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Smart Energy Systems Applied at Urban Level: The Case of the Municipality of Bressanone-Brixen

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ABSTRACT

The present paper focuses on the energy system of the municipality of Bressanone-Brixen, located in the North of Italy. The aim of this paper is to investigate various possible energy scenarios for this case study in order to improve the overall efficiency of the system. The different scenarios include high penetration of photovoltaics at urban level, considering the maximum rooftop PV potential of the local area. Different solutions have been analyzed in order to study the handling of the consequent excess of electricity production. Electric storage and a solution combining heat pumps and thermal storage have been evaluated to maximize the local use of the generated electricity. A deterministic approach (without the use of an optimization algorithm) and a heuristic optimization approach have been applied to evaluate the different possible configurations. The present analysis can be of interest for other cities in a mountain environment where the production from renewables is limited by orographic constraints, energy consumption per capita is higher and stronger resiliency to climate change is needed.

Keywords:

Energy scenarios;
District heating;
Photovoltaics;
EnergyPLAN;
Optimization;
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1. Introduction

The European 20-20-20 targets, defined in 2006, together with a 20% reduction in greenhouse gases emissions and a 20% improvement in energy efficiency, set up the objective of 20% energy generation from renewables within 2020. European countries have chosen different strategies to achieve these goals. Italy has set up its targets per sector in the PAN document (Patto d'Azione Nazionale) and has implemented a national legislation based on subsidies for renewable energy sources (RES). Municipalities, on the other hand, have different instruments to implement renewable energy support strategies. The Covenant of Mayors is a European movement, involving regional and local authorities that want to increase energy efficiency and RES integration in order to achieve the 20% CO_2 reduction objective by 2020 [1].

The aim of this paper is to develop different future scenarios with high penetration of renewable energy for the municipality of Bressanone and develop a methodology that can be replicated in many other similar settlements present in mountain areas. The area is handled as a single node. Each quantity of electricity exchanged with the grid is considered import/export. Although this can be seen as a strong assumption, this type of analysis is of importance for two reasons. The first one is that, at the moment the grid is used to balance production surplus and deficits (hence avoiding the need for storage) while in the future there might be situations

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in which several neighboring regions simultaneously experience excess photovoltaics (PV), thereby saturating the balancing possibilities of the grid. The second one is that, in order to achieve the objectives of the Covenant of Mayors, the single municipalities have to implement local future scenarios studies and practical interventions.

The municipality of Bressanone-Brixen is a small town with about 20000 inhabitants and an alpine climate (elevation: about 560 m). It has joined the Covenant of Mayors in 2013 and already prepared a Sustainable Energy Action Plan (SEAP [2]), where information concerning its current energy system and possible future actions can be found. The considered area is particularly interesting due to the good availability of data – as a direct consequence of the SEAP preparation – and to the existence of a widespread district heating (DH) network. Moreover, it is located within the Alpine region, recently addressed by a specific EU strategy involving, among other aspects, climate change and energy challenges. In literature there are several studies analyzing energy scenarios at regional or urban level, showing the interest of investigating more sustainable energy systems with finer granularity than at national scale [3–5]. For example, Wänn *et al*. [6] have inspected the importance of energy scenario analysis at regional level in Ireland, highlighting the enhanced importance of data accuracy at this scale.

The reference scenario used in this paper is based on energy consumption and production data for the year 2010. The analysis of the reference baseline allows for the evaluation of different solutions to increase the overall system efficiency. Different RES high penetration scenarios are implemented with the objective to increase RES production and to reduce CO_2 emission, at the same time taking into account economic costs. Solar energy, for its intrinsic characteristics, is the renewable source that most suits city constraints (e.g. the small availability of space) [7, 8]. In particular, here a strong increase of PV is considered. As a consequence, the study of the role of storage systems, thermal and electric, becomes of high importance, in order to deal with the possible excess electricity production caused by the mismatch between solar availability and energy demand [9–11].

When considering excess electricity production, the most direct solution to avoid RES curtailment is of course to take into account electric storage [12]. Related technologies, especially batteries, are the subject of continuous research, also due to their high potential for the transportation sector [13]. However, in spite of these efforts, associated costs are still very high. It is therefore important to look for alternative solutions, possibly involving hybrid electric-thermal solutions. Thanks to the much lower costs of thermal storages, this can indeed be convenient, provided efficient conversion technologies are used. This is a direction already mentioned in several papers, but still far from being explored in detail. Hedegaard et al. [14] provide an example of this approach to enhance the integration of wind energy, where a coupling with large heat pumps and different thermal storage options is analyzed. Other combinations of hybrid solutions are given by Mohammadi et al. [15], investigating the optimum size of electric and thermal energy storages for a micro-grid, Østergaard et al. [16], investigating solutions that couple the electric and the thermal sector for the Municipality of Aalborg (wind energy, low-temperature geothermal resources, biomass, district heating, and energy saving), and Kiviluoma [17], proposing a model that combines heat and power production and simulates electric vehicles.

