Optimal Sustainable Transport Solutions Integrated into a Nordic Municipal Energy System

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***Abstract*—In Nordic environments the cold climate, large-scale industries, and a high share of electric heating drive energy consumption and create significant peak electricity demand in municipal energy systems. Prospects for decarbonizing the transport sector by electrification escalate these challenges, while availability and sustainability concerns limit biofuel use. Local authorities are committed to contributing to national climate goals, while considering local objectives for economic development, increased energy self-sufficiency and affordable energy costs. This research combines these goals into a multi-objective optimization problem (MOOP), and solves the MOOP by interfacing the energy systems simulation tool EnergyPLAN with a multi-objective evolutionary algorithm (MOEA) implemented in Matlab. In this way, the study generates optimal solutions for integrated electricity, heating and transport sectors and valuable insights are offered to decision makers in local authorities. Piteå (Norrbotten County, Sweden) is a typical Nordic municipality and serves as a case study for this research. Results show that CO_2 emissions from the integrated system can be reduced up to 60% without a considerable increase of total annual costs, and that in the same range of emission reductions it is economically more convenient to invest in electric personal vehicles, light trucks and busses.**

Keywords—multi-objective optimization, renewable energy, electrified transport, biofuels, EnergyPLAN

I. INTRODUCTION

Global energy-related CO_2 emissions grew by 1.7% in 2018 reaching 33.1 Gt CO_2, transport being responsible for 24% or 8.0 Gt CO_2 [1], [2]. Transport is now the largest end-user of energy in developed countries and is the fastest growing in developing countries [3]. Sustainable transport plays an important role in achieving the Sustainable Development Goals of the 2030 Agenda and in complying with the UNFCCC Paris Agreement [4].

In Sweden, Norway and Finland GHG emissions from domestic transport only show a slow downwards trend in recent years, road vehicles being responsible for about three-quarters of transport CO_2 emissions [5]–[7]. By 2050, European GHG emissions from transport shall be at least 60% lower than in 1990 [8]. Sweden will have no net total GHG emissions by 2045, and the Swedish climate framework defines a 70% emission reduction target for the domestic transport sector by 2030 relative to 2010 [9]. In addition to the CO_2-tax, promulgated in 1991, Sweden introduced a quota obligation scheme, which requires emission reductions of 21% for diesel and 4.2% for petrol by 2020 (15.8% combined). By 2030 the proposed combined reductions are 52.5% (60.0% for diesel and 27.6% for petrol), and by 2045 they shall reach 90.8% [10]. Norway will be carbon neutral in 2050 [11]. Finland aims to halve transport emissions by 2030 compared to 2005 levels [12]. Denmark is to cover at least 50% of its energy demand from renewables in 2030, while the share of renewables for transport will amount to 8.7% in 2020 and will increase steadily to 12.9% in 2030 [13].

All societal sectors have to contribute to achieve climate and energy targets. Nordic municipalities aim for lower CO_2 emissions, higher energy self-sufficiency and increased local value creation. Such commitments are expressed, e.g., in the participation in local and international initiatives such as the Covenant of Mayors (CoM) [14] and by specific city targets (the two largest Danish cities, Copenhagen and Aarhus, aim to become carbon neutral by 2025 and 2030, respectively [13]). This paper continues with a focus on Sweden and points out differences to Norway, Finland and Denmark in the discussions.

In Sweden, growing population and industrial development have the potential to increase electricity consumption from 126 TWh in 2017 to 152 TWh by 2050. Electrification of the transport sector will add from 10 to 16 TWh to this projected electricity demand [15]–[17]. Integration of higher intermittent renewable energy shares requires adaptations in the electricity system, including measures for grid balancing and additional transmission line capacities. Sweden´s responsible authority for the power transmission system (Svenska Kraftnät) has recently pointed out that grid capacity poses a bottleneck for increased electricity demand [18].

The effects of electrified transport on the distribution grid and on the integration of renewables have been extensively studied [19]–[24]. Research includes studies about the impacts on transmission grid, on requirements for backup generation capacity and on decentralized energy schemes [25]–[28]. Specific features are required to analyze transport system integration, such as hourly energy balances for at least a one year period to assess cross-sectoral impacts of intermittent renewables and stationary and mobile electricity storage solutions. The deterministic energy systems simulation tool EnergyPLAN provides such features and has been utilized to research the implications of an increasingly electrified transport sector [29]–[33]. Optimization approaches include: a) the integration of a transport module into the Balmorel energy system model [34], [35]; b) utilizing the TIMES model generator for long-term integrated transport and energy modeling [36]–[39]; c) LP and MILP models, dynamic programming and multi-objective evolutionary algorithms [40]–[44]; d) combinations of different approaches, including multi-objective optimization interfaced with EnergyPLAN [45]–[48].

Decarbonization of the transport sector remains a significant challenge [49], calling for further research and analysis on the integration of transport in energy systems. A municipal perspective in the Nordic context is also required. A medium size municipality could reduce electricity consumption by 10% and peak electricity demand by 20%, by converting from electric to nonelectric heating [50]. Increased biofuel utilization in the transport sector offers investment opportunities for existing forest and pulp industries. While transport electrification in the Nordic countries poses challenges to the already high electricity consumption per capita and per unit GDP in the European context [51], significant potentials for onshore and offshore wind-, hydro- and solar power exist to meet future electricity demands [52].

This study aims at identifying the optimal energy system configurations for a typical municipality in the Nordic context where electricity, heating and transport sectors are integrated and at highlighting how these sectors influence each other under different conditions. A multi-objective optimization approach is used, which combines the functionality of the deterministic energy systems simulation tool EnergyPLAN and a multi-objective evolutionary algorithm implemented in Matlab. The Nordic municipality of Piteå, located on the coast of the Gulf of Bothnia in Norrbotten County (Sweden), serves as case study.

