Ahmed, S., Truong, N L. (2022)
Analysis of future carbon-neutral energy system: The case of Växjö Municipality, Sweden
Smart Energy, 7: 100082
https://doi.org/10.1016/j.segy.2022.100082

Smart Energy 7 (2022) 100082

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy

Analysis of future carbon-neutral energy system – The case of Växjö Municipality, Sweden

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ARTICLE INFO

Keywords:
Carbon-neutral energy system
Carbon capture and storage
Intermittent renewable energy
Future energy supply
Transport electrification

ABSTRACT

In line with the Swedish target of carbon neutrality by 2045, the municipality of Växjö in Kronoberg County has set its own target to be carbon neutral in 2030. Currently, the Municipality's partially decentralized energy system relies heavily on interconnected electricity supply from the national grid, and fuels imports from other parts of Sweden. Under this circumstance, several concerns arise, including: in which ways future demand changes induce supply changes, and whether a future carbon-neutral energy system will be less costly in a sustained-electricity supply condition. In this study, techno-economic evaluations are conducted for different carbon-neutral scenarios for Växjö's future energy system in 2030 and 2050, using an hour-by-hour dynamic energy simulation tool of EnergyPLAN. Projections for the future energy demands for Växjö were developed and modeled, based on the development strategies and on the national sustainable future scenarios in Sweden. Results for the Växjö's carbon-neutral scenarios showed that the current energy system is sufficient to satisfy future heat demand. However, fulfilling demands of electricity for all sectors and fuels for transport and industry is a challenge. In the short term and at increased energy demand and price, being carbon neutral is technically viable without major changes in energy supply technologies. However, in the long term, investment for intermittent renewable energy resources, together with carbon capture and storage is considered to be viable financially. Therefore, planning for a carbon-neutral Växjö based on local investments showed to be a feasible strategy.

1. Introduction

Reducing greenhouse gas (GHG) emissions has been targeted by European member states, starting from the 2012 Energy *Efficiency Directive* to reduce energy consumption or intensity by 20% in 2020 [1]. Which increased in the 2030 Climate and Energy Framework; existing ambition and overall cut of GHG to be 55% by 2030 [2]. In the Nordic region, Sweden is leading this transition. Currently, the country has 98% renewable electricity production, significant energy efficiency measures, and fuel shifting in the industry, and the residential sectors [3]. The country also aims to become fossil fuel free by 2045 [4]. It has already decoupled its energy intensity from its economic growth by 20% in 2018, and moving toward a 50% reduction in 2030 compared to 2008 and 2005 levels respectively [3,5]. Even so, fossil fuel is dominant in the transport sector despite the introduction of biofuels, and different alternative transport options. In line with these national goals, the municipalities within Sweden sat advanced sustainability targets. So far, many municipalities have announced their pathways and plans of reaching carbon neutrality within the coming decade.

To reach this target, energy system analysis could be used to estimate how to fulfill the increasing energy demand while reducing CO_2 emissions to a specific level. An energy system analysis covers the overall system demands from imported-,local-, and intermittent renewable energy (IRE) resources, and from the least costly sustainable options [6]. Especially, decentralized energy systems require more modeling, optimization and scenario analysis [7–9]. Focusing only on electrical network stability, matching the demand and the supply was the first step, but, given the fluctuating nature of the demand side, the supply side had to be the dependent variable in this process. This was costly since power operators had to lower or surge their production accordingly, when most systems consumers pay a fixed price per unit of electricity [10]. Therefore, concepts like demand side-management, demand-response, and smart grids were developed [11–13]. Afterward, concepts like smart renewable-energy system, were coined which includes various interlinkages between all of the energy system components of conversion technologies, supply and demand, in addition to

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https://doi.org/10.1016/j.segy.2022.100082
Received 30 December 2021; Received in revised form 8 April 2022; Accepted 15 June 2022
Available online 18 June 2022

utilizing energy from variant renewable sources [14,15].

There are different studies investigating options towards a more sustainable energy society. Treffers et al. [16] studied the technical only sustainable energy scenario in the Netherlands aiming at 80% carbon emissions reduction for the year 2050 against a Business as Usual (BAU) scenario using the Intergovernmental Panel on Climate Change (IPCC) model [17]. The sustainable scenario was implemented on an independent sectoral level for the demand side: increasing energy efficiency, energy saving, and recycling in the industrial sector, and using hydrogen fuel cells and biofuels for future transportation. For residential and public buildings, reduced heat and electricity demands were projected by using efficient appliances, compact and well-insulated buildings, district heating, solar thermal, and heat pumps. The energy supply side consisted of nearly two thirds of bio-energy from imported biomass, and the rest was a mixture of wind, photovoltaic (PV) cells and fossil fuels. Synergies and trade-offs between sectors were not realized yet, thus it can be considered a blueprint for a sustainable energy system.

Studies, e.g. Refs. [14,18], showed that costs for the energy system in 2050 will shift from fuel costs during operation to initial investments, once targets to be carbon neutral are to be achieved. In most of the cases, the transport sector is the challenge. In the study of a 100% renewable energy system for Denmark by 2050, with the first step being a partial renewable energy system in 2030, two key challenges of significantly increasing the electricity supply from renewable sources, and the integration of the transport sector are to be met. This ultimately included all of demand-side management processes, technological shift towards electrification, and bio-fuels and hydrogen as energy carriers [18]. A report for Ireland context gave more details into the required steps for shifting to a smart energy system focusing on the transport sector [14]. Both studies agreed on including all the energy sectors in the analysis, secondly the possibility of technological changes within the system, and thirdly to consider the hourly demand fluctuation for all energy types. However, for Ireland model, the changes of energy demand over time were excluded. Also, the current Ireland energy system was fossil fuel-based and unlike Denmark where the energy system was considered more sustainable due to the wider use of combined heat and power plants (CHP) and large-scale electrical heat pumps (EHP). In another dimension, Child et al. [19] demonstrated the viability of having a 100% sustainable energy system by 2020 in Åland of Finland, by including electricity and fuel imports from Sweden and Finland. Also, an isolated energy island mode or open to import/export mode for different sustainable settings in 2030 has been addressed. In most scenarios, electricity was produced from IRE sources or imported from sources considered to be renewable. Sustainable heat supply can be met by maxing the use of district heating and individual electric heat pumps. Different energy storages of IRE were investigated in correlation with the transport sector in forms of vehicle to grid (V2G) and power to gas (P2G) options. The least costly scenarios were those with half electrical vehicles (EV), half imported bio-fuels, and 100% EV, with the argument for the latter considered more sustainable was that V2G can create a buffer for the mismatch between renewable power production and its final use. Additionally, this will lead, in the context of Åland for example, to reduce the annualized overall system cost when compared to importing biofuels or the other storage option of P2G.

