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Towards Optimal Sustainable Energy Systems in Nordic Municipalities

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Received: 27 November 2019; Accepted: 30 December 2019; Published: 7 January 2020



Abstract: Municipal energy systems in the northern regions of Finland, Norway, and Sweden face multiple challenges: large-scale industries, cold climate, and a high share of electric heating characterize energy consumption and cause significant peak electricity demand. Local authorities are committed in contributing to national goals on CO₂ emission reductions by improving energy efficiency and investing in local renewable electricity generation, while considering their own objectives for economic development, increased energy self-sufficiency, and affordable energy costs. This paper formulates a multi-objective optimization problem about these goals that is solved by interfacing the energy systems simulation tool EnergyPLAN with a multi-objective evolutionary algorithm implemented in Matlab. A sensitivity analysis on some key economic parameters is also performed. In this way, optimal alternatives are identified for the integrated electricity and heating sectors and valuable insights are offered to decision-makers in local authorities. Piteå (Norrbotten, Sweden) is used as a case study that is representative of Nordic municipalities, and results show that CO₂ emissions can be reduced by 60% without a considerable increase in total costs and that peak electricity import can be reduced by a maximum of 38%.

Keywords: municipal energy system; multi-objective optimization; renewable energy sources; EnergyPLAN

1. Introduction

The UNFCCC Paris Agreement aims at strengthening global responses to limit the increase of global average temperature to 1.5 °C above pre-industrial levels. In the EU climate and energy framework the targets set by 2030 on greenhouse gas (GHG) emission reduction, renewable energy share, and energy efficiency improvement are 40% (from 1990 levels), 32%, and 32.5%, respectively [1]. Sweden's binding target set by 2030 on GHG emission reduction was decided to be 40% from 2005 levels [2]. Global energy-related CO₂ emissions continue to increase and have risen by 1.7% to 33.1 GtCO₂ in 2018 [3]. Sweden's territorial CO₂ emissions from electricity generation and heating have dropped from a 2005 level of 9.3 MtCO₂ and reached 5.38 MtCO₂ in 2017 [4].

The project Arctic Energy, funded through the EU-program "Interreg Nord," was implemented by partner institutions from Finland, Sweden, and Norway between 2016 and 2018, and it provided energy systems analyses and simulations of future scenarios in order to support decision-makers of Nordic municipalities in their efforts to achieve GHG emissions targets and increase energy self-sufficiency, while ensuring secure and affordable energy supply [5]. This work continues the studies performed during the Arctic Energy project and investigates optimal alternatives for sustainable energy systems in Nordic municipalities with a focus on electricity and heating sectors.

Studies on Nordic municipal energy systems generally cover the heating sector, typically presenting the optimization of district heating (DH) systems. They include combined heat and power solutions,

integration with industrial excess heat supply, solar heating, thermal energy storage, and investigations into next or 4th generation DH [6–9]. Further studies look into the potential of balancing intermittent renewable power production with power-to-heat solutions [10–13] and into the optimization of demand response measures [14]. Other research addresses various system aspects of heating demand and supply for buildings not served by DH. They include investigations into energy efficiency and renovation measures, demand management and user behavior, low or near-zero energy buildings, environmental impacts of biomass heating, and conversion of heating technologies [15–18].

In the recent past, electric heating shares have been between 70 and 80% in Norway [19], 32% in Finland [20], and 26% in Sweden [21]. Electric heating demand contributes to high peak electricity demands in the Nordic electricity sector, as illustrated by the Swedish case: minimum electricity consumption in Sweden was 8.6 GW on 16th July 2017, and maximum was 26.6 GW on 5th January 2017 [22]. Sweden's responsible authority for the power transmission system (Svenska Kraftnät) expects capacity bottlenecks in the electricity supply of Swedish cities in the near future [23,24]. A typical medium size municipality in Sweden could reduce the annual electricity consumption by 10%, and the peak electricity demand by 20%, by converting from electric to non-electric heating [25].

Approaches to optimize energy systems have become more diverse and the number of studies into optimal solutions to support local decision-making processes has been increasing. Single-objective optimization methods typically focus on minimizing costs and provide the single best solution for one scenario, whereas multi-objective evolutionary algorithms generate a large number of optimal trade-off alternatives for conflicting objectives, including minimizing costs and reducing GHG emissions, maximizing intermittent renewable capacities, and minimizing curtailing and system losses. Optimal alternatives can then be subjected to multi-criteria decision-making methods in order to analyze a number of attributes [26–28]. Multi-Agent systems have also been proposed to model behavior and interactions between agents, which are key elements to generate robust, scalable, and context-aware energy optimization solutions [29]. Modelling tools for community scale energy systems and energy systems with large shares of variable renewables have been reviewed in [30–33].

EnergyPLAN is an advanced simulation tool, developed by Aalborg University [34], which allows the integration of the major sectors of any energy system (electricity, heat, transport, and industry) and supports the modelling of a stepwise transition to a sustainable energy system. EnergyPLAN has been applied in many instances at national, regional, and city level as well as on off-grid systems on islands [35–41]. Researchers have interfaced EnergyPLAN with optimization methods to find optimal solutions for multi-objective optimization problems. Bjelic et al. [42] analyzed the impact of the EU 2030 framework on the costs of the national energy system of Serbia. The approach of Mahbub et al. [43] provided an additional set of optimal solutions for the case of Aalborg municipality. Prina et al. [44] devoted particular attention to the analysis of energy efficiency in buildings. Thellufsen et al. [45] investigated a DH scenario in the Irish energy system and utilized the hourly simulation capability of EnergyPLAN in combination with the Irish energy system model, which is implemented in TIMES (The Integrated MARKAL-EFOM System).

The aims of this paper are to identify optimal alternatives for the integration of increased shares of local renewable electricity generation with a mix of heating technologies in the heating sector not connected to DH and to study the resulting interaction between electricity and heating sectors. The research investigates the multiple requirements of a Nordic municipality for a sustainable energy supply, which include the reduction of CO₂ emissions, the increase of energy self-sufficiency through investments in local renewable electricity generation, the reduction of peak electricity demand caused by electric heating and, of course, the minimization of total annual energy system costs. The study further evaluates the effect of uncertain exogenous variables, such as electricity price, discount rates, and biomass price by performing a sensitivity analysis on these parameters.

This research interfaces EnergyPLAN with a multi-objective evolutionary algorithm (MOEA) implemented in Matlab [46], which has been successfully applied in a number of real-engineering problems, most recently on the optimization of a DH network expansion [47]. The energy system

of Piteå municipality (Norrbotten, Sweden) is used as a representative case study for municipalities located in the northernmost regions of the Nordic countries.

The paper is structured as follows. Section 2 describes the methodology applied, the simulation and optimization tools and the key parameters of the municipal energy system model. Section 3 outlines the case study of Piteå, and Section 4 presents and discusses the main features of the optimal alternatives for the integrated electricity and heating sectors. Finally, Section 5 provides conclusive remarks and suggestions for further research.

2. Methodology

The deterministic simulation tool EnergyPLAN is used in this paper to model the electricity and heating sectors of the energy system of a Nordic municipality. EnergyPLAN executes a techno-economic analysis simulating the interactions between the modeled sectors on an hourly basis for a period of one year in very short processing times [37,48]. For a detailed description of EnergyPLAN, the reader is referred to the documentation available at [34].

This section defines the multi-objective optimization problem (MOOP) and describes the applied MOEA and the interface that has been implemented to exchange information with EnergyPLAN. Moreover, the values for key parameters of the energy model are discussed, such as electricity price, biomass price, discount rate, technology costs, and grid emission factors.

2.1. The Multi-Objective Optimization Problem for a Generic Municipal Energy System

2.1.1. Objective Functions

The objective functions to be minimized are the total annual system costs C_{tot} and the system CO₂ emissions Em_{sys} of the electricity and heating sectors of a municipal energy system.

The total annual system costs C_{tot} calculated by EnergyPLAN are the sum of:

- The annualized capital cost C_{ann} of each component in the modelled energy system, which considers capital cost, expected lifetime, discount rate dr and fixed operation and maintenance (O&M) costs.
- Variable O&M costs.
- Fuel costs, which depend on biomass price p_{bio} .
- Costs/revenues from the import/export of electricity from/to the grid, both calculated with the spot price p_{el} .
- System CO₂ emissions Em_{sys} calculated by EnergyPLAN are the sum of:
- CO₂ emissions due to the electricity imported from the national grid, Em_{imp} , considering a grid emission factor EF_{grid} .
- CO₂ emissions due to fossil fuel use within the boundaries of the municipal energy system.

