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EPLANopt optimization model based on EnergyPLAN applied at regional level: the future competition on excess electricity production from renewables

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ABSTRACT

To face environmental and energy security issues, planning an energy system with high penetration of renewables is becoming increasingly important. The EPLANopt model couples a multi-objective evolutionary algorithm to EnergyPLAN simulation software to study the future best energy mix. In this study, EPLANopt is applied to the case study of Niederösterreich, an Austrian region, to inspect the best configurations of the energy system at 2050. This model is used to inspect the competition between different renewable energy integration options. Storage systems, power to gas, power to heat or power to mobility are all integration options taken into account to study their competition in presence of electricity excess from renewables.

The results show that in order to decarbonize the energy system the increase of the installed power of renewables is not enough to reach the CO_2 reduction objective. Integration methods like the already mentioned storage systems, power to gas, power to heat or power to mobility become relevant. In particular the results show a deep energy efficiency refurbishment coupled to power to heat through heat pumps. Power to gas presents a relevant role in the integration of the excess of electricity from renewables. However, at the increase of electric mobility penetration the available excess of electricity is reduced and the deployment of power to gas decreases.

Keywords:

Photovoltaics;
Wind;
EnergyPLAN;
Multi-objective optimization;
Energy scenarios;

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1. Introduction

In recent years, energy planning [1] is becoming a fundamental discipline in supporting policy-makers in the definition of the energy strategy. The first energy targets have been set at European level through the "2020 climate and energy package" in 2007 [2], and the "2030 climate and energy framework" [3] in 2014. After that an increasing number of regions in Europe have started developing their own regional energy targets and strategies to achieve them in line with the European and national ones.

This study concentrates on the Niederösterreich region placed in the north-east of Austria. The public administration of Niederösterreich commissioned to Eurac research the development of energy scenarios and hourly simulations in order to receive support in the definition of the regional energy strategy at 2050. To accomplish this scope, it has been decided to use the EPLANopt model [4,5] developed by Eurac research through the coupling of the simulation software EnergyPLAN [6–8] developed by Aalborg university [9] and a Multi-Objective optimization algorithm.

The EPLANopt model is characterized by an hourly time-step, single-node approach and by the integration of the three primary sectors of the energy system: electricity, heat and transport sectors. These characteristics make it appropriate for the final scope of this work.

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The hourly time-step is particularly important when modelling energy system with high penetration of variable renewable energy sources (VRES). Poncelet et al. [10] showed the importance of the time resolution in energy system modelling. They demonstrated how the resolution in time should be prioritized compared to the resolution in techno-economic detail and how the use of a low number of time-slices (usually 12 time-slices) produces an error that cannot be considered negligible.

Another characteristic of EPLANopt tool is the single-node approach and thus considering the transmission grid as ideal, without losses or bottlenecks. This assumption can introduce errors and underestimation of the needed installed capacity of renewables to decarbonize the energy system. However, the particular case study at regional level does not show any relevant bottlenecks in the transmission grid. Therefore, the error introduced by a single-node modelling can be considered negligible.

The third cited characteristic is sector coupling. Several papers have shown the advantages of sector coupling modelling compared to single sectors modelling approach. In this regards, it is important to mention the contribute of Aalborg University in the definition of the smart energy system concept through which they showed the advantages of studying the interactions and synergies between different energy sectors to maximize efficiency and reduce costs [7,11]. Lund in [11] and Connolly et al. [12] introduced the concept of the smart energy system and the opportunities and synergies among energy sectors. In [13] Mathiesen et al. inspected the smart energy system concept with particular attention to the integration of the transport sector.

Other examples of studies inspecting sector coupling using different methods are the following. In [14] Nastasi et al. highlighted the importance of hydrogen as an energy vector to link the electricity and heat sector. Prina et al. [15] demonstrated the advantages of sector coupling at district heating level. Bramstoft et al. [16] through the studying of the decarbonisation pathways of Sweden at 2050 showed the advantages of the integrated modelling of transportation, electricity, gas, fuel refinery, and heat systems. Ben Amer et al. [17] used Balmorel model on the Greater Copenhagen case study integrating the electricity and heat sectors. Heinisch et al. [18] showed the advantages of coupling the electricity, heating and transport sectors focusing on urban areas. Lund et al. [19] underlined the importance of moving beyond the electricity-only approach and towards an integrated cross-sector approach. Osorio-Aravena et al. [20] analyzed how to reach a fully renewable-based energy system in Chile through the integration of the power, heat, transport and desalination sectors. Van Leeuwen et al. [21] presented an energy scheduling model to optimize the transition towards 100% renewable through the integration of the electricity and heating sectors.

The energy target at 2050 for Niederösterreich is the reduction of CO_2 emissions by 80% with respect to the value of 1990 [22]. This target can be met only through a deep transformation of the energy system by exploiting the entire potential for VRES. High penetration of VRES produces high shares of over-generation. It is important to study the best mix of flexibility options which allow to integrate this available electricity production from VRES.

Colbertaldo et al. [23] in order to analyse the 100% renewable electricity system for California inspected the role of storage focusing on hydrogen storage via Power-to-Gas. Bellocchi et al. [24] studied the positive interactions between electric vehicles and VRES generation to decarbonize the energy system. They demonstrated how the over-generation from VRES can be absorbed by the increase of the electric mobility share. The over-generation from VRES is limited by the maximum potential of VRES sources which depends on the availability of the considered territory. Therefore it is important to study the best use of this available over-generation from VRES to decarbonize the energy system. There is the need to inspect the best mix of flexibility options able to integrate the limited over-generation form VRES in a system with high shares of electric mobility penetration.

Several studies have already coupled an optimization algorithm to EnergyPLAN software. In fact, EnergyPLAN software requires a very short computational time due to its greedy heuristic modelling based on internal priorities defined a priori. This study inspects through an optimization analysis the future competitiveness of flexibility options on the limited availability of VRES over-generation.

Table 1 shows and compares different studies coupling EnergyPLAN with an optimization tool. These studies show different flexibility options as decision variables. Batas Bjelić et al. [25] within their Single-Objective (SO) optimization tool concentrated the flexibility options in the electricity sector. Mahbub et al. in [26] and in [27] considered as flexibility options within

Table 1: List of different studies coupling EnergyPLAN tool with an optimization algorithm and the considered flexibility options as decision variables

Model and references	Investment Optimization	Flexibility options within the decision variables
EnergyPLAN [7,8]	–	–
Batas Bjelić et al. [25]	SO	Demand response, electric storage
Mahbub et al. [26]	MO	Heat pumps
Mahbub et al. [27]	MO	Heat pumps
EPLANopt [4]	MO	Hydrogen storage, heat pumps and thermal storage
EPLANopt [5]	MO	Pumped hydro storage, batteries, heat pumps
EPLANopt in this study	MO	Heat pumps, Batteries, power to gas

the decision variable list only heat pumps to efficiently convert electricity in heat. Prina et al. [4] implemented heat pumps and thermal storage in the district heating to convert the excess electricity production from VRES in the heat sector. Moreover, they have considered hydrogen storage composed by electrolysers and fuel cells as electric storage within the decision variable to be optimized. Prina et al. [5] used in their optimization two types of electric storage (pumped hydro storage and batteries) and heat pumps as decision variables. This is the first study considering together with the electrification of the heat and transport sectors through heat pumps and electric mobility the use of stationary storage (batteries) and power to gas through hydrogen generation and injection in the gas grid. Thus allowing the optimization to make the best techno-economic choice for the considered case study.