In designing a smart energy system for a city, besides dealing with the local issues, regional and global issues are also of concern. Using renewable energy sources of, for example biomass and wind power could influence its availability for other applications from national and global perspectives and these are to be accounted for in analysis [20]. In other words, the design and planning for an energy system have to be adjusted based on the city or the municipality's share of national and international renewable sources.

In the municipality of Växjö in Kronoberg County, the south of Sweden, a target of being carbon neutral by 2030 has been set [21]. Different options and alternatives are being developed based on the current contexts of local demand and resources together with the general national trends. This study aims at investigating scenarios of how the energy system in Växjö will look like in 2030 and 2050 under the context of a carbon-neutral society from a techno-economic perspective. The current resources and energy supply capacities are evaluated and balanced with the dynamic demand. Different options to maximize the self-sufficiency of energy consumption, based on the local context, are considered and the resulting quantity of energy being exchanged with the national energy networks are investigated. Besides, the impacts of technological changes occurring in the energy supply system consequently to demand changes together with the cost of the carbon-neutral options are evaluated.

2. Study descriptions and methodology

2.1. Studied area and contexts

Växjö Municipality (Fig. 1) has an area of approximately 1.91 thousand km^2 and a population of approximately 94 thousand people, based on 2019 statistics [22] and is divided into eleven residential areas of which the city of Växjö holds the majority of the Municipality's citizens of more than 72% [22,23]. In the remaining residential areas, Rottne, Ingelstad, Lammhult, Braås, and Gemla are the more populated with a population just under ten thousand inhabitants and Åryd, Åby, Furuby, Tävelsås, and Nöbbelee are the least populated ones, with less than two thousand residents each [23]. Within this study, the terms “Växjö”, and “the Municipality” will be used to refer to the whole territory of Växjö Municipality.

2.2. Energy resources, demand and supply

Demand for energy in Växjö has been classified into different uses within the energy sectors in the past years. Fig. 2 presents the historical trend for the energy demand development following the steady increase of population. During the last 10 years, heat demand had a positive correlation factor of 0.74 with the population growth, meaning when the population was growing, the demand for heating was rising. On the contrary, there is a negative correlation of −0.61 with electricity demand, meaning that the electricity demand reduced despite the population growth. Demand for district cooling started in 2011 and continued upward with a positive correlation of 0.9. This may be due to the increased population and the increased average outdoor temperature [25]. Energy for transport demand had a low positive correlation of 0.13 with population growth. However, it can be seen that energy demand for transport was highest throughout the years and only slightly reduced in recent years.

The statistics of energy supply in Växjö during 1993–2019 (Fig. 3) shows that the overall energy supply has been relatively increased from less than 2000 GWh in 1993 to reach a peak of approximately 2700 GWh in the cold year of 2010. Then total energy demand has declined and stabilized to approximately 2400 GWh during the last five years.

The energy system of Växjö is considered to be partially decentralized [27] with a part of electricity and fuels are being imported from other parts of Sweden. Fig. 4 shows the Municipality's energy balance, starting from the energy supply of renewable energy resources, non-renewable fuels, and electricity imported to the Municipality. Primary energy resources are then partly used by local energy facilities beefore distributed to energy users in different sectors.

Details of the final energy demand (Table 1) showed that heat is the most important final energy type, covered 38% of the total final energy demand, and majorly fulfilled in the form of district heat by the systems in Braås, Ingelstad, Rottne and Växjö City (Fig. 5). The remaining heat demand was covered mostly by individual heat production units of oil boilers, biomass boilers and electrical heat pumps. The cooling demand for public and commercial buildings is currently fulfilled by a district cooling network and is produced in the same facility of district heating in Växjö City.

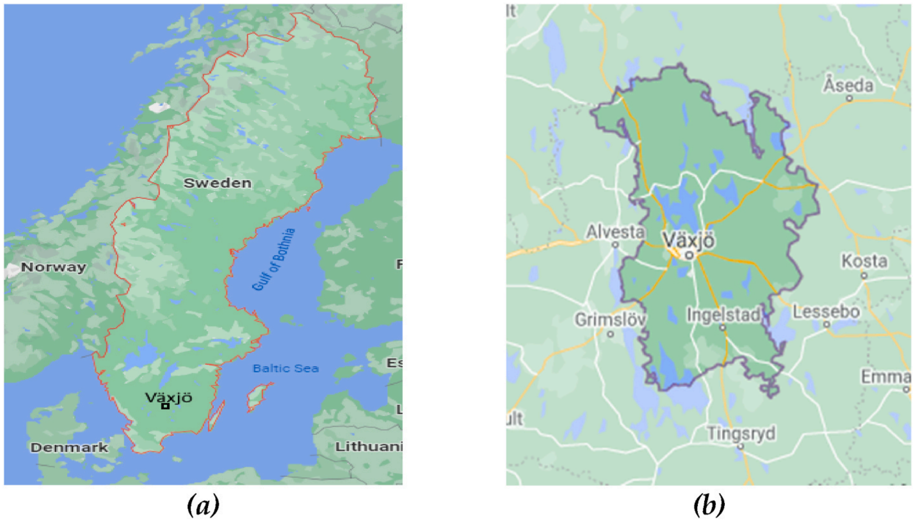


Fig. 1. Location of Växjö Municipality in Sweden (a), and the map of Växjö Municipality (b) [24].

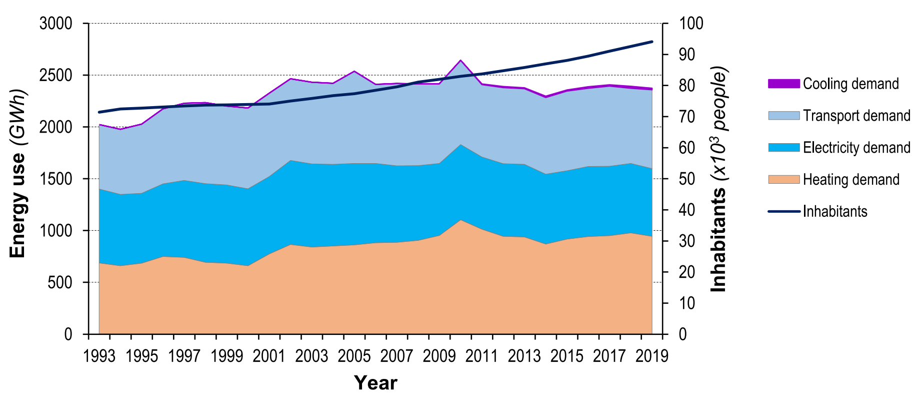


Fig. 2. Historical changes of energy-related demands and population trends in Växjö [26].

