Analysis of Smart Energy System Approach in Local Alpine Regions - a Case Study in Northern Italy

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Abstract

Increasing electrification of final uses can be a viable solution towards low-carbon energy systems, when coupled with local renewable power generation. Mountain areas can already benefit from high shares of hydro-power generation, but, at the same time, rely on oil products for transport and for the heating sector in remote areas where natural gas infrastructures are not available. This research work evaluates potential scenarios for the electrification of transport and heating sectors, by coupling the simulation tool EnergyPLAN with a multi-objective optimization algorithm to analyse economic and environmental aspects. Results show that the largest benefits are expected from the electrification of the heating sector. Indeed, a CO_2 emissions reduction up to 30% can be reached by acting on the transport sector alone, while up to 65% combining it with measures on heating, industry and agriculture sectors and additional electricity generation from photovoltaic systems. Moreover, the use of heat pumps can lead to significant CO_2 emissions decrease with only to a slight increase in the overall annual costs thanks to lower variable costs that partly compensate the higher required initial investment and electricity storage deployment. The optimization analyses also highlight the effect of progressive penetration of electric vehicles in the private cars fleet and hydrogen trucks in the light-duty vehicles one.

Keywords: energy systems, renewable energy sources, end-use electrification, sector coupling, decarbonization

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1. Introduction

Energy systems worldwide are facing an energy transition, which is driven by multiple global and local trends: decarbonization policies, increased use of Renewable Energy Sources (RES) [1], interest in the exploitation of local resources to limit energy dependency and in implementing measures to avoid massive air pollution in large urban centers. In addition, strong changes are required to both users and producers to enhance their efficient interaction such as in buildings [2] looking for their flexibility and their further contribution to the amount of automated and controlled energy [3, 4]. These challenging issues require careful actions plans, to be designed from a precise evaluation and quantification of the current situation, together with the analysis of future alternative pathways based on simulated scenarios accounting carefully for performance gap considerations [5]. Multiple research works have been performed on energy systems simulation, to assess the potential climate and environmental impacts. Several tools to support energy planning and scenarios development are available [6, 7], and are being widely applied in energy and environmental research to provide long-term projections at different scales, from Countries and regions [8, 9] to macro-areas [10] and even to simulate global energy supply strategies [11]. The suitability of each tool depends on the specific application of interest since it must be capable of focusing on different aspects and suitable for different territorial scales. Energy systems modelling can include various target groups (policymakers, scientific and research communities, companies), various purposes (data analysis, forecasting, simulation optimization, etc.), conceptual frameworks (top-down: focusing on economic theory, bottom-up: technological focus, hybrid: combination of previous ones). Both top-down and bottom-up approaches have specific advantages and limitations and they are described by Herbst et al. [12]. Energy systems models include both open source software and commercial solutions. Some of the most used tools are MARKAL/TIMES, RETScreen, HOMER, LEAP and EnergyPLAN. The MARKAL/TIME family [13, 14] are energy/economic/environmental tools used to explore energy-system scenarios that minimise the cumulated systems costs. They have been used over medium to long-term time horizons mostly at the global, multi-regional and national/state level for countless studies, including the simulation of integrated policies at the national and pan EU level [15, 16]. The RETScreen International Clean Energy Project Analysis Software, is a decision support tool used to [17]evaluate the energy production, life-cycle costs and greenhouse gas emission reductions for various types of energy efficient and renewable energy technologies [18]. HOMER [19], a techno-economic optimisation tool for stand-alone and grid-connected power systems serving both electric and thermal loads, is used to evaluate the economic and technical feasibility for technology options in the electricity and heat sectors [20]. LEAP [21] is a modelling tool that simulates all sectors and technologies and their costs, including external ones for pollutants and decommissioning. It has been mainly used to analyse national energy-systems and compare different scenarios [22]. The EnergyPLAN software [23, 24], developed by Aalborg University, is based on a bottom-up approach and is among the most comprehensive tools to describe future energy systems in a very short computational time. EnergyPLAN [25], whose features are summarized in Section 2.1, is a deterministic input/output model that integrates the three main sectors of an energy system: electricity, heat and transport [26]. The software tool is able to simulate an energy system given specific inputs, but it cannot be used to find the best mix of technologies through an optimization process. Energy-

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PLAN is based on internal priorities to solve the dispatch problem and therefore is very fast in computational time. The use of internal priorities to solve the dispatch problem means that an order of technologies is defined a priori to cover the energy demand. This is not the case, for example, in a model based on linear programming or mixed integer linear programming where the dispatch problem is solved finding the least cost energy dispatch. This order defined in EnergyPLAN gives priority to renewable energy sources, followed by conventional sources from the ones with the highest efficiency to the ones with the lowest. This characteristic makes it suited to be coupled to an external optimization algorithm. Some research studies have combined EnergyPLAN with an expansion capacity optimization algorithm within a short-term bottom-up energy system model. Bjelic et al. [27] launched EnergyPLAN within the single-objective optimization program GenOpt to identify the minimal increase in the costs of the national energy system for Serbia under the EU 2030 framework. Mahbub et al. [28] coupled EnergyPLAN to a Multi-Objective Evolutionary Algorithm (MOEA) programmed in Java to evaluate the Pareto front of best configurations of the energy system. M. G. Prina et al. [29] have realized the EPLANopt model, developed in Python, also coupling the EnergyPLAN software to a MOEA. The element of novelty introduced by this latter study has been the particular focus on the heating sector including energy efficiency of buildings within the optimization through the introduction of a cost-curve describing the costs versus the energy savings.

Similarly to the aforementioned approaches, this paper proposes a tool which integrates a multi-objective optimization algorithm to EnergyPLAN. The element of novelty of this paper is the integration of the transport sector within the optimization where Electric Vehicles (EV) penetration impact is not anymore evaluated in the form of a parametric analysis [30] but EV share and all the related input variables become an input of the optimization routine itself. The multi-objective optimization is performed considering as targets the total annual costs and CO_2 emissions. The analysis, developed at local level, is applied to an Alpine region whose power sector is characterized by an abundance of electricity production from hydroelectric power plants, which can be further exploited by increasing the electricity-based technologies in the heating and transport sectors.

Electrification, indeed, is considered a promising driver of renewables integration [31]. Transition to electricity-driven heating is coming to the building sector with large deployment of Heat Pumps [32] which allow the buildings to offer higher flexibility to the Power Grid players [33]. While, the increasing adoption of EV has been seen as a diverse emission allocation strategy and a further technology for improving smartness and demand response capacity of buildings [34]. Switching to electricity the aforementioned sectors allows a direct use of available renewable electricity removing the local CO_2 emissions from the combustion process of boilers and automotive engines and an acceleration of sustainable energy targets [35]. This is the case of the Valle D'Aosta region analysed by the authors of the paper.

The paper is organized as follows. Section 2 presents the methodology that has been used to simulate the energy system, along with a description of the optimization tool, decision variables, constraints and objectives. Section 3 presents in detail the case study, by illustrating the current energy balance, as well as the assumptions that are at the basis of the future scenarios. In Section 4 results are presented and discussed, while Section 5 reports the main conclusions and some policy indications.

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2. Methodology

This section presents the methodology used in this study, underlining the main features of the simulations performed with EnergyPLAN and the characteristics of the simulation tool that has been developed.

2.1. EnergyPLAN software

EnergyPLAN software is a tool for energy systems analysis developed and maintained by the "Sustainable Energy Planning Research Group" at Aalborg University (Denmark) since 1999 [25]. The main purpose of the tool is to assist energy planning by simulating the operation of a particular energy system, considering the interconnections among the different energy sectors.