In this paper, beyond the exchange of electricity with the grid, both electric and thermal storages are considered, contributing to highlight the significant potential of solutions coupling the electric and the thermal sector. Of course, the amount of electricity which can be conveniently transformed into heat depends on the thermal energy demand, which is hence analyzed in detail. As far as the electric-thermal interaction is concerned, this article combines PV with large heat pumps and a seasonal thermal storage, in connection with a district heating network. This is different from previous studies, where seasonal storages were considered only in connection with solar thermal energy [18].

In terms of methodology, the paper proposes a comprehensive approach, combining different models and optimization algorithms. The starting point is the EnergyPLAN software, used to evaluate the reference scenario of Bressanone-Brixen. This allowed to check energy balances and validate the consistency of SEAP data. Then, an ad-hoc developed model was used, to evaluate the coupling between electric and thermal sector with a slightly higher level of detail than feasible in EnergyPLAN (a few additional parameters for the description of thermal storage systems are included, see below). Finally, an optimization algorithm has been applied to the model (see [19] for a similar approach with EnergyPLAN), thereby identifying the best combinations of installed capacities (including the possibility to sell/buy electricity to/from the grid) in order to minimize CO_2 emissions and costs. These are conflicting objectives, so that the framework of multi-objective optimization has to be used, where solutions are given by the set of optimal (i.e., non-dominated) configurations lying on the so-called Pareto front [20].

In this way, this paper aims at identifying combinations of technologies which bring the considered system closer to a smart energy system, exploiting the synergies between electric and thermal sector in order to maximize efficiency and reduce costs.

The article is structured as follows: Section 2 presents the adopted methodology, describing the reference scenario, the PV potential in the studied area, the technologies taken into consideration, the developed models and the parametric and optimization approaches. Section 3 deals with the results of the work and the Pareto front of the best solutions on the two chosen objectives: total annual costs and CO_2 emissions. In Section 4 conclusions are drawn.

2. Methodology

The reference scenario of the municipality of Bressanone-Brixen has been built using a bottom-up approach [21]. A large number of models for simulating and analysing the integration of renewable energy into various energy systems have been analysed in detail by Connolly *et al* [22]. The EnergyPLAN software has been chosen for this study considering its intrinsic characteristics [23] and the considered problem. EnergyPLAN is a deterministic input/output model that permits to integrate the three main sectors of any national energy system, i.e. electricity, heat and transport [24, 25]. For this reason it is particularly suited to study high penetration of renewables with possible exchange of energy between sectors. The program is a descriptive and analytically programmed computer model for hour-by-hour simulation of a regional or national energy system. As a result, it is appropriate for the paper's purpose because the hourly time step allows for a better evaluation of the non-programmable renewable energies production and the operation of electric and thermal storage. The main inputs of the EnergyPLAN model are the installed capacity of each source and the hourly distribution of energy demand and of renewable energy availability during the whole year. The main outputs are total costs, CO_2 emissions and hourly production for each source. Studies on future sustainable energy systems including 100 percent renewable systems using EnergyPLAN are constantly being published within academic journals [26, 27]. Studies using EnergyPLAN applied at local or urban level are also available [28]. H. Lund *et al*. [29] have analyzed two different models: EnergyPLAN and another one, H_2RES, specifically designed for island energy system. They have evaluated the results of the two models on the same case, the island of Mljet, Croatia, concluding that both models come to more or less the same results. P. A. Østergaard *et al*. have analyzed the case study of the municipality of Aalborg concluding that it is possible to cover all the energy needs through the use of locally available sources and thus through low-temperature geothermal heat, wind power and biomass [30].

The reference scenario shows different opportunities to increase the efficiency of the energy system: (i) increasing PV capacity in order to reduce the import from the grid, (ii) increasing PV capacity and electric storage in order to reduce both the import from and the export to the grid, or even (iii) replacing gas boilers within the district heating network with seasonal thermal storage and large heat pumps that exploit the excess electricity production by PV systems [31–37]. The cases (ii) and (iii) are peak shaving techniques, as they allow for the storage of energy and the later use during peak hours of the load.

