new investments* in the following. The total energy conversion capacity of type *i* in the model is:

$$P_i = P_{2014,i} + P_{new,i}.$$

Investments performed in 2014 or earlier were assumed to be sunk costs and were not included in the calculation. The specific capital expenses $c_{2014,i}$ relating to the production capacity $P_{2014,i}$ were therefore set to zero for all *i*. The scrap value of existing investments was furthermore set to zero. Investments in new energy conversion units in each 2029 scenario were calculated for each type *i* by taking the difference between the installed capacity of that type and subtracting the installed capacity in the 2014 scenario:

$$C_i = 0 * P_{2014,i} + c_{new,i} * P_{new,i}$$

The capital expenses for new investments were scaled based on the energy conversion capacity using the following expression for the economies of scale:

$$c_{scaled,i} = c_{standard,i} \left(\frac{P_{scaled,i}}{P_{standard,i}}\right)^{\alpha}$$

Here α is the scaling exponent, which takes on values from 0-1 based on how well the capital expenses for an energy conversion technology of type *i* scale with size. An expression for the total investment costs in energy conversion type *i* is obtained by combining the last two equations:

$$C_i = C_{standard,i} \left(\frac{P_{new,i}}{P_{standard,i}}\right)^{\alpha} * P_{new,i}$$

The annualized capital expenses for new investments of type *i* were calculated using the following annuity loan down payment formula:

$$C_{annualized,i} = \frac{r}{1-(1+r)^{-n_i}} * C_i$$

where *r* denotes the interest rate and n_i denotes the expected lifetime of the energy conversion facility of type *i* in years.

The total system costs, including capital expenses, were obtained by summing the total system costs as calculated using the *Sifre* model and the annualized capital expenses for each energy conversion technology:

$$C_{total} = C_{Sifre} + \sum_i C_{annualized,i}$$

The assumed standard specific investment costs, standard capacities, scaling exponents and plant lifetimes for all energy conversion technologies in the model can be found in Table A. 1. A socio-economic interest rate of 4% was assumed. All cost values in this work are given in 2014 Euros.

2.4.2 Electricity and fuel prices

The electricity and fuel prices used in the model, along with references, are shown in Table A. 6. Electricity prices are inserted in the model in the form of hourly time-series. The electricity price time series for 2014 is the historical electricity Nord Pool spot price in Western Denmark. The time series used for the 2029 scenarios are from one of Energinet.dk's scenario simulations. The 2029 price time series originate from the same simulation as the wind and photovoltaic generation time series described in section 2.2.7. The prices of fossil fuels were inserted in the form of hourly time series for the 2014 scenario and as a constant (average) projected value for the 2029 scenarios. The prices of biomass were entered as constant (average) values in all scenarios.

2.5 Assessment indicators

The scenario results were compared based on the four indicators described in Table 4. The total system socio-economic cost is the sum of the fuel cost, O&M costs, the annualized investment costs and the CO_2 emission costs excluding any taxes and/or subsidies. The CO_2 emission factors recommended by the Danish Energy Agency [24] were used for calculating the total CO_2 emissions for each scenario. The total system energy efficiency is defined as the ratio of the total end-user energy outputs to the total primary energy inputs in the system.

Table 4 Indicators used for comparing the results of scenarios A-E. All values are compared on an annual basis.

Indicator	Unit	Description
Total energy system socio-economic cost	€/year	The sum of the fuel cost, O&M costs, the annualized investment costs and the CO_2 emission costs.
Total system CO_2 emissions	ton CO_2/year	Net CO_2 emissions arising from Sønderborg municipality's energy consumption.
Total biomass consumption	%	Relative to the total locally available residual biomass resources.
Total system energy conversion efficiency	%	The ratio of the total energy outputs to the total energy inputs in the energy system.

Since we do not apply any weighting, all the indicators are equally important. Thus, the optimal energy system configuration is one with the lowest total socio-economic costs, lowest total CO_2

emissions, a total biomass consumption close to or under the local available residual biomass resources and the highest total energy system efficiency.

3 Results

The energy flows in each scenario are shown with Sankey diagrams in section 3.1. Selected time series are depicted in section 3.2. Scenario indicators are explained and discussed in section 3.3.

3.1 Energy flows

3.1.1 Scenario 0

Figure 3 presents the energy flows in scenario 0, "Calibration". As the right-hand side of the diagram shows, about 40% of the final energy consumption in Sønderborg municipality consists of heat, out of which 47% is supplied by district heating. These values agree with historical data for 2014 discussed in section 2.2.6.

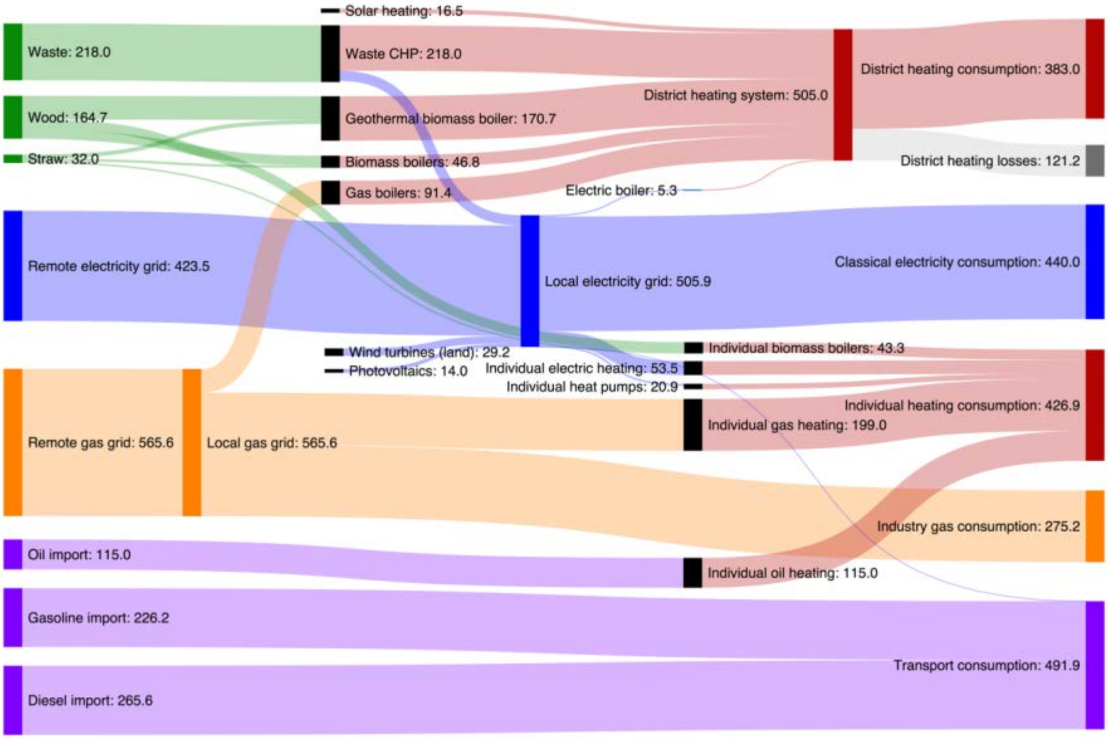

Figure 3 Sankey diagram of the model results of the scenario 0 (2014 calibration). All numbers in GWh/year.