In particular, EnergyPLAN assesses the operation of a pre-selected energy system configuration by balancing energy demand and supply driven by a set of priorities. The computational time is very short and different energy systems configurations can be compared with respect to energy and/or economic indicators.

General inputs required by the software are the total annual production/demand for the different sectors, the capacity and efficiency of the units installed, the hourly distribution of the total annual production/demand as well as a set of cost parameters (investment costs, operation and maintenance costs, fuel prices, carbon taxes, interest rate, etc.). The main outputs of the model include energy balances and resulting annual production from different sources, fuel consumption, import and export of electricity, CO_2 emissions and total annual cost of the system.

The tool simulates the operation of an energy system with an hourly resolution, including electricity, heat and transport sectors and their possible interactions, analysing the energy system as a whole, with a Smart Energy System approach based on a holistic approach that conveniently exploits synergies through sector coupling. It has been widely used in the literature [36] to perform the analysis and design of energy systems either at regional/municipality scale [37, 38, 39], national [40, 41] or even European scale [42], to model high-share renewable energy systems [43, 44] taking into account the use of emerging technologies and possible flexibility measures to accommodate fluctuating RES electricity generation.

The definition and comparison of multiple scenarios is the basis to evaluate potential technological alternatives to reach the desired targets, which are usually defined based on environmental or economic goals. However, while EnergyPLAN allows a manual definition of a number of scenarios, the use of a dedicated algorithm allows the automation of this process, increasing the number of alternatives that can be effectively generated and compared to reach the desired objectives.

2.2. Optimization tool

As described above, EnergyPLAN is a deterministic input/output model that simulates the operation of a given system on an hourly basis. The model follows predetermined criteria set by the user and solves the energy balances between the demand for electricity, heating and transport and the required energy supply from a variety of technologies.

Instead of manually defining a single scenario and assessing its impact on the energy system, the aim of running an optimization is to ultimately let the algorithm select

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a variety of possible techno-economic optimal configurations acting on different energy sectors, based on specific targets to be optimized.

The tool used in this research work performs a multi-objective optimization (as illustrated in Figure 1), using MATLAB® MOEA function *gamultiobj* [45], that finds a Pareto front for multiple objective functions using a controlled, elitist genetic algorithm (a variant of NSGA-II [46]). It was specifically designed to work with EnergyPLAN exploiting a MATLAB function developed by Santana et al. [47] and available on the EnergyPLAN website [25].

The MOEA performs the expansion capacity optimization while EnergyPLAN software carries out the operational simulation throughout the entire year. The overall model is classified as short-term model. It allows to find the best energy mix in terms of the selected objectives for the future target year chosen for the analysis. In this particular case, the selected future target year is 2050. The selected objectives are the total annual costs and the annual CO_2 emissions, which should be both minimized. The genetic algorithm produces an initial population of random solutions. Each solution is composed by a list of decision variables on which the expansion capacity optimization is performed. For each decision variable a range of potential values is defined with a minimum and a maximum bound. The genetic algorithm then evaluates each solution by running EnergyPLAN for the selected future target year, substituting the values of the decision variables which characterized the solution in it. EnergyPLAN returns the values of the objective functions, in this case the total CO_2 emissions and the total annual costs, on which each solution is evaluated and compared to the others. By means of the operators that are typical of the genetic algorithms (such as selection, crossover and mutation) the optimization algorithm moves forward until the convergence is reached and the final Pareto front is found [30].

2.2.1. Decision variables, constraints and objectives

Given the particular focus of the study on transport and heating sectors, the decision variables object of the optimization process are represented by those variables that fully characterise the measures implemented in such areas of the energy system (Section 3.2). As discussed above, the objective functions to be minimised are the total annual costs and the CO_2 emissions.

It is worth pointing out that, with respect to the heating sector, a preliminary analysis was carried out to asses the impact of the progressive penetration of Heat Pump (HP) replacing conventional oil boilers, demonstrating the HP beneficial role not only in terms of CO_2 emissions but also with regard to total annual costs, being variable costs reduction, related to the cost of fuel usage, capable to overcome the increase in investment costs. As a result, variables related to the heating sectors were not chosen as decision variables as all Pareto solutions would have been characterised by the highest level of HP penetration.

Despite a significant abundance of hydroelectric generation amply exceeding electricity demand, mismatch between demand and supply might still arise depending on the particular distribution of the electrical load. In fact, as shown in Figure 3, at the highest level of end-use electrification, a small share of electricity demand (2% of total) is covered through import. As a result, Electricity Storage Systems (ESS) are also included within the set of decision variables to add additional flexibility to the energy system. In particular electrochemical storage, as in Li-ion batteries, is taken into account as a widely

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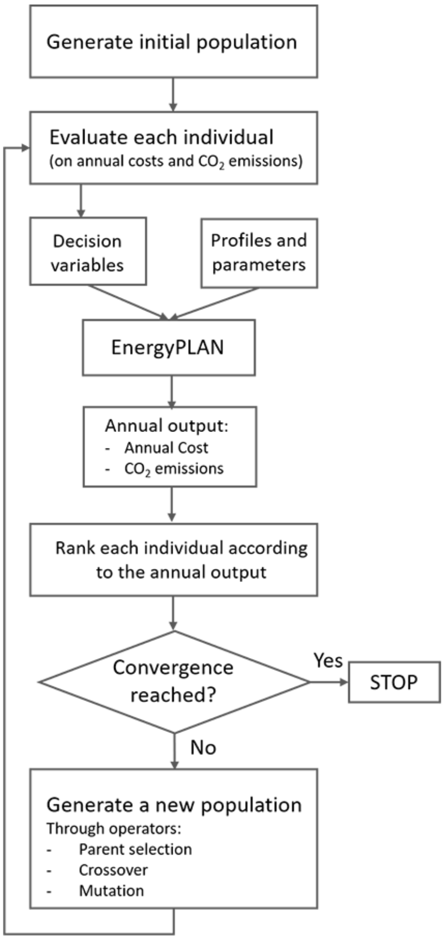

Figure 1: Diagram of the optimization model

acknowledged solution to accommodate renewable surplus and characterised according to EnergyPLAN requirements, i.e. storage maximum power and capacity.

The optimization decision variables, therefore related to Light-Duty Vehicles (LDV) and Heavy-Duty Vehicles (HDV) in the transport sector only, are the following:

1. LDV petrol consumption: x_1;
2. LDV diesel consumption: x_2;
3. Number of diesel HDV: x_3;
4. Electricity storage power: x_4;
5. Electricity storage capacity: x_5;

EV are assumed to potentially replace conventional cars covering up to 80% of the total LDV fleet, keeping the overall number of vehicles unchanged with respect to 2015 as well as the average annual driving distance. The number of EV can be defined as follows:

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$$n_{EV} = \left(Mvkm_{LDV} - \frac{x_1}{(\frac{kWh}{km})_{petrol_{LDV}}} - \frac{x_2}{(\frac{kWh}{km})_{diesel_{LDV}}} \right) \times \left(\frac{kWh}{km} \right)_{EV_{LDV}} \quad (1)$$

Where:

- $Mvkm_{LDV}$ represents the product of the total number of vehicles and the weighted average of km driven by the entire LDV fleet;
- $(\frac{kWh}{km})_{petrol_{LDV}}$ is the energy consumption of petrol LDV category per km driven;
- $(\frac{kWh}{km})_{diesel_{LDV}}$ is the energy consumption of diesel LDV category per km driven;
- $(\frac{kWh}{km})_{EV_{LDV}}$ is the energy consumption of EV category per km driven.