2.1.2. Decision Variables

The decision variables of the MOOP deal with the way in which the demands of the electricity and heating sectors of the municipal energy system are covered.

The decision variables in the electricity sector are the installed capacities (in MW) for electricity generation technologies, such as hydropower, biomass-fired power, solar power, wind power. Lower bounds for the considered ranges of these variables can be set to zero or to existing installed capacities, whereas upper bounds can be set to limits depending, e.g., on the available areas found in municipal master plans for local renewable electricity generation technologies. Within the considered ranges, the values of the installed capacities are discretized according to the typical capacity of single electricity generation devices, e.g., a single wind turbine.

The decision variables in the heating sector are the amounts of heat (in GWh) supplied during a year by heating technologies both in district and individual heating systems, such as fossil fuel boilers,

biomass boilers, electric boilers, heat pumps. The lower bound for the ranges of these variables is zero, and the upper bound is the annual heating demand that has to be covered by these technologies.

2.1.3. Constraints

Satisfying electricity and heating demand at any given time are the typical constraints in energy system modelling. EnergyPLAN calculates electric energy balances as a result of given demands, component behaviors, and selected regulation strategies. It imports or exports electricity from the grid utilizing the defined transmission line and provides warnings when certain limits are exceeded. Peak electricity import $P_{el,maximp}$ is an important output of the calculations, because Nordic countries have a high share of electric heating that results in extreme peak demand during the heating period. $P_{el,maximp}$ is most relevant for municipalities in which transmission line capacities can become a bottleneck. The same bottleneck could limit the installation of new local electricity generation capacity, or could lead to curtailing, because of the increase of electricity export to the national grid. Peak electricity export $P_{el,maxexp}$ is therefore another output to be monitored.

Heating demand is balanced at any time, as the sum of the values of the decision variables related to the heating supply must be equal to the annual heating demand.

2.2. The Optimization Algorithm and the Interface with EnergyPLAN

The multi-objective evolutionary optimization algorithm (MOEA) described in [46] was adapted to search for the optimal trade-offs of the defined MOOP. The main feature of this MOEA is a diversity-preserving mechanism that treats diversity as a meta-objective in the evaluation phase. In order to reduce the computational effort, a consolidation ratio [49] is adopted as the criterion to terminate the search process. The numerical results, including those that this paper presents, prove that the solutions effectively converge toward the Pareto optimal front and that they are well distributed.

Figure 1 gives an overview about the interface between the MOEA and EnergyPLAN modelling and simulation procedure and about the wrapper software that has been developed for the exchange of information.

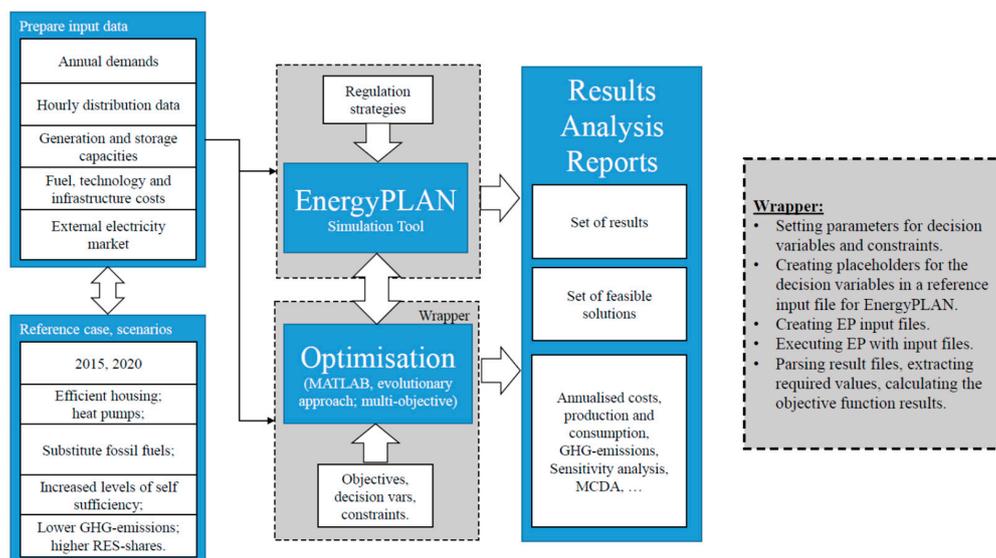


Figure 1. Schematic diagram of the interface between EnergyPLAN (simulation) and the multi-objective evolutionary algorithm (MOEA) (multi-objective optimization).

2.3. Model Parameters and Uncertainties

Energy system analysis has to deal with multiple uncertainties related to technical, environmental, and economic parameters. In this study, sources of uncertainty for local renewable energy production

include site-specific climate data and the capacity factors of the different technologies. Different CO₂ emission accounting methods can lead to significant differences in emission factors. The estimation of costs is directly affected by the economic parameters, such as technology costs, electricity and fuel prices, and discount rates.

2.3.1. Electricity Price p_{el}

Calculated costs for imported electricity and revenues for exported electricity are included in the economic objective function of the MOOP. These are based on the hourly electricity spot price p_{el} for the Nordic electricity system as available from the NordPool power market [22]. The selection of p_{el} value is based on the historical price trend of Nordic power market, where the average annual electricity spot price moves between a long term low of 21 EUR/MWh in 2015 and 50 EUR/MWh by the end of 2018. The considered values for the annual average p_{el} in the sensitivity analysis are then 20, 40, and 60 EUR/MWh.

2.3.2. Biomass Price p_{bio}

The price of biomass (pellets) p_{bio} affects the costs associated with the heating sector that is not supplied by DH. Swedish pellet prices from 2010 to 2018 show a range of the annual average p_{bio} between 34.39 EUR/MWh in 2017 and 38.03 EUR/MWh in 2011 [50] (including delivery for household supply). In EnergyPLAN cost database for 2020 p_{bio} for household supply consists of two parts: biomass price and delivery costs. Delivery costs are kept constant in the sensitivity analysis, and the considered values for p_{bio} are 26.25, 35.0, and 43.75 EUR/MWh. This price setting reflects a development of the future p_{bio} within $\pm 25\%$ from the 2018 annual average of 35.0 EUR/MWh.

2.3.3. Discount Rate dr

Discounting in energy system analysis considers two perspectives: social dr , for evaluating costs and benefits from a societal perspective, and individual dr , for evaluating investment decisions [51]. Applied social dr in energy studies ranges between 1% and 7% and the dr for industrial investors ranges from 6% to 15% [51,52]. In the sensitivity analysis of this study the considered values for dr are 3%, 9%, and 15%.

2.3.4. Technology Costs

Technology cost parameters are available from the EnergyPLAN package [34]. References of EnergyPLAN cost database include the catalogues of energy technology data published by the Danish Energy Agency and Energinet, JRC Technical Reports and the ETRI projections for 2010–2050 [53–55]. It is assumed in this study that technology costs are sufficiently reliable, especially with the consideration that all the technologies associated with the decision variables are mature.

2.3.5. Weather Conditions

Annual heating demand and annual electricity generation from windpower, hydropower, and solar PV can vary significantly in different years because of the weather conditions. In this work the weather data set used refers to a specific period of only one year (2015), although the study of selected years with extreme weather data would address uncertainties arising from unpredictable weather conditions.

2.3.6. Grid Emission Factor EF_{grid}

The European Joint Research Center (JRC) published National and European Emission Factors for Electricity consumption (NEEFE) [56,57]. JRC recommends that NEEFE are applied in the emission inventories of the municipalities that signed the EU Covenant of Mayors for Climate and Energy (CoM), a network of local governments committed to implementing EU climate and energy objectives.

Most Swedish signatory municipalities historically created their emission inventories applying the EF_{grid} of the Nordic electricity mix, which considers import dependencies of the Nordic electricity market 2015 [58]. Currently no Swedish institution regularly updates EF_{grid} values for the Nordic electricity mix. Table 1 presents the different EF_{grid} values for Sweden in 2015.

Table 1. Grid emissions factors EF_{grid} in Sweden 2015.

Sweden, EF_{grid} 2015	Value	Unit
NEEFE (IPCC standard)	0.0150	tCO ₂ /MWh
NEEFE (IPCC standard+)	0.0160	tCO _{2eq} /MWh
NEEFE (LCA)	0.0380	tCO _{2eq} /MWh
Nordic electricity mix 2015	0.0665	tCO _{2eq} /MWh
Nordic electricity mix 2010	0.1000	tCO _{2eq} /MWh

Different CO₂ emission accounting methods lead to significant differences in EF_{grid} values. The energy system model in this paper neglects the CO₂ emissions from local renewable energy production, as for CoM signatory municipalities all local renewable energy generation can be considered as CO₂ free [56], so that CO₂ emissions are merely a consequence of imported electricity Em_{imp} according to the selected value of EF_{grid} .