The paper is structured as follows. Section II describes the methodology followed, the simulation and optimization tools and the parameters used in the municipal energy system model. Section III outlines the case study of Piteå and section IV presents and discusses the main features of the optimal alternatives for its energy system. Finally, section V provides conclusive remarks and suggestions for further research.

II. Methodology

The integrated energy system model including the electricity, heating and transport sectors of a Nordic municipality is built using the deterministic simulation tool EnergyPLAN, with year 2015 serving as reference, and years 2020 and 2030 serving as future scenarios. EnergyPLAN is one of a few freely available energy system modelling tools that support the integration of the major energy sectors and simulate energy balances on an hourly basis for a period of one year, which is crucial for analyzing the impacts of intermittent renewable energy generation and of storage solutions. It executes techno-economic analyses of modeled scenarios in very short processing times [53], [54]. For a detailed description of EnergyPLAN, the reader is referred to the documentation available at [55].

A multi-objective optimization problem (MOOP) is formulated in order to minimize simultaneously annual energy system costs and CO_2 emissions. A multi-objective evolutionary algorithm (MOEA) implemented in Matlab [56], which has been successfully applied in a number of real-engineering problems (most recently on the optimization of a district heating network expansion [57]), is interfaced with EnergyPLAN. The MOEA and a wrapper software (the interface to EnergyPLAN) are adapted to the requirements of this research.

A. The multi-objective optimization problem for a municipal energy system

1) Decision variables

The decision variables of the MOOP formulated in this study are related to the ways in which the energy demands of the electricity and heating sectors and the transport demand are covered.

The decision variables for the electricity sector are three and represent the additional installed capacities (in MW) for renewable electricity generation technologies within the municipal geographical boundaries: solar power (solarPV), onshore (windON) and offshore wind power (windOFF). Minimum values can be set to zero or to existing installed capacities, whereas maximum values can be set to limits depending, e.g., on 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.

In the heating sector, district heating (DH) is not considered in the MOOP as DH from renewable sources already supplies most densely populated areas. The three decision variables are related to the individual heating sector (i.e. buildings not connected to DH) and represent the annual amounts of heat energy (in GWh) supplied by biomass boilers (BioB), electric boilers (ElB) and heat pumps (HP). Fossil fuel boilers were not considered as policies in Nordic countries foresee a complete phase out of this individual heating technology by 2020. Minimum value of the range of these decision variables is zero, and maximum value is the annual heating demand that has to be covered by these technologies.

The four decision variables in the transport sector represent the aggregated shares of the following four fuel types that are used to satisfy the annual transport demand of people and goods according to different transport modes (expressed in Mkm/year): biofuels (LB), fossil fuels (LF, petrol and diesel combined), electricity for dump charge electric vehicles (ElD) and electricity for smart electric vehicles with vehicle-to-grid function (ElG). The aggregated shares of the four fuel types are then distributed by the transport sector model into fuel type shares within each transport mode considered and finally converted into fractions of the annual transport demand through the vehicle efficiencies (in km/kWh) of the different transport modes. The range of these decision variables is between 0% and 100%, with the limitations that will be discussed in section III.B.

2) Objective functions

The objective functions to be minimized are the total annual system costs C_{tot} and the system CO_2 emissions Em_{sys} of the electricity, heating and transport sectors of the 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 modeled energy system, which considers capital cost, expected lifetime, discount rate dr and fixed operation and maintenance (O&M) costs.
- Variable O&M costs and fuel costs.
- Costs/revenues from the import/export of electricity from/to the grid, both calculated with the electricity spot price p_{el}.

System CO_2 emissions Em_{sys} calculated by EnergyPLAN are the sum of:

- CO_2 emissions due to the electricity imported from the national grid, Em_{imp}, considering a grid emission factor EF_{grid}.

- CO_2 emissions due to fossil- and biofuel use within the boundaries of the municipal energy system, considering fuel emission factors $EF_{fuel,f}$ and $EF_{fuel,b}$, respectively.

3) Constraints

Balancing energy supply and demand is the typical constraint in energy system modeling. EnergyPLAN calculates energy balances as a result of given demands, modeled supply components and selected regulation strategies, providing warnings when certain limits are exceeded.

EnergyPLAN satisfies electricity demand with modeled electricity generation and storage components, using the national grid to compensate uncovered demand with import and generation surplus with export. Peak electricity import $P_{el,maximp}$ and export $P_{el,maxexp}$ are important parameters for Nordic municipalities, as they experience extreme peak electricity demand during the heating period. In case the required import of electricity exceeds a set capacity of the transmission line, EnergyPLAN provides the warning "PP/Import problem". Electricity export to the grid becomes relevant when local electricity generation is increased to improve the degree of self-sufficiency. This study, instead of constraining transmission line capacity, analyzes the impacts of the different solution alternatives on $P_{el,maximp}$, and $P_{el,maxexp}$.

Heating demand is covered at any time, as installed capacities are set to be always sufficient.

In the transport sector the combinations of the four decision variables are constrained to always fulfill the demand of the different transport modes. The transport model allows to restrict the use of biofuels per transport mode in anticipation of limited and sustainable biomass potentials and in consideration of existing legislation on quota obligations [10].

B. Model parameters and uncertainties

Modeling energy systems involves a large number of technical, environmental and economic model parameters, and the analysis of future scenarios has to deal with uncertainty on them. 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 CO_2 emission accounting methods can lead to significant differences in emission factors. The estimation of costs is directly affected by economic parameters, such as technology costs, electricity and fuel prices and discount rates. No costs include taxes or VAT.