Technical features for EV were assessed considering the real specifications of circulating EV and assuming that Plug-in Hybrid Electric Vehicles (PHEV) make up 15% of EV fleet while Battery Electric Vehicles (BEV) cover the remaining 85% share to be in line with future projections concerning EV fleet composition [48]. Also:

$$n_{EV} + n_{conventional} = n_{total_{LDV}} \quad (2)$$

Where:

- $n_{total_{LDV}}$ is the total number of LDV (which remains constant);
- $n_{conventional}$ is equal to the sum of petrol and diesel LDV.

Costs for EV and conventional cars were obtained from a weighted average of the current fleet assuming an investment period of 10 years, as specified in Section 3.2. In particular, in order to take into account a conservative discount in EV purchasing costs, in the optimization process EV purchasing price is equal to an average of current EV price and the average price of conventional cars.

As concerns HDV, diesel trucks are assumed to be in part replaced by fuel-cell trucks, under the assumption that the overall number of HDV stays stable as compared to 2015 level.

$$n_{diesel_{HDV}} + n_{H_2 HDV} = n_{total_{HDV}} \quad (3)$$

Where:

- $n_{total_{HDV}}$ is equal the total number of HDV.

The maximum share of H_2 trucks replacing conventional alternatives, the efficiency and costs for diesel and H_2 trucks and other parameters have been set according to the values indicated in Section 3.2.

The optimization of Valle d'Aosta energy system was performed considering three different cases, indicated as Opt1, Opt2 and Opt3, each of them including the implementation of different measures on the energy sectors (Section 3.3).

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2.3. Additional focus on supply chain emissions

The analyses performed by EnergyPLAN as well as the objective functions on the optimization tool are based on the CO_2 emissions caused by fuel combustion. Moreover, in accordance with the usual practice at international level, the emissions from biomass are considered to be net zero due to the fact that the carbon dioxide that is emitted has been captured by the biomass itself during its life.

These assumptions have been considered to provide consistent results with the common energy modeling approaches that are usually considered for future scenarios. However, an additional focus based on the final results is provided, by considering the emissions related to the entire supply chain of each energy source. These additional emissions are generated during the fuel processing and transport phases, both for fossil fuels and for biomass-based fuels.

The emission factors that have been used for the calculations are reported in Table 1. These values include both the CO_2 itself and other chemical compounds that have an impact on global warming (e.g. CH_4, N_2O, etc.), and therefore they are expressed as CO_2 equivalent. While for fossil fuels the upstream emissions are generally much lower that the direct emissions, the upstream emissions for biomass can be relevant, especially for transport biofuel (that require complex transformation phases). However, the consideration of the life cycle of the power plants and the equipment is not included in this analysis.

Table 1: Emission factors of fuels - CO_{2eq} emissions (g/kWh). Sources: [49, 50]

Fuel	Combustion	Upstream	Total
Gasoline	262.8	50.4	313.2
Diesel oil	262.8	57.6	320.4
LPG	237.6	28.8	266.4
Natural Gas	201.6	50.4	252.0
Biodiesel	0.0*	198.0	198.0
Biogas	0.0*	64.8	64.8
Wood Biomass	0.0*	76.4	76.4

* direct CO_2 emissions for biomass are considered to be a closed cycle.

3. Case study

Valle d'Aosta is the smallest Italian region, located in the North-Western mountain area, bordering with Switzerland and France. Covering an area of 3,263 km^2, and with about 128,000 inhabitants, it is characterized by an energy system common to other areas in the Alpine Region. Buildings heating is strongly dependent on oil products, due to the fact that some areas of the region are not reached by the natural gas network. However, thanks to the availability of several forest areas, the use of local wood biomass is quite diffused, although often as self-supply of final users rather than an organized and tracked supply from specialized companies.

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Moreover, thanks to the availability of several rivers, the region has seen a strong development of hydroelectric power plants in the past decades, and multiple small plants are still under development nowadays. As of 2015, 140 hydro plants were operating in the region, for a total nominal net power of 951 MW and 3.5 TWh of annual production [51], more than three times the local electricity demand.

Another specific feature of the region is the importance of the touristic sector, which is composed by roughly 1,100 different operators, providing additionally 55,000 places (without considering holiday houses), which is almost half of its inhabitants [52]. This fact has strong consequences on different aspects, including energy consumption and waste management, and per-capita statistic indicators may be strongly influenced in comparison with other regions.

Valle d'Aosta has been identified as case study for this work to evaluate how such a strong electricity generation excess could be exploited to support the use of local RES and decrease the need of importing fossil fuels, by increasing the electricity penetration in the buildings and transport sectors.

3.1. Reference Model

A reference model for Valle d'Aosta energy system has been defined with reference to the year 2015 and characterised in terms of energy demand and supply, based on the latest available data, derived from official local energy balances [53]. According to the Regional Ministry of production Activities, Energy, Labour and Environmental policies of Valle d'Aosta, the gross final energy consumption was 4.44 TWh in 2015. End-use energy demand by source is reported in Table 2 for the main sectors: buildings, transport, industry and agriculture.

Table 2: Final Energy Consumption in Aosta Valley (GWh) (2015, [53])

Sector	Nat. gas	Oil	RES	Coal	Heat	Electricity	Total	RES %
Buildings	414.7	859.2	473.5	0.4	73.4	504.7	2,325.8	42%
Transport	0.1	1,150.4*	-	-	-	-	1,150.5	3%
Industry	423.7	145.9	13.9	-	-	366.7	950.2	40%
Agriculture	-	19.9	0.1	-	-	4.8	24.8	20%
Total	838.5	2,175.4	487.5	0.4	73.4	876.2	4,451.3	32%

* Including biofuels blending (around 40 GWh).

As for energy consumption in buildings (which include residential and services sectors), fossil fuels and biomass consumption has been allocated entirely to space heating purposes and no electric boilers have been considered (due to their use often limited to produce domestic hot water). Heat pumps supplied 30.95 GWh of heat in 2015 with a Coefficient Of Performance (COP) equal to 2.48 (calculated from the available data from [53], considering the average over multiple years), thus leading to an electricity consumption of 12.48 GWh. In the current study, the electricity cooling demand and the solar thermal production are not included, due to the lack of reliable data and their marginal importance considering the characteristics of the Region.

Hourly distributions for individual heating were derived from the HotMaps project that provides heating profiles for different NUTS2 regions (Valle d'Aosta: ITC2) in a

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public online repository [54]. In the absence of hourly data for this particular region, the electricity hourly distribution for Northern Italy area has been used and derived from Terna, the grid operator for electricity transmission in Italy, with reference to 2015 [55]. This assumption represents an approximation of the model, but it is justified by the fact that although Valle d'Aosta is a small mountain region, the distribution of final electricity demand in the different sectors is comparable to other regions in Northern Italy. Considering 2015, electricity demand in industry reaches 42% of final electricity demand, which is slightly lower than other regions in Northern Italy (with ratios between 37% and 50%, as calculated from data available for each region [51]). Although the role of tourism leads to a higher impact of consumption in buildings, given the absence of more detailed data this approximation appears reasonable.

Electricity transmission and distribution losses account for 208.4 GWh/year, leading to an overall electricity demand of 1,084.6 GWh/year. These losses are relatively high for a final consumption of 876.2 GWh (reaching thus 19.2% of the overall demand), due to the significant electricity excess that is transported in the region and exported. In addition, since the natural gas losses are not explicitly mentioned in the regional energy balance [53], they are calculated as difference between the total import of natural gas and its final energy consumption, reaching a value of 4.56%.

Table 3 shows a deeper focus on the energy consumption in the transport sector divided by fuel, since it is one of the specific aspects considered in this work. The largest share is related to road transport, while rail transport entails a marginal share of diesel (around 13 GWh), and air transport only a limited consumption of jet fuel. The Liquefied Petroleum Gas (LPG) consumption is related to private cars, while natural gas is mainly devoted to the operation of passenger buses in some municipalities. There is currently no electricity consumption in the transport sector due to the fact that there are no electric railways in Valle d'Aosta. Since no official plans to electrify the rail sector are currently available, and its effect would still remain limited, this work considers diesel trains also for the future scenarios.