3. The Piteå Case Study in EnergyPLAN

A case study for the Piteå municipal energy system was implemented by the authors in EnergyPLAN as part of the Arctic Energy project between 2016 and 2018 [5]. Piteå municipality, located in Norrbotten county of Sweden, participated in the project and can be considered as a representative municipality in the Nordic context. Piteå became a signatory to the CoM in 2009, submitted the Sustainable Energy Action Plan (SEAP) to CoM in 2010 [59], and has renewed its commitment to CoM in 2017 [60]. In the 2010 SEAP Piteå sets the following targets for the municipality and its energy sector to be achieved by 2020:

- Reduce GHG emissions of the entire municipality by 50% (base year 1998).
- Convert all fossil fuel fired boilers for heating and industrial processes.
- Reduce net energy demand by 20% for apartment and commercial buildings and 10% for single-family homes (base year 2008).
- Supply electricity and heating demand with 100% renewable sources.
- Become a net exporter of renewable electricity.

The SEAP also details a number of measures to be implemented and a progress report presents achieved results by 2013 [61].

Piteå had 41,548 inhabitants by 2015. 145 MW of wind power, 40.9 MW of hydropower, 256 kWp of PV were installed within the municipal boundaries. Industrial biomass fueled combined heat and power (CHP) plants, with an aggregated power production capacity of 78 MW, supplied about 53% of the own electricity demand of these industries. The total final electricity consumption of Piteå municipality was 1453 GWh in 2015, of which 1117 GWh were supplied from local generation and the remainder was imported from the national grid. DH supplied 269 GWh of heat in urban areas, mainly utilizing industrial excess heat. Heat consumption in buildings not connected to DH was 238 GWh, of which 166 GWh were provided by electric heating, including heat pumps, and 70 GWh from biomass boilers. More key figures about Piteå are presented in Table 2 with references to the sources.

Table 2. Piteå municipality, key figures 2015.

Population, Land Area	Value	Unit	References *
Population	41,548	[1]	[62]-BE0101
Population expected by 2030	43,069	[1]	[63]
Land area	3086	[km ²]	[62]-MI0802AA
Main Cities (Population >1000); Housing	Value	Unit	References *
Piteå (administrative seat)	23,067	[1]	[62]-BE0101
Bergsviken	2251	[1]	[62]-BE0101
Rosvik	1848	[1]	[62]-BE0101
Norrjärden	1562	[1]	[62]-BE0101
Roknäs	1259	[1]	[62]-BE0101
Hortlax	1128	[1]	[62]-BE0101
Housing-number of dwellings	19,273	[1]	[62]-BO0104AE, BO0104AG
In residential buildings	11,509	[1]	
In apartment buildings	7384	[1]	
In other buildings	380	[1]	
Energy Consumption/Production	Value	Unit	References *
Total final energy consumption	5901	[GWh]	[62]-EN0203AE
Total final electricity consumption	1453	[GWh]	[62]-EN0203AE, [64]
Municipal electricity production	1117	[GWh]	[62]-EN0203AD, [65]
Industrial CHP	499	[GWh]	[66]
Hydropower	221	[GWh]	[62]-EN0203AD, [67]
Windpower	397	[GWh]	[62]-EN0203AD
Total heat production by DH	269	[GWh]	[62]-EN0203AC, [64]
Industrial waste heat	257	[GWh]	[66]
Heating centers (boilers)	11	[GWh]	[65]
Total heat energy consumption (no DH)	238	[GWh]	[62]-EN0203AE, [65,68,69]
Electricity (direct)	146	[GWh]	[62]-EN0203AE, [65,68,69]
Electricity (heat pump)	20	[GWh]	[62]-EN0203AE, [65,68,69]
Biomass	70	[GWh]	[62]-EN0203AE, [65,68,69]
Oil	2	[GWh]	[62]-EN0203AE, [65,68,69]

* references to SCB [62] include the internal reference code to the specific data.

3.1. Case Study Decision Variables

The choice of the decision variables in this case study is strictly related to the peculiar features of the municipal energy system in Piteå.

In the electricity sector, the decision variables are the installed capacities (in MW) for three local renewable electricity generation technologies: utility scale solar PV systems (PV), onshore wind turbines (WindON), and offshore wind turbines (WindOFF). A possible expansion of hydropower capacity is not considered because of environmental legislation [70]. Biomass-fired CHP plants are not considered because the heating demand satisfied with DH is already covered with waste heat from industries, and the DH network already connects the most densely populated areas in the municipality. In this study the capacity of the transmission line is set to unlimited and resulting values for electricity import and export are discussed.

In the heating sector, it is assumed that DH will continue to operate as it presently does. Accordingly, the decision variables are related to individual heating systems, and they are the amounts of heat (in GWh) supplied during a year by biomass boilers (BioB), heat pumps (HP) and electric heating (EIB).

Table 3 shows the levelized costs of electricity $LCOE$ in EUR/MWh and the annualized capital cost C_{ann} in EUR/MW for the considered renewable electricity generation technologies, and C_{ann} in EUR/unit for the considered heating technologies. The EnergyPLAN cost database provided technology cost

parameters to calculate these values, which will be important for later discussions. A 50/50% mix of air–air heat pumps and ground source heat pump types is considered for HP according to sale statistics [71]. $LCOE$ takes into account the technology costs for 2020 and considers average capacity factors for the Nordic location. It is important to note that C_{ann} for renewable electricity generation is lowest for PV and highest for WindOFF, while $LCOE$ is lowest for WindON and highest for PV due to the different capacity factors.

Table 3. $LCOE$, C_{ann} for PV, WindON, and WindOFF; C_{ann} for EIB, BioB, and HP (calculations based on 2020 technology cost parameters as provided by the EnergyPLAN cost database).

		$LCOE$ [EUR/MWh]		
Renewable Energy Technology	Capacity Factor	$dr = 3\%$	$dr = 9\%$	$dr = 15\%$
Solar PV (PV)	12%	47	85	130
Wind onshore (WindON)	30%	33	50	70
Wind offshore (WindOFF)	40%	43	68	99
		C_{ann} [EUR/kW]		
Renewable Energy Technology		$dr = 3\%$	$dr = 9\%$	$dr = 15\%$
Solar PV (PV)		50	89	136
Wind onshore (WindON)		86	130	184
Wind offshore (WindOFF)		149	239	347
		C_{ann} [EUR/unit]		
Heating Technology		$dr = 3\%$	$dr = 9\%$	$dr = 15\%$
Electric heating (EIB)		177	316	481
Biomass boiler (BioB)		933	1212	1543
Air-air heat pump (AAHP)		185	239	300
Ground-source heat pump (GSHP)		1069	1619	2272
Heat pump mix: GS-AA-HP (HP)		711	1001	1339

3.2. Selected Scenarios Simulated with EnergyPLAN

The model of the Piteå municipal energy system was built in EnergyPLAN and a number of scenarios were simulated for reference before coupling the model to the optimization algorithm (Figure 2) [5].

The “Base2015” scenario was simulated to analyze the situation in the year 2015. With technology costs for 2015, an average p_{el} for the Nordic electricity system of 40 EUR/MWh and a dr of 9%, C_{tot} resulted equal to 81.9 MEUR (Figure 2). The calculated value for Em_{sys} was 37.4 ktCO₂, neglecting the CO₂ emission from local renewable energy generation as recommended by JRC to CoM signatory municipalities to consider as CO₂ emissions free [56]. This is a consequence of a 374 GWh grid electricity import with a grid emission factor for the Nordic electricity mix of 0.1 tCO_{2eq}/MWh, the same applied in the emission inventory for Piteå as presented in the Piteå SEAP [59].

Technology costs for 2020 (see Section 2 and Table 3) and an average p_{el} for the Nordic electricity system of 40 EUR/MWh were used as standard parameters in all scenarios related to year 2020. The “Demand2020” scenario simulated a variation of the demand in electricity and heating sectors with respect to the 2015 situation, because of the achievement of the following 2020 targets mentioned in Piteå SEAP: the conversion of fossil fuel heating into renewable heating, considering a mix of biomass and heat pump solutions, and the implementation of energy efficiency measures in the building sector. This resulted in a reduction of electricity import (358 MWh) and Em_{sys} (35.8 tCO_{2eq}/MWh, 5.8% less than Base2015). The calculated C_{tot} (with $dr = 9\%$) was 78.1 MEUR, 4.6% less than in Base2015, but if 2020 technologies costs were applied to the 2015 situation (Base2015-costs2020 scenario) then the reduction in C_{tot} would be 2.4% only (Figure 2).