The paper is structured as follow: a materials and methods section presents the EPLANopt model and its main characteristics, a section on the Niederösterreich case study with all the assumptions, results section presents the main outcomes of the model and conclusive remarks are provided in the last section.

2. Material and methods

The EPLANopt [4,5] method is a bottom-up short-term energy system model. Bottom-up models accurately describe the energy system's internal relationships and allow the user to inspect the future alternatives of the energy system and the potential synergies between energy sectors. These models does not usually describe the connections between the energy sectors and the economics of a nation, region or municipality. These models differentiates from top-down model [28] which instead are characterized by less details in the energy sector but describe the relations with other interconnected sectors such as employment, social growth, public welfare etc.. Short-term models inspect the alternatives of the energy system in a future target year. These differentiates from long-term models [29] which study and inspect the entire transition between the current state of the energy system up to a future target year.

The EPLANopt model is the result of a coupling between the EnergyPLAN software [6–8] and an expansion capacity optimization algorithm. The EnergyPLAN software is a deterministic simulation model, it is suited to describe future scenarios with high degrees of VRES, it simulates one-year period with an hourly time-step and it integrates the three primary sectors of the energy system. The model has been applied at different scales: at European level [30], at national level [31–41], at regional level [42,43], to towns and municipalities [15,44] and to small island [45–48].

In this work, EnergyPLAN has been adopted with the following characteristics: i) The version of EnergyPLAN used in this work is the 12.1, ii) the technical simulation option is implemented, iii) for electric mobility dump charge is chosen, iv) power to gas is modelled through two main variables, the hydrogen produced and the capacity of the electrolyser.

The electrolyser will start producing hydrogen in the time-step in which there is over-generation of electricity from VRES and injecting it into the gas grid. This has been implemented in EnergyPLAN through the electrofuels sheet, CO_2 hydrogenation section, by setting to zero the parameters of the carbon recycling and the electrolyser efficiency equal to 0.7. The variables SynGridGas [TWh/year] under Output section, which corresponds to the produced hydrogen, and the MaxCap variable under the flexibility section, which represents the capacity of the electrolyser are chosen within the optimization. The decision variables are the technologies on which is performed the expansion capacity optimization analysis.

These two variables, produced hydrogen and capacity of the electrolyser, are chosen as decision variables together with a list of other technologies such as variable renewable energy sources, electric storage etc.. The complete list is introduced in chapter 3. The optimization varies their values in order to find the best energy mix for the considered case study. Hence, finding the right combination of excess electricity production, size of the electrolyser, produced hydrogen etc..

The choice of using dump charge is driven by the public authority of Niederösterreich. This, as opposed to smart charge, produces a fixed electricity demand from the transport sector which does not provide flexibility to the entire system.

The multi-objective expansion capacity optimization algorithm is based on a Multi-Objective Evolutionary Algorithm (MOEA) [49–51] which allows the assessment of the Pareto front of optimal solutions. The multi-objective approach allows the modeller to find the optimal solutions not only under minimization of an economic objective but also considering an environmental one. The considered objectives for this particular case are the minimization of the total annual costs (objective which is usually adopted in expansion capacity optimization problems for energy system models) and minimization of annual CO_2 emissions. Equation 1 shows the objective functions of the multi-objective minimization problem. The main constraints to which the optimization is subjected describe how the value of the decision variables should remain in a fixed range defined by the decision variables' lower $DV_i^{(L)}$ and upper $DV_i^{(U)}$ bounds. Other constraints such as balance between demand and generation at each time-step or storage behaviour with initial content equal to final content are defined within the EnergyPLAN software.

$$\text{Optimization function} \quad \min_{DV} \begin{bmatrix} Total\ Annual\ Costs\,[M€] \\ Annual\ CO_2\ Emissions\,[kt] \end{bmatrix} \quad (1)$$

$$\text{Subject to} \quad DV_i^{(L)} \leq DV_i \leq DV_i^{(U)}$$

It is possible to conclude by saying that the operational simulation of the year is performed through EnergyPLAN software while the expansion capacity optimization is achieved through the MOEA.

First of all the EnergyPLAN input file for the energy system of Niederösterreich has been created. Through the simulation of this input file is possible to obtain the current state of the energy system (the considered year for the Baseline is 2016 as the most recent available data belong to it). The Reference Scenario (RS) describes the future energy system (for this study is the year 2050) preserving the energy mix of the Baseline. Therefore it presents the same energy mix of the Baseline but considers all the costs of the technologies and fuels at 2050.

3. Niederösterreich case study

The considered case study is the Region of Niederösterreich in the North-East of Austria. This region counts about 1.6 Million inhabitants [52]. Regarding its energy system (see Figure 1) a large share of the final energy consumption is requested by the heat sector, which cover the 40%, and by the transport sector (29%) while the electricity sector and the industry sector counts for lower shares, respectively 19 and 12%. The data are provided directly by the public administration department of Niederösterreich in charge of the energy consumption monitoring.

Figure 2 shows a comparison between the heat and electricity demand during the year. It is possible to observe how in winter the heat demand is 3–4 times higher than the electricity demand.

The decision variables chosen for this particular case study together with their minimum and upper bounds are listed in table 2. The decision variables have been decided together the public administration of Niederösterreich. They can be grouped in different sub-classes: i) VRES such as rooftop photovoltaic (1050 equivalent hours) and wind power (2000 equivalent hours), ii) flexibility options such as lithium-ion batteries and power to gas and iii) decision variables in the heat sector which consist of solar thermal, energy efficiency of buildings and heat pumps. For energy efficiency of buildings the cost-curve estimated in [4] has been scaled and applied to the Niederösterreich case. Energy efficiency of buildings is modelled through the use of an external code which is described in detail in a previous study [4].