District heating is generated on waste, biomass (wood and straw), natural gas and solar heat. Individual heating uses natural gas, heating oil, biomass and electricity. At present, electricity is mostly imported from the Western Danish electricity grid but also partially generated locally using waste, onshore wind turbines and photovoltaics. The energy resources used currently for transport are crude oil derivatives. Only a minor share of electricity produced and imported is used for district heating, individual heat pumps and electric boilers, with most of the electricity demand being classical consumption.

3.1.2 Scenarios A - E

Figure 4 shows the energy flows in scenario A, "Municipal plan". As the right-hand side of the diagram shows, about 47% of the final energy consumption in Sønderborg municipality consists of heat, out of which 64% is supplied by district heating.

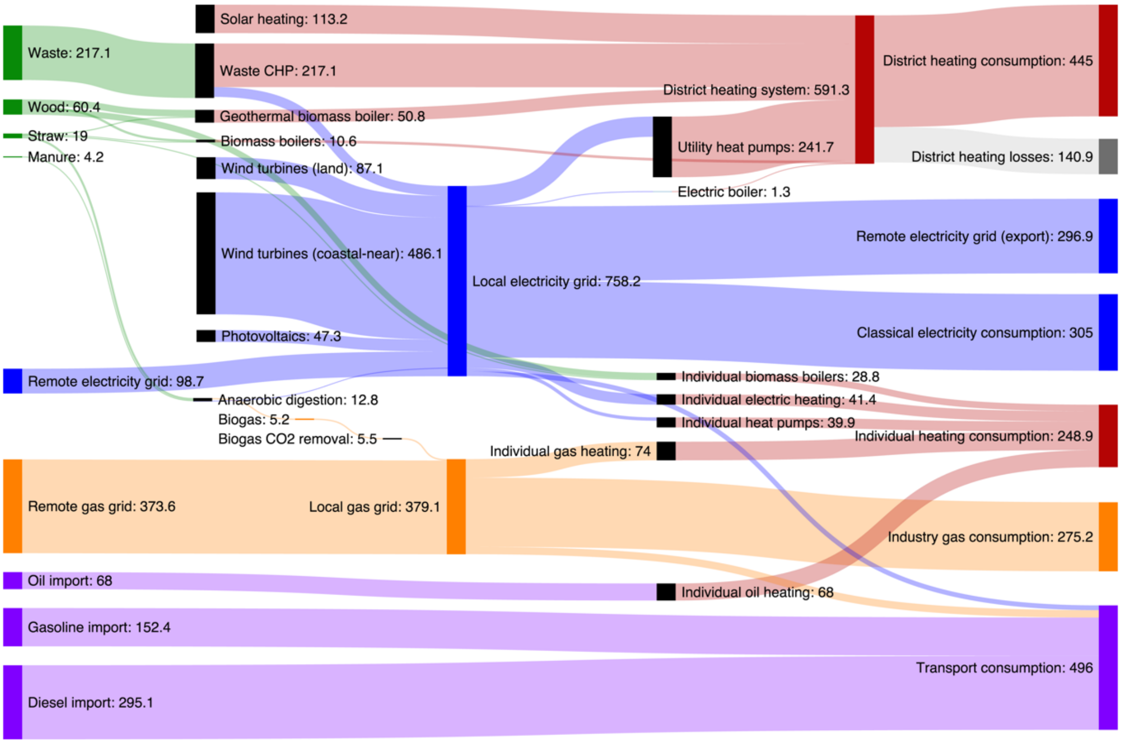

Figure 4 Sankey diagram of the model results of the scenario A. All numbers in GWh/year.

A significant portion of electricity generation comes from wind turbines, not only feeding the local grid, but also being exported. The transport consumption is assumed to stay at the same level. While smaller than present amount of biomass is used, new conversion pathways are implemented: anaerobic digestion and biogas. Natural gas imports are reduced by 34% compared to 2014.

Figure 5 depicts the energy flows in scenario B, "Biomass". While the share of heat in the final energy consumption and district heating share are the same as in scenario A, less electricity is exported.

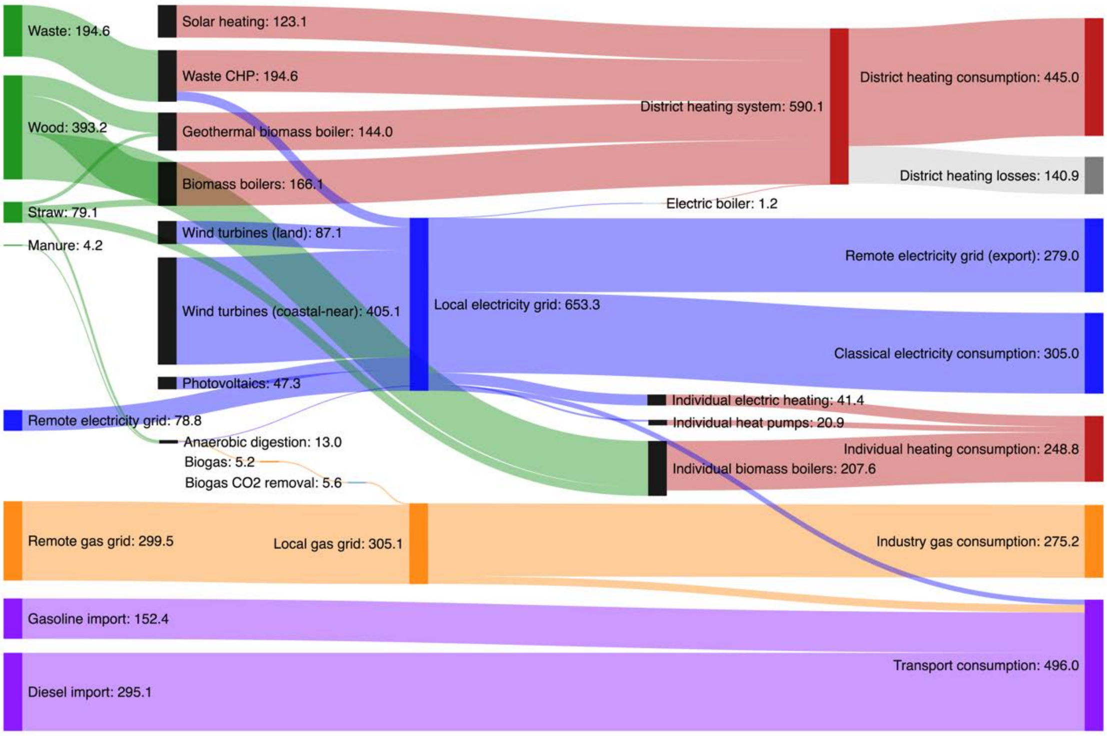

Figure 5 Sankey diagram of the model results of the scenario B. All numbers in GWh/year.

Scenario B has a very high wood consumption, and it is used mainly for individual heating. Transport consumption stays at the same level as in scenarios 0 and A.

Figure 6 shows the energy flows in scenario C, "Electrification". The share of heat in the final energy consumption and district heating share are the same as in previous scenarios. The main difference is that almost no biomass is utilized for energy generation and wind energy is the main resource used.