In the absence of specific data on the percentage of biofuels used in the region, the national average of biofuels blending in oil products equal to 3.5% has been assumed (authors' calculation from [56]). Due to the very strong predominance of biodiesel with respect to bioethanol in Italy (the first reaching 98% of biofuels consumption), the share of biofuels has been totally allocated to diesel consumption.

Table 3: Final Energy Consumption in Valle d'Aosta (GWh) (2015, [53])

Fuel	Consumption (GWh)
Diesel	820.0*
Petrol	304.0
LPG	20.0
Jet Fuel	7.2
Natural gas	0.1

* Including biodiesel blending.

Centralized heat and power generation has been modelled in EnergyPLAN with reference to regional energy balances technical report for 2015 [53], compared with other

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sources [51, 57]. The thermo-electric power plants include both Combined Heat and Power (CHP) not associated with District Heating (DH) and CHP supplying DH networks. The former account for an installed electric capacity of 3.2 MW and an electricity production of 6.4 GWh as reported by [51]. The latter account for an installed electric capacity of 9.2 MW and an electricity production of 8.6 GWh [57], thus leading to a total 12.4 MW gross installed capacity and 15.0 GWh electricity generated by thermal plants. Concerning DH networks, technical features of the generation units are fully described in the annual report provided by the National Association of Urban Heating (AIRU) [57]. Table 4 shows the technical parameters and energy consumption of the above-mentioned units of the DH networks that are in operation in Valle d'Aosta region.

Table 4: Operating parameters and energy consumption: CHP and boilers for DH networks - values for 2015

Parameter	Units	CHP	Aux boilers	DH boilers	Total
Electric capacity	[MW]	9.2	-	-	9.2
Thermal capacity	[MW]	10.6	66.5	26.6	103.7
Electric efficiency	[-]	24.1%	-	-	
Thermal efficiency	[-]	56.9%	91.0%	77.5%	
Fossil fuel consumption	[GWh]	6.6	27.7	-	34.3
Biofuel consumption	[GWh]	29.1	-	50.2	79.3
Electricity generated	[GWh]	8.6	-	-	8.6
Heat generated	[GWh]	20.3	25.2	39.0	84.5

In the absence of additional information, DH distribution has been taken from the Italian case study available in the EU-funded project Heat Roadmap Europe database [58].

Renewable energy capacities and overall annual production are listed in Table 5. The electricity production from hydroelectric power plants is around 3.5 TWh and it is roughly four times the demand (excluding losses).

Table 5: RES installed capacity and annual electricity production - values for 2015

Renewable source	Capacity [MW]	Annual production [GWh]
Hydro	950.7	3,465.0
Photovoltaic	21.8	24.1
Onshore wind	2.6	3.8

3.2. Scenarios

Future scenarios for Valle d'Aosta energy system are simulated considering different degrees of penetration of low-carbon technologies. The authors performed some preliminary technical analyses with EnergyPLAN (without the optimization tool) to compare a

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limited number of alternatives before expanding the analysis by exploiting the capabilities of an optimisation analysis. Considering a progressive electrification for the private transport sector, Fuel Cell Vehicles (FCV) within the freight transportation and an increasing degree of penetration of HP as major drivers, a total number of 16 scenarios are identified (from the combination of four alternatives for HP and four for EV). As for the technical analyses, they can be assumed to represent intermediate steps towards the decarbonization of the Region (therefore corresponding to intermediate future years from current situation to 2050) or to represent alternative scenarios at a given year (2050).

3.2.1. Technology assumptions

In all the simulated scenarios, the authors assumed a 10% reduction of heat demand in the building sector, due to the expected standards in terms of energy efficiency for new buildings, renovations and appliances efficiency (authors calculation from [59] data for Italy and taking into account territorial characteristics).

In the transport sector, a progressive electrification for passengers cars (LDV) has been considered as well as a certain degree of replacement of Diesel trucks with FCV as concerns heavy-duty vehicles (HDV). Four scenarios have thus been identified, assuming 0%-20%-50%-80% of electric vehicles for private mobility (BEV and PHEV make up respectively 85 and 15% of EV fleet) and 0%-10%-20%-30% for H_2 HDV respectively (Table 7). The environmental and economic impact of EV and FCV replacing conventional alternatives is thus evaluated in the form of a parametric analysis where both technologies are gradually increased. In this regard, FCV maximum share is conservatively set at a much lower than EV to reflect the current significantly smaller market for FCV [60] with H_2 vehicles featuring, in 2050 projections, a share between 20–30% in the light-commercial and heavy vehicles fleet [61].

In the building, industry and agriculture sectors a progressive electrification to cover the heating demand and a gradual phase out of oil, taking into account the specific features of Valle d'Aosta, in terms of morphology, economic sectors, etc., has been also assumed. The HP installed capacity is set to cover a share of the heating demand in the building sector of 10%, 30%, 60% in HP-low, HP-mid and HP-high scenarios respectively (compared to 2% in the reference scenario of 2015). The COP value for future scenarios has been estimated considering a 25% increase with respect to 2015 and calculated according to the information reported in [53], resulting in an average overall value of 3.06.

Solar heating in the Region is negligible [53], and it assumed not to increase in the future scenarios due to the morphology and meteorologic conditions of the Region. The installed PV capacity is assumed to double in HP-high scenario with respect to the reference case, with a linear progression from current 21.75 MW [53] to 43.51 MW, according to what estimated in the regional Energy and Environmental Actions Plan [62].

Authors assumed a decrease of 10% of annual hydroelectric generation as a consequence of the future impacts of climate change on hydro-power productivity, in accordance with [63] results, which has performed a specific research on the future impacts of climate change on hydro-power productivity in Valle d'Aosta.

DH share in the HP-scenarios changes with respect to 2015 as a consequence of the current and future implementation of two gas-fired DH systems in Aosta and Cervinia which were not yet fully operational in 2015. Moreover, a gradual phase-out of diesel

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boilers in DH systems is considered, as well as a decrease of the total heat supply from DH in the scenarios with high HP penetration. Finally, as concerns the agricultural sector, authors assumed a gradual increase in the production of biogas and bio-methane from agro-industrial and farming residues (in parallel with HP development, ranging from 0 GWh in 2015, to 15.59 GWh in HP-low, 31.18 GWh in HP-mid and 46.76 GWh in HP-high). In the industry sector, a gradual decrease in the oil share is considered, by converting the main industries (located in areas reached by natural gas grid) towards natural gas and electricity.