1) Electricity spot price p_{el}

Costs for imported electricity and revenues for exported electricity are included in the objective function C_{tot}. Calculations consider the hourly electricity spot price p_{el} for the Nordic electricity system as available from the NordPool power market [58]. 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. An average annual electricity spot price of 40 EUR/MWh is considered for both years 2020 and 2030. The range for the annual average p_{el} in the sensitivity analysis is then set to ±20 EUR/MWh from this central value.

2) Biomass price p_{bio} for heating

The price of biomass (pellets) p_{bio} is relevant for the portion of the heating sector not supplied by DH. Swedish pellets prices (including delivery for household supply) 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 [59]. This study sets p_{bio} at 35.0 EUR/MWh in 2020 and assumes a price of 40 EUR/MWh in 2030.

3) Transport fuel prices $p_{fuel,f}$ and $p_{fuel,b}$

In 2016 petrol and diesel production costs were at 0.4 EUR/liter and biofuel production costs for different biofuels and production pathways were between 0.7 and 1.2 EUR per liter petrol equivalent [60], [61]. By 2030 fuel costs are projected to approach each other with 0.5–0.6 EUR/liter for fossil fuels and 0.6–0.9 EUR/liter for biofuels [61], [62]. Equal prices per liter petrol equivalent $p_{fuel,f} = p_{fuel,b} = 0.53$ EUR/liter (58.2 EUR/MWh) are implemented in 2020, and 0.63 EUR/liter (69.2 EUR/MWh) in 2030, excluding taxes and VAT. This assumption derives from EU state aid regulations, which do not allow undue subsidies for fuels resulting in unfair competition and over-compensation (Article 107(1) of the Treaty on the Functioning of the European Union; Guidelines on State aid for environmental protection and energy 2014-2020 (2014/C 200/01)) [63], [64].

4) Discount rate dr

In energy system analysis, discounting considers two perspectives: social *dr*, for evaluating costs and benefits from a societal perspective, and individual *dr*, for evaluating investment decisions [65]. The social *dr* applied in energy studies ranges between 1% and 7%, whereas the *dr* for industrial investors ranges from 6% to 15% [65], [66]. In the sensitivity analysis of this study the considered values for *dr* are 3%, 9% and 15%.

5) Technology costs for electricity and heating

Technology cost parameters for electricity generation and heating units are available from the EnergyPLAN package for the years 2015, 2020, 2030 and 2050 [55]. References of the 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 [67]–[69]. It is assumed that technology cost parameters are sufficiently reliable for the scope of this study; therefore, no sensitivity analysis was conducted on these parameters.

6) The transport model and vehicle parameters

EnergyPLAN provides modeling of four transport modes: Bikes, personal vehicles, buses, and trucks. This study considers three transport modes and four fuel types. The first transport mode combines personal vehicles and light trucks (PV+LT or abbreviated as PV only), the second models buses (BU) and the third heavy trucks (HT). Within the first mode, the transport model distinguishes between vehicles with internal combustion engine (ICEV), run on fossil fuels (PVf) or on biofuels or multi-fuels (PVb), and electric battery vehicles (BEV), using dump charge (PVed) or smart charge with the functionality "Vehicle to Grid – V2G" (PVeg). In the second transport mode, busses can be run on fossil fuels (BUf), biofuels (BUb) or can use electricity as fuel, again distinguishing between dump charge (BUed) and smart charge V2G busses (BUed). Only fossil fuel heavy trucks (HTf) and biofuel heavy trucks (HTb) are considered in the third transport mode.

Transport demand is determined by travelled distance per vehicle of a given transport mode per year (km/year). The number of vehicles per transport mode in the studied area determines the annual transport demand per transport mode (Mkm/year), which can be converted into a fuel demand using vehicle efficiencies in km/kWh. In 2018 in Sweden personal vehicles travelled 11 550 km/year, light trucks 12 780 km/year, busses 49 200 km/year and heavy trucks 31 700 km/year [70]–[72].

Prices for PVs vary widely between European countries. The 2017 average price (including taxes) of PVs was 28 855 EUR in EU28, 47 276 EUR in Norway, 37 047 in Denmark, 33 988 in Finland and 33 026 EUR in Sweden. Considering price trends and deducting a VAT of 25%, this study sets the PVf price at 28 000 EUR in 2020 and at 30 000 in 2030 [73]. Table I presents vehicle prices and other parameters for passenger vehicles/light trucks, busses and heavy trucks.

TABLE I. VEHICLE PRICES AND EFFICIENCIES 2020 AND 2030

Vehicle type	2020 [EUR]	2030 [EUR]	2020 km/kWh[b]	2030 km/kWh[b]
PVf[a]	28 000	30 000	1.48	1.55
PVb	30 800	31 500	1.48	1.55
PVed	36 400	33 000	4.97	5.22
PVeg	39 200	36 000	4.97	5.22
BUf[c]	210 000	220 000	0.24	0.25
BUb	240 000	240 000	0.19	0.23
BUed	350 000	264 000	0.67	0.70
BUeg	380 000	286 000	0.67	0.70
HTf[d]	180 000	200 000	0.22	0.23
HTb	210 000	220 000	0.17	0.18

[a] [73], [74]; [b] [72], [75] 2030 km/kWh values assuming a 5% vehicle efficiency improvement; [c] [75]–[77]; [d] [78]–[80], a 50/50% mix of 26 t (straight truck) and 40 t trucks (trailer) was assumed. Fixed O&M are lower for electric vehicles.