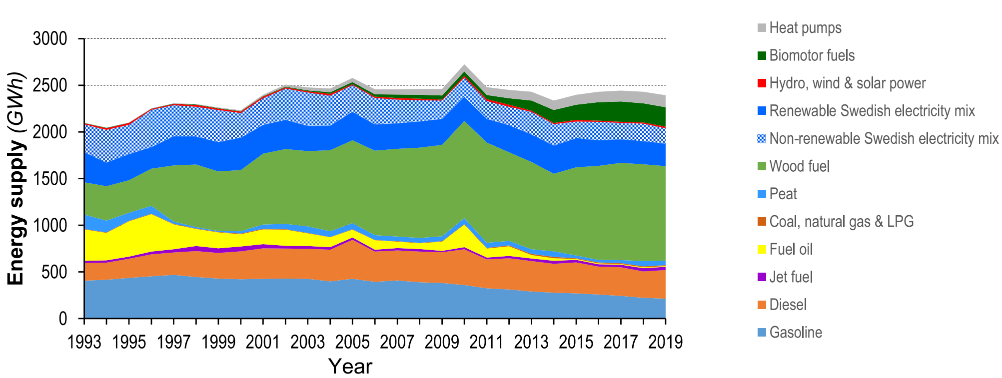


Fig. 3. Energy supply by fuel types in Växjö during 1993–2019 [26].

Electricity is the second important final energy type, covered approximately 29% of the total final energy demand. This is being fulfilled by both local infrastructures and the national power grid (Fig. 6). In 2019, around 200 GWh has been coproduced by the CHP units in the district heating system (DHS) in Växjö city. Besides, a total of 16.7 GWh has been produced by local hydropower plants (8.8 GWh), rooftop solar PV systems (6.1 GWh) and onshore wind turbines (1.71 GWh).

2.3. Methodology

The methodology used to balance the supply and demand in this study follows the steps described in Ref. [28] for shifting cities' energy system from fossil fuels to sustainable energy resources. We use the existing boundary of the Växjö Municipality as the study boundary and all the transactions of energy via this boundary are accounted as energy imported and exported accordingly. The local energy system is expanded further by zeroing the total yearly energy demand in relation to the population change. The methodology used here is divided into

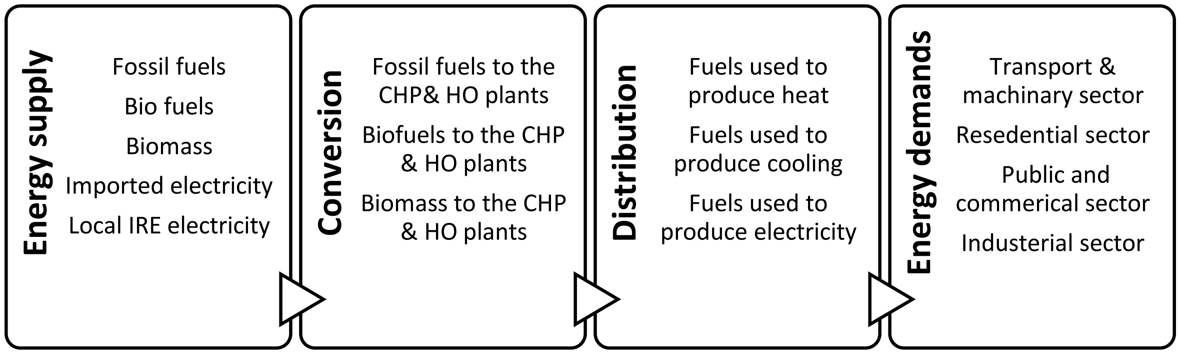


Fig. 4. Energy balance data for Växjö Municipality in 2019 [26].

Table 1
Växjö's energy demand (GWh) by sectors in 2019 [26].

Demand type	Transport & machinery	Residential	Industry	Public & commercial	Total
•Electricity demand excl. for transport and heat pumps		186	119.5	304.5	610
•District heat demand		477	22	244	743
•Individual heat demand		96	2.5	13.5	112
-Small-scale oil boilers		1		3	
-Small-scale biomass boilers		60		8	
-Electricity for electrical heat pumps		35	2.5	2.5	
•District cooling demand				15	15
•Oil & LPG for industry			16		16
•Biomass for industry			9		9
•Coal for different uses	0.10				0.10
•Energy for transport	761				761
-Jet fuel	33				
-Diesel	307				
-Bio-diesel (FAME, HVO, Synthetic diesel)	169				
-Petrol (gasoline)	214				
-Bio petrol (bio-gasoline and ethanol)	12				
-Biogas	21				
-Electricity	5				
Total	*761*	*759*	*169*	*577*	*2266*

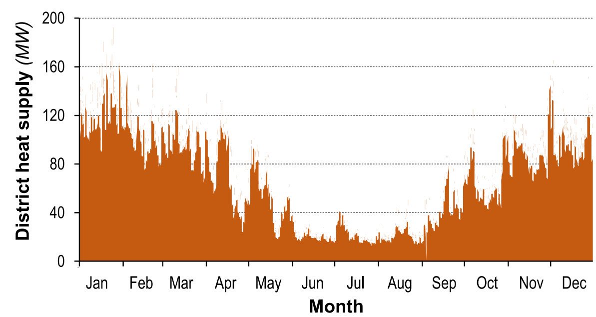


Fig. 5. Hourly district heat supply in Växjö Municipality during 2019 [26].

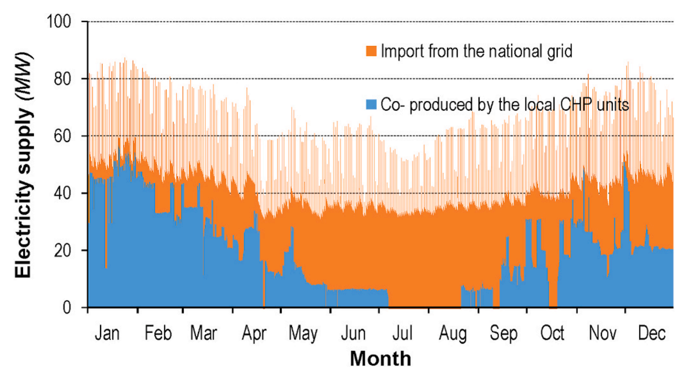


Fig. 6. Self-generated and imported electricity in Växjö municipality during 2019 [26].

three steps. Firstly, a reference balanced energy system model for the studied area is developed to reflect its current energy system. Here, data and assumptions of the year 2019 are used as a reference. This includes an aggregation of the total energy demand and supply in all energy use sectors, and hence covers fuels, heat, and electricity demands as well as co-generation of heat and electricity, IRE electricity production, and imports of fossil- and biofuels and electricity at an hourly interval. Secondly, future energy demand scenarios in 2030 and 2050 for the studied are developed, taking into account the changes at the national level which presented by different energy use scenarios from the Swedish Energy Agency [29]. The energy demand for each sector at the local are assumed to be correlated with both local population trend and the trend of energy use at the national level. Thirdly, the energy system for each scenario is modeled to reflect the changes occurring in the energy system, and to define the quantity of both the energy supply being added to the system and carbon emissions to be reduced together with the exchanged energy via the case study's border.