Table 6: Share of energy demand in buildings, industry, agriculture and share of vehicles in transport sector for the future HP scenarios (2050)

Sector	Source	Scenarios			
		Ref	HP-Low	HP-Mid	HP-High
Buildings	HP Heat	2.0%	10.0%	30.0%	60.0%
	Oil	46.0%	15.0%	10.0%	0.0%
	Biomass	24.0%	24.0%	24.0%	24.0%
	DH Heat	3.9%	8.6%	7.8%	6.5%
	NG	23.7%	42.3%	28.2%	9.5%
Industry	Oil	25.0%	19.6%	14.2%	8.8%
	NG	72.6%	78.0%	83.4%	88.9%
	Biomass	2.4%	2.4%	2.4%	2.4%
Agriculture	Oil	99.4%	82.8%	66.3%	49.7%
	Biomass	0.6%	17.2%	33.7%	50.3%
Transport	Diesel LDV	55% - 5%	55% - 5%	55% - 5%	55% - 5%
	Petrol LDV	45% - 15%	45% - 15%	45% - 15%	45% - 15%
	Electr. LDV	0% - 80%	0% - 80%	0% - 80%	0% - 80%
	Diesel HDV	100% - 70%	100% - 70%	100% - 70%	100% - 70%
	H2 HDV	0% - 30%	0% - 30%	0% - 30%	0% - 30%

Table 7: Values for energy demand and shares of vehicles in the transport sector in the future transport scenarios (2050)

Vehicle type	Scenarios							
	0%EV		20%EV		50%EV		80%EV	
	share	[GWh]	share	[GWh]	share	[GWh]	share	[GWh]
Electric LDV	0%	0.0	20%	36.5	50%	91.1	80%	145.8
Diesel LDV	55%	317.1	15%	79.7	10%	53.1	5%	26.6
Petrol LDV	45%	304.0	65%	387.6	40%	238.8	15%	90.2
Diesel HDV	100%	462.9	90%	328.6	80%	292.1	70%	255.6
H_2 HDV	0%	0.0	10%	35.2	20%	70.4	30%	105.7

3.2.2. Economic assumptions

The economic analysis is performed to calculate the total annual cost of the energy system for each of the aforementioned 16 future scenarios in 2050. Data input for the

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analysis, that include future fuels prices, carbon tax, investment costs as well as the operation and maintenance costs for each technology, are taken from the "Italy Baseline Scenario for 2050" in [59] and from the HRE4 cost database, available on EnergyPLAN website [64]. As defined in 3.2, the heating sector is characterized by a 10% reduction in the regional heat demand; however the economic analysis is intended for a specific year, 2050, and the costs of the transition (financial measures to enhance the energy efficiency in buildings) are not considered. Concerning the transport sector, the authors assumed constant investment costs for conventional vehicles (passenger cars and diesel trucks). The cost of passenger cars is set to 21.64 k€, calculated as the average cost of the vehicles sold in Italy [65], and the cost of diesel heavy trucks is set to 68k€ [66]. The cost of electric cars is assumed to vary from the current one (43.86 k€ [65] in the 20%EV scenario) to cost parity with conventional cars in the scenario with the highest penetration of EV vehicles (80%EV scenario). The costs of EV charging stations is included in the form of a linear dependency between EV penetration and annualised costs related to the necessary infrastructure for EV charging, as follows:

$$C_{EV infrastructure} = (24.89 \times EV_{share} + 78.5)\, M€ \quad (4)$$

Costs trend is derived from Ref. [67] for the Italian case and scaled back according to Valle d'Aosta region vehicle fleet. Discount period for infrastructure investments is taken as 30 years.

The cost of fuel-cell trucks is assumed to vary from the current one (334 k€ [66] in the 0%EV scenario) achieving a 30% reduction of the price difference between conventional and fuel-cell trucks when they reach the maximum diffusion of 30% (254.20 k€ in the 80%EV scenario). An investment period of 10 years is assumed for passenger cars [65], while an investment period of 6 years is assumed for trucks [66]. In the evaluation of the total annual cost of the system, the revenue/expense from electricity import/export are not taken into account, since the objective of this analysis is to foster the highest exploitation of the excess electricity.

On the basis on this preliminary analysis, optimized scenarios have been defined to evaluate the best energy systems configurations aiming at minimizing both system costs and CO_2 emissions.

3.3. Optimized scenarios

The optimization of Valle d'Aosta energy system was performed considering the three different cases described in the following:

- Opt1: all the energy sectors remain unchanged with respect to the reference scenario (Ref), except for a 10% decrease in heat demand due to energy efficiency measures in buildings, a 10% reduction in hydroelectric generation to take into account climate change impact and transport (see Section 3.2), where EV and FCV are allowed to replace conventional alternatives respectively in the LDV and HDV fleet;
- Opt2: same as Opt1, including also the highest share of HP and oil phaseout in fulfilling heat demand according to HP-high measures related to the buildings sector only (Table 6);

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- Opt3: starting from Opt2, extends measures also on industry and agriculture sectors that basically consist in a shift from oil to natural gas consumption, the highest usage of biogas and an increased photovoltaic generation as described in Section 3.2.

The multi-objective optimization is then performed by means of the optimization tool described in Section 2.2 implementing the objective functions, decision variables and constraints described in Section 2.2.1.

In particular, the following parameters are set:

- $Mvkm_{LDV}$ equal to 1,163 km;
- $\left(\frac{kWh}{km}\right)_{petrol_{LDV}}$ equal to 0.5128, obtained from Unione Petrolifera future projections for petrol cars [68];
- $\left(\frac{kWh}{km}\right)_{diesel_{LDV}}$ equal to 0.4568, obtained from Unione Petrolifera future projections for diesel cars [68]:
- $\left(\frac{kWh}{km}\right)_{EV_{LDV}}$ equal to 0.1568, obtained by considering a 15% powertrain efficiency increase in future scenarios as compared to the current level;
- $n_{total_{LDV}}$ is equal to 141,000 units [69];
- $n_{total_{HDV}}$ is equal to 46,580 units [69];
- $n_{conventional}$ is equal to the sum of petrol and diesel LDV.

The costs for EV and conventional cars were set to 32.75 k€ and 21.64 k€ respectively obtained from a weighted average of the current fleet costs assuming an investment period of 10 years [65]. The cost for diesel trucks and H_2 trucks were respectively set to 68 k€and 115 k€, assuming an investment period of 6 years [66].

The maximum share of H_2 trucks replacing conventional diesel ones was set to 30%; the efficiency for diesel and H_2 truck was set respectively to 1.98 and 1.91 kWh/km [66].

As mentioned in Section 2.2.1 electricity storage is also included in the optimization process as a decision variable, whose maximum power and available capacity are defined starting from the highest level of electrification of end-uses and set to those values capable to eliminate completely electricity import (i.e. 300 MW and 17 GWh). Storage costs are projected to 2050 and derived from Ref. [70] for Li-ion batteries; they are set to 71 €/kW and 84 €/kWh for investment costs per unit of power and unit of energy respectively while operation and maintenance costs are set to 7.5 €/(kW year) and 3 €/MWh, with an investment period of 13 years.

4. Results and discussion

4.1. Preliminary scenarios

Simulations outcomes show that the electrification of the final uses can lead to a significant reduction of the CO_2 emissions in Valle d'Aosta Region, reaching up to a 65% decrease with respect to the reference case (2015) acting on both the transport and heating sectors.

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The simulation of the 16 scenarios performed by using EnergyPLAN allows to highlight the effect of separate measures in the transport and heating sectors, as well as the combined effect of both. Figure 2 illustrates a comparison of all scenarios that have been evaluated in this work.

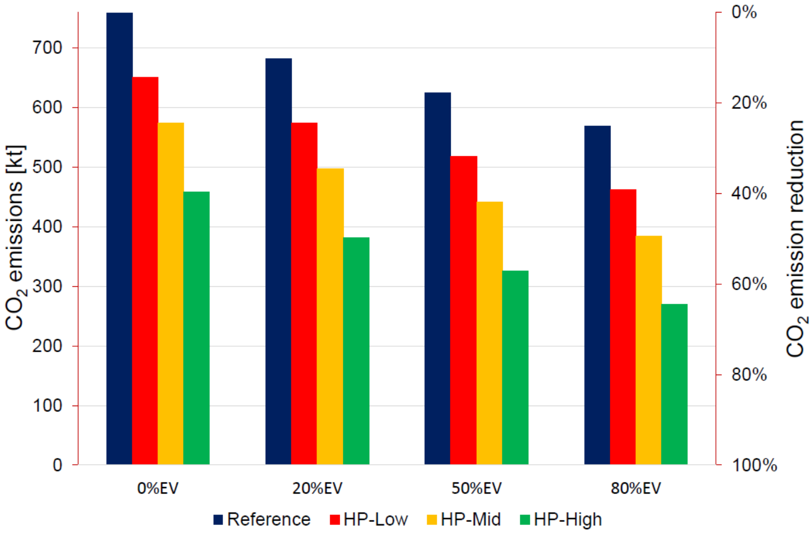

Figure 2: CO_2 emissions for different scenarios

The potential for decreasing CO_2 emissions is evident, from the current value of 759 kt (5.9 t/capita) to 269 kt (2.1 t/capita) in the best scenario, where both HP and EV reach their maximum technical potential. It has to be reminded that per-capita figures are affected by the high number of tourists visiting the region both in summer and winter, as well as the significant passenger and freight traffic that passes through the region to reach France and Switzerland.