Improved efficiency, electrification and increased biofuel use are climate measures that reduce CO_2 emissions in transport sectors. The Global Fuel Economy Initiative (GFEI) assumes that new light duty vehicles will halve their fuel consumption by 2030 (relative to 2005 levels) by cost effective fuel economy and full hybridization (no plug-in vehicles) [49]. A vehicle efficiency improvement of 5% by 2030 from 2020 levels is assumed here for the entire vehicle fleet.

7) Grid emission factor EF_{grid}

The European Joint Research Center (JRC) published National and European Emission Factors for Electricity consumption (NEEFE) for 2015 [81], [82]. JRC recommends that NEEFEs are applied in the emission inventories of the signatories to CoM and that all local renewable energy generation can be considered as CO_2 free [81]. This research investigates the effects of different NEEFEs: i) a low value for Nordic countries is the NEEFE of Sweden: $EF_{grid,low}$ = 0.016 tCO_{2eq}/MWh, ii) a medium value is the NEEFE of Finland: $EF_{grid,med}$ = 0.156 tCO_{2eq}/MWh and iii) a high value is the NEEFE of Denmark: $EF_{grid,high}$ = 0.333 tCO_{2eq}/MWh [81], [82].

8) Fuel emission factors $EF_{fuel,f}$, $EF_{fuel,b}$

In this research diesel and petrol emissions are combined, as required by EnergyPLAN, by setting $EF_{fuel,f}$ = 94 $kgCO_{2eq}$/GJ (0.338 tCO_{2eq}/MWh) according to the EU directive on renewable energy (RED) [83]. RED provides total GHG emissions $EF_{fuel,b}$ for cultivation, processing, transport and distribution of biofuels. They are in the range of 11.2 $kgCO_{2eq}$/GJ (waste cooking oil biodiesel, 88.1% reduction from $EF_{fuel,f}$) to 63.5 $kgCO_{2eq}$/GJ (palm oil biodiesel, open effluent pond, 32.5% reduction) depending on biofuel production pathways. HVO diesel, which in 2016 had the highest share in the Swedish biofuel market (71%) [16], has an $EF_{fuel,b}$ between 4.7 and 32.9 $kgCO_{2eq}$/GJ (65% to 95% reduction from $EF_{fuel,f}$) depending on production processes [60]. In EnergyPLAN only one value is considered for $EF_{fuel,b}$, it is set at 37.6 $kgCO_{2eq}$/GJ (0.135 tCO_{2eq}/MWh) to reflect a 60% reduction with respect to $EF_{fuel,f}$ (reduction levels for other relevant biofuels are in this range [84]).

9) Weather conditions

Annual heating demand and annual electricity generation of wind-, hydro- and solar power can vary significantly in different years due to weather conditions. In this work, weather data from the considered location are used from year 2015, which is the base year for the implemented case study. Studying years with extreme weather data would address uncertainties arising from unpredictable weather conditions.

III. THE PITEÅ CASE STUDY

Piteå municipality, located in Norrbotten county of Sweden is a representative municipality in the Nordic context. Piteå hosts large-scale forestry, pulp and paper industries, which dominate the economic sectors. Urban areas are heated by district heating, fueled by industrial excess heat and biofuels, and areas not connected to DH mainly use electricity and biofuels for heating. Industries and heating characterize electricity consumption, while long distances in the sparsely populated area characterize transport demand. A case study with a focus on electricity and heating sectors for the Piteå municipal energy system was implemented in EnergyPLAN as part of the INTERREG project Arctic Energy between 2016 and 2018 [85]. Based on this case study optimal solutions for the integration of electricity and heating sectors have been investigated in [86]. This paper builds on that work and includes the transport sector as well.

Key figures about Piteå's electricity, heating and transport sectors in 2015 are presented in Table II with references to the sources. Table II also shows projections for the years 2020 and 2030, which are based on expected population and GDP growths and assumed efficiency gains [15]–[17], [87]–[89].

Piteå became a signatory to the CoM in 2009, submitted the Sustainable Energy Action Plan (SEAP) to CoM in 2010 [87], and has renewed its commitment to CoM in 2017 [90]. In 2010, Piteå determined the following targets for the municipality by 2020 as compared to 2008 levels:

- Reduce GHG emissions of the entire municipality by 50%.
- Convert all fossil fuel fired boilers for heating and industrial processes.
- Reduce net energy demand by 20% for apartment and commercial buildings and by 10% for single-family homes.
- Supply electricity and heating demand with 100% renewable sources.
- Become a net exporter of renewable electricity.
- Reduce GHG emissions from transport by at least 10% by 2020.

TABLE II. PITEÅ MUNICIPALITY, KEY FIGURES 2015, PROJECTIONS FOR 2020 AND 2030

Piteå municipality, key figures 2015	***Unit***	***2015***	***2020***	***2030***
Population[a, c]		41 548	42 055	43 069
Piteå (administrative seat)[b, c]		23 067	23 405	24 081
Land area[d]	km2	3 086	3 086	3 086
Housing - number of dwellings[e]		19 273	20 100	21 753
In residential buildings		11 509	11 726	12 159
In apartment buildings		7 384	7 874	8 854
In other buildings		380	440	740
Total final energy consumption[f]	GWh	5 901	N/A	N/A
Total final electricity consumption[g]	GWh	1 453	1 433	1645
Municipal electricity production[h]	GWh	1 117	1437	2497
Industrial CHP[i]	MW | GWh	78 | 499	78 | 499	78 | 499
Hydropower[j]	MW | GWh	40.9 | 221	40.9 | 221	40.9 | 221
Windpower[k]	MW | GWh	145 | 397	248.2 | 712	625 | 1766
Solar PV[l]	kWp | GWh	256 | 0.20	5 | 5.4	10 | 11
Total heat production by DH[m]	GWh	269	269	242
Industrial waste heat[i]	GWh	257	257	232
Heating centers (boilers)[n]	GWh	11	11	10
Total heat energy consumption (no DH)[o]	GWh	238	211	190
Electricity (direct)	GWh	146	101	60
Heat pump	GWh	20	60	100
Biomass	GWh	70	50	30
Oil	GWh	2	0	0
Transport modes (road)[p]				
Personal vehicles (PV)		24 310	25 460	27 484
Light trucks (LT)		2 445	2 818	3 315
Heavy trucks (HT)		560	622	703
Busses (BU)		29	61	67
Transport fuels (road)[p]	GWh	303	324	207 - 270[q]
Petrol	GWh	125	113	
Diesel, biofuel share (%)	GWh | %	157 | 15%	188 | 25%	See
Electricity	GWh	1	3	scenarios.
Etanol	GWh	14	13	
Gas	GWh	6	7	