The “Balanced2020” scenarios were inspired by the net-export 2020 target in Piteå SEAP, because they simulate the condition in which there is a near-zero balance between electricity import and export considering a one year period. In each Balanced2020 scenario this condition was achieved by investing in additional capacities of a different mix of renewable electricity generation technologies (PV, WindON and WindOFF) starting from the Demand2020 situation. EnergyPLAN is able to deliver fast results for integrated energy system studies and the user can analyze different options in order to approach defined conditions for the modelled energy system. The options for the mix of technologies are chosen by the user on the basis of available domain knowledge. A condition such as a near-zero balance is relatively easy to achieve when only few technologies are included in the set of options, thanks to the EnergyPLAN feature that allows the user to perform a series of simulations in one run with up to 11 different values for a parameter (in this case the capacity of one renewable electricity generation technology).

Comparing the simulated Balanced2020 scenarios with Demand2020 (Figure 2), C_{tot} ($dr = 9\%$) increase between 2.2% and 12.9%, while CO_2 emissions are reduced to a minimum of 20.6 kt CO_2 (−42.5%) in the Balanced2020-WindON-OFF-PV scenario (with 145 MW WindON, 100 MW PV and 60 MW WindOFF additional capacities). Base2015 $P_{el,maximp}$ (168.3 MW) is reduced in the Demand 2020 scenario to 164.7 MW (−2.1%), and further reduced to a minimum of 157.8 MW in the Balanced2020-WindON-OFF scenario.

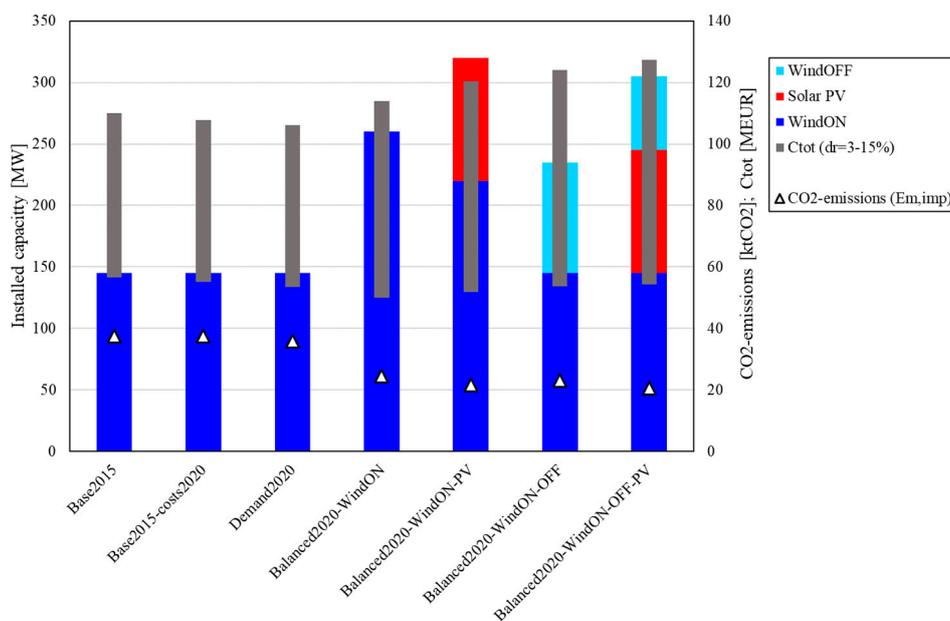


Figure 2. Selected reference scenarios simulated in EnergyPLAN for the Piteå municipal energy system; $p_{el} = 40$ EUR/MWh, $p_{bio} = 35$ EUR/MWh.

Balanced2020 scenarios provide possible alternatives to achieve the near-zero balance condition as created by an EnergyPLAN user, without an indication whether the corresponding CO_2 emission reductions are obtained with a minimum cost increase. On the contrary, the multi-objective optimization approach shall provide better knowledge of the alternatives that represent the optimal trade-offs between the two conflicting objectives of the MOOP.

3.3. Setup of Parameters for the MOOP

The starting point of the optimization runs is the energy system model of Piteå municipality with the parameters of Demand2020 scenario. It is worth noting that in this scenario the only CO_2 emissions are those due to electricity import, since no fossil fuel is used either in the electricity or heating sector, and, therefore, Em_{sys} is equal to Em_{imp} .

Table 4 lists the chosen ranges and the discretization steps for the decision variables of the MOOP defined in this study. Maximum PV capacity (100 MW) was determined by limiting land use to about 0.1% of the available land area of Piteå municipality. The discretization step of 1 MW reflects the utility scale for ground-mounted solar PV systems. The discretization steps for WindON and WindOFF were set according to the capacity of single wind turbines typically installed in such wind developments in recent years. Minimum WindON capacity of 145 MW was the existing installed capacity in 2015, whereas the maximum was set to 505 MW in order to allow for the installation of one hundred additional wind turbines of 3.6 MW each [72]. Maximum WindOFF capacity was set to 330 MW considering the available area declared in the wind development plan of Piteå and in published project plans for this area [72,73]. Higher technical potentials exist anyway for all technologies. The decision variables for the heating sector (EIB, BioB, and HP) are continuous and the sum of the amounts of heat supplied by the three technologies has to satisfy the annual heating demand of the individual heating sector (i.e., the demand from buildings not connected to DH, 211.7 GWh according to the Demand2020 scenario).

Table 4. Decision variables for local renewable electricity generation and heating technologies.

Renewable Electricity Generation Technology	PV [MW]	WindON [MW]	WindOFF [MW]
Minimum	0	145	0
Discretization step	1	3.6	6
Maximum	100	505	330
Heating Technology	BioB [GWh]	HP [GWh]	EIB [GWh]
Minimum	0	0	0
Discretization		Continuous	
Maximum = heating demand	211.7	211.7	211.7

4. Results and Discussion

Two different sets of optimization runs were performed considering the decision variables of (a) electricity sector only and (b) integrated electricity and heating sectors. Within each set, the optimization runs are repeated with different values of the economic parameters discussed in Section 2 to implement sensitivity analysis. Initial test runs confirmed sufficient diversity and convergence toward the Pareto front, considering that the termination criterion on the consolidation ratio is satisfied, as described in Section 2. The electricity sector only runs were then configured with 100 individuals and 300 generations, whereas integrated electricity and heating sectors runs were configured with 200 individuals and 500 generations.

The figures in the following subsections present the Pareto fronts plotting C_{tot} vs. CO₂ emission reduction with respect to Demand2020 scenario, and the Pareto sets of optimal solutions plotting the optimal values of the decision variables vs. CO₂ emissions reduction with respect to Demand2020 scenario. The effects of the optimal solutions on $P_{el,maximp}$ are also discussed.

4.1. Electricity Sector Only

Figure 3 presents the optimal results obtained about the case study considering the capacities of the three renewable electricity generation technologies (PV, WindON, and WindOFF) as the decision variables of the MOOP. These technologies differ widely in C_{ann} , which is affected by dr and $LCOE$ (in the latter the capacity factor is also an important parameter, see Table 3). The different values of the economic parameters considered in the sensitivity analysis have a significant impact on the cost objective function of the MOOP. In fact, these parameters will affect the relative weights in C_{tot} of investment costs and operational costs/revenues due to electricity import/export: for a constant p_{el} , a higher dr will increase C_{ann} and in turn C_{tot} , whereas a higher p_{el} will dampen the growth of C_{tot} as electricity export will generate larger revenues when installed generation capacities increase.

This plays a fundamental role in determining which combinations of technologies are the optimal trade-offs among the conflicting objectives of the MOOP.

WindOFF has the highest C_{ann} of the three technologies and a $LCOE$ between WindON and PV because of the highest capacity factor (40%); on the other hand WindON, in spite of having a higher C_{ann} than PV, has a lower $LCOE$ thanks to the higher capacity factor (30% vs. 12%, see Table 3). In the 3×3 diagrams in Figure 3 C_{tot} is dominated by the investment costs when a) $p_{el} = 20$ EUR/MWh, which is below all $LCOEs$ with all dr ; b) $p_{el} = 40$ EUR/MWh with $dr = 9\%$ and 15% ; c) $p_{el} = 60$ EUR/MWh with $dr = 15\%$. In these cases, WindOFF contributes to the optimal solutions only when both WindON and PV have already reached their considered maximum installed capacities, meaning that further CO₂ emission reductions from that condition are only possible with investments in WindOFF, which are the least convenient for those values of the economic parameters.