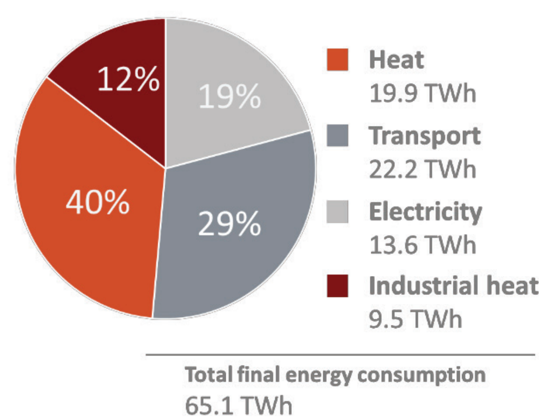

Figure 1: Niederösterreich total final energy consumption by sector

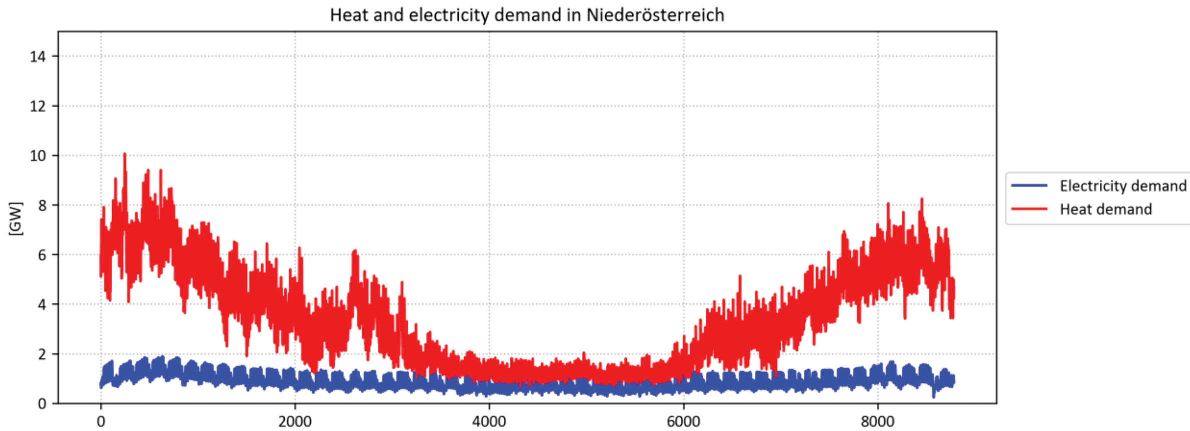

Figure 2: Comparison between the heat and electricity demand during the year

Table 2: List of Decision variables and their lower $DV_i^{(L)}$ and upper $DV_i^{(U)}$ bounds

Decision variables	Current value (2016), $DV_i^{(L)}$	Maximum potential, $DV_i^{(U)}$
Residential PV [MW]	250	4750
Wind power [MW]	1500	4000
Lithium-ion batteries [GWh]	0	20
Power to gas, H2 produced [%]	0	15
Power to gas, Electrolyser max capacity [MW]	0	250
Solar thermal [GWh]	450	800
Energy efficiency of buildings [%]	0	75
Heat pumps [%]	0	100

The maximum potential is chosen for VRSE through an analysis of the technical availability of installable capacity. For other sources such as lithium-ion batteries and power to gas Electrolyser a number large enough to perform the optimization on it and small enough not to enlarge too much the domain of the optimization and increase the computation time without an added value. For energy efficiency of buildings and heat pumps the values are driven by the cost curve of energy efficiency measures [4].

Additional assumptions on this last decision variables are the following: The installation of heat pumps is allowed in the model only after deep energy refurbishment of buildings. Domestic Hot Water (DHW) in buildings reached by district heating network is supplied by district heating itself. For the other individual buildings there are two different demands: DHW and heating demand. The heating demand can be reduced through energy efficiency refurbishment. The DHW share instead is not influenced by energy efficiency. The optimization decides which share of renovated buildings should install heat pumps (Figure 3 shows the theoretical decrease of final energy consumption due to energy efficiency with the assumption of 100% installation of heat pumps in renovated buildings). In the individual sector, at the increase of the energy efficiency share, heat pumps substitutes different type of boilers with the following priorities: 1) Coal boilers, 2) Oil boilers, 3) Electric boilers, 4) Natural gas boilers and 5) Biomass boilers.

Additional assumptions are the following: i) constant demographic situation from 2016 to 2050, ii) energy consumption of industry sector has been assumed to remain constant, iii) Wien international Airport jet fuel consumption is not considered in the analysis, iv) export price for electricity equal to 35 €/MWh [53], v) import price for electricity equal to 45 €/MWh [53], vi) emission factor of imported electricity equal to 170 kg/MWh [54]. This value is the Austrian average value for the year 2013. It has been assumed to keep it constant also for future scenarios in order to push the local system towards a carbonization process without counting on the imported electricity. vii) The electricity generation from hydropower is assumed to remain constant between 2016 and 2050 (current electricity generation from Hydro equal to 7.16 TWh), viii) The electricity generation from Biomass power plant is assumed to remain constant between 2016 and 2050 (biomass consumption equal to 14.45 TWh), ix) Transport demand in terms of driven km and modal split has been assumed constant, x) Power to gas costs are those of the electrolyser installed capacity (400 €/kW, lifetime= 15, O&M=3% of the investment cost). Other costs of the power to gas flexibility option are not included because the injection of hydrogen goes directly into the existing gas grid.

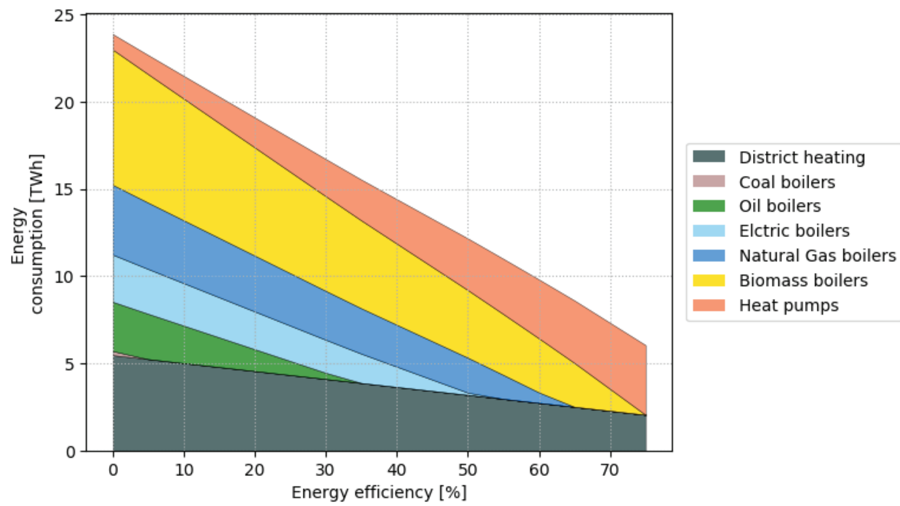

Figure 3: Theoretical decrease of final energy consumption due to energy efficiency