In this study, energy supply scenarios are technically and economically investigated for reaching a self-sustained energy system in terms of heat- and electricity supply, together with minimizing carbon emissions and capturing the remaining quantity of carbon emissions in the system. The dynamic simulation tool of EnergyPLAN is used for the analysis. This is an advanced energy system analysis tool developed by Aalborg University in Denmark and designed to heuristically evaluate multiple objectives and outputs based on deterministic inputs [30] and being used to model regional, country, and micro levels of islands and municipalities of energy systems [14,18] [19,20,31,32]. The tool has features to cover both economic and technical aspects of an energy system as well as component systems of heating, cooling, electricity, transport, etc.. The economic inputs cover the technologies' investment and operation and maintenance (O&M) costs, fuels cost, interest rate, CO_2 taxes, and external electricity market costs. Consequently, primary energy use, annualized system costs, level of carbon emissions, share of renewable energy, imported and exported electricity and their costs, as well as critical excess electricity in the system can be derived [33].

To develop the scenarios of future energy demands and supply during 2030 and 2050, national energy demand scenarios that align with the sustainability target are identified, based on Swedish Energy Agency [29] and followed the European Commission recommendations and Times Nordic model. Here, three scenarios are considered, including: (i) *EU Reference,* when the national economic and energy trends follow the European Commission recommended prices of emissions and fossil fuels; (ii) *Additional measures,* emphasizing the increased taxation of fossil fuels in road transportation as well as aviation, but no significant changes in marine shipping, and with a continuation of easing taxes on biofuels, and (iii) *Electrification*, involving the similar adjustments as in Additional measures scenario and with the increasing electrification rate in all sectors. This scenario includes more EV, hybrid and plugged-in hybrid vehicles in transportation, and the widespread of informatics technology in residential sector together with technological shifts in the industry sector. In all these scenarios at the national level, electricity demand will increase, and this is opposite to the final energy demand for the transport sector which will decrease to certain levels depends on the decarbonization pathway. Heat demand will decrease slightly until 2030 in all the scenarios except in the electrification scenario, and then increase in 2050. On the contrary, energy demand for industry will increase, mostly in the form of electricity, until 2030, then reduce until 2050 in all the scenarios except for the high electrification scenario [29].

Based on the changes of the specific energy use per capita in the different scenarios at the national level, corresponding future energy demand for Växjö Municipality are developed, considering the similar trend as of the national level for each sector [29]. The quantity of different types of energy demand in the future in the studied area is then derived considering its projected trend of population growth (Fig. 7). Fig. 8 shows how the final energy demand for each year in the studied area are derived from the national energy demand scenarios.

The energy demand in each scenario is used as inputs to model the consequent changes in the energy supply system. In the national scenarios of future development, Sweden as a whole is targeted to be a net electricity exporter by increasing onshore-, offshore wind power and solar PV production, as well as extending service life of current nuclear power plants or investing to new plants [29]. For the context of Växjö Municipality, only onshore wind power and solar PV are assumed to be expanded locally for electricity supply. In terms of installed capacity, the ratios of 74% and 26% for wind power and Solar PV, respectively, are assumed for new installations, based on the optimal capacity mix suggested for Europe without storage [34]. Besides, representative grid and balancing costs of 13 and 6.75 € are considered for each MWh of electricity produced by wind power and solar PV, respectively [35]. As for heat supply, the same conversion technologies in the reference scenario are considered. However, the share of each technology for the total heat demand vary and optimized according to scenarios. Uses of fossil fuels in transport sector are estimated based on the reference situation (showed in Table A1 of the Appendix) and according to each scenario that strongly depend on the quantity of biofuel being used and the electrification of this sector [29]. The options for the carbon neutral involve the investment for bioenergy with carbon capture and storage (BECCS) to offset the remaining CO_2 emissions and carbon costs are also evaluated. This option is based on the plan of installing a BECCS system in the existing biomass-based CHP plants to capture up to 180,000 tons of CO_2 by 2030 [36,37]. The captured CO_2 is assumed to be transported by road to a dedicated terminal in the North Sea before being handled by an offshore storage process.

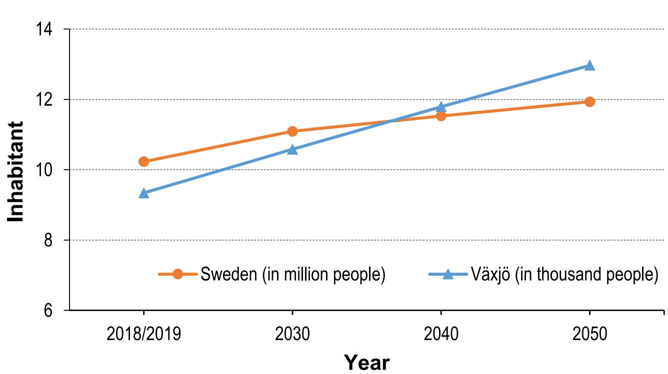


Fig. 7. Projection of population growth in Sweden and Växjö [26,29].

In the reference model and the developed demand models, the distribution losses of electricity and district heat in the study area are assumed to be equal to 10.7% and 13.9%, respectively, based on the national average during 2010–2019 [38]. However, distribution losses of fuels within the local system are assumed to be negligible and excluded in the analysis.

Costs and performance of the involved energy conversion technologies are based basically on the available updated regional data [40–42]. Scenarios were developed further to explore the technical possibility of reducing carbon emissions beyond the national levels. Here, the BECCS technology is applied in the existing district heat production plant to create negative CO_2 emission to offset the emissions from transport sector due to the use of fossil fuels that are still demanded in 2030 and 2050. The post-combustion BECCS technology is taken into accounted together with a transport distance of 150 km for the captured CO_2 to the storage terminal. All the costs associated with this process are accounted, based on [41]. A quantity of electrical penalty of 0.25 and 0.225 MWh are considered for each ton of CO_2 being capture in 2030 and 2050, respectively [41].