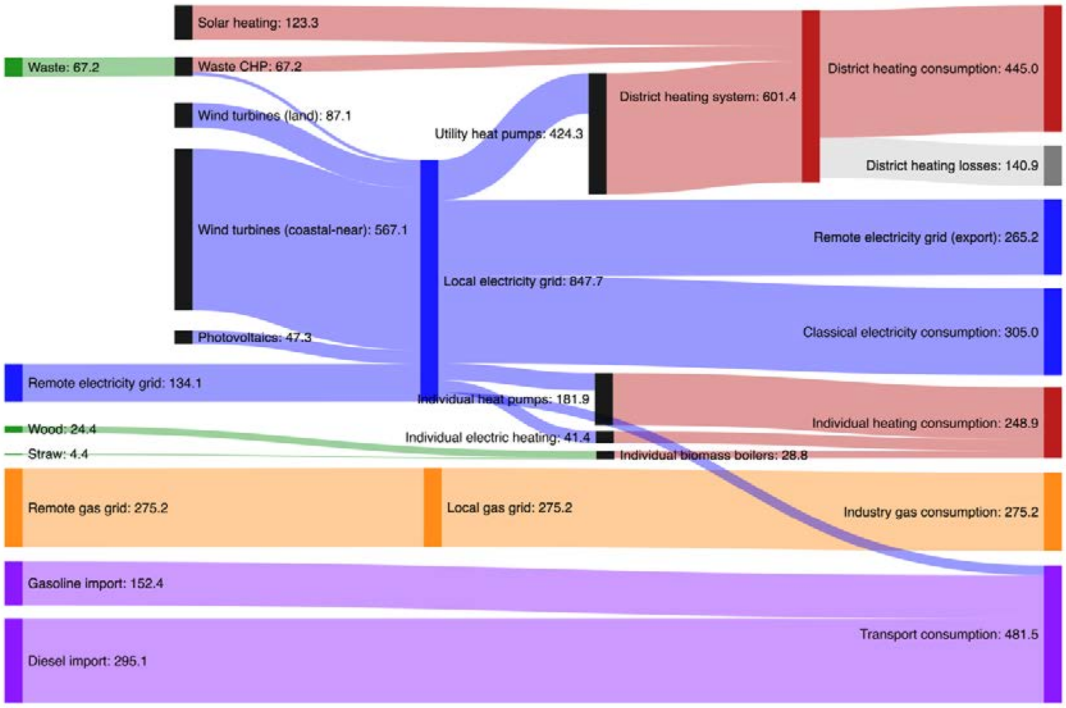

Figure 6 Sankey diagram of the model results of the scenario C. All numbers in GWh/year.

Figure 7 depicts the energy flows in scenario D, "Electrolysis". The share of heat in the final energy consumption and district heating share are the same as in previous scenarios. In this scenario new technologies are implemented: gasification and electrolysis, as well as biogas methanation for improving the heat value of biogas.

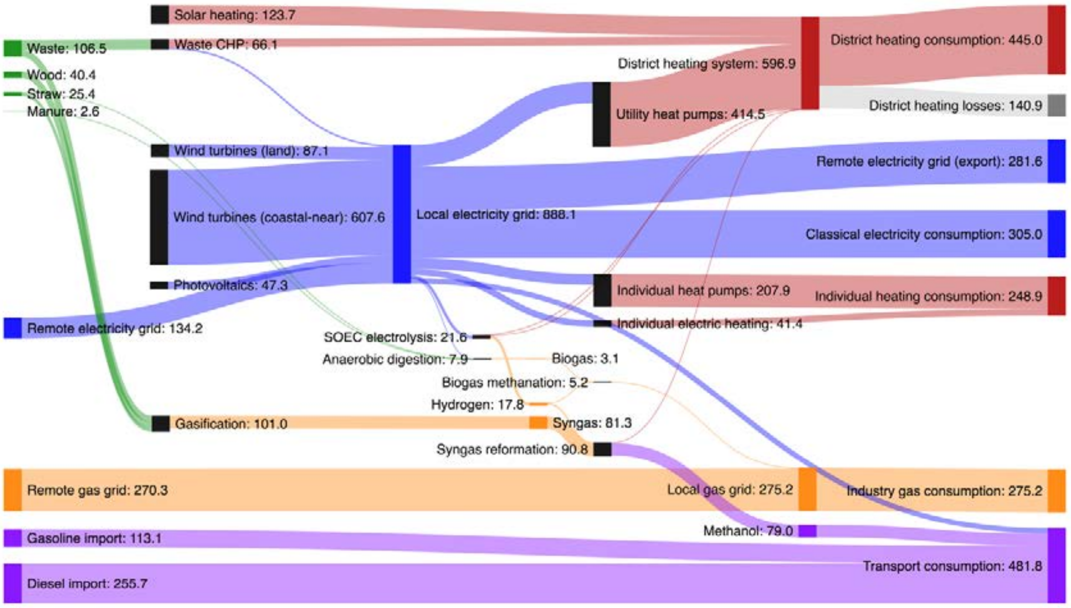

Figure 7 Sankey diagram of the model results of the scenario D. All numbers in GWh/year.

Figure 8 shows the energy flows in scenario E, "Reversible electrolysis". The share of heat in the final energy consumption and district heating share are the same as in previous scenarios. In this scenario, the novel technology of solid oxide fuel cells is implemented.

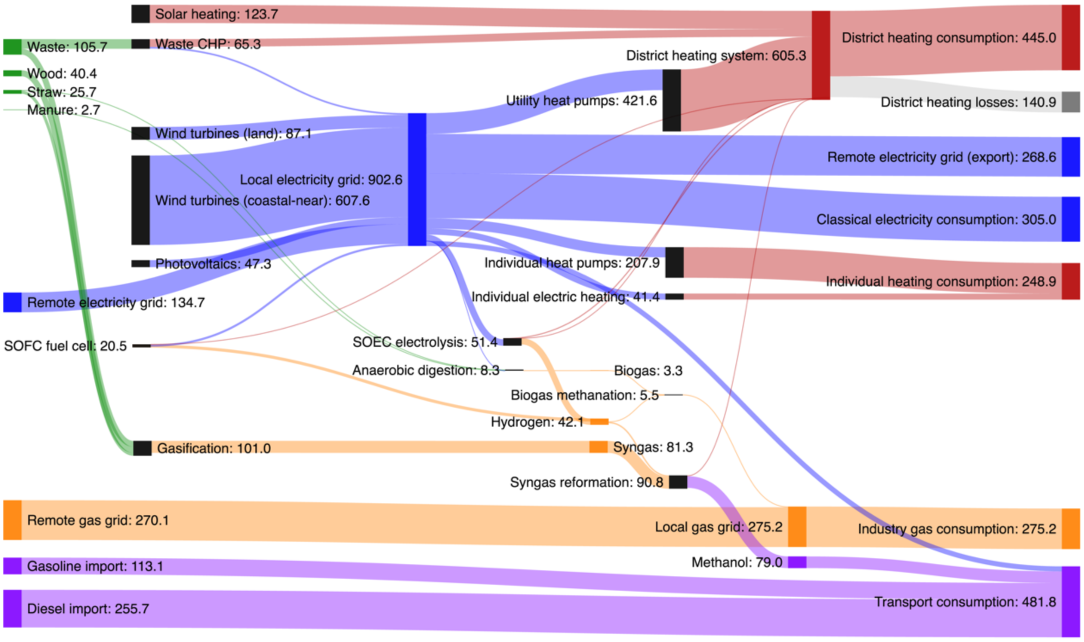

Figure 8 Sankey diagram of the model results of the scenario E. All numbers in GWh/year.