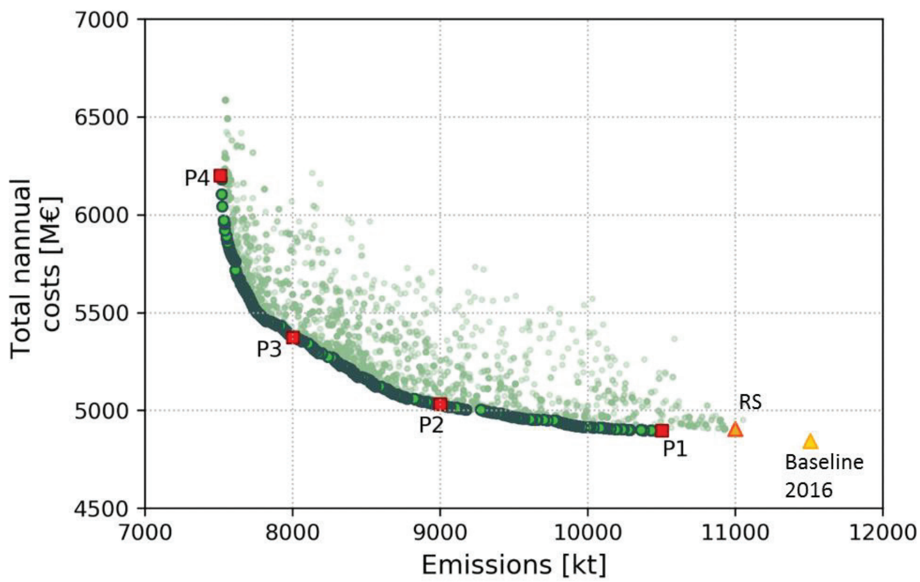

Figure 4: Evaluated scenarios: Baseline 2016, Reference Scenario, clouds of dominated solutions and Pareto front of optimal solutions. Four scenarios are selected to inspect the results on the Pareto front: P1, P2, P3 and P4

4. Results and discussion

The optimization problems that have been developed are the following:

- Without taking into account electric mobility
- Considering electric mobility penetration at 25, 50, 75 and 100%. Different level of penetration of electric mobility have been considered by simply introducing some conversion factors in kWh/100km for each fuel based vehicle [55] assuming the transport demand in terms of driven km constant. The value used are the following: 52.78 kWh/100 km for petrol fuelled cars, 46.11kWh/100 km for gasoil fuelled cars and 13.61 kWh/100 km for electric vehicles. The use of these conversion factors allows the evaluation of the electricity demand generated from electric mobility. This value is set in EnergyPLAN and then the optimization analysis is run in order to evaluate the hourly operational simulation and the impacts of electric mobility on the values of the optimized decision variables.

Starting from the first case, the optimization has been executed and the final results are analysed. Figure 4 shows the Baseline 2016, the RS 2050 and Pareto front of optimal solution for the case without electric mobility penetration. Four solutions on the Pareto front have been chosen in order to better understand the final results (P1, P2, P3, and P4). These solutions are chosen to map the entire Pareto front, thus a similar distance is taken between them. This selection is performed choosing the most extreme solutions and two in the middle. The final aim is to catch the trends of the decision variables among the optimal Pareto fronts solutions.

Figure 5 shows for the reference scenario and for the solution from P1 to P4 the evolution of the contributions which constitute the electricity demand in a week in summer and in winter. Moving from P1 to P4, it is possible to observe the decrease of electricity demand due to energy efficiency and the substitution of electric boilers with heat pumps and the increase of electricity demand due to heat pumps and power-to-gas. Electrolysers uses the over-generation from VRES to produce hydrogen. For this reason the electricity demand due to power-to-gas is visible in the hours of the day in which there is availability of over-generation from VRES. This concept is even more clear looking at the Figure 6 which shows the electricity generation from the different sources. It can be noticed the increase of electricity demand (difference between the blue curve, electricity demand of the reference scenario, and the red curve, the electricity demand of the considered scenario). It is also possible to highlight the introduction of batteries in scenario P4 which substitute fossil fuel power plants in covering of the electricity load in the hours of the day in which the generation of VRES is not enough to cover the demand.

Figure 7 shows the final energy consumption in the different sectors of the energy system. The industry sector energy consumption remains constant due to the considered assumptions. Transport demand remains also constant because in these scenarios mobility is not taken into account. The heat demand decreases (moving from RS to P4) due to energy efficiency of buildings and due to the substitution of conventional boilers with heat pumps. In the electricity demand, a decrease of electric boiler demand and an increase of heat pumps and power-to-gas can be observed.

Figure 8 shows the total annual costs of the system in the five considered scenarios. Energy efficiency measures and heat pumps investments costs raise gradually thus inducing a significant reduction of purchasing costs for natural gas and heating oil. A cost increase in the electricity sector is visible due to solar and wind energy, in scenario P4 also by the use of batteries. Power to Gas is barely noticeable from a cost viewpoint.

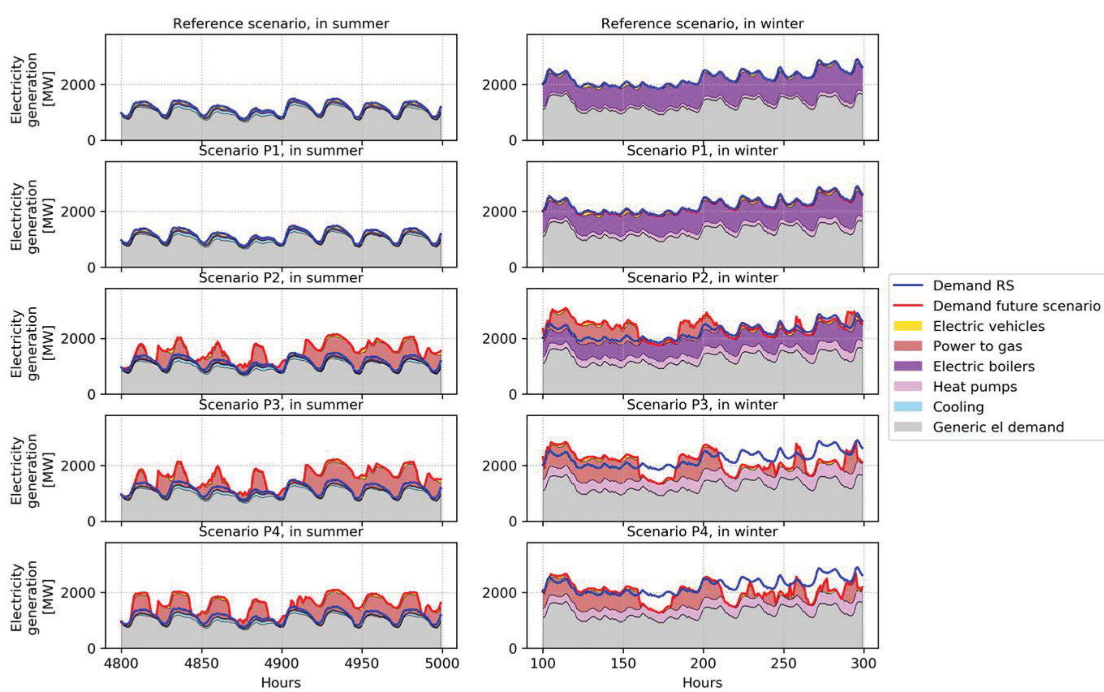

Figure 5: Hourly electricity demand: different contributions for two weeks of the year (one in summer and one in winter) for the scenarios RS, P1, P2, P3 and P4