[a, b][91][*]-BE0101; [c][88]; [d][91]-MI0802AA; [e][91]-BO0104AE, BO0104AG; [f][91]-EN0203AE total final energy consumption is not within the scope of this study; [g][91]-EN0203AE, [92] 2020 estimates consider efficiency measures as proposed in Piteå SEAP, for 2030 it is assumed that electricity consumption increase follows national estimations [15]–[17]; [h][91]-EN0203AD, [93]; [i][94], no growth estimates for energy generation in paper and pulp industries are available; [j][91]-EN0203AD, [95] environmental legislation does not permit expansion of hydropower [96]; [k][91]-EN0203AD; [l][95]; [m][91]-EN0203AC, [92] for 2020 it is assumed that district heating production increases due to population growth and housing growth is balanced by energy efficiency measures, for 2030 additional 10% heating demand reductions are assumed; [n][93], 2020 and 2030 values remain about the same as heating centers are only used during industrial outages; [o][91]-EN0203AE, [93], [97], [98], estimates for 2020 are based on proposed SEAP measures, for 2030 additional 10% heating demand reductions are assumed, electric heating and biomass continue to reduce and heatpumps increase; [p] Vehicle statistics and trends up to 2022 available from Trafa, fuel consumption calculated with person and goods kilometers per year and fuel consumption data from Trafa and RUS [70]–[72], trends up to 2030 for transport modes based on Trafa 2022 estimates, extrapolated to 2030 based on population and GDP-growth trend projections [88], [91]-0000028G, TK1001AC, [89]; [q] The Swedish Energy Agency assumes massive reductions in transport energy consumption in its Four Futures report by 2050 – between -25% and -74% from 2014 levels. The ranges given for Piteå are interpolated for 2030 from 2015 levels [99] *) references to SCB [91] include the reference code to the specific data.

Piteå SEAP also details a number of measures to be implemented and a progress report presents achieved results by 2013 [100], which allows to assume that 2020 targets will be met. Municipal targets for 2030 are not set yet, but it is expected that they will closely follow national and county targets. Norrbotten county climate and energy targets for 2030 include [101]:

- GHG emissions in Norrbotten should be at least 47% lower than in 2005.
- The GHG emitted must generate at least 3.5 times higher value than in 2005.
- The share of renewable energy should have increased to 70% while energy consumption should be at least 20% lower than in 2005.
- The proportion of renewable fuels in the transport sector should be higher than 80%.

A. Selected scenarios simulated with EnergyPLAN

The model of the Piteå municipal energy system was built in EnergyPLAN and a small number of simulated scenarios were selected for reference before coupling the model to the optimization algorithm (Fig. 1).

“Base2015” scenario simulates the situation in 2015 and validates the energy system model.

“Demand2020” scenario implements 2020 projections and simulates a situation complying with the 2020 demand side measures mentioned in Piteå SEAP, i.e. the conversion of fossil fuel heating into renewable heating and the implementation of energy efficiency measures in the building sector.

The net-export 2020 target in the Piteå SEAP inspired “Balanced2020” scenario, which builds on the Demand2020 scenario and achieves a near-zero balance between electricity import and export in a one year period by adding capacities of a mix of renewable electricity generation technologies (solarPV = 5 MW, windON = 188.2 MW and windOFF = 60 MW).

"Projected2030" scenario implements 2030 projections (Table II). In the transport sector the following vehicle fleet composition was assumed, according to a transition towards a fossil independent vehicle fleet [102]: 30% electric vehicles (PV+LT+BU); 60% biofuel vehicles (PV+LT+BU); 80% biofuel heavy trucks (HT).

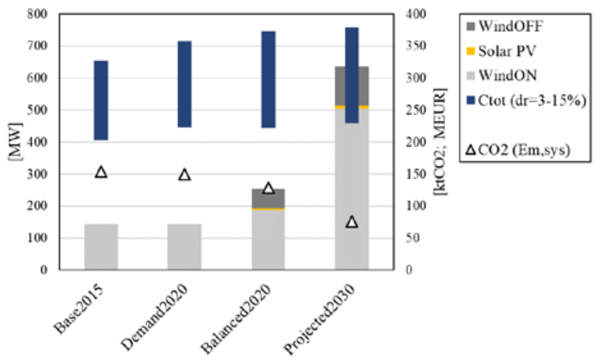

Fig. 1. Selected scenarios for the Piteå municipal energy system, simulated in EnergyPLAN. Main parameters: p_{el} = 40 EUR/MWh, *dr* = 3, 9 and 15%; technology costs for 2015, 2020 and 2030; EF_{grid} = 0.156 tCO_{2eq}/MWh

The Balanced2020 and Projected2030 scenarios presented in Fig. 1 provide one possible alternative to achieve the targets for 2020 and the projections for 2030, respectively, without indications whether the reduced CO_2 emission Em_{sys} are obtained with a total annual cost C_{tot} that is the lowest possible. The multi-objective optimization approach shall provide better knowledge of the range of alternatives that represent the optimal trade-offs between the two conflicting objectives of the MOOP.