3.2 Time series

The dynamics of the simulated system can be depicted with time series curves. Using data from scenario E, which incorporates both electrolysis and fuel cells, we produced the curves for energy prices, heat pump operation and SOEC and SOFC operation.

Figure 9 depicts hourly electricity and district heating prices excluding taxes and subsidies (socio-economic costs) over the year 2029.

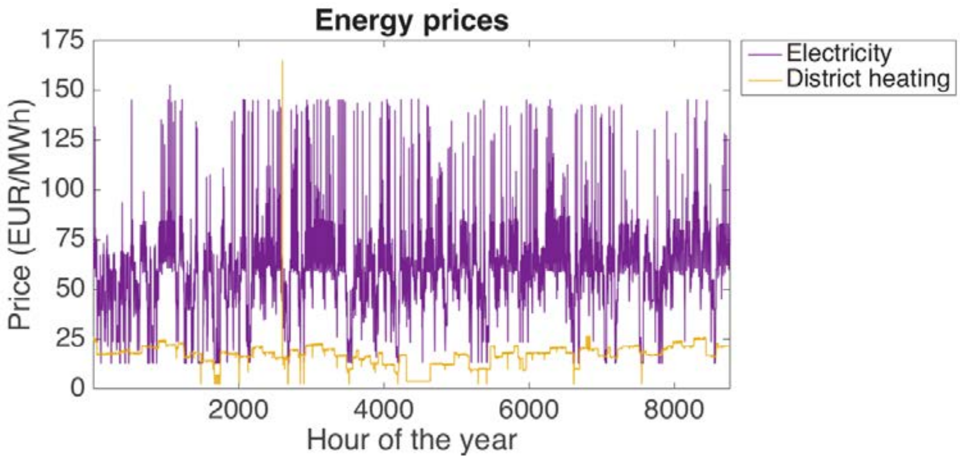

Figure 9 Electricity and district heating prices (excl. taxes and subsides) over the year (EUR/MWh).

While electricity prices are an input to the model, district heating prices are calculated based on the fuel cost, the operation and maintenance cost and the heat demand. As Figure 9 shows, district heating prices are rather stable over the year, slightly decreasing around mid-year - the hottest months, where only hot water is needed. The reason for this price drop is that the waste incineration plant located in Sønderborg can produce heat cheaper than other units due to free fuel. Electricity spot price varies over the year, so no single seasonal pattern can be observed.

Figure 10 depicts electricity and district heating prices over hours 720-1440 of the year, approximately corresponding to the second month of the year, February. While district heating prices are rather stable in the winter season, electricity prices vary significantly between 12-150 EUR/MWh.

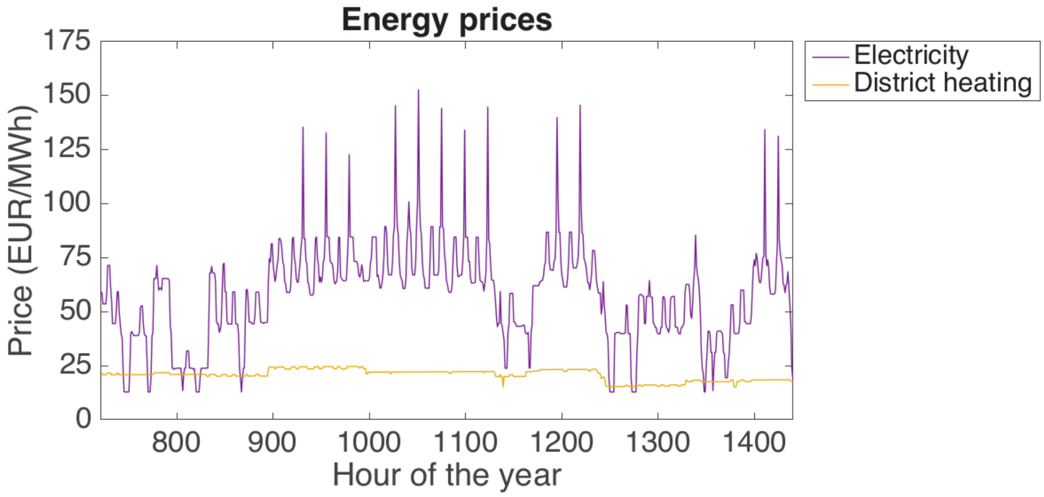

Figure 10 Electricity and district heating prices (excl. taxes and subsides) over hours 720-1440 of the year (EUR/MWh).

Figure 11 compares the heat pump operation with electricity and district heating prices over hours 720-1440 of the year, corresponding to the month of February.

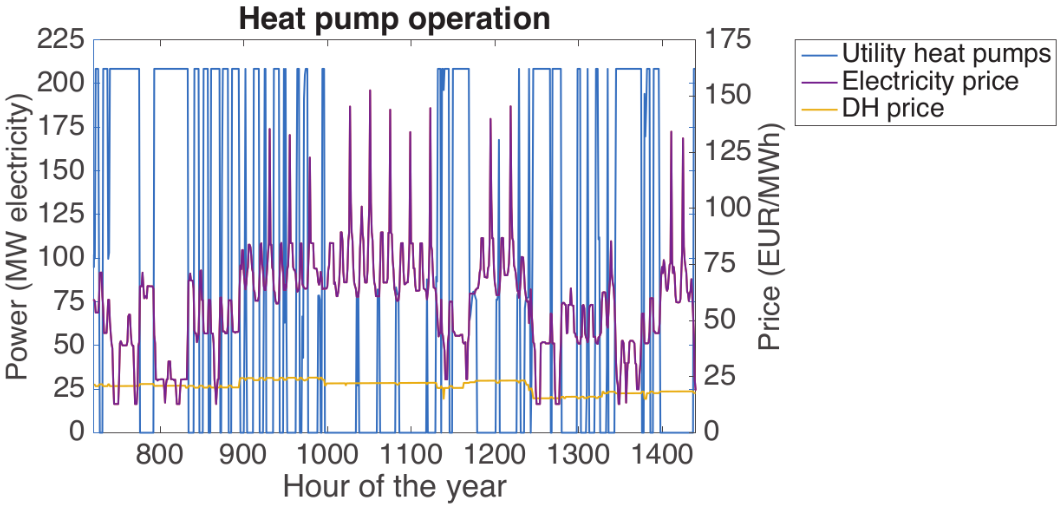

Figure 11 Hourly operation of heat pumps in relation to the electricity and district heating price over the month of February.

As Figure 11 shows, the operation of heat pumps is inversely proportional to the electricity price: while the lower electricity price gives incentives for heat pump operation, the higher price causes the heat pumps to decrease their operation.

Figure 12 compares the solid oxide electrolysis and fuel cell operation with electricity and district heating prices over hours 720-1440 of the year, corresponding to the month of February.