Figure 2 also allows comparing the separate effect of buildings and transport electrification. The most interesting savings are expected from the electrification of buildings heating, which includes also some minor measures in the industry and agriculture sectors. A reduction up to 40% can be reached (459 kt - first green bar on the left), thanks to the removal of existing inefficient boilers that are often operated on oil products. On the other hand, the separate effect of the electrification of the transport sector only, can lead to 25% CO_2 savings (569 kt - last blue bar on the right).

Figure 3 shows a comparison of the energy consumption by source in the two extreme scenarios, i.e. the reference scenario (Ref) and the “80%EV/HP-High” scenario. The total primary energy consumption of the region decreases from 4.7 TWh in the reference to 3.5 TWh in the other scenario, but also a strong source shift is noticeable. A strong decrease of the share of oil products, down to 12.7%, is counterbalanced by an increase of renewable electricity (from 22.9% to 45.6%) and minor increases of biomass and natural gas (the latter decreasing in absolute terms). In the “80%EV/HP-High” scenario a small amount of electricity needs to be imported from neighbouring regions, although the electricity export remains far larger. Although limited to 2.0% of final energy consumption

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in the highest end-use electrification scenario, resorting to electricity import is due to the non-perfect matching of demand and supply profiles despite a large abundance of renewable energy still exists. This side effect could be possibly limited by installing energy storage systems or trough demand response strategies; in this specific regard section 4.2 also include electricity storage to maximize the usage of available renewable sources.

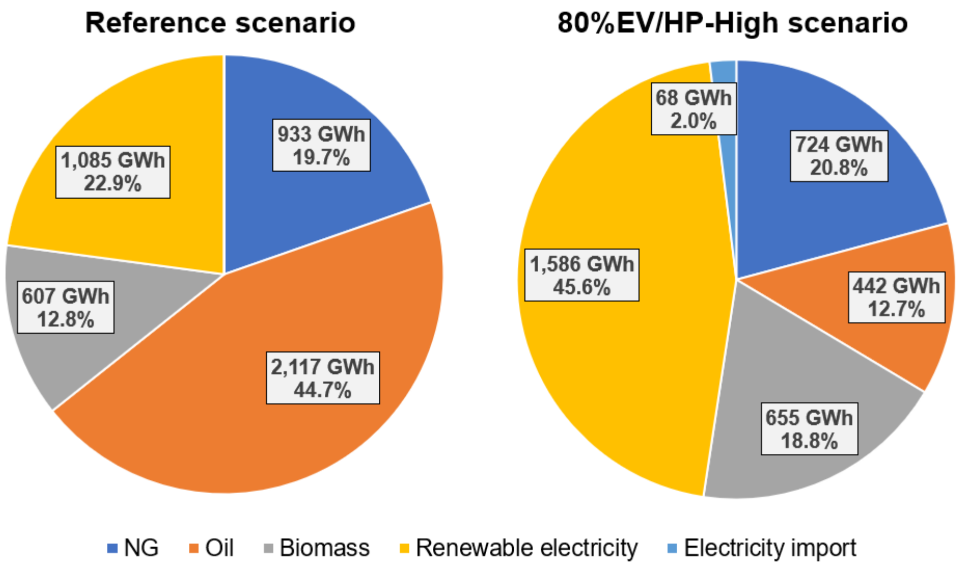

Figure 3: Comparison of final energy consumption between reference scenario (Ref) and 80%EV/HPHigh scenario

The second aspect that has been considered in these preliminary scenarios is the cost of the system. The cost analysis suggests that investing in HP is more convenient than investing in EV, considering the same level of CO_2 savings (see Figure 4).

Large penetrations of HP in buildings do not affect significantly the total annual cost of the energy system. In the HP-High scenario the total cost is less than the scenarios with lower share of heat pumps. This is because the higher investment cost of heat pumps is compensated thanks to the large reduction of variable costs related to expenses for fuels, since electricity is often cheaper than fossil fuels, especially when oil products need to be transported in mountain locations.

On the other hand, the large integration of electric vehicles and hydrogen trucks increases the total annual cost of the energy system. The rise of the total annual cost is reducing with the increase of the penetration of electric transport technologies, because of the assumptions mentioned in section 3.2.2 (the achievement of parity cost for electric vehicles, and the reduction of the cost for hydrogen trucks in the 80%EV scenario).

4.2. Optimized scenarios

Optimized scenarios, as defined in Section 3.3, consider the effect of (1) transport electrification, (2) transport and buildings electrification and (3) transport and buildings electrification together with additional measures in industry and agriculture. The Pareto fronts for the optimized solutions are reported in Figure 5.

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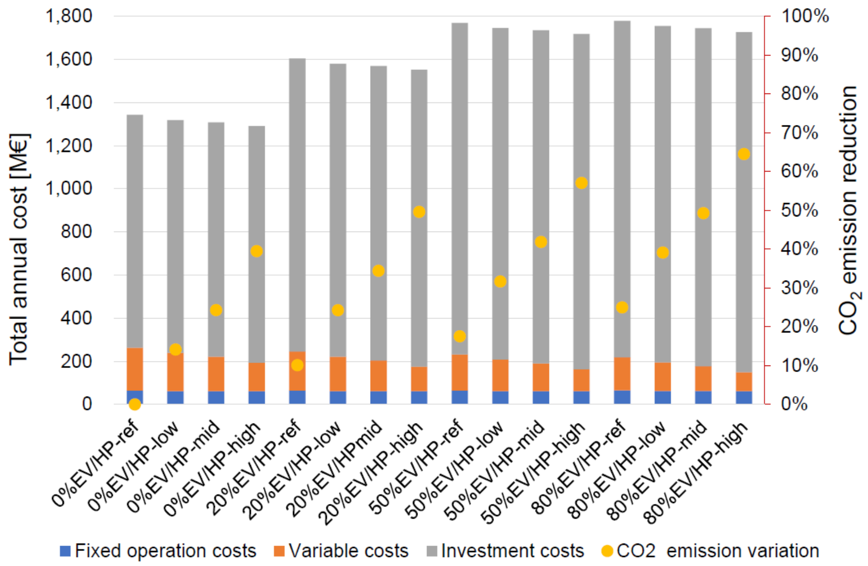

Figure 4: Total annual cost and CO_2 emissions reductions for different scenarios