B. *Setup of the energy system model for the optimization runs*

The choice and the range of the decision variables in the MOOP about this case study is strictly related to the peculiar features of the municipal energy system in Piteå. The starting point for the optimization is the Projected2030 scenario.

Table III and IV list the chosen ranges and the discretization steps for the decision variables of the MOOP for the 2030 scenario. A minimum solarPV capacity of 10 MW is assumed to be installed by 2030. A maximum solarPV capacity of 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 solarPV systems. Minimum windON capacity of 505 MW is the assumed installed capacity in 2030, whereas the maximum was set to 865 MW in order to allow for the installation of 100 additional wind turbines of 3.6 MW each [103]. Maximum windOFF capacity was set to 660 MW considering the available area declared in the wind development plan of Piteå and in published project plans for this area [103], [104]. 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.

In the heating sector, it is assumed that DH will continue to operate as it presently does, supplying the 2030 demand. The decision variables for the individual heating sector (ElB, 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, 190 GWh according to the Projected2030 scenario.

In the transport sector, the transport demands in Mkm/y of the three modelled transport modes (PV+LT: 365.1 Mkm/y; BU: 3.3 Mkm/y; HT: 22.2 Mkm/y) have to be supplied by the four fuel types, the aggregated shares of which are the decision variables. By 2017 19 TWh or 22% of the Swedish road transport energy consumption of 88 TWh came from renewable fuels, including electricity [105]. The Swedish investigations into a fossil free vehicle fleet by 2030 in cooperation with the Swedish Energy Agency estimate the additional biofuel potential to be between 22 to 32 TWh by 2030 [60]. In this study, biofuels (LB) are limited to 60% for PV+LT and HT can only run on fossil fuels (LF) or biofuels (LB).

TABLE III. DECISION VARIABLES FOR LOCAL RENEWABLE ELECTRICITY GENERATION AND HEATING TECHNOLOGIES (2030)

Renewable electricity generation technology	***solarPV***	***windON***	***windOFF***
Minimum [MW]	10	505	0
Discretization step [MW]	1	3.6	6
Maximum [MW]	100	865	660
Heating Technology	***BioB***	***HP***	***ElB***
Minimum [GWh]	0	0	0
Discretization		Continuous	
Maximum [GWh]	190	190	190

TABLE IV. DECISION VARIABLES FOR TRANSPORT FUELS (2030)

Transport modes and fuels	***LF***	***LB***	***ElD***	***ElG***
PV+LT	0-100%	0-60%	0-100%	0-100%
BU	0-100%	0-100%	0-100%	0-100%
HT	0-100%	0-100%	0	0
Discretization		Continuous		

IV. RESULTS AND DISCUSSION

This section presents the results of several optimization runs performed for the year 2030 around a central reference case in which EF_{grid} = 0.156 tCO_{2eq}/MWh, average annual electricity spot price p_{el} = 40 EUR/MWh, discount rate *dr* = 9%, pellets price p_{bio} = 40 EUR/MWh, transport fuel prices per liter petrol equivalent $p_{fuel,f} = p_{fuel,b}$ = 0.63 EUR/liter petrol equivalent, excluding taxes and VAT. Sensitivity analyses were performed by varying:

a) Grid emission factor NEEFE ($EF_{grid,low}$ = 0.016 tCO_{2eq}/MWh as in Sweden, $EF_{grid,med}$ = 0.156 tCO_{2eq}/MWh as in Finland and $EF_{grid,high}$ = 0.333 tCO_{2eq}/MWh as in Denmark).

b) Electricity price (average annual electricity spot price p_{el} = 20, 40 and 60 EUR/MWh).

c) Discount rate (*dr* = 3%, 9% and 15%).

Optimization runs were configured with 200 individuals and 300 generations. Fig. 2 to Fig. 6 in the following subsections present the Pareto fronts plotting CO_2 emission reduction [%] in the x-axis (with respect to Projected2030 scenario considering a 100% fossil fuel transport sector), C_{tot} [MEUR] on left y-axis, and the corresponding optimal values of the decision variables (or other relevant quantities) on right y-axis. The values of $P_{el,maximp}$ and $P_{el,maxexp}$ for the optimal solutions are also shown in some cases.

The discussion of the results starts from some remarks on the central reference case, the results of which are shown by the diagrams in the middle columns Fig. 2 to Fig. 6. In the electricity sector (Fig. 2, middle column) maximum capacities of windON and solarPV are used by almost all solutions, while windOFF is not considered up to emission reductions of about 61%. At lower emission reduction individual heating is completely supplied by HP, then for reductions higher than about 67% BioB heating replaces HP. During this transition, the growth of windOFF capacity is slowed down, showing that there is a significant interaction between the two sectors in the balance of electricity supply and demand, and that replacing heat pumps with biomass boilers is cheaper than investing on more offshore wind turbines in order to further reduce CO_2 emissions. After individual heating is completely supplied by BioB, the growth of windOFF capacity helps reducing the emissions related to imports from the grid.

At minimum C_{tot} the transport sector (Fig. 3, middle column) contributes to CO_2 emission reductions with the full electrification of PV and BU (dump charge – PVed and BUed), while heavy trucks (HT), which cannot be electrified, remain dependent on fossil fuels (LF). As CO_2 emissions are decreased, smart charge electric vehicles gradually replace dump charge ones (ElG are slightly more expensive, but they can dampen electricity import and hence lower the emissions related to the grid), until PV and BU are all smart charge at around 61% emission reduction. From this point, only the use of biofuels (LB) to replace fossil fuels (LF) and ElG can further reduce emissions in the transport sector, because of the lower electricity import from the national grid. At the lowest CO_2 emissions HTb totally replace HTf, BUb totally replace BUeg and also part of PVeg is replaced by PVb (only a part due to the limitations on the use of LB).