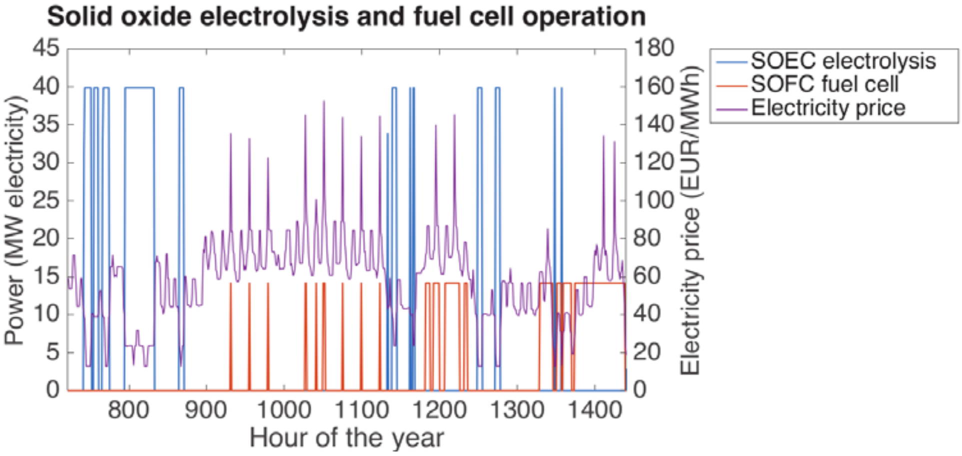

Figure 12 Hourly operation of electrolysis and fuel cells in relation to electricity price over the month of February.

Figure 12 shows how the electricity price dictates the operation of the electrolysis and fuel cells. The model used, Sifre, forces the SOEC/SOFC and the heat pumps to operate intelligently based on the price. Similar to heat pumps, electrolysis cells operate primarily when the electricity price is low. Fuel cells, which release electricity by converting the chemical energy from the fuel, operate in periods of high electricity prices.

The connection between electricity prices and operation of heat pumps and SOEC/SOFC illustrates the need for advanced smart control mechanisms to achieve cost-efficient operation of the future energy system not only in the simulation, but also in reality.

3.3 Indicators

This study aims to investigate how Sønderborg can become a low-CO_2 emitting municipality in 2029 in an energy-efficient and cost-effective way, considering the limited locally available residual biomass resources. Therefore, the results are evaluated and compared using the following indicators: the ratio of outputs to inputs, the total annual socio-economic system costs, the annual CO_2 emissions by sector and the fraction of biomass consumption. As Figure 13 shows, the lowest total annual energy inputs are for scenarios: C, D and E, which are also very similar (D and E are almost identical).

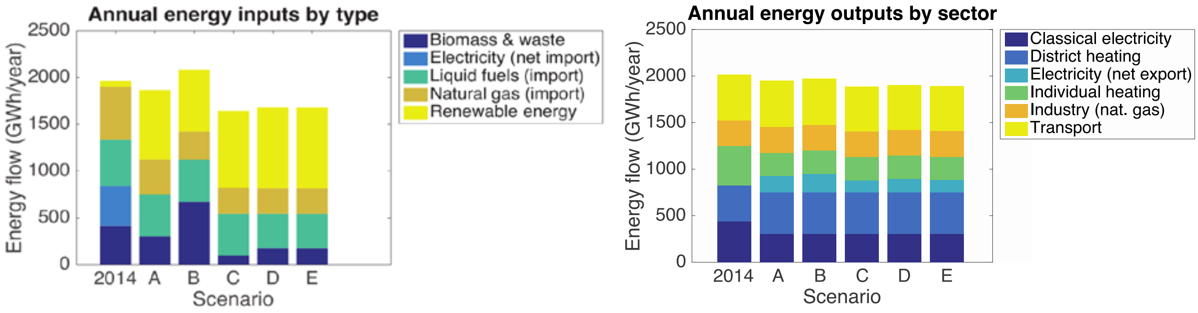

Figure 13 Total annual energy inputs by energy source (left) and outputs by sector (right).

Scenario B has the largest overall input, due to intentionally increased biomass consumption. Sønderborg in all the future scenarios is a net exporter of electricity, in contrast to the calibration scenario where the majority of the electricity consumed in the municipality was imported. In case of annual energy outputs, the main differences between 2014 and future scenarios concern the share of classical electricity and the amount of exported electricity. The sectoral division of energy demand in scenarios A-E is the same, thus the sectoral differences among them are also small. Nonetheless, if energy outputs are divided by energy inputs, scenario C shows to be most efficient.

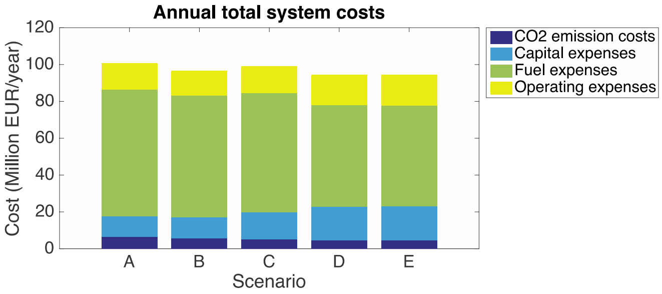

Figure 14 Total annual socio-economic system costs in scenarios A-E.

Figure 14 depicts the annual socio-economic system costs for scenarios A-E only. Scenarios D and E achieve the lowest costs (scenario E being less expensive by roughly 60,000 EUR), which is due to savings in fuel expenses and CO_2 emission costs. Moreover, the share of costs changes as the amount of renewable energy and electrification increases, because the fuel costs become less important and the energy system becomes more capital cost intensive.

The annual CO_2 emissions are shown in Figure 15. As expected, the emissions in 2029 drop substantially, compared to 2014.

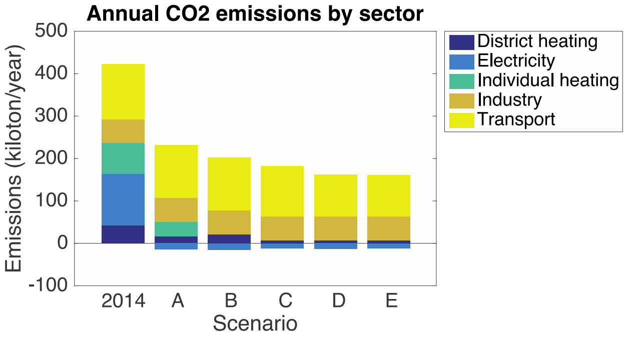

Figure 15 Annual CO_2 emissions by sector in each scenario. In scenarios A-E, the electricity sector in Sønderborg municipality has negative CO_2 emissions due to net export of electricity.

Scenarios D and E result in lowest emissions, mainly due to CO_2 reduction in individual supply and district heating, as well as electricity. Transport and industry remain the main CO_2 emitters.

Table 5 shows the total annual biomass consumption fraction in each scenario. In all the scenarios wood constitutes a dominating part of biomass consumption. The total biomass consumption is highest in scenario B and lowest in scenario C.

Table 5 Annual biomass consumption as a percentage of the annual local biomass resource of each type (measured in terms of energy content).