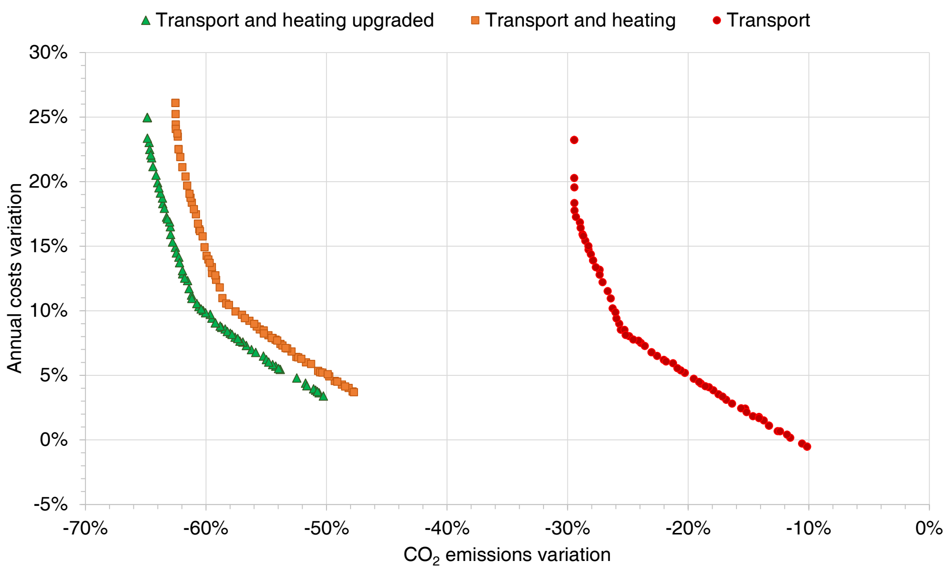

Figure 5: Pareto fronts for the three optimized cases

The effect already noticed in the previous scenarios are highlighted again, i.e. the larger advantages that can be obtained, mostly in terms of CO_2 emissions, from HP deployment in comparison with the electrification of transport. The additional benefits that can be achieved by implementing measures related to industry and agriculture remain limited. To summarize, a reduction of CO_2 emissions up to 30% can be obtained by

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acting on the transport sector; a 63% decrease can be obtained acting only on transportation and heating and a 65% reduction combining measures in industry and agriculture with an increased photovoltaic generation. As for "Opt2" and "Opt3" scenarios, the Pareto fronts start at higher annual costs as compared to "Opt1" since ESS need to be in place to face the arising electricity import due to the large use of HP, due to the hourly mismatch between heat demand and renewable power.

The shape of the fronts shows different linear segments with different slopes, which are related to the deployment of the technologies considered in the transport sector as well as the usage of ESS if electricity import is to be avoided, as can be inferred from Figure 6. In particular, Figure 6 displays the results for the scenario (Opt3) that includes all the measures involved, with a focus on the LDV and HDV fleet composition (Petrol, Diesel, Electric LDV and Diesel, H_2 HDV) and on ESS, whose power and capacity ratings are normalized with respect to their upper boundaries. The plot highlights how the optimization tool gives preference to the adoption of EV in passenger cars, while hydrogen trucks are introduced in the systems only when the penetration of EV is close to its maximum. Even at the lowest level of EV and H_2 trucks, electricity import would be in place to accommodate the highest share of HP that characterises all the scenarios on the Pareto front (see Section 3.3 for the assumptions). Despite proved to be a small amount even at the highest level of end-use electrification of Valle d'Aosta energy system, electricity import can be entirely replaced by ESS only deploying relatively high power and capacity to accommodate demand-supply discrepancies.

The deployment of ESS grows rapidly when CO_2 emissions decrease between 63% to 65%, this is necessary to accommodate an additional negligible share of EV (from 78% to 80% only) and a remaining 13% share of H_2 trucks within HDV without resorting to electricity import from neighbouring regions.

Thanks to the economic benefits that can be obtained from HP deployment in terms of variable costs reduction, as already noticed from the previous scenarios, and despite the necessary deployment of ESS, a 48–50% emissions decrease can be obtained without a significant increase in additional annual costs (4–5% only) in comparison with the current case. As EV share grows, so do annual costs, at a rate of approximately 0.7% increase in annual costs for every percentage point of CO_2 emissions reduction. However, to reach higher emissions savings (above approximately 60%) the deployment of hydrogen trucks originates a higher marginal cost: the same decrease with hydrogen trucks requires a 2.6% cost increase. ESS deployment peaks at the very left-hand side of the Pareto front to allow the highest level of electrification of the energy system. This increase is chosen by the optimisation algorithm to reach the maximum decrease in CO_2 emissions that, however, comes at the price of the steepest slope of the curve.

It has to be reminded that all the scenarios include some efficiency measures (especially a 10% decrease of heat demand in buildings), which have an important role in limiting the total costs in comparison with the current situation.

4.3. Focus on supply-chain emissions

The results presented in the previous analysis are limited to direct CO_2 emissions originated from fuel combustion for all fuels. To be in coherence with the common practice in energy and climate modeling, biomass combustion is considered as carbon neutral. However, an additional quantification of the indirect emissions can be performed,

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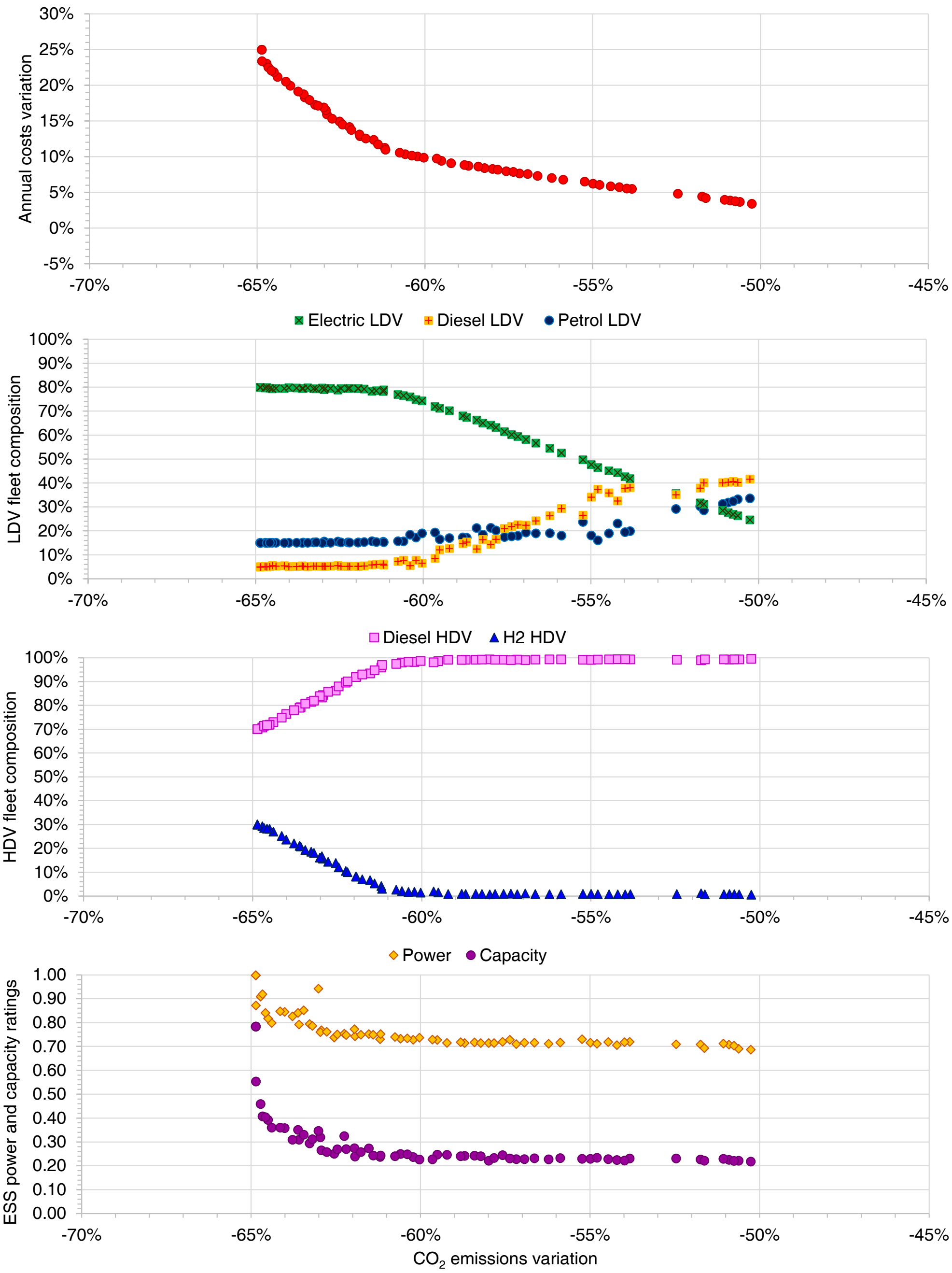

Figure 6: LDV and HDV fleet compositions, ESS ratings for the maximum HP penetration (Opt3)

including emissions from the up-stream processes (fuel extraction, transformation and transport).