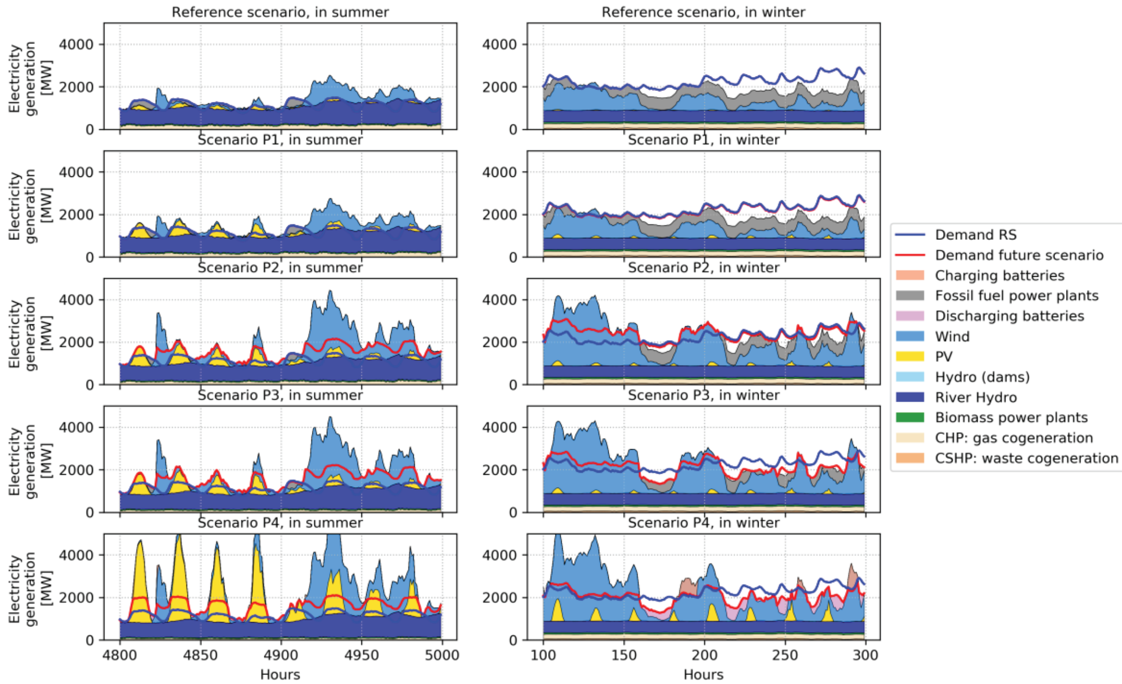

Figure 6: Hourly electricity dispatch for two weeks of the year (one in summer and one in winter) for the scenarios RS, P1, P2, P3 and P4

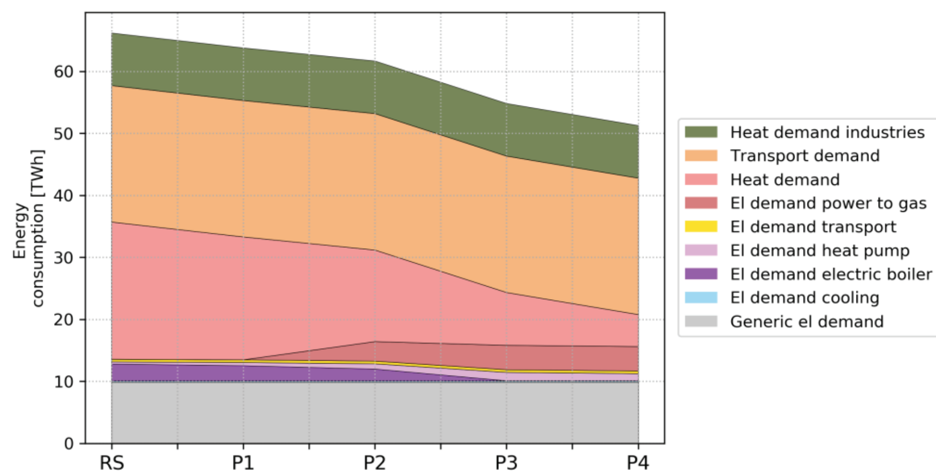

Figure 7: Energy consumption in the four main sectors of the energy system: electricity, heat, industry and transport for the scenarios RS, P1, P2, P3 and P4

Figure 9 shows the final results in the graph total annual costs vs. CO_2 emissions for the cases considering increasing shares of electric vehicles (EV). The increase in e-mobility leads to a gradual reduction of emissions and to a reduction of the total costs based on the high efficiency of electric motors and the reduction of fossil fuels. Even in the final scenario, the target set cannot be achieved without the inclusion of energy efficiency measures in the industry sector. Four solution have been selected to inspect the final results. In order to consider comparable solutions, scenarios at the same point on the Pareto front have been chosen. Starting from scenario P3 on the Pareto front not considering electric mobility the scenarios P3-25, P3-50, P3-75 and P3-100 have been selected. These points have the same relative position on the Pareto front. This latter means that the solutions have been chosen on the respective Pareto front maintaining the relative distance in terms of CO_2 emissions of point P3 from the extreme points of its front: P1 and P4.