A. Sensitivity analysis on grid emission factor EFgrid

The sensitivity analysis for different grid emission factors EF_{grid} is presented in Fig. 2 to Fig. 4 and is performed to compare the optimal municipal energy systems of different Nordic countries, characterized by different power generation mixes.

With $EF_{grid,low}$ (left columns) the solutions with lowest C_{tot} (CO_2 emission reductions around 50%) have only windON capacity (up to the maximum) in the electricity sector, complete HP supply in the heating sector and only dump charge vehicles in the transport sector (except for fossil fueled heavy trucks). The cheapest way to reduce CO_2 emissions is then to introduce LB, which replaces LF in heavy trucks, ElD in busses and part of ElD in PV+LT due to the implemented constraint on maximum biofuel usage. For CO_2 reductions higher than 60% new electricity generation capacity is installed (solarPV and windOFF), there is a transition from HP to BioB, and, since LB is limited for PV+LT, PVeg become part of the solution instead of PVed.

With $EF_{grid,high}$ (right columns) up to about 66% CO_2 emission reductions are achieved with windON and solarPV capacities fully installed and with HP in the heating sector, while in the transport sector dump charge vehicles are replaced by smart charge ones. WindOFF joins the electricity generation mix at CO_2 emission reductions higher than 66%. At about 70% reduction the transition from HP to BioB starts to occur and then, at reductions above 72%, LB replaces LF and part of smart charge fleet.

Peak electricity import $P_{el,maximp}$ (Fig. 4) is reduced as fewer electric vehicles are part of the transport fleet, as biomass heating is introduced and as local electricity generation capacities are increasing. On the other hand, peak electricity export $P_{el,maxexp}$ closely follows local electricity generation capacities. Only minor effects on import and export demands can be observed by switching between dump and smart electric vehicles. More detailed investigations, including variations in charging profiles of electric vehicles, would be required to highlight these effects in order to exploit them.

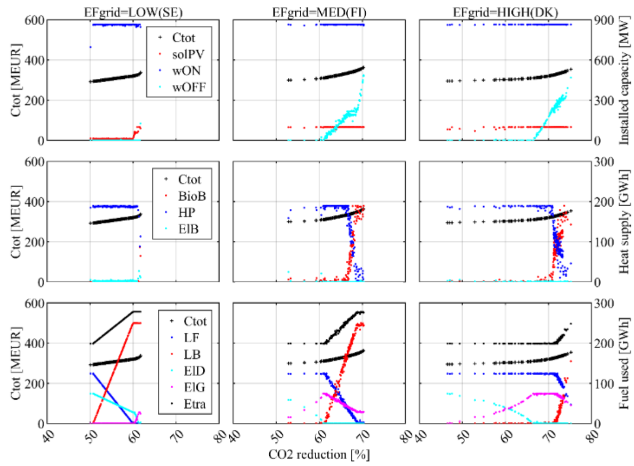

Fig. 2. Energy sectors with different grid emission factors EF_{grid}

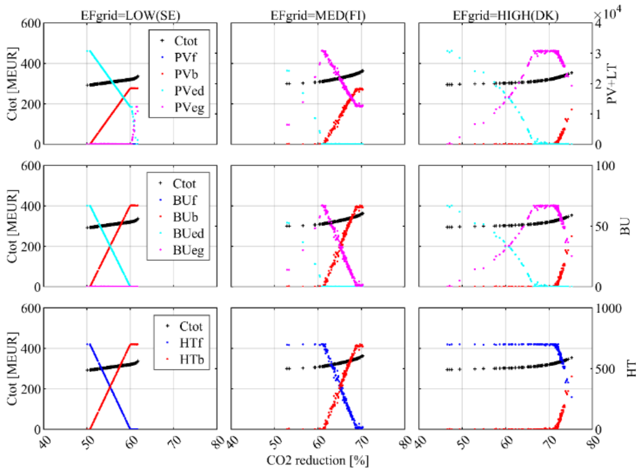

Fig. 3. Transport modes with different grid emission factors EF_{grid}

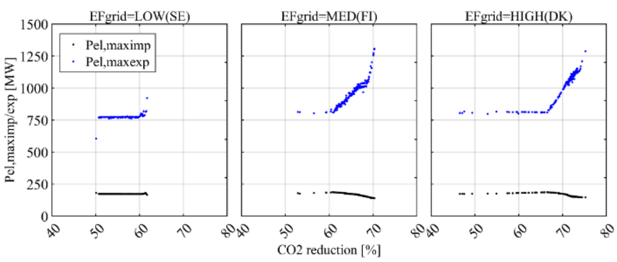

Fig. 4. Peak electricity import/export with different grid emission factors EF_{grid}

B. Sensitivity analysis on electricity price p_{el}

A low p_{el} of 20 EUR/MWh (Fig. 5 and Fig. 6, left column) makes it less favorable to invest in electricity generation to reduce CO_2 emissions, so at minimum C_{tot} windON is far from its maximum capacity. ElG, the share of which is already higher than in the other diagrams at minimum C_{tot}, completely replaces ElD at CO_2 emission reductions of about 55% and remain at that level until 60% emission reductions, while windON capacity increases. At emission reductions higher than 60%, LB starts to replace LF and part of ElG. The transition from HP to BioB occurs at lower emission reductions compared to higher electricity prices, which is rather unexpected since HP are cheaper than BioB, but on the other hand, investment in electricity generation is economically disadvantageous due to the low additional revenue created from electricity exports with a low p_{el}.