In all the analysis, costs for energy conversion and supply system are considered. However, associated costs for technology changes at end users are assumed to be incurred at the end of life of the technology and are excluded in the balance. Table 2 shows the projected electricity- and fuel prices at the national level for Sweden. These prices have taken into account the change of electricity demand in each scenario. Besides, a carbon tax of 30 and 91 €/ton CO_2 by 2030 and 2050, respectively, are accounted [29]. In the financial analysis, a discount rate of 3% and an exchange rate of 1€ = 10 SEK are used [43].

3. Implementation and results

3.1. Energy demand

Table 3 shows the details of different final energy demand from different scenarios for 2030 and 2050 in Växjö. In general, the total final energy demand slightly reduced in 2030 but increased in 2050, in comparison to 2019 (Fig. 9). The major trend in all the scenarios is the increased electricity and heat demand. The heat demand for the building sector increases, following the trend of population. However, the per capital heat demand reduces to (7.1–7.36) and (7.09–7.31) MWh per person in 2030 and 2050, respectively in comparison to 7.9 MWh/person in the reference year of 2019. Details of heat demand from different installations of each scenario are presented in Table A2 of the Appendix. In both the scenarios of EU-reference and Additional measures, heat demand reduces in 2030 due to higher building efficiency, additional use of heat pumps in detached houses, and warmer climate that lead to lower heat demand. On the contrary, in the electrification scenario, heat demand which is covered by CHP plants is expected to increase as a result of increased electricity prices that makes district heating production more appealing.

However, in the transport sector, final energy use is reduced mainly due to the fuel switching together with the improved efficiency in this

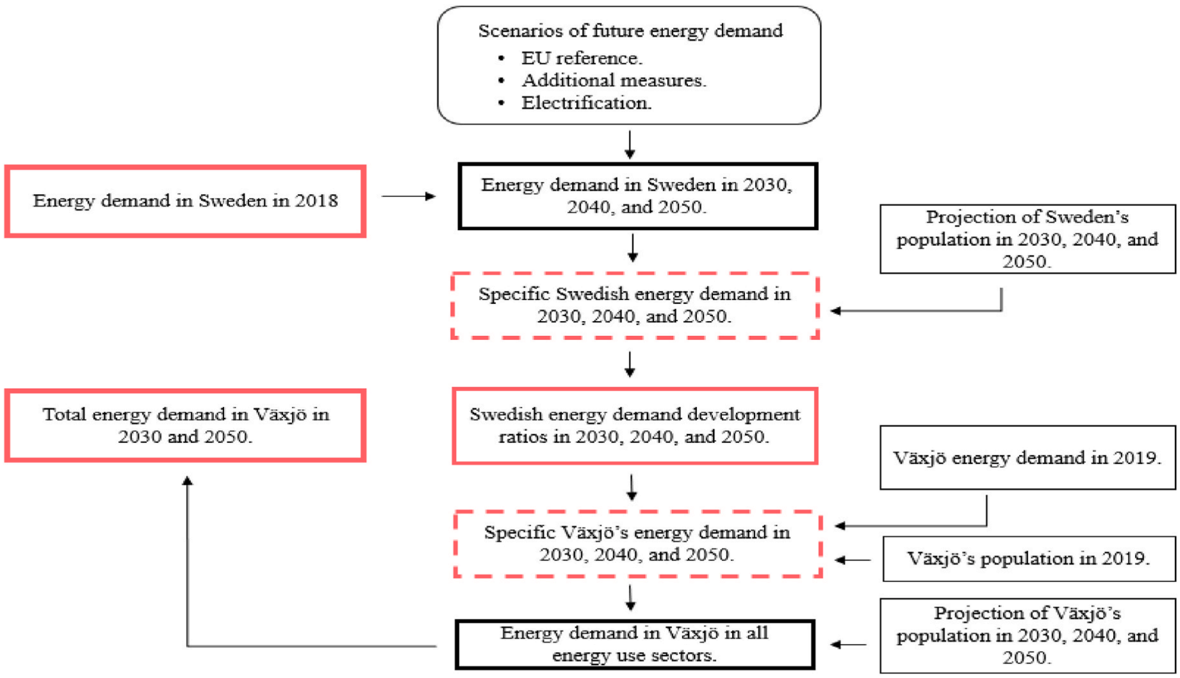


Fig. 8. Developing energy demand scenarios for Växjö based on national energy demand scenarios.

Table 2
Projected electricity- and fuel prices (€/MWh) according to national scenarios [29].

Type	Unit	Year	
		2030	2050
• Electricity			
- Rererence EU & Additional scenarios	€/MWh	31.2	47.9
- Electricication scenario	€/MWh	36.5	49.6
• Gasoline	€/lit	1.49	2.03
• Diesel	€/lit	1.16	1.56
• HVO	€/lit	1.60	1.60
• FAME	€/lit	1.28	1.28
• Ethanol	€/lit	0.96	0.96
• Biogasoline	€/lit	2.03	2.03

sector. The detailed breakdown of fuels and electricity use for the transport sector (Table A3 of the Appendix) showed that the substantial reduction of fossil-based fuels links with the increased biofuel and the use of EV. As a result, electricity for transport sector increase up to four times in 2030, and up to thirteen times 2050 in comparison to the reference year 2019. However, this sector is still based largely on both liquid fossil- and biofuels.

3.2. Energy supply

The requirement of fuels and electricity for all the sectors in Växjö in 2030 and 2050 (Table 4) derives different alternatives of energy supply. Fig. 10 shows the balance of the energy supply in Växjö based on either external sources or locally installed IRE resources together with the corresponding quantity of CO_2 emissions. In the cases relying on external sources, approximately 510–520 GWh and 600–740 GWh of electricity are to be mobilized in 2030 and 2050, respectively. For the option of self-sufficient electricity, investments for local IRE resources are required to produce such quantity of electricity. However, the national power grid plays a role of balancing the mismatch between the periods of electricity production and use.

The result shows that scenarios of final energy use influence the CO_2 emission reduction strongly. However, in all the scenarios, certain quantity of CO_2 emissions are to be sequestered once the target of carbon neutral is determined. The introduction of BECCS technology for the target of carbon neutral demands more electricity, up to 1.9–5.8% and 1.4–3.3% in comparison to the total quantity of electricity to be imported/produced in 2030 and 2050, respectively (Table 5).