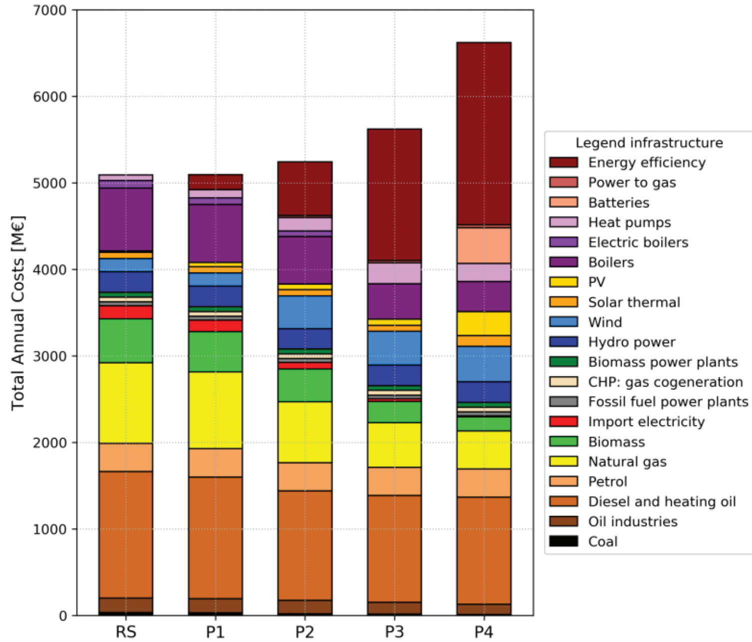

Figure 8: Total annual costs for the scenarios RS, P1, P2, P3 and P4

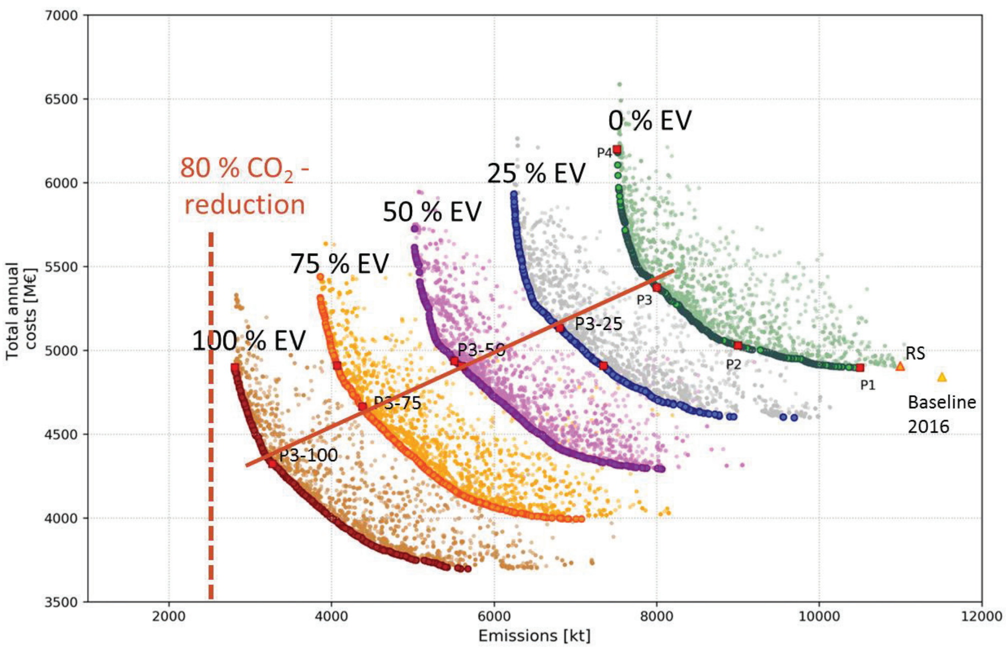

Figure 9: Pareto fronts evaluated for different penetrations of EV, Baseline 2016, Reference Scenario, scenarios from P1 to P4 on the 0% EV Pareto front. Scenarios from P3-25 to P3-100 chosen at the same point on the Pareto front of P3

Figure 10 and 11 shows respectively the hourly electricity demand and hourly electricity generation for the five considered scenarios: RS, P3-25, P3-50, P3-75 and P3-100. It is possible to notice the increase of electricity demand due to electric mobility. Power-to-gas increases for low level of electric mobility penetration but then disappear due to the reduction of the availability of VRES over-generation. It is also possible to notice the use of batteries which become relevant in order to cover the peak of demand in the evening due to the recharge of electric vehicles.

Figure 12 shows the final energy consumption in the different sectors of the energy system. The industry

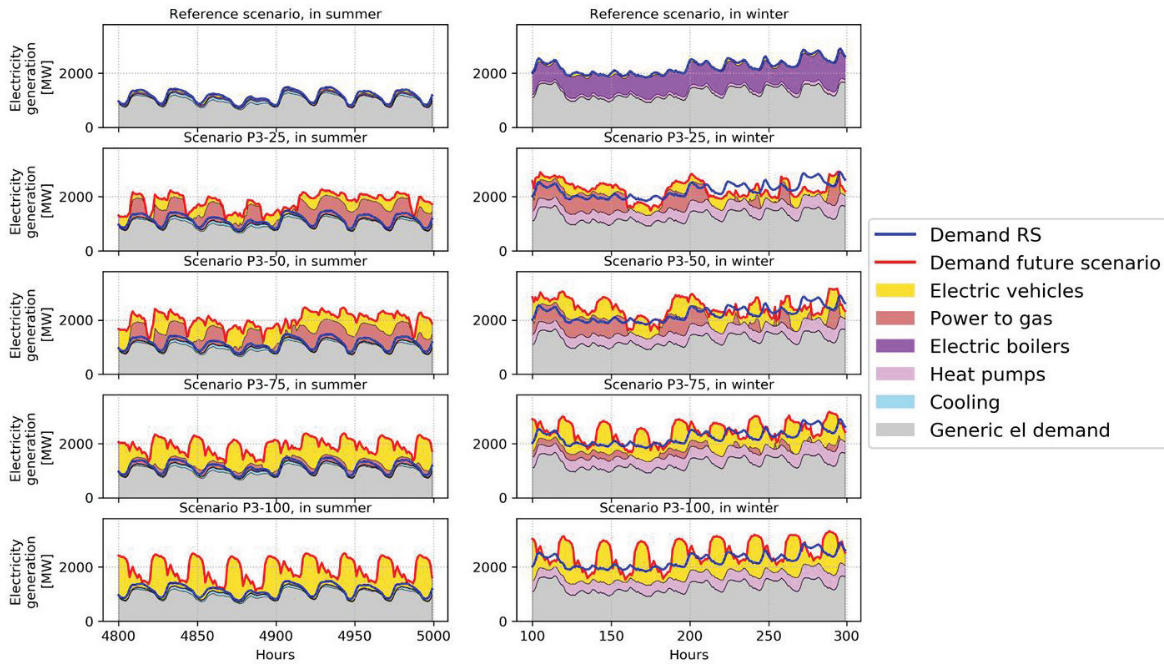

Figure 10: Hourly electricity demand: different contributions for two weeks of the year (one in summer and one in winter) for the scenarios RS, P3-25, P3-50, P3-75 and P3-100