Considering the PV potential on the reference area, different capacities of PV, large heat pumps and electric and thermal storage have been inspected with the aim of finding the best technology mix to reduce CO_2 emissions and total costs of the system.

In order to describe in more detail the behavior of a small case study like this one, a model has been designed to depict the connections between photovoltaics excess electricity production, large heat pumps (HPs) and thermal storage (STO). As explained below, the model closely follows the EnergyPLAN approach, but, while focusing on a restricted number of technologies, adds a few variables that provide more flexibility for the storage analysis. Following the EnergyPLAN approach means using the same assumptions on two main topics: costs analysis and internal priorities. EnergyPLAN cost analysis is characterized by the conversion of all the investment costs into annual cost thanks to a specific formula. The same formula is used in the developed model. In order to satisfy any energy demand a mechanism of priority is used by EnergyPLAN. This order is given as following: renewable energy sources are the first to satisfy the demand followed by traditional sources ordered by efficiency. The same internal logic is used in the developed model.

A combination of different software tools has been chosen in order to better analyze an urban case like this one. The order in their operation is the following:

1. The EnergyPLAN software has been used to describe the reference situation. It produces as outputs the values of CO_2 emissions and total annual costs of the system, the distribution of residual heat demand in the District Heating network (i.e., the part of DH demand not satisfied by cogeneration and hence covered by back-up boilers) and the distribution of the residual electricity demand (i.e., the part of electricity demand not satisfied by cogeneration and by the existing renewable generation, hence the part currently covered by the grid). In practice, the term residual here refers to the part of demand that is not satisfied through cogeneration and the existing renewable generation, both on the thermal and the electric side. It is only this residual part which is included in the optimization process described below, where a larger share of renewable energy sources is considered in order to reduce overall emissions.
2. Another model, called PV-STOth, is then used to describe the interactions between photovoltaics, large heat pumps and thermal storage and to consider new parameters not existing in EnergyPLAN, such as storage transmission capacity, storage initialization and storage efficiency. The PV-STOth model takes as inputs from EnergyPLAN the residual distributions mentioned above, as well as the partial values of CO_2 emissions and total annual costs calculated for the rest of the energy system. Other inputs (not taken from EnergyPLAN) are the values of the capacity of PV, large HPs and thermal storage. With these ingredients, the developed model permits to calculate the interactions hour by hour between PV, large HPs and thermal storage and also the total CO_2 emission and annual costs. The PV-STOth model is composed by different steps executed in the following order: i) thermal demand analysis, ii) excess electricity analysis, iii) electricity demand analysis, iv) CO_2 emissions analysis and costs analysis. This latter phase calculates the emissions and costs of the overall system considering the contributions of the reference system found through EnergyPLAN and the new contributions of the solution composed by PV, HPs and thermal storage found through the PV-STOth model.
3. The connection of PV-STOth with an optimization tool permits to find the best configurations under CO_2 emissions and total annual costs minimization, Figure 1. Actually, before applying a numeric optimizer, a deterministic approach has been used to analyze the different possibilities to use the excess electricity production from PV: exchange to the grid, electric storage or shift to the thermal side with large heat pumps and thermal storage. The optimization approach focuses only on the optimization of this latter scenario, composed by high PV penetration, large heat pumps and seasonal thermal storage. The optimization tool recalls iteratively the PV-STOth model recalculating for each new configuration the values of the total annual costs and CO_2 emissions of the system. The output of this model is hence the best technology mix in terms of capacities of PV, HPs and thermal storage for the analyzed case study.

2.1. Reference scenario

The reference scenario is based on energy consumption and production data for the year 2010. All information has been taken from the Sustainable Energy Action Plan of the city of Bressanone-Brixen [2]. Currently about 65% of Bressanone's electricity demand which is about 110 GWh is supplied by the national grid. The local production of electricity is covered, mainly, through methane and biomass cogeneration with a small share of electricity produced by RES. The heat sector is divided in two parts: the district heating (DH) network and the individual consumption. The district heating network is