As operational costs/profits start to counterbalance investment costs, the slope with which C_{tot} increases as CO₂ emissions are reduced decreases, up to the point in which the Pareto front does not contain solutions with small CO₂ emission reduction. With $p_{el} = 40$ EUR/MWh and $dr = 3\%$ all solutions feature WindON at the maximum capacity, starting from emission reductions of 58% at minimum C_{tot} with zero capacity of WindOFF and PV. This means that is no longer economically convenient to look for solutions that achieve CO₂ emissions reductions below 58% because of the large profits that can be achieved by exporting the electricity generated with WindON, which has to be exploited at the maximum considered capacity. From this condition, WindOFF provides better trade-offs than PV and increases its capacity up to the maximum, resulting in emission reductions of about 80%. Only when all available wind capacities are fully utilized PV becomes part of the solution set, further reducing emissions by 85%.

With more significant operational profits due to $p_{el} = 60$ EUR/MWh (at $dr = 9\%$), emission reduction at minimum C_{tot} is even slightly higher than 60% and, again, all optimal solutions feature WindON at its maximum capacity. As the optimal C_{tot} increases from its minimum value both PV and WindOFF are convenient enough from the economic point of view to be featured in the solution set.

Finally, when the revenues from exported electricity totally prevail over investment costs ($p_{el} = 60$ EUR/MWh and $dr = 3\%$), all $LCOEs$ fall below p_{el} and the two objectives of the MOOP are no longer conflicting. In this case only one optimal solution exists, featuring maximum installed capacities for all three technologies. Please note that, as expected, all the Pareto optimal set of solutions obtained for different values of p_{el} and dr end up in this same solution (which also corresponds to maximum CO₂ emission reduction, 85%), since this is due to the upper limit chosen for the ranges for the decision variables.

It is important to observe that, in spite of its low capacity factor (12%) due to the Nordic location, PV is shown to be more economically convenient than WindOFF in six out of the nine considered combinations of the economic parameters.

Figure 4 shows the reductions achieved in peak electricity import $P_{el,maximp}$ with the optimal solutions obtained considering the three renewable electricity generation technologies (all diagrams correspond to those in the same position in Figure 3). In Piteå municipality $P_{el,maximp}$ can be reduced from 165 MW (Demand2020 scenario) to 129 MW (−21.8% or 36 MW) by installing maximum capacities for all the three technologies. A Svenska Kraftnät report on wind power integration estimates the minimum availability factor of wind power across Sweden at 6% [74]. If this 6% were applied to the additional 690 MW capacity of WindON and WindOFF installed in the Demand2020 scenario, the wind turbines would provide 41.4 MW as a minimum, confirming the reliability of the simulation results from EnergyPLAN.

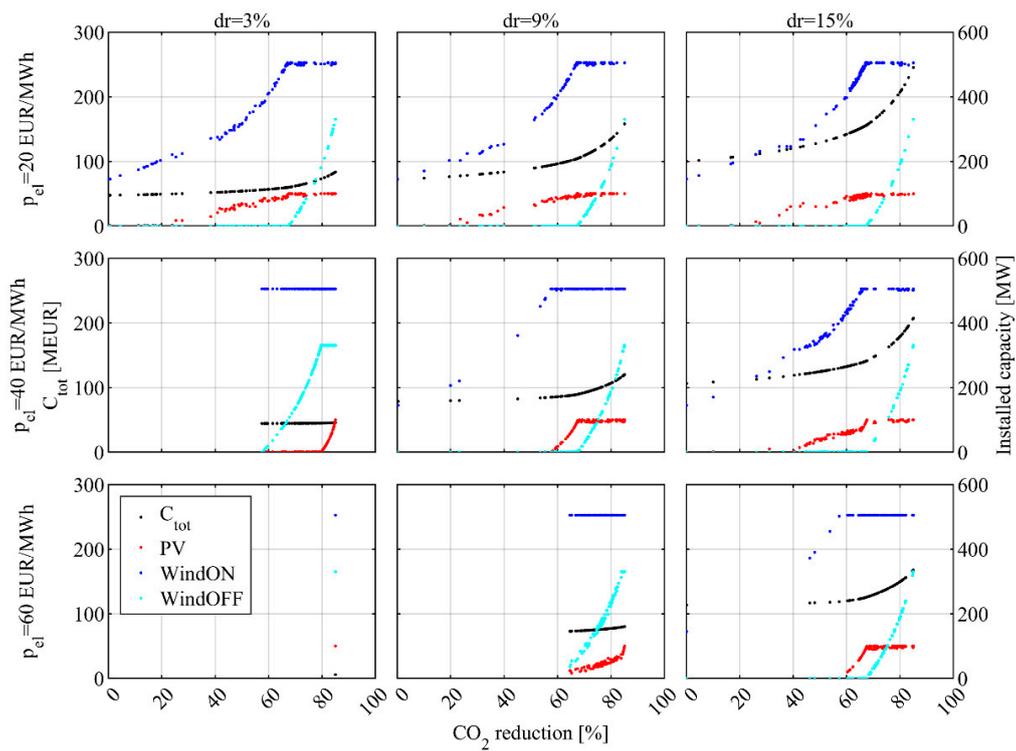


Figure 3. Electricity sector, optimal results with three decision variables (PV, WindON and WindOFF), sensitivity analysis for p_{el} and dr .

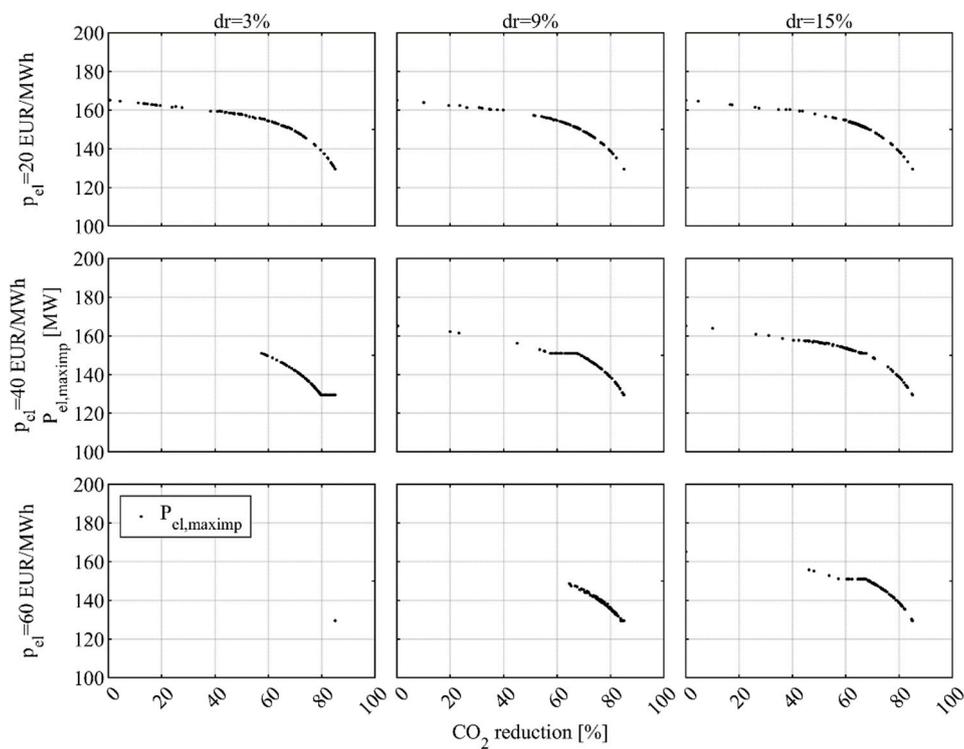


Figure 4. Electricity sector, $P_{el,maximp}$ with three decision variables (PV, WindON and WindOFF) sensitivity analysis for p_{el} and dr .

4.2. Integrated Electricity and Heating Sectors

This subsection presents the results of the optimization runs in which all the six decision variables of the MOOP are considered (PV, WindON, WindOFF, EIB, HP, BioB). This means that the electricity and heating sectors are considered integrated and optimized together, enabling the analysis of potential interactions between these sectors. Figure 5 duplicates the number of diagrams in the 3×3 grid already used in Figure 3, since the optimal values of decision variables related to the electricity sector are shown separated from those related to the heating sector for sake of clarity. In Figure 5a low p_{el} (20 EUR/MWh) is paired with high p_{bio} (43.75 EUR/MWh), in Figure 5b the central values of p_{el} and p_{bio} are paired (40 EUR/MWh and 35 EUR/MWh, respectively), and in Figure 5c high p_{el} (60 EUR/MWh) is paired with low p_{bio} (26.25 EUR/MWh). These combinations of p_{el} and p_{bio} values are paired in turn with all the considered values for dr .