Table 6 presents the breakdown of the installed capacity of IRE resources and BECCS systems for the target of carbon neutral. In all these scenarios, the national power grid is involved to balance the fluctuation

Table 3
Final energy use in Växjö from different scenarios in 2030 and 2050.

Parameter	*Year & scenario*					
	2030			2050		
	EU reference	Additional measures	Electrification	EU reference	Additional measures	Electrification
Population (thousand inhabitants)	106	106	106	130	130	130
Electricity, excl. transport (GWh)	711	711	714	840	840	995
Oil for industry (GWh)	14	14	13	11	14	11
Biomass for industry (GWh)	10	10	10	13	13	13
Coal (GWh)	0	0	0	0	0	0
Heating (GWh)	827	827	855	985	984	1013
Cooling (GWh)	16	16	16	17	17	17
Fuels and electricity for transport sector (GWh)	625	622	546	505	495	362
Total energy demand (GWh)	*2202*	*2200*	*2153*	*2370*	*2362*	*2413*

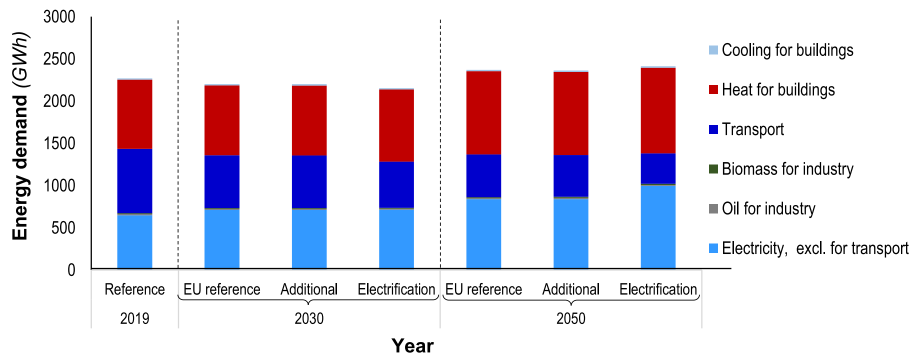


Fig. 9. Scenarios of final energy use in Växjö during 2030 and 2050 in comparison to 2019.

Table 4
Fuels and electricity to be fulfilled by external sources or additional installations in Växjö from different scenarios in 2030 and 2050.

Parameter	*Year & scenario*					
	2030			*2050*		
	EU reference	*Additional measures*	*Electrification*	*EU reference*	*Additional measures*	*Electrification*
Fossil oil	480	240	210	360	180	130
Biomass	1130	1160	1180	1350	1360	1400
Biogas	20	20	20	20	20	20
Biofuels	130	370	320	100	280	180
Electricity	550	540	530	620	600	750
Total	*2310*	*2330*	*2260*	*2450*	*2440*	*2461*

of IRE resources. Fig. 11 demonstrates the monthly profile of electricity supply in 2030 and 2050 by different energy resources for the Electrification scenario. Due to the hourly and seasonal variation of electricity use and production, the export and import of electricity is necessary to balance the system (as showed in Fig. 11b and 11d).

At the defined capacities of wind power and solar PV together with the existing CHP units (Table 5), large quantity of electricity, up to 29% total electricity use, is being exchanged with the national power grid (Fig. 12).

3.3. Added technology costs

Table 7 shows the annualized costs for each technology in all the scenarios for the target of carbon-neutral Växjö. BECCS technology including compressing, liquification and pretreatment is the predominant factor to define investment cost and electricity consumption [39]. The high investments for local IRE resources in each scenarios reduces the costs for electricity import.

Fig. 13 shows the additional system costs for the two options of carbon neutral in Växjö in comparison to the conventional option relying on the national energy system. In general, it is costly to be carbon neutral in the short term of 2030 and within the three scenarios of energy demand, the Electrification scenario shows to be more attractive. However, in the long term of 2050, the carbon-neutral option do not cause major changes in energy costs. The electrification scenario, together with the investment to local IRE resources could cause a large reduction of annualized costs in comparison to the option of relying fully on the national energy system.

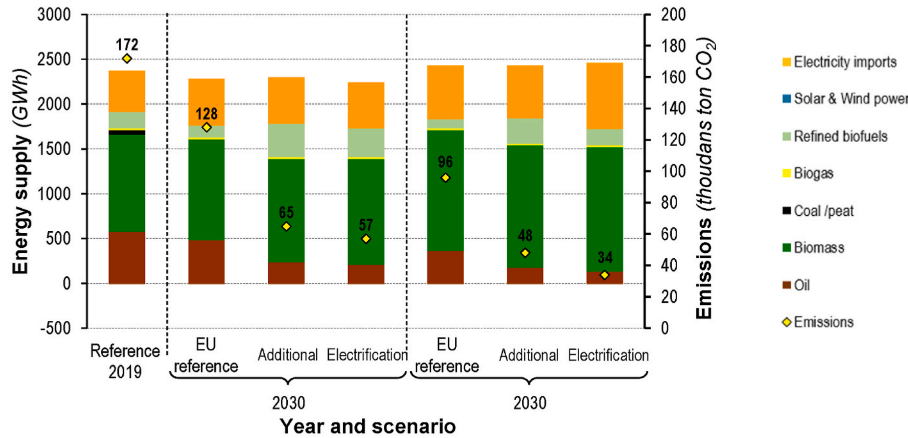
4. Discussion and conclusions

This study shows that an energy system analysis and simulation can provide an insight to understand an integrated energy system and to set energy and emission targets based on relevant policies and feasible technological solutions. Scenarios of future energy demand for developing a carbon-neutral system can therefore be derived and evaluated, and this study has initiated a techno-economic study about the feasibility for Växjö Municipality to be carbon neutral in the near future.