Biomass type	2014	A	B	C	D	E
Manure	0.0%	8.1%	5.7%	0.03%	3.5%	3.7%
Straw	36.5%	8.1%	25.0%	1.4%	8.0%	8.1%
Waste	145.3%	97.6%	129.8%	44.8%	71.1%	70.1%
Wood	1003%	393.6%	2070%	128.5%	212.8%	212.8%

None of the scenarios fulfills all goals, namely performing best in all indicators: energy system efficiency, socio-economic costs, CO_2 emissions and biomass consumption. Considering two criteria: total system cost and CO_2 emission levels, scenario D and E are optimal, while providing a lot of biomass consumption savings. Moreover, scenario E shows that the addition of reversible electrolysis is linked to decreased system costs compared to scenario D, and this addition could be valuable when considering the possibilities of balancing supply and demand in the electricity system. However, considering the two other criteria: output/input efficiency and total biomass consumption, scenario C performs best. We deem all the indicators equally important in achieving a sustainable energy system, that is why no definitive answer on which scenario to choose can be given, considering the assumptions taken in this study.

The scenarios developed in this work (B-E) perform better on all the indicators than the scenario that is based on Sønderborg's strategic energy plan (scenario A). We therefore suggest that by considering a greater variety of energy system configurations (with e.g. more electrification and novel energy conversion technologies) than foreseen in most strategic energy plans, Sønderborg municipality (and other similar municipalities) could design a more energy and cost effective energy system while keeping the biomass consumption close to the locally available limits and substantially lowering the system's CO_2 emissions.

3.4 Sensitivity analysis

3.4.1 Biomass price changes

Figure 16 depicts how CO_2 emissions and annual system costs change when different biomass prices are implemented in the model.

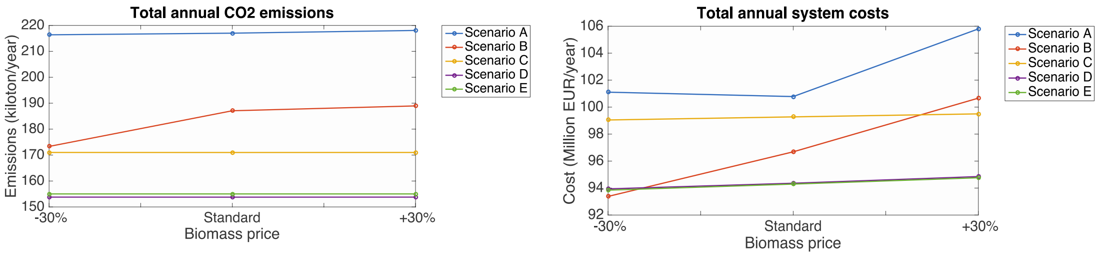

Figure 16 Changes in total annual CO_2 emissions (left) and total annual system costs (right), depending on the price of biomass.

Changing the biomass price does not influence the overall scenario rank order for CO_2 emissions, therefore scenarios D and E still perform best on these criteria. However, it slightly affects scenario B, due to its high consumption of biomass. A 30% decrease in biomass price would cause a 7% drop in CO_2 emissions in case of scenario B. This is caused by the large biomass-fired capacity in scenario B, which enables replacing natural gas and waste production capacity with biomass capacity in case of lower biomass prices, thus reducing the CO_2 emissions. On the contrary, other scenarios do not have a possibility of changing the operation depending on biomass prices, because their biomass-fired production capacity is not as large as in scenario B.

If biomass prices were to increase, the total annual system costs of scenario A would grow by 5%. In scenario B, a 30% biomass price increase would cause 4% higher system costs and a 30% biomass price decrease would lower the total annual system costs by 3%, making this scenario the most cost-effective choice in case of lower biomass prices. This again is because of a high dependency of scenario B on the biomass resource. Thus, increasing the biomass price by approximately 22% or higher influences the overall scenario rank order for CO_2 emissions, so scenarios D and E would not be optimal in such case.

3.4.2 Electricity price changes

Figure 17 depicts how CO_2 emissions and annual system costs change, when different electricity prices are implemented in the model.

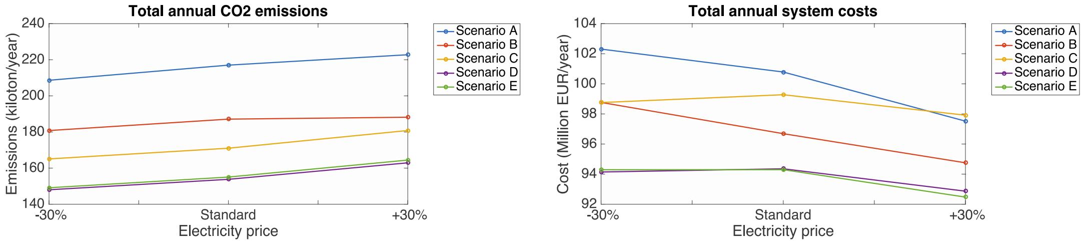

Figure 17 Changes in total CO_2 emissions (left) and total annual system costs (right), depending on the price of electricity.

Changing the electricity price does not influence the overall scenario rank order for CO_2 emissions, so scenarios D and E still perform best on this criterion. In case of 30% lower electricity prices, 4% lower CO_2 emissions in scenarios A, D and E and 3% lower CO_2 emissions in scenarios B and C would occur. 30% higher electricity prices would cause CO_2 emissions to rise by 3% in scenario A and by 6% in case of scenarios C, D and E. This is due to increasing generation using fossil-fuels.

Changing the electricity price influences the total system costs in all scenarios to some extent, especially scenarios A and B, where electricity exports are greatest. Sønderborg is a net exporter of electricity in all future scenarios, moreover the revenue from exported electricity is also higher when the prices are high. The change in system costs is most visible in scenario A: an increase of 30% in electricity price causes a 3% total system cost decrease.

3.4.3 Fossil fuel price changes

Figure 18 depicts how CO_2 emissions and annual system costs change, when higher and lower fossil fuel prices are implemented in the model.

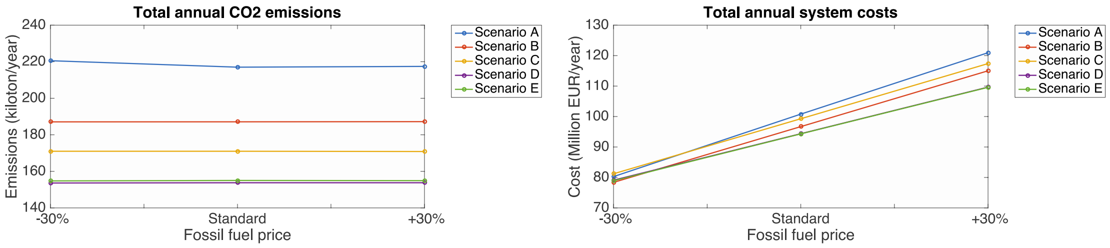

Figure 18 Changes in total CO_2 emissions (left) and total annual system costs (right), depending on the price of fossil fuels.

Fossil fuel price changes do not influence CO_2 emission levels, because the fossil fuel power plants, individual heating and transport are used in the same way irrespective of the fossil fuel price. Besides, the demand for the individual heating and transport fuel has to be satisfied even though the fuel prices are high.