From the diagrams in Figure 5 it is apparent that the optimal decision variable values for the renewable electricity generation technologies follow in general the same trends as in Figure 3, but with some significant differences related to the interaction with the heating sector. Looking at the optimal decision variable values associated with heating technologies, the diagrams show that EIB disappears from the optimal solutions already in the early stages of CO₂ reduction. No significant increase of renewable electricity generation capacities above their lower bounds is registered within this range of emission reductions, after which a 100% heating supply with HP represents the best trade-off for the heating sector. Only then the optimal solutions start to feature increasing renewable electricity generation capacities, widely following the same patterns as in the electricity only cases, until the point in which BioB in the heating sector becomes economically more convenient to further reduce emissions.

A higher share of BioB determines a drop of the electricity demand in the overall municipal energy system, which reduces electricity import and, in turn, mitigates related emissions Em_{imp} . Thus, the transition from HP to BioB causes a significant interaction with the decision variables related to the electricity sector. The substitution of HP with BioB is so beneficial, both in terms of costs and in reducing electricity demand, that the capacities of the renewable electricity generation technologies decrease during the transition while CO₂ emissions are reduced.

This transition from HP to BioB occurs at different levels of CO₂ emissions reductions depending on the values of the economic parameters. For the same values of p_{el} and p_{bio} , the transition is shifted toward lower emissions by a lower dr as the difference in investment costs between the two technologies becomes less significant. On the other hand, for the same values of dr , the transition is shifted toward lower emissions by a higher p_{el} and/or a lower p_{bio} (biomass fuel costs are another term, relatively less significant, in C_{tot}). Finally, the transition is more gradual for a higher dr .

Comparing the results of the integrated electricity and heating sectors (Figure 5) with those of the electricity sector only (Figure 3), it can be observed that the same emission reductions can be achieved with lower installed capacities of the renewable electricity generation technologies. In fact, the transition in the heating sector from the current technology mix to HP and, for higher emission reductions, to BioB reduces electricity demand and results in lower emissions because of less import from the grid.

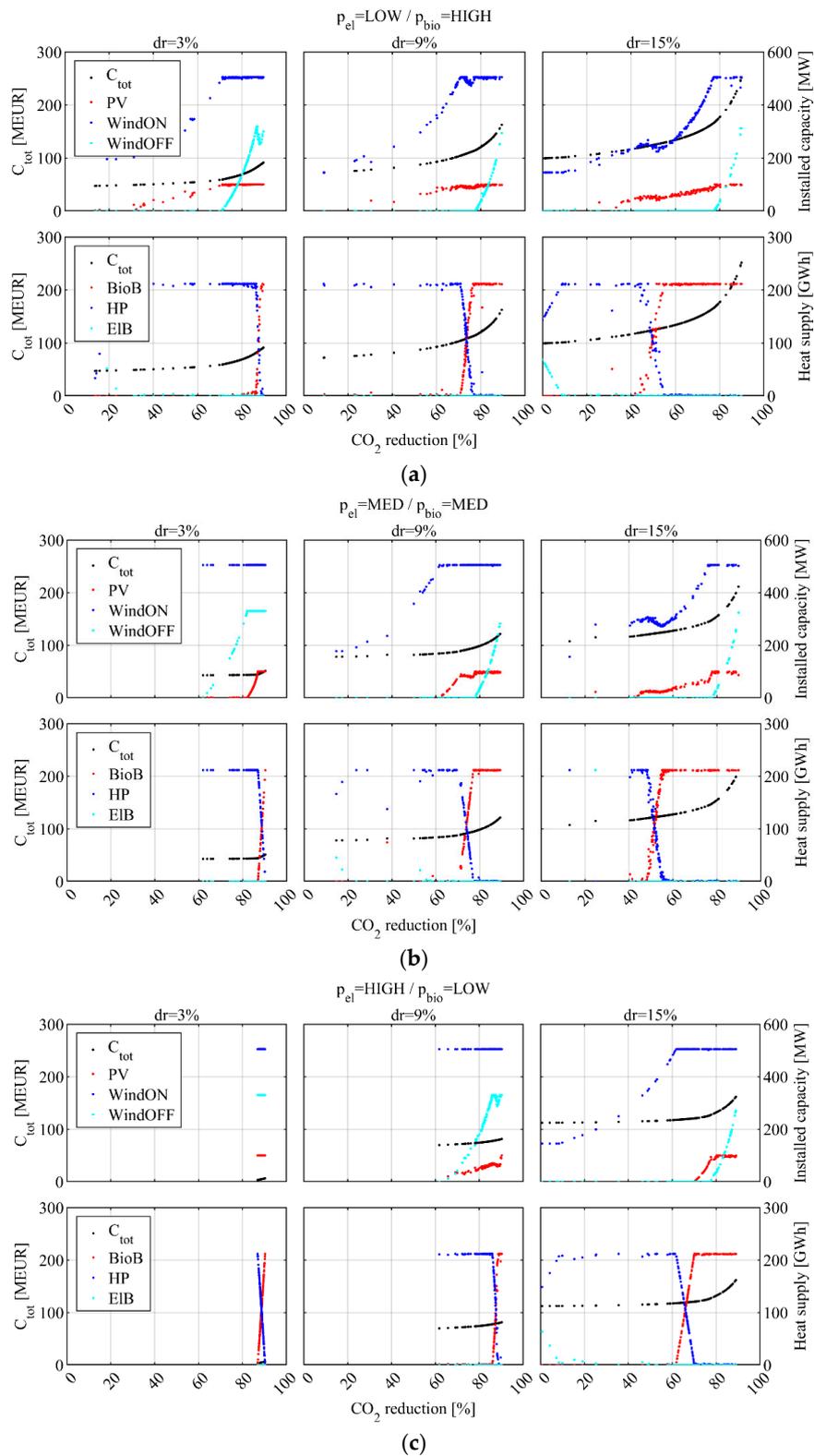


Figure 5. Electricity and heating sectors, on top: (a) for the combination $p_{el} = \text{LOW}/p_{bio} = \text{HIGH}$, in the middle: (b) with $p_{el} = \text{MED}$ $p_{bio} = \text{MED}$, bottom: (c) with $p_{el} = \text{HIGH}/p_{bio} = \text{LOW}$. Optimal results with all decision variables for the electricity sector in rows 1, 3, and 5 (PV, WindON and WindOFF), decision variables for the heating sector in rows 2, 4, and 6 (BioB, HP, EIB), C_{tot} in all diagrams, nine cases in total for sensitivity analysis on p_{el}/p_{bio} and dr .

The trend of $P_{el,maximp}$ vs. CO₂ emission reductions is shown in Figure 6. It can be interpreted as the composition of two effects: (i) as in the electricity only case $P_{el,maximp}$ decreases because of the growth of the installed capacities of PV, WindON and WindOFF; (ii) during the transitions from one heating technology to another $P_{el,maximp}$ follows the trend of the overall electricity demand, i.e., it is reduced when HP replaces EIB and then when BioB replaces HP. Minimum $P_{el,maximp}$ is 103 MW, with a 38% reduction from the 165 MW in Demand2020 scenario, and it is of course achieved with 100% BioB supply of the individual heating sector and with maximum installed capacities of PV, WindON, and WindOFF.