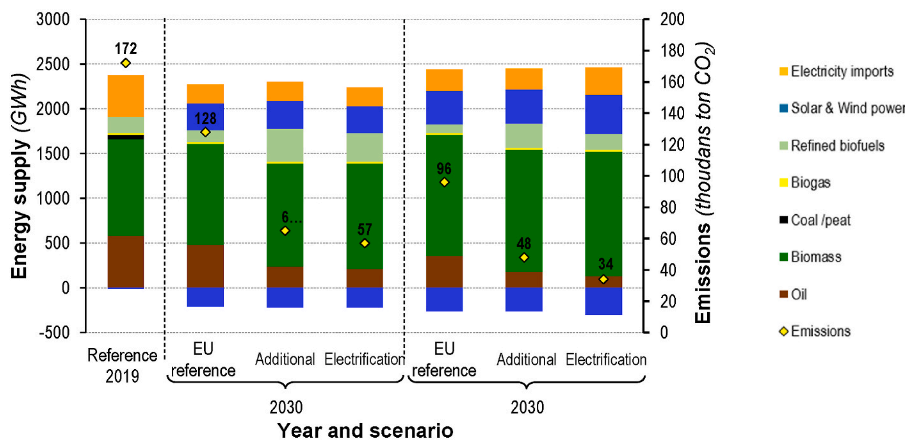
Estimation of the demand and supply options for 2030 and 2050 has been derived and the results show that the integration between the different energy sectors is crucial to achieve the target of carbon neutral. Currently, fossil fuels are used majorly in the transport sector, and the different pathways of decarbonizing this sector require the contribution of different resources, including biomass, refined biofuels and electricity. The increased demands of biomass of up to 9% and 29% in 2030 and 2050, respectively for the scenario with high electrification rate are accounted. However, use of refinery biofuels for transport sector varies and is highest in the scenario of high fossil fuel price, up to 2.8 times in comparison to the 2019 level. Here, the increased shares of biofuels were assumed to be fulfilled by the national energy system. Therefore, production capacity, resource use and consequences for such a production at the national level were not considered in this analysis and this could be an area to further investigation.

In all the scenarios, there are still demands of fossil fuels for the transport sector. The increasing shares of electro-fuels such as hydrogen from certain resources such as wind power can create a buffer for further expansion of such IRE resources [19,20,44]. However, costs associated with such an option in the transport sector are to be taken into account. Calculation of the carbon abatement costs in this sector may be necessary to evaluate the reference costs and the attractiveness of fossil fuel minimization. The further analysis to break down the complexity of this sector that involves various vehicle types and performance characteristics of which different corresponding carbon taxation schemes [45] are required and this could be considered for future work. The biggest emphasis can be on increasing electrification that has benefits of creating flexible demand and supply from smart charging systems in electric-based vehicles [46–48].

The electricity demand in the study area of the reference year of 2019 was met largely by electricity imports and the fulfillment of increased electricity demand in the future depends strongly on scenarios of power supply. Assumptions made for the involved levels of IRE resources in 2030 and 2050 were theoretical via different scenario designs



(a)



(b)

Fig. 10. Balance of energy supply and CO_2 emissions in 2030 and 2050 in Växjö when the system is fulfilled by external sources (a), and by locally produced IRE resources (b). The negative values indicate the quantity of electricity being exported.

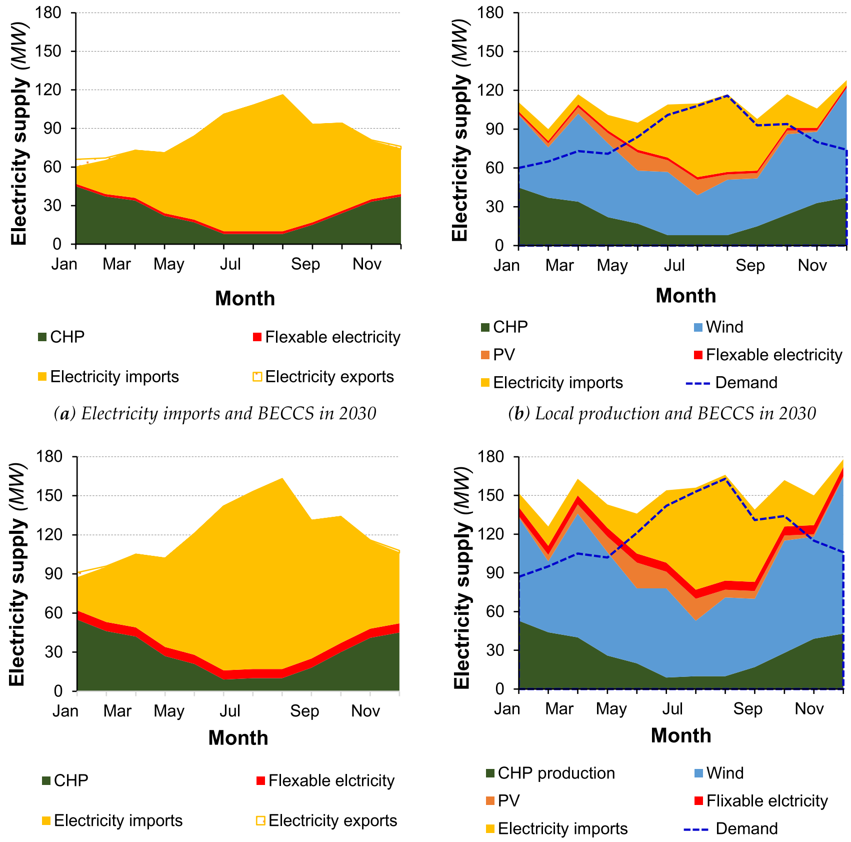
Table 5
Electrical penalty for BECCS for different scenarios in 2030 and 2050 (GWh).

Years scenario	2030			2050		
	EU reference	Additional	Electrification	EU reference	Additional	Electrification
Electricity penalty	32.0	16.3	14.2	21.6	10.8	7.65

Table 6
Installed capacity of wind power and solar PV for the options based on local IRE resources and BECCS for the target of carbon neutral in 2030 and 2050.

Parameter	Year & scenario					
	2030			2050		
	EU reference	Additional measures	Electrification	EU reference	Additional measures	Electrification
CCS system (TCO_2/hr)	*15*	*7*	*7*	*11*	*5*	*5*
Solar PV (MW)	*60*	*60*	*60*	*70*	*70*	*86*
Wind power (MW)	*172*	*172*	*172*	*198*	*198*	*244*

and showed to be cost-efficient. In reality, factors such as legalization and public perception for granting permits for wind turbine installations can be a large barrier in Sweden that hinder wind power investments [49,50]. Similarly, the level of required solar PV installations which showed to be achievable due to the large expansion potentials of this technology [34,51] depends largely on the promoted economic drivers and business models. In all the cases analyzed, the national power grid is vital to balance the mismatch between production and consumption. The different possibilities to levelize such mismatch can be further explored in further investigation. The trend of increasing heat demand in Växjö showed to be different from the trend from the national scenarios for the whole Sweden. This is mostly due to higher expected



(a) Electricity imports and BECCS in 2030
(b) Local production and BECCS in 2030
(c) Electricity imports and BECCS in 2050
(d) Local production and BECCS in 2050

Fig. 11. Electricity production and imported from the national power grid in the Electrification scenario in 2030 and 2050.