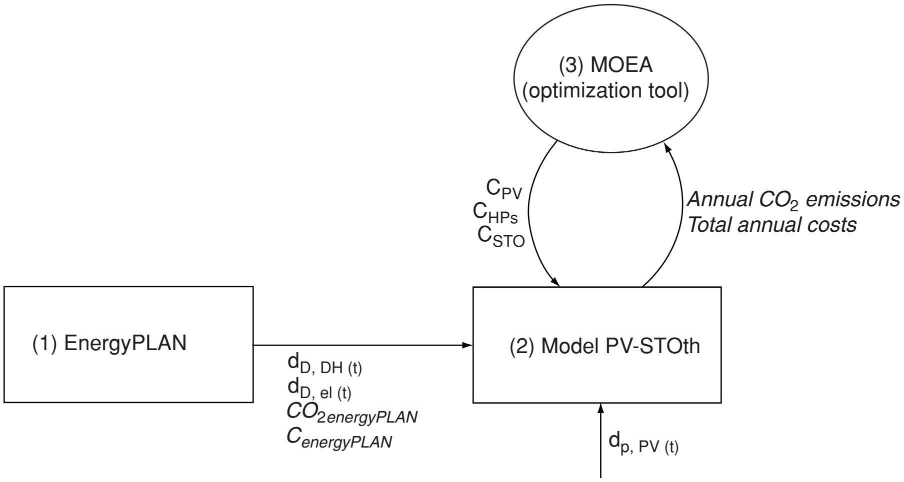

Figure 1: Interaction, inputs and outputs of the used models. $d_{D,DH}(t)$ and $d_{D,el}(t)$ are the distribution of residual heat demand in the District Heating (DH) network and the distribution of the residual electricity demand (see text on how residual is intended). $CO_{2EnergyPLAN}$ and $C_{EnergyPLAN}$ are the CO_2 emissions and total annual costs of the part of system that remains constant (i.e., it is not included within the optimization). The quantity $d_{P,PV}(t)$ is the distribution of PV production during the year and is an input of the PV-STOth model. C_{PV}, C_{HPs} and C_{STO} are the installed capacity of PV, heat pumps and thermal storage that are optimized through the Multi Objective Evolutionary Algorithm.

supplied by methane and biomass cogeneration for the 64.5% of the total demand, the rest is provided by methane back-up boilers. Individual consumers (i.e., consumers not connected to DH) rely on oil, methane (industrial users only) and biomass boilers, with a little share of solar thermal and a small production from heat pumps. The district heating network has a thermal storage of 30 MWh. The combined heat and power (CHP) plants used to supply the network are operated with a production profile as constant as possible, where some units are switched off during summer and thermal storage or back-up boilers are used to cover the peaks. This is because, thanks to the experience acquired by the company running these plants in these years, their operation is planned on half day basis and the result is a constant profile of production on monthly basis for economic purposes.

Within the industry sector the two main used fuels are oil and natural gas. The transport sector presents a predominance of diesel with smaller shares of petrol, LPG and natural gas. The reference scenario was built and validated using the EnergyPLAN model [23]. The final results of the reference scenario are shown in Table 1. The validation has been done on the annual CO_2 emissions value. Indeed the value of the CO_2 emissions calculated in the SEAP document (112.47 kt) differs by less than 0.5% from the value found with the EnergyPLAN software.

Table 1: Main input and output of the simulation made through EnergyPLAN of the Bressanone's reference scenario [2].

	Variables	Values	Units
Main inputs	Electricity demand	110.13	GWh/year
	Heat demand	217.60	GWh/year
	Transport demand	172.70	GWh/year
Main outputs	RES electricity prod.	11.06	GWh/year
	RES share of elec. prod.	10	%
	CO_2-emission	113	kt
	TOTAL ANNUAL COSTS	60000	k€

2.2. PV potential

The estimation of the PV potential in South Tyrol, which includes the municipality of Bressanone has been already analysed in detail. Moser *et al.* [38, 39] found out a rooftop maximum PV potential of 155 MW for the municipality of Bressanone-Brixen. Considering only rooftops areas with an annual insolation higher than 1200 kWh/m^2, the value reduces by 61% resulting to 60 MW. Filtering out the historical town center accounts for a further reduction of 12% with a final real PV potential of 53 MW.

Another study has been carried out by EURAC research within the Solar Tyrol project [40]. This work analysed the rooftop PV potential of the area through satellite data with a resolution better than 1 m. The final results have shown a final rooftop PV potential of 55 MW. Hence, it is safe to assume a rooftop PV potential for the city of Bressanone-Brixen of approximately 50 MW. The reference scenario presents a total share of electricity produced by RES equal to 10% of the overall electricity demand (Table 1).

In order to analyze RES integration at the increasing of the PV capacity, two parameters have been considered: the generation factor γ and the integration function RE(γ). Here, γ is the average renewable power generation factor. At $\gamma = 1$ the installed capacity of RES is able to satisfy the electricity demand without taking into account contemporaneity of production and demand. On the other hand when both $\gamma = 1$ and $RE(\gamma) = 1$, a perfect integration and a 100% renewable energy system is achieved, thanks to contemporaneity of production and demand and/or an ideal storage with no losses [12, 41].