A high p_{el} of 60 EUR/MWh (Fig. 5 and Fig. 6, right column) favors local electricity generation (all capacities are maxima) as electricity exports generate high revenues and have a favorable effect on C_{tot}. In this situation, the transition from HP to BioB occurs at the highest emission reductions, since it is more convenient to export high amounts of electricity. Accordingly, the reduction of CO_2 emissions starting from minimum C_{tot} is all due to the fuel mix in the transport sector. ElG start to replace ElD as in the other diagrams, but then, before the replacement is complete at about 64% emission reductions, LB becomes a part of the fuel mix and gradually replaces LF and ElD and also, at higher emission reductions, a part of ElG.

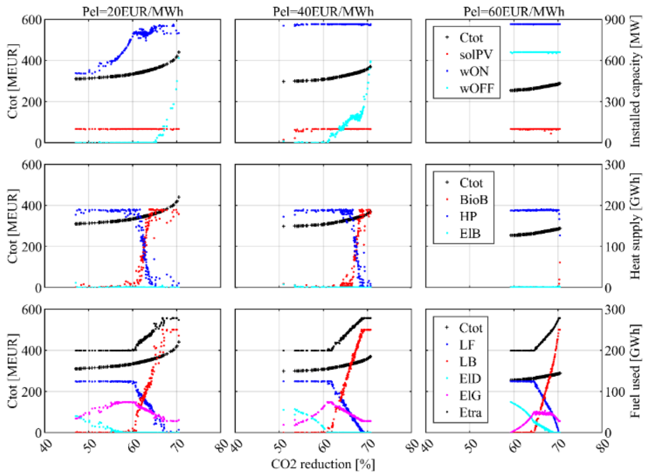

Fig. 5. Energy sectors with different electricity prices p_{el}

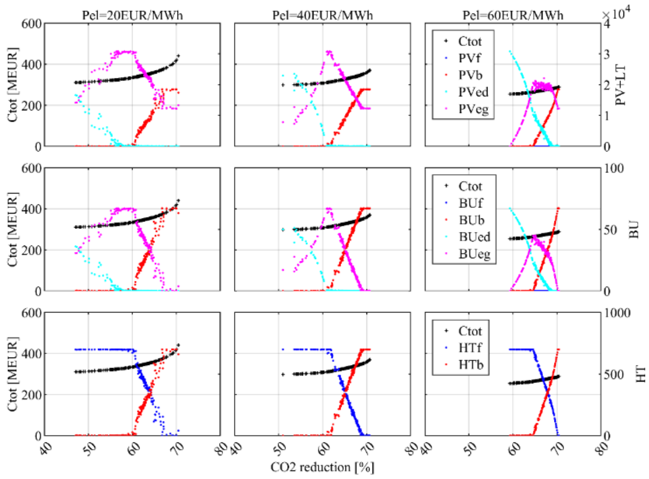

Fig. 6. Transport modes with different electricity prices p_{el}

C. *Sensitivity analysis on discount rate dr*

With *dr* = 3% technologies with high capital costs become most favorable and all allowed electricity generation capacities are fully utilized as C_{tot} is much lower. The trend of the optimal values of the decision variables in this case is very similar to that in the high electricity price case (Fig. 5 and Fig. 6, right column), where electricity generation is favored by high revenues from electricity export.

On the contrary, *dr* = 15% increases the investment cost term in C_{tot} significantly, and the interaction between electricity and heating sectors is similar to what is observed for the case with p_{el} = 20 EUR/MWh (Fig. 5 and Fig. 6, left column). In spite of the higher capital costs, electric vehicles (together with HTf) are the only present in the optimal fleet up to 60% emission reductions, then at lower emission LB replaces LF and electric vehicles (except for a part of smart charge vehicles due to the limitations on LB usage).

V. CONCLUSIONS

Exploiting local renewable energy resources, integrating different sectors and using electricity storage options can provide economically favorable solutions to the energy supply of Nordic municipalities, considering at the same time CO_2 emission reduction targets and the aim of increasing energy self-sufficiency.

The main conclusions can be summarized as follows:

- The methodology combining the simulation tool EnergyPLAN with a multi-objective evolutionary algorithm has been proven to effectively find optimal solutions for competing objectives about integrated energy systems.
- Choices for local renewable electricity generation technologies and capacities are highly sensitive to economic conditions and grid emission factors.
- Electric heating is never part of optimal solutions. Heat pumps completely supply individual heating demand over wide ranges of CO_2 emission reduction, but at the lowest emission levels biomass heating replaces heat pumps.
- In the central reference case, for CO_2 emission reductions lower than about 60% it is economically more convenient to invest in electric personal vehicles, light trucks and busses, in spite of higher capital costs. Better vehicle efficiencies (km/kWh) and lower maintenance costs result in lower overall costs with respect to the other alternatives. To achieve higher emission reductions, biofuels need to replace the remaining fossil fuels and also part of electricity used in the transport sector in order to reduce the emissions related to electricity import from the grid.
- CO_2 emissions can be reduced by about 60% without significant increases in total annual costs.

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, heating and transport options and provides valuable insights on other performance indicators, such as peak electricity import. Local decision makers can now be made aware about the whole spectrum of trade-off solutions and take more informed decisions for promoting a pathway towards a sustainable energy system for their municipality.

Future studies shall investigate the integration of electricity, heating and transport sectors with stationary electricity storage options, as mobile storage and V2G functionality only show small effects on reducing peak electricity imports and exports. 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, a refining of the transport model should be implemented to allow for optimal distribution of biofuels among the transport modes.

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