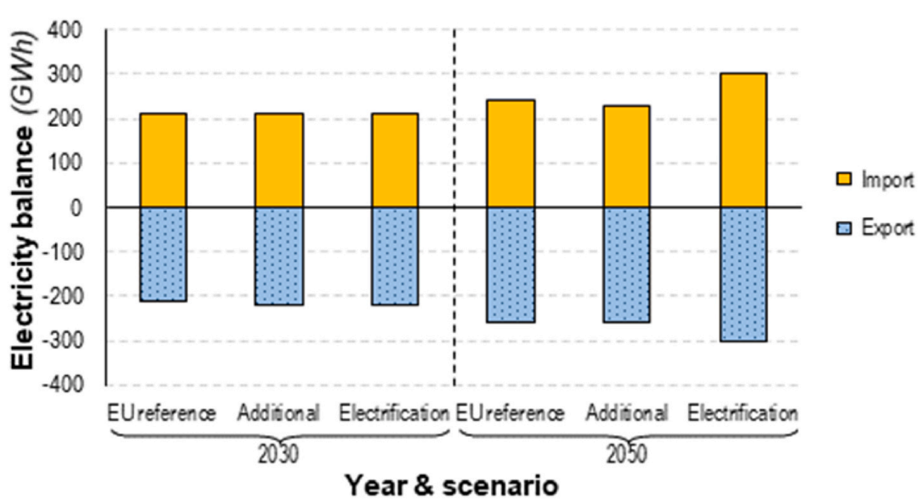


Fig. 12. Balance of electricity supply and demand.

population growth in Växjö compared to Sweden. As a result, heat demand is expected to increase in all the scenarios even though specific heat use per capita is reduced, from 7.9 MWh/person in 2019 to approximately 7.36–7.31 MWh/person in 2030 and 2050, respectively. Nevertheless, the current heat supply system capacity is expected to meet this increased demand due to the changed heat demand patents from district heat users and the available capacity as backup sources at the local facilities. Also, the same trend of cooling demand are expected and the existing district cooling facility is expected to cover these change.

In summary, the modeling results under the future scenarios of energy demand and supply in Växjö Municipality expresses an increase in the final energy demand from all the sectors except the transport sector. While future heat demand can be met with added variable costs and minor changes in the supply system, the long-term electricity demand can increase up to 72% in 2050 in comparison to 2019 and this could drive the market of green electricity investments. The increased electrification in transportation has less significant carbon reduction potentials which is consistent with the national projection of reduced electrification efficiency gains beyond 2050 scenarios [29]. The

Table 7
Technology costs in Växjö for the different scenarios in 2030 and 2050.

Scenario & technology	Installed capacity	Initial investment (M€)	Annual O&M costs (M€)	Variable costs (M€)
EU reference - 2030				
•BECCS	15	44.6	1.34	6.01
•Solar PV	60	49.4	0.49	
•Wind power	172	172.0	4.45	
Additional - 2030				
•BECCS	7	20.8	0.62	3.05
•Solar PV	60	49.4	0.49	
•Wind power	172	172.0	4.45	
Electrification - 2030				
•BECCS	7	20.8	0.62	2.67
•Solar PV	60	49.4	0.49	
•Wind power	172	172.0	4.45	
EU reference - 2050				
•BECCS	11	24.6	0.78	4.29
•Solar PV	70	48.0	0.48	
•Wind power	198	178.2	5.13	
Additional - 2030				
•BECCS	5	11.2	0.36	2.14
•Solar PV	70	48.0	0.48	
•Wind power	198	178.2	5.13	
Electrification - 2030				
•BECCS	5	11.2	0.36	1.52
•Solar PV	86	59.2	0.59	
•Wind power	244	219.6	6.32	

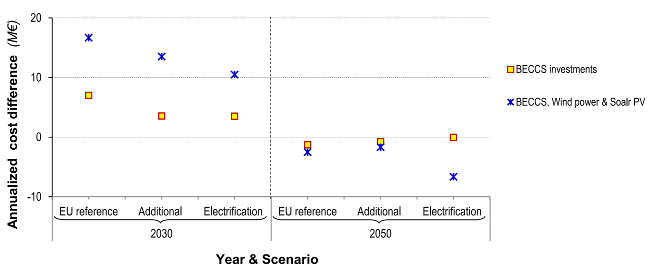


Fig. 13. Annualized system costs for being carbon neutral in Växjö in different scenarios in 2030 and 2050.

analyzed results showed that it is technically viable for Växjö Municipality to become carbon neutral by 2030 and 2050 based on the local and national resources. In the short term, certain additional costs is needed to achieve this target. However, in the long term, it is financially viable to be carbon neutral. Also, the choices of relying on electricity imports from the national power grid could become more expensive than the options based on local IRE resources. However, in all the cases, the national power grid will play a significant role for balancing the mismatch of the demand and the supply capability at the local level. The consequences in terms of resources use, emissions, and costs of such balance are complex and can be further analyzed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors gratefully acknowledge data support from Växjö Municipality and Växjö Energi AB.

Appendix

Table A1
Statistics of vehicles in Växjö [53].

Vehicle type	Year				
	2020	2019	2018	2017	2016
Passengers cars	44,549	44,182	43,584	43,066	42,815
Trucks	4841	–	–	4664	4493
Towing vehicles	203	–	–	188	131
Busses	17	–	–	12	10
Motorcycles	2416	–	–	2264	2202
Mopeds	868	–	–	565	540
Tractors	3077	–	–	2948	2896
Snow vehicles	63	–	–	50	52
Scooters	695	–	–	641	603
Trailers	10,967	–	–	10,229	9855

Table A2
Technology and its corresponding heat produced (GWh) for different scenarios in 2030 and 2050

Technology	Year & Scenario						
	2019 Reference	2030			2050		
		EU reference	Additional	Electrification	EU reference	Additional	Electrification
CHP	683	692	692	716	845	845	871
Heat only boilers	65	66	66	69	80	80	83
Individual oil boilers	5	4	4	4	5	4	4
Individual biomass boilers	68	65	65	65	54	54	54
Total	*820*	*827*	*827*	*855*	*985*	*984*	*1013*

Table A3
Fuel use (GWh) for different scenarios in transport sector in 2030 and 2050

Fuel type	2019 Reference	Year & Scenario					
		2030			2050		
		EU reference	Additional	Electrification	EU reference	Additional	Electrification
Fossil jet fuel	33	31	21	21	30	20	20
Diesel	307	295	104	87	227	78	51
bio-diesel	169	127	351	303	97	264	179
Petrol	214	130	93	82	82	57	32
Bio-petrol	12	7	19	17	3	11	6
Biogas	21	20	20	16	18	18	9
Electricity	5	14	14	20	48	46	64
Total	*761*	*625*	*622*	*546*	*505*	*495*	*362*

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