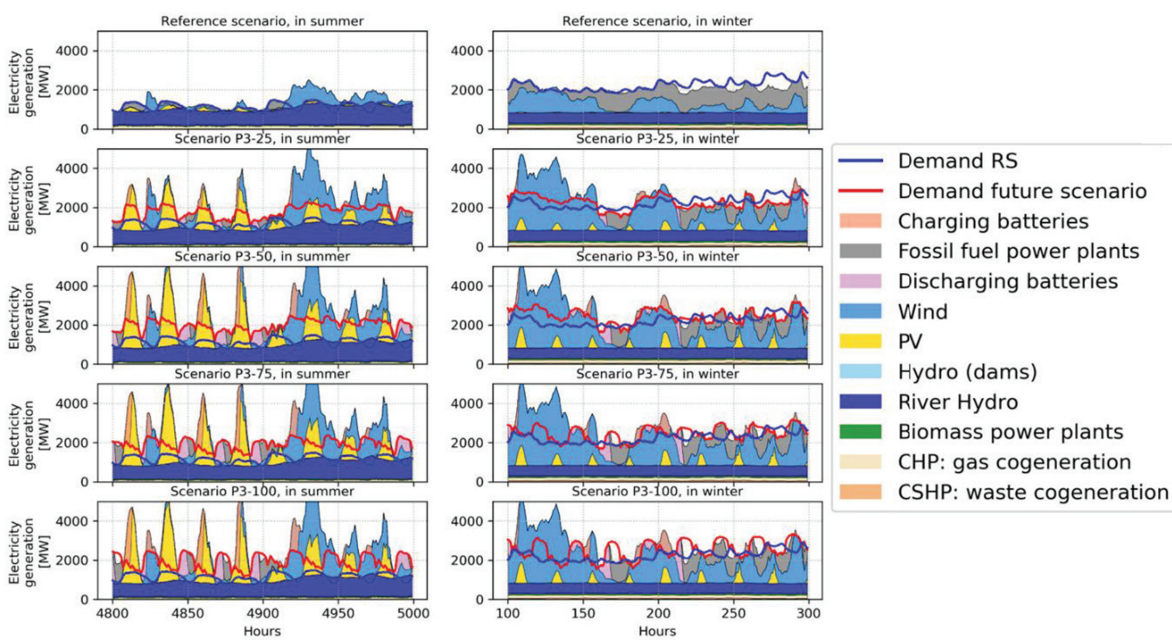

Figure 11: Hourly electricity dispatch for two weeks of the year (one in summer and one in winter) for the scenarios RS, P3-25, P3-50, P3-75 and P3-100

sector energy consumption remains constant due to the considered assumptions. Transport demand decreases due to the shift to electric mobility. The heat demand decreases (moving from RS to P3-25) due to energy efficiency of buildings and due to the substitution of conventional boilers with heat pumps. In the electricity demand, it is possible to observe the increase of electricity demand from power-to-gas in P3-25 and P3-50. For higher shares of electric mobility, P3-75 and P3-100, there is a decrease of electricity demand due to

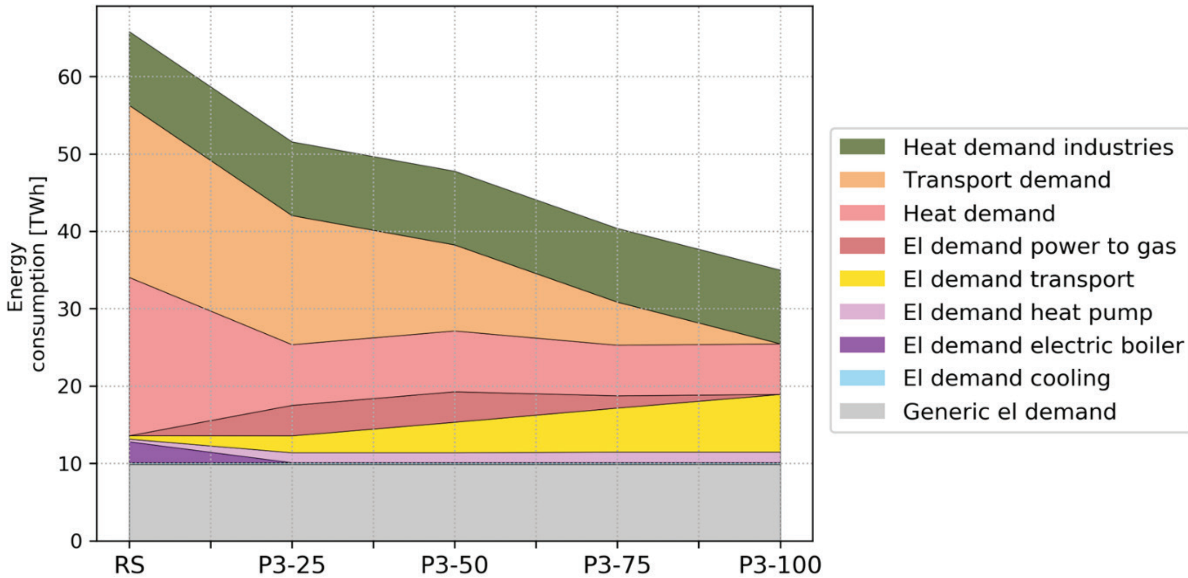

Figure 12: Energy consumption in the four main sectors of the energy system: electricity, heat, industry and transport for the scenarios RS, P3-25, P3-50, P3-75 and P3-100

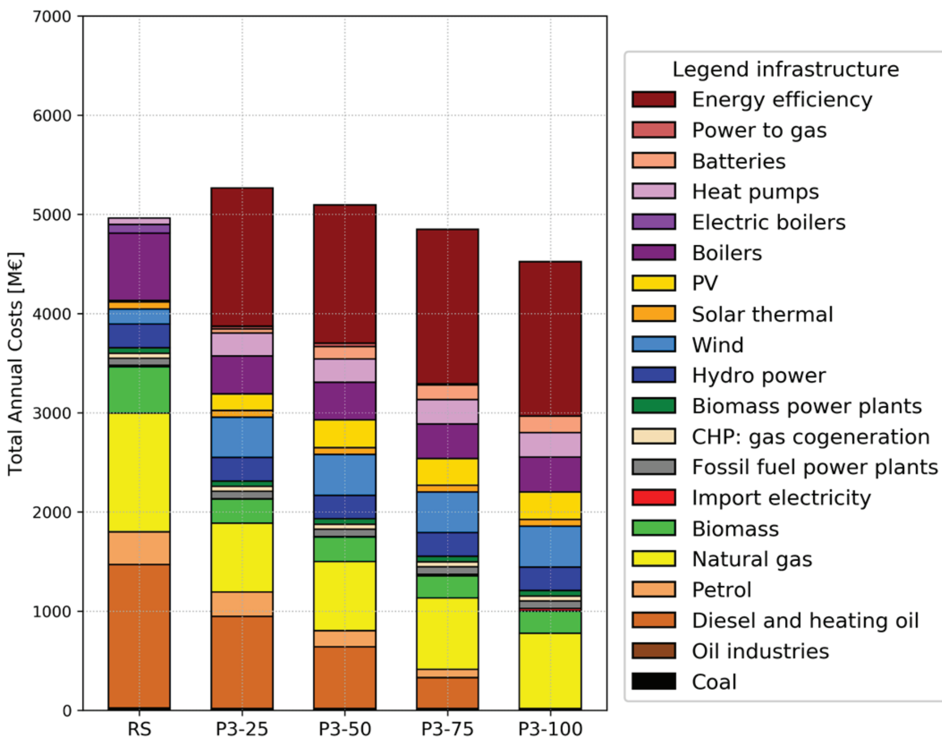

Figure 13: Total annual costs for the scenarios RS, P3-25, P3-50, P3-75 and P3-100

power-to-gas. This is mainly due to the fact that high shares of electric mobility produce an increase of electricity demand which absorb the previous over-generation from VRES. The lower availability of over-generation makes other flexibility options different from power to gas more cost-effective.

Figure 13 shows the change in the total cost of the energy system in each considered scenario. The gradual increase in electrified transport sector causes a significant reduction in petrol and diesel consumption in addition to the decline of fossil heating fuels due to buildings renovation. Due to the high efficiency of electric vehicles, the necessary increase in power consumption and associated costs is much lower, resulting in a step-by-step reduction in the total energy system cost of approximately 10%.