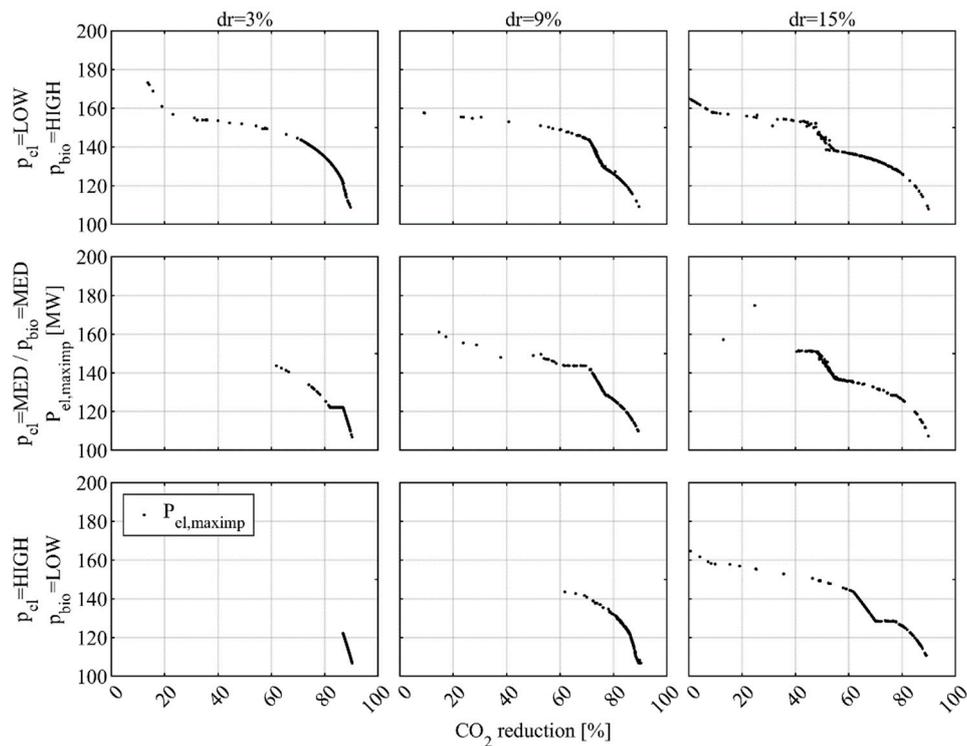


Figure 6. Electricity and heating sectors, $P_{el,maximp}$ with all decision variables, sensitivity analysis for p_{el} and dr .

As a final note, the comparison in Figure 7 between the optimal C_{tot} obtained with and without the individual heating sector shows that C_{tot} is always lower, for the same level of CO₂ emissions, when heating technologies are included in the set of decision variables. At 80% emission reductions, the costs are 1%, 7%, and 16% lower for $dr = 3\%$, 9% , and 15% respectively. This underlines the importance of integrating and optimizing the electricity and heating sectors together, as these results are not trivial.

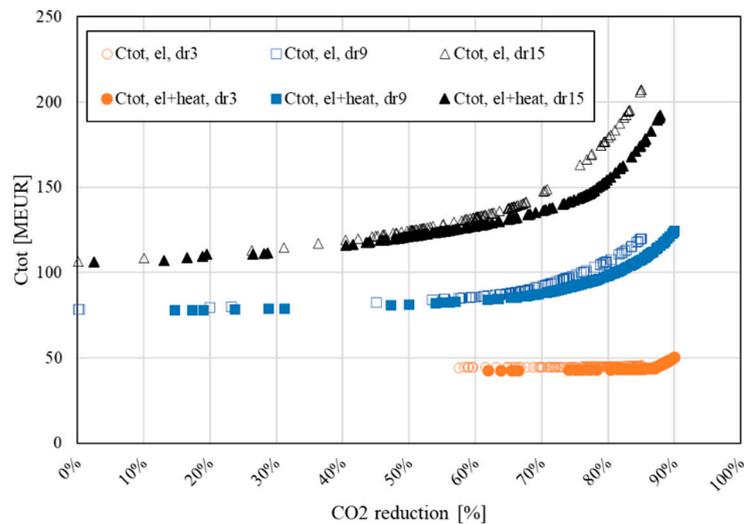


Figure 7. C_{tot} compared for electricity only and integrated electricity and heating, $p_{el} = 40$ EUR/MWh, $p_{bio} = 35$ EUR/MWh.

4.3. Duration Curves for Electricity Import/Export

The load on the supplying transmission line(s) is an important aspect to monitor in a municipal energy system. In this case study the connection with the national grid is modelled as a single transmission line with unlimited capacity. Figure 8 plots the duration curves of electricity import/export for the municipal energy system of Piteå according to the EnergyPLAN scenarios Demand2020 and Balanced2020 and the optimized solutions at 60% and 80% emission reduction for the middle range values of $p_{el} = 40$ EUR/MWh, $p_{bio} = 35$ EUR/MWh, and $dr = 9\%$. The leftmost point of the duration curve for the power import/export is $P_{el,maximp}$ and rightmost one is $P_{el,maxexp}$ with a negative sign. Figure 9 presents the corresponding installed capacities of PV, WindON, and WindOFF.

The EnergyPLAN Demand2020 scenario was the starting point for the optimization cases (see Section 3), featuring installed WindON capacity is 145 MW. $P_{el,maximp}$ is 165 MW and electricity import exceeds 100 MW for about 400 h, while $P_{el,maxexp}$ is 86 MW.

The EnergyPLAN Balanced2020 scenario achieves 42.5% emission reductions compared to Demand2020 by installing a total local electricity generation capacity of 305 MW, resulting, as intended, in an annually balanced import/export of electric energy. $P_{el,maximp}$ is 160 MW and necessary import exceeds 100 MW for about 200 h. $P_{el,maxexp}$ is 204 MW and export exceeds 100 MW for about 400 h.

The optimized solutions for the electricity sector only feature a total installed capacity of 523 MW for 60% emission reductions and 776 MW for 80% (the heating sector remains as in Demand2020 and Balanced2020). $P_{el,maximp}$ is 151 MW (138 MW) for the 60% (80%) emission reduction case, with electricity import exceeding 100 MW for about 100 h (45 h). $P_{el,maxexp}$ is 437 MW (684 MW), with electricity export exceeding 100 MW for about 3300 h (4700 h), and 400 MW for 20 h (1200 h).

Optimizing the integrated electricity and heating sector results in total installed capacities of 479 MW for 60% emission reductions and in 637 MW for 80% (individual heating demand is completely supplied by heat pumps in the former case and by biomass boilers in the latter). $P_{el,maximp}$ is 151 MW (149 MW) for the 60% (80%) emission reduction case, with electricity import exceeding 100 MW for about 100 h (70 h). $P_{el,maxexp}$ is 413 MW (514 MW), with electricity export exceeding 100 MW for about 3100 h (3700 h), 400 MW for 4 h (170 h).

The decrease of $P_{el,maximp}$ is relatively small in the optimized cases, between 8.5% and 16.4% compared to the Demand2020 scenario. This is due to low wind speed during some cold winter days with high electricity demand, so that large installed capacities only have a minor impact on the import peak while having a major one on the export peak. Accordingly, only storage solutions can significantly lower $P_{el,maximp}$ without causing a disproportional increase of $P_{el,maxexp}$. In fact, a significant increase

of $P_{el,maxexp}$ can be observed for all cases, from 135% to 500% compared to Demand2020 scenario the higher are the installed capacities. The real capacity of transmission lines eventually pose a limitation to the expansion of such large-scale local electricity generation, which is technically possible in many of the Nordic municipalities as the technical wind potential is vast as is the available land area.

The differences in $P_{el,maximp}$ between the cases in which the individual heating sector is supplied by heat pumps (60% emission reduction) or by biomass boilers (80% emission reduction) are limited as the two different electricity demands are paired with different amounts of installed capacities. It is worth noting, however, that the duration of high electricity import is significantly shortened compared to Demand2020 scenario, and that the integration between electricity and heating sector has a more limited effect on the growth of $P_{el,maximp}$.

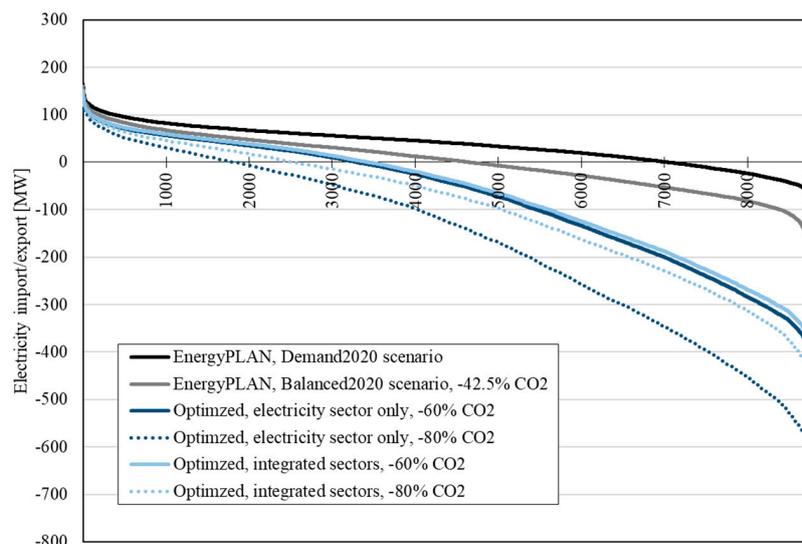


Figure 8. Duration curves for electricity import (positive)/export (negative) [MW].