However, the changes in fossil fuel price have a large impact on total system costs. Scenario A results in 20% higher or lower total system costs in case of fossil fuel price changes, scenario B: 19%, scenario C: 18%, scenario D and E: 16%. Moreover, the scenario rank order changes: with lower fossil prices, scenario B performs best, while with increasing prices, scenario E is optimal.

These up-and-down fluctuations are significant, but clearly scenarios D and E show less dependence on fossil fuel prices, which is a benefit considering the price unpredictability.

3.4.4 Local versus national biomass consumption

Although the focus of this study is the municipality of Sønderborg, a question arises: if all Denmark was to use the same amount of biomass per capita, as each scenario uses, how large would the Danish national biomass consumption for energy purposes be?

As of the 1st quarter of 2016, there were 74,732 inhabitants in Sønderborg municipality [25] and a total of 5,717,000 inhabitants in Denmark. Table 6 shows the amount of biomass used in each scenario and how it corresponds with the required national level.

Table 6 Comparison of locally-used biomass in each scenario and corresponding national amount of biomass.

Scenario	Unit	A	B	C	D	E
Locally-used amount	GWh	625	1000	200	250	250
Per capita consumption	GWh/inhabitant	0.008	0.013	0.003	0.003	0.003
Corresponding national amount	GWh	47,813	76,500	15,300	19,125	19,125
Corresponding national dry matter amount (assuming 17.5 GJ/t)	t	9,835,817	15,737,143	3,147,429	3,934,286	3,934,286

Corresponding national dry matter amount (assuming 9 GJ/t)	t	19,125,200	30,600,000	6,120,000	7,650,000	7,650,000

The total future Danish biomass production potential was calculated to range between 7.2 and 11.1 million tons dry matter. [26] Depending on the assumptions regarding types of biomass used and their energy content, the national biomass resource would suffice only in case of scenarios C-E. Substantial imports would be required to cover biomass demand in case of scenarios A and B.

4 Discussion

Due to savings in fuel expenses, CO_2 emission costs, as well as CO_2 reduction in individual supply and district heating, scenarios D (Electrolysis) and E (Reversible electrolysis) perform best regarding total system cost and CO_2 emissions, but scenario C (Electrification) is optimal if overall output/input efficiency and low biomass use are prioritized.

With lower fossil fuel prices, scenario B performs best, while with higher fossil fuel prices, scenario E is optimal. Considering the volatility of fossil fuel prices, the risk of choosing these scenarios is rather high.

The biomass scenario would cost the least if biomass prices were to decrease substantially. Taking into consideration the developments on the world biomass market, this situation is however unlikely. The world biomass market, especially for wood pellets, is increasing and for example, in 2013 the EU was responsible for 85% of the energy-related global wood pellet consumption [27]. Moreover, Denmark is likely to import a substantial part of its biomass consumption, becoming susceptible to changing global market prices. [28]

While the goal of the previous Danish government was to achieve CO_2-free electricity and heat supply in 2035, this policy has been changed, leaving only an overall CO_2 reduction goal. This means that in the short and middle term the progress may show less ambitious, causing prices of less common technologies, like electrolysis, to rise, depending on which fuel it replaces (natural gas or oil).

The outcomes of the scenario modelling may be influenced by the relatively high share of district heating in Sønderborg in 2029: 64% of heat supply, which makes the results less applicable for similar cities outside Denmark where there is no or very little district heating.

Changes in heat consumption caused e.g. by heat savings in the form of improved insulation etc. have in all scenarios been assumed to remain the same as in the municipal plan scenario A, but it could be relevant to assess various heat savings share in the further work.

The value of reversibility of solid oxide electrolysis cell could be defined as the total cost difference between scenarios D and E. Scenario E, where the reversible solid oxide fuel cells are used, is slightly less expensive (by 60,000 EUR or 1,470 EUR/MW electrolysis installed) than scenario D.

The addition of reversible electrolysis in scenario E could be valuable for balancing supply and demand in the electricity system. While analyzing these benefits in detail may form part of further work, this value could be estimated either by comparing to an alternative technology or analyzing current prices for frequency containment reserve. The alternative technology for reserve capacity could be the cheapest peak power technology, e.g. natural gas turbines. They may, however, not be able to provide the rapid frequency reserve service such as reversible electrolysis could. Another approach might be to analyze the capacity payments for electricity system performance markets today. For example, current payments on frequency containment reserve (primary reserve) correspond to about 60,000 EUR annually.[29] Although this service is the highest paid, there may be many other suppliers to compete with, as well as cheaper suppliers can enter the market in the future, so this estimate is debatable.

Transport and industry remain the main CO_2 contributors, so further work could also look at these sectors. In this article, the "low-hanging fruits" were considered, because transport is considered one of the toughest sectors to change towards sustainability in the short timeframe. For example, we assume that hydrogen cars will not have a breakthrough by 2029, and that transport will rather transition towards electricity. However, the possible relevance of hydrogen cars in the farther future cannot be ruled out and hydrogen storage and fuel cell technologies may become cost-effective by then.

Municipalities are usually not energy system stakeholders as such, but have a right to influence their energy mix, since in Denmark, municipal heat planning projects have to show socio-economic feasibility before being carried out. While the socio-economic perspective does not mirror the actual private economic conditions, by excluding changing taxes and subsidies, it does show the viability of the project. In reality, for making investments happen, a private-economic analysis would be required from a point of view of customers and investors. Further work could include taxes and subsidies to portray scenarios in private-economic terms.

We assumed that the import of waste can be regulated to match the demand. In 2014, the waste was supplied from both local and imported municipal waste. However, with increasing recycling rates and new waste incineration plants being built in Europe, waste might be a “scarce resource” in the future. This could be a subject for further studies to investigate a scenario where import of waste outside a municipality is not allowed.

Since we do not formally weigh the indicators or calculate any overall performance factor composed of the differently weighted indicators, the conclusion of this study is rather qualitative, emphasizing that a good scenario must perform well on all indicators compared to the other scenarios. A quantitative analysis could give a more definitive answer, but would not necessary lead to more robust conclusions due to assumptions behind the weighting factors.

5 Conclusion

This article has outlined how the Danish municipality of Sønderborg can approach its CO_2 reduction goals by 2029. By constructing and modelling five energy scenarios, we investigated the effect of energy conversion pathways on the system, including total system cost, total energy system efficiency, net system CO_2 emissions and total biomass consumption.

While from private-economic perspective biomass combustion is among the cheapest renewable energy technologies for Danish utilities to invest in at the moment, the modelling conducted has demonstrated that a number of other pathways are available for Sønderborg to achieve low CO_2 emissions in a cost-effective way from a socio-economic perspective. Nonetheless, these pathways result in different outcomes in environmental and economic terms.

Considering all the indicators, scenario D and E are optimal from a system cost and CO_2 emission perspective, while providing a lot of biomass consumption savings. Moreover, scenario E shows that the addition of reversible electrolysis actually results in the decreased total system cost, even if the benefits of balancing supply and demand in the electricity system are not considered. The sensitivity analysis has shown that scenario D and E perform best even if changes are implemented in electricity and fossil fuel price. Only a drop in biomass prices would make scenario B least costly.