Figure 7 reports the distribution of direct emissions per energy source, in comparison with total indirect emissions. The current predominance of oil products emerge clearly, together with the fact that indirect emissions in the reference scenario represent an additional 30% of direct emissions. The largest share of indirect emissions is caused by oil products (55%), followed by bio-energy (24%) and natural gas (21%). In the optimum scenario, with the highest penetration of both HP and EV, indirect emissions represent 45% of the direct emissions, and their distribution on the energy sources is rather different: 48% from bio-energy, 30% from natural gas and 22% from oil products. This variation is the result of a strong decrease of oil products, which leads to an increase of the share of bio-energy consumption in the region.

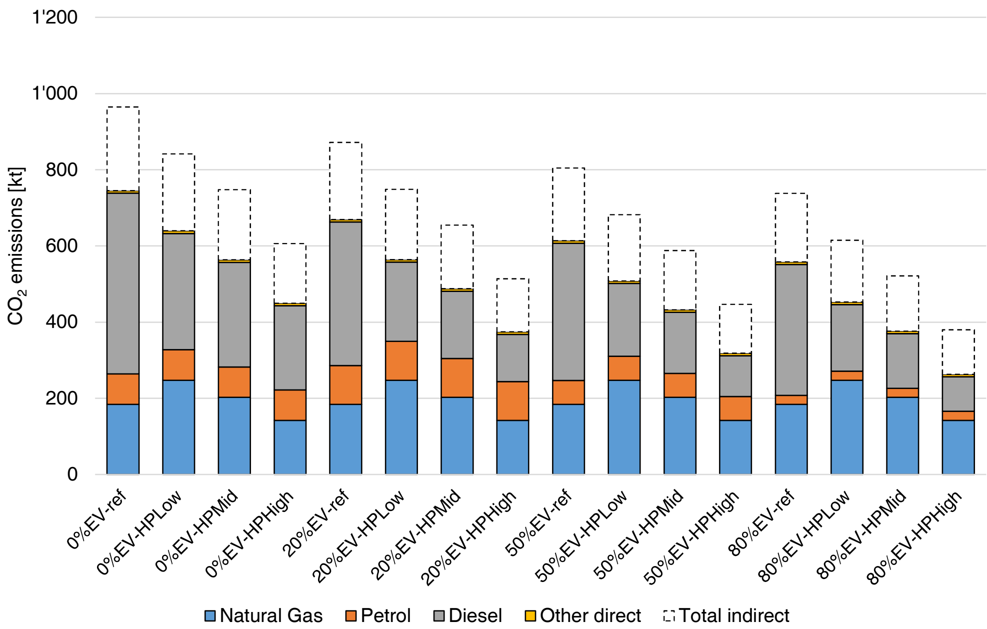

Figure 7: CO_2 emissions per energy source and total indirect emissions

Taking into account both direct and indirect emissions, the maximum savings reach 61% in the best scenario, in comparison with the 65% savings of direct emissions presented in the previous analyses. The reason lays in the fact that total emissions include impacts from wood biomass, which remains an important source of local renewable energy also in the best scenario. While the differences are relatively limited, it is important to consider other aspects related to indirect emissions. While the decrease of energy consumption generally leads to parallel emission savings, some further actions may be implemented, such as limiting the import of wood biomass by exploiting the local resources (thus decreasing the share of emissions related to fuel transport).

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5. Conclusions

This work presents a comparison of alternative scenarios to maximize the local use of renewable electricity production in an Italian alpine region, which is facing a large power generation excess from RES, currently exported to neighbouring regions. Therefore, changes in quality of energy demand is foreseen by means of electrifying transport and heating sectors, including some efficiency measures and combining measures in industry and agriculture, together with and increased photovoltaic generation. Electricity storage systems are included to maximize the use of available RES. The increase of electrification degree of the transport sector is integrated in the optimization tool through the development of a cost-curve for electric mobility. Then, a multi-objective optimization has been performed considering as targets the total costs and the CO_2 emissions. The analysis highlights the relation between the potential of CO_2 emissions reduction and total annual costs for different measures, including the deployment of heat pumps for building heating, electric vehicles in the private cars fleet and hydrogen trucks in the HDV fleet. The results show that the largest benefits are expected from the electrification of the heating sector, which can lead to CO_2 emissions reduction up to 40% while, the integration of transport electrification can bring an additional 20% and some measures in industry and agriculture account for 5%. Moreover, the deployment of HP allows for a 48–50% CO_2 emissions decrease without a significant increase in additional annual costs (4–5% only) in comparison with the current case, thanks to lower variable costs that partly compensate the higher investment that is required and the installation of ESS. In addition to the deployment of HP, by increasing EV share, annual costs increase at a rate of approximately 0.7% every percentage point of CO_2 emissions reduction. However, to reach higher emissions savings (above approximately 60%) the deployment of hydrogen trucks originates a higher marginal cost: the same marginal decrease with hydrogen trucks requires a 2.6% cost increase. Referring to Light and Heavy transport, the H2HDV option results as the most expensive one to replace diesel HDV requiring up to 10% higher cost variation for around 3% of CO_2 emissions reduction while, the amount of investments required from H2LDV in substituting the diesel and petrol LDV is not so expensive. Indeed, with a similar increase of 10% in annual costs, the CO_2 emissions reduction is of more than 20%. Therefore, this latter option is economically feasible with a light incentive scheme such as the new car buy bonus offered by many EU Countries to increase the efficiency of the National car fleet as well as to sustain the automotive industry.

These scenarios highlight the interesting opportunities occurring in some mountain regions, characterized by a surplus of available local RES electricity but, at the same time, by high oil products consumption for non-electrified sectors. HP and EV are already becoming viable alternatives to traditional solutions in heating and transport sectors, respectively. Although a dedicated policy support might still be required to foster their wider deployment. Moreover, the electrification of the transport sector is still hindered by limited ranges and a sparse charging infrastructure. The change in the quality demand by increasing the electricity demand compared to the fuel one must be coupled with the best choice in other supply such as the remaining fossil fuel quotes or the biomass to choose. For this reason, an upstream CO_2 emission analysis was implemented and the so-defined indirect emissions were counted for the identified sources. Consequently, it is noteworthy that the amount of indirect emissions can balance the reduction due to

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the highest implemented share of HP for heating sector within the same percentage of integrated electric vehicles.

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Acronyms

BEV Battery Electric Vehicles

CHP Combined Heat and Power

COP Coefficient Of Performance

DH District Heating

EV Electric Vehicles

ESS Electricity Storage Systems

FCV Fuel Cell Vehicles

HDV Heavy-Duty Vehicles

HP Heat Pump

LDV Light-Duty Vehicles

LPG Liquefied Petroleum Gas

MOEA Multi-Objective Evolutionary Algorithm

PHEV Plug-in Hybrid Electric Vehicles

RES Renewable Energy Sources

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