Some considerations on the change in the nature of the costs needs to be done. Figure 14 and 15 shows the total annual costs for scenarios RS and P3-100. The arrows shows the different nature of the costs. The ones directed outside from the region represents the external expenses. The ones that bend back represent the investments on the territory and represent an added value for the local economy. It is possible to observe how not only

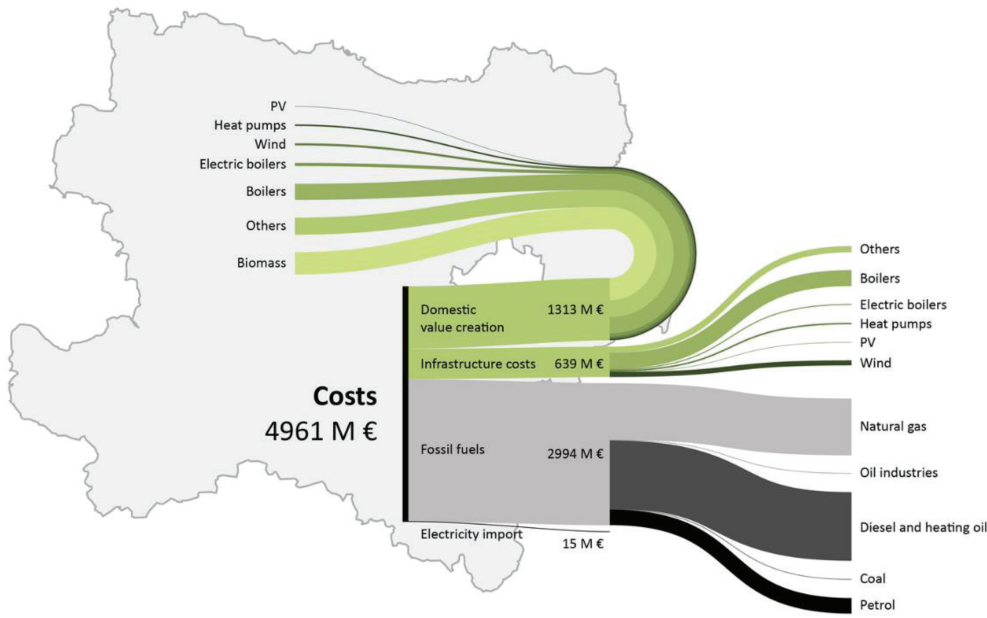

Figure 14: Subdivision of investments in the region and import of technology and raw materials for reference scenario at 2050

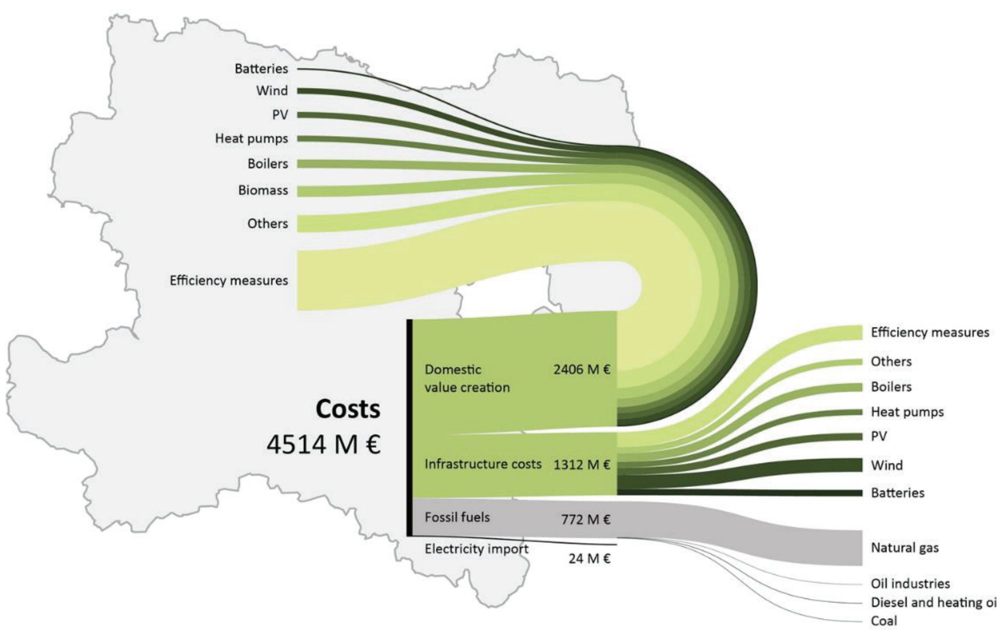

Figure 15: Subdivision of investments in the region and import of technology and raw materials for scenario P3-100 at 2050

the P3-100 scenario has lower costs compared to the RS but also that the nature of these costs represent a huge opportunity for the local economy. The subdivision between the costs directed externally and the ones which bend back as possible added value on the territory have been provided by the public administration of Niederösterreich. They have analysed for each source the share of production processes made on the territory and the share made externally. It is not the aim of this paper to go in detail about this subdivision. Nevertheless, it is possible to generalize this result to different case studies by saying that if a country has limited fossil fuels reservoirs the grey scale arrows will be directed externally and the green scale arrows will bend back as possible added value creation. These costs in fact could be exploit by the creation of local production lines. These results by showing the decrease of fossil fuels costs and the increase of costs of renewable energy technologies, energy infrastructure and energy efficiency highlight the economic opportunities of the energy transition.

5 Conclusions

The EPLANopt energy system model has been applied to the case study of Niederösterreich. The final results have shown how the objective of 80% CO_2 emission reduction is an ambitious target that can be met only with a strong sustainable transformation of the energy system. The key transformations are the energy efficiency of buildings, the electrified transport sector and a deep exploitation of the renewable energy potential. However these alone are not enough to meet the 2050 energy target. A contribution to decarbonisation from the industry sector is needed.

The study has been an opportunity to inspect the best use of VRES over-generation. The over-generation from VRES is limited by the maximum potential of VRES sources which depends on the availability of the considered territory. There is the need to inspect the best mix of flexibility options able to integrate the limited over-generation form VRES in a system with high shares of electric mobility penetration. The results have shown how electric mobility at high penetration cannibalizes power-to-gas due to the reduction of the available over-generation from VRES.

The results have also shown how this transformation of the energy system is a relevant economic opportunity as a large shift from costs for fossil fuels to investments in on place technologies and infrastructures is taking place.

It is important to underline how the choice of the decision variables, mainly selected through a collaborative process with the public administration of Niederösterreich, affect the final results. In fact, the selection of additional flexibility options as decision variables such as demand side management, different type of storage systems or electric vehicles with smart charge could help the integration of VRES in the system. The consequence could be a further reduction of the CO_2 emissions and therefore energy scenarios closer to the energy targets at 2050.

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