The results also show that it is not advisable for each Danish municipality to increase biomass consumption, especially if sourcing it locally is impossible. By complementing combustion with modern energy conversion technologies such as wind turbines, photovoltaics and heat pumps, it is possible to achieve climate goals cost- and energy-efficiently. Although solid-oxide electrolysis is rarely used on a large scale in today's energy system, our results show that it is worthwhile to consider as one of the elements of a sustainable city of the future.

The modelling tool used, Sifre, has proven suitable for urban-scale application: it is flexible, has a rich technology representation and links to the rest of the national energy system by electricity prices.

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Appendix A

Table A. 1 Economic data for the energy conversion units included in the model.

Conversion unit	Specific CAPEX (€/MW)	Standard capacity (MW)	Scaling exponent	Variable OPEX (€/MWh)	Fixed OPEX (€/MW)	Plant lifetime (years)	Data source
Natural gas boilers	100,000	10	0.7	0.00	3,700	35	[30]
Biogas boilers	100,000	10	0.7	3.20	3,700	35	[30]
CHP (natural gas)	600,000	100	0.7	0.00	0.00	25	[30]
CHP (waste)	8,500,000	75	0.7	0.00	173,170	20	[30]
Geothermal + absorption HP	800,000	12	0.7	5.40	0.00	20	[30]

Biomass boilers	800,000	12	0.7	5.40	0.00	20	[30]
Electric boilers	75,000	10	0.7	0.50	1,100	20	[30]
Heat pump (utility)	575,000	5.0	0.7	2.68	3,918	20	[30]
Solar heating	250,512	1.0	1.0	0.57	0.00	20	[30]
Individual biomass boilers	642,308	0.013	1.0	0.00	2,000	20	[31]
Individual electric heating	800,000	0.005	1.0	0.00	10,000	30	[31]
Individual gas heaters	480,000	0.013	1.0	0.00	10,800	22	[31]
Individual oil heaters	293,333	0.023	1.0	0.00	1,611	25	[31]
Individual heat pumps	1,000,000	0.01	1.0	1.34	0.67	20	[31]
Photovoltaics	1,100,000	0.9	1.0	34.00	0.00	30	[30]
Onshore wind turbines	1,290,000	0.9	1.0	14.00	0.00	20	[30]
Offshore wind turbines	2,430,000	5.0	1.0	19.00	0.00	25	[30]
SOEC electrolyzers	590,000	5.0	0.85	0.00	15,000	20	[30]
SOFC fuel cells	0	0.9	0.85	0.00	2,68	20	[30]
Anaerobic digestion	3,400,000	12.3	0.7	31.00	0.00	20	[30]
Biogas CO_2 removal	292,950	12.0	0.7	0.00	7,324	15	[30]
Biogas methanation	674,748	18.9	0.7	0.00	16,869	20	[30]
Gasifiers	555,436	100	0.7	0.00	44,435	25	[30]
Syngas reformation	1,884,966	100	0.7	0.00	56,549	20	[30]

Table A. 2 The energy inputs, outputs and efficiencies (defined as energy outputs divided by the energy inputs) of all electrolysis, fuel cell, gas and liquid fuel production processes that are included in the model. The energy input fractions refer to the energy contents. Lower heating values are used. In the processes that yield heat as a byproduct, the heat is utilized in the district heating network.

Conversion process	Energy inputs	Energy outputs	Efficiency	References
Electrolysis (SOEC)	Electricity (85%) Heat (15%)	Hydrogen	82% (total)	[17]
Fuel cell (SOFC)	Hydrogen (100%)	Electricity Heat	60% (electricity) 95% (total)	[17]
Anaerobic digestion	Manure (32.7%) Straw (65.6%) Electricity (1.7%)	Biogas (65% CH_4, 35% CO_2)	40% (total)	[30],[32]
Biogas upgrade	Biogas (59.4%) Hydrogen (40.6%)	SNG	91% (total)	[30]
Gasification	Wood (40%) Waste (40%) Straw (20%)	Syngas Heat	82% (syngas) 92% (total)	[30]
Reformation to methanol	Syngas (100%)	Methanol Heat	68% (methanol) 93% (total)	[33]

Table A. 3 The energy inputs and efficiencies for all types of individual heating included in the model. In all cases, the only energy output is heat for space heating and domestic hot water supply.

Conversion unit	Energy inputs	Efficiency	References
Gas boilers	Natural gas (100%)	100%	[34]
Oil boilers	Heating oil (100%)	100%	[34]
Biomass boilers	Wood (85%) Straw (15%)	80% (2014) 90% (2029)	[34]
Electric heating	Electricity (100%)	99%	[34]

Heat pumps	Electricity (100%)	COP 3.0	[34]

Table A. 4 The conversion units for district heating production in the model. The energy inputs, outputs and efficiency of each type of unit are listed.

Conversion unit	Energy inputs	Energy outputs	Efficiency	References
Biomass boilers	Wood Straw	Heat	100%	[20]
Geothermal abs. heat pump + biomass boiler	Geothermal Wood Straw	Heat	100%	[20]
CHP (natural gas)	Natural gas	Heat, electricity	80%	[20]
CHP (waste)	Waste	Heat, electricity	100%	[20]
Natural gas boilers	Natural gas	Heat	100%	[20]
Biogas boilers	Biogas	Heat	100%	[20]
Electric boilers	Electricity	Heat	100%	[20]
Solar heating	Solar energy	Heat	-	[20]
Heat pumps	Electricity	Heat	COP 3.0	[20]

Table A. 5 The locally available residual biomass in Sønderborg municipality. For the 2014 scenario, values corresponding to the year 2009 were used, due to lack of more recent data. The values for 2029 are based on a scenario forecast for the availability of biomass for energy purposes in Denmark [35].

Biomass type	Availability in 2014 (GWh/year)	Availability in 2029 (GWh/year)	Reference
Wood	39	46	[26]
Straw	207	771	[26]
Manure	180	183	[26]
TOTAL	**426**	**1,000**	

Table A. 6 Electricity and fuel prices used in the model for years 2014 and 2029. The electricity price refers to the Western Danish (DK1) electricity spot price. Time series with an hourly resolution were used as an input for the price of electricity in 2014 and 2029, as well as for the price of fossil fuels in 2014. The 2029 electricity price time series are from a model forecast made by Energinet.dk. In the case of hourly time series, the average price level of the year is shown in parenthesis in the table.

Fuel	Unit	Price 2014	Price 2029	Reference
Electricity	€/MWh	2014 time series (avg. 30.68)	2029 time series (avg: 58.09)	Energinet.dk
Wood	€/GJ	6.68	7.71	[36]
Straw	€/GJ	4.40	4.40	[36]
Manure	€/GJ	2.93	2.93	[37]
Natural gas	€/GJ	2014 time series (avg: 6.11)	8.82	Energinet.dk,[36]
Waste	€/GJ	0	0	[37]
Gasoline	€/GJ	2014 time series (avg: 22.36)	34.02	[38],[36]
Diesel	€/GJ	2014 time series (avg: 21.32)	30.60	[38],[36]
Heating oil	€/GJ	2014 time series (avg: 20.65)	29.64	[38],[36]
CO$_2$ emissions	€/ton	6.04	27.38	[36]