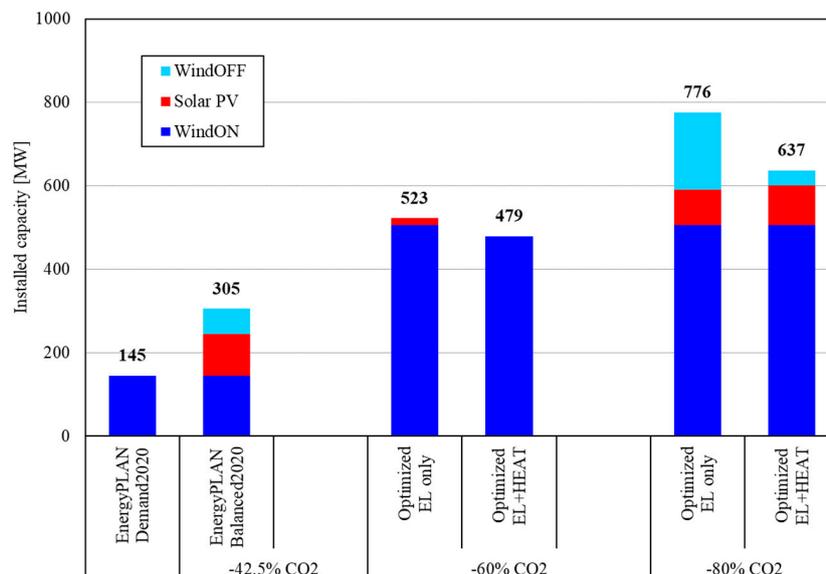


Figure 9. Installed capacities for selected scenarios and cases.

4.4. Near-Zero Electricity Import/Export Balance Condition and CO₂ Emissions

Some solutions within the set of the optimal trade-offs are close to the near-zero electricity import/export balance condition, as discussed in the scenarios simulated with EnergyPLAN for Piteå

(Section 3). Table 5 offers a comparison between the EnergyPLAN simulation results for Demand2020 and Balanced2020 scenarios and the optimal solutions closest to the near-zero balance condition from the results presented in Section 3 (with $p_{el} = 40$ EUR/MWh, $p_{bio} = 35$ EUR/MWh and $dr = 9\%$). The renewable electricity generation technology used in these optimal solutions is WindON exclusively, with at most a small PV capacity. The optimal results obtained for integrated electricity and heating sectors at this near-zero balance condition provide a solution with the individual heating sector totally supplied by heat pumps. The comparison shows that optimal C_{tot} values are 7.8% (electricity only) and 9.8% (integrated electricity and heating) lower than Balanced2020 scenario C_{tot} . Both optimized solutions provide emission reductions of about 36% with a cost increase of 4.6% (electricity only) or 2.5% (integrated electricity and heating) compared to Demand2020 scenario. The optimal solutions also result in lower $P_{el,maximp}$ compared to Demand2020 and Balanced2020 scenarios.

Table 5. Selected results approximating near-zero electricity import/export-balance.

	Unit	EnergyPLAN Demand2020	EnergyPLAN Balanced2020	Pareto Optimal Set (Electricity Only)	Pareto Optimal Set (Electricity and Heating)
Imp/Exp-balance	[GWh]	0.3	−6.5	−60.6	−1.55
Solar PV	[MW]	0	100	6	0
Wind ON	[MW]	145	145	288	253
Wind OFF	[MW]	0	60	0	0
Heating (BioB E B HP)	[GWh]	50.4 60 101.3	50.4 60 101.3	50.4 60 101.3	0 0 211.7
Total ann. cost	[MEUR]	77.7	88.2	81.3	79.6
CO ₂ reduction	[%]	-	42.5%	36.8%	36.2%
$P_{el,maximp}$	[MW]	165.4	160.0	158.7	152.7

Annual average $p_{el} = 40$ EUR/MWh; $p_{bio} = 35$ EUR/MWh; $dr = 9\%$

5. Conclusions

This paper exploited the benefits of combining EnergyPLAN, an energy system analysis and simulation tool, with a multi-objective evolutionary algorithm to investigate the optimal alternatives for the development of the integrated electricity and heating sectors of a municipal energy system in the Nordic context. Total annual costs and CO₂ emissions were defined as objective functions to be minimized, sensitivity analyses on key economic parameters were performed and the impact on electricity import/export was also analyzed.

The results for the case study about Piteå (Norrbotten, Sweden), chosen as a representative municipality in the Nordic context, showed that CO₂ emission reductions of at least 60% can be achieved without a considerable increase of total annual costs. Cost increases are always lower when electricity and heating sectors are integrated, since lower installed renewable electricity capacities are required to achieve given emission reductions. CO₂ emission reductions higher than 60% can be achieved either by increased local renewable electricity generation or by replacing HP with BioB. After the introduction of biomass boilers, only larger renewable electricity generation capacities (usually WindOFF at this point, since WindON and solar PV, in spite of the low 12% capacity factor in the Nordic region, may have already reached their maximum installed capacities depending on the economic conditions) can further reduce emissions, with steeper cost increases. At 60% emission reductions, peak electricity import reduces by a maximum of 8%, while peak electricity export increases by about 400%, posing a challenge on the available transmission lines. At highest emission reductions peak electricity import $P_{el,maximp}$ can be reduced by up to 38%.

The results obtained for Piteå municipality are of course case dependent. However, the conclusions can be extended to the entire Nordic region as the majority of the population is concentrated in municipalities similar to Piteå. By utilizing available potentials for WindON and solar PV, as well as by implementing a heat pump strategy for the heating demand not served by district heating, significant reductions of carbon emissions can be achieved without noteworthy increases of total annual energy system costs. For coastal areas, in economic conditions with high electricity prices and low discount rates, offshore wind capacities can feasibly contribute to emission reductions. A biomass heating

strategy is indicated if reductions of peak electricity import are targeted, although the increase of peak electricity export related to the large expansion of local electricity generation also suggests the use of storage solutions.

The methodology of interfacing EnergyPLAN with a MOEA, together with an extensive sensitivity analysis on uncertain economic parameters, creates a wide set of optimal combinations of renewable electricity generation and heating options minimizing total annual costs and CO₂ emission reductions. With this set of combinations, local decision-makers can now be made aware about the whole spectrum of optimal trade-off solutions and take more informed decisions for promoting a pathway toward a sustainable energy system for their municipality.

Future studies shall investigate the integration of electricity and heating sectors with different electricity storage options, including stationary and mobile storage, with peak electricity import/export and total annual system costs to be minimized. In the model of the heating sector, it would be important to consider district heating technology options such as large-scale heat pumps, solar thermal energy and thermal storage. Finally, analyzing impacts of policy developments, including CO₂ targets, CO₂ prices, and subsidies for technologies, and evaluating the potentials for local value and job creation are other areas for possible future work.

Author Contributions: R.F.: conceptualization; data curation; formal analysis; investigation; methodology; software; roles/writing—original draft. E.E.: supervision; validation; writing—review and editing. A.T.: formal analysis; methodology; software; supervision; validation; writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Interreg Nord funded project Arctic Energy-Low Carbon Self-Sufficient Community (ID: 20200589).

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BioB	Biomass boiler heating
C_{ann}	Annualized capital cost
C_{tot}	Total annual system cost
CHP	Combined Heat and Power
CoM	EU Covenant of Mayors for Climate & Energy
DH	District heating
dr	Discount rate
EF_{grid}	Grid emission factor
EIB	Electric boiler heating and direct electric heating
Em_{imp}	CO ₂ emissions of the electricity imported into the geographical scope of the model
Em_{sys}	CO ₂ emissions of the modelled integrated energy system (electricity and heating)
EU	European Union
GHG	Greenhouse gas
HP	Heat-pump
IPCC	Intergovernmental Panel on Climate Change
JRC	European Joint Research Center
LCA	Life Cycle Assessment
LCOE	Levelized cost of electricity
MEUR	Millions of euros (equivalent to M€)
MOEA	Multi-objective evolutionary algorithm
MOOP	Multi-objective optimization problem
NEEFE	National and European Emission Factors for Electricity consumption
O&M	Operation and maintenance

p_{bio}	Biomass price
p_{el}	Electricity price
$P_{el,maxexp}$	Annual peak (maximum) electricity export from the geographical scope of the model
$P_{el,maximp}$	Annual peak (maximum) electricity import from the geographical scope of the model
PV	Photovoltaic; also in this paper: utility scale solar photovoltaic systems
SEAP	Sustainable Energy Action Plan
TIMES	The Integrated MARKAL-EFOM System
UNFCCC	United Nations Framework Convention on Climate Change
WindON	Onshore windpower
WindOFF	Offshore windpower

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