Figure 2 shows the increasing of the renewable integration function RE(γ) at the increasing of the γ factor and so at the increasing of the PV capacity. Each 10 MW of installed power of photovoltaic produces an increase of γ equal to 0.1 using a final annual Yield of 1100 kWh/kWp. Hence, each 10 MW of installed power of photovoltaics produce 11 GWh of annual electricity production, exactly 10% of the total annual electricity demand. The curve rises linearly until $\gamma < 0.29$ because there is no overproduction in this phase. With increasing γ, overproduction (i.e. export to the grid) occurs more and more frequently (no storage devices are assumed to be present). From the hourly exports one can estimate the required storage capacity and hence the total costs connected to the implementation of a storage system.

Figure 3 shows the evolution of the total annual costs and CO_2 emissions of the system at the increasing of the PV capacity. Each point presents an increase of 1 MW of PV capacity. Starting from the reference scenario the increasing of PV capacity produces a very steep decrease of the CO_2 emissions and a slight decrease of the total annual costs. With higher values of PV capacity overproduction occurs more and more and the installation costs are no more contrasted by the savings in reduced imported electricity. For this reason, the overall costs start rising and the environmental benefits of increasing the installed capacity by 1 MW decrease.

2.3. New technologies

In order to study possible uses of the excess electricity production, three technologies have been taken into consideration: large heat pumps, seasonal thermal storage and batteries [42].

Heat pumps are a relatively mature technology. Their scope is to move heat from a low-temperature source to a warmer one. Large heat pumps usually take heat from the ambient (input heat) and convert it to a higher temperature (output heat) through a closed process. Compression heat pumps can operate in different temperature ranges depending on the fluid used in the internal thermodynamic cycle. At the moment, one of the most interesting technologies for large heat pumps is represented by CO_2 heat pumps. These heat pumps operate in a trans-critical cycle. Heat pumps exploiting CO_2 (refrigerant R-744) or similar refrigerants (e.g., Tetrafluoroethane, R-number R134a, a refrigerant with negligible ozone-depletion potential) can be used to

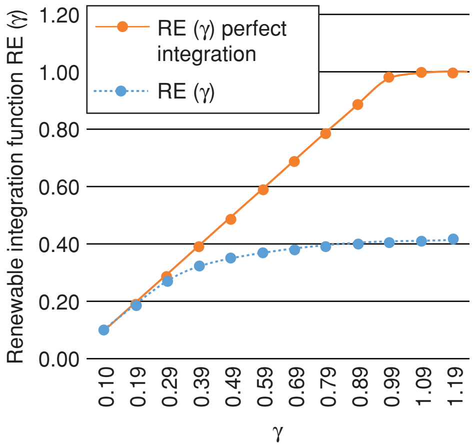

Figure 2: Renewable integration function RE(Y) for the case study of Bressanone-Brixen compared to the perfect integration case.

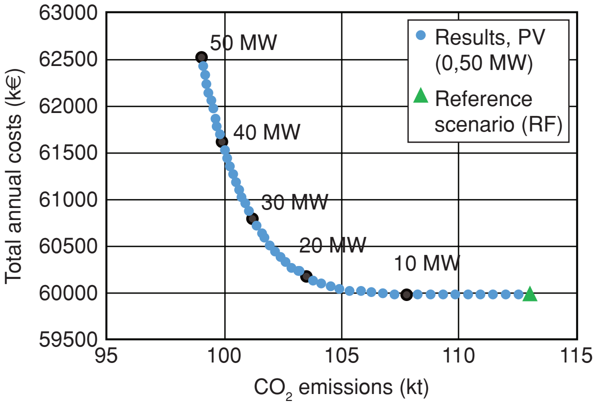

Figure 3: Total annual costs and CO_2 emissions of the whole energy system of Bressanone-Brixen increasing the PV capacity from 0 to 50 MW with a 1 MW step.

cover relatively high-temperature ranges. For example, existing models of CO_2 heat pumps can exploit a source at about 20 °C to deliver heat to a sink at about 80 °C with a nominal coefficient of performance (COP) of about 4 [43]. Of course, depending on the refrigerant type, the machine size, and the operating temperatures, COP values can vary. In general, it can be considered a reasonable estimate to assume an average COP of 3 for the large heat pumps considered here [44, 45].

One of the best seasonal thermal storage fluids is water for its intrinsic characteristics. It is cheap, non-toxic and has a high heat capacity. The cost of a water thermal storage depends on the container of the water. There are two main possibilities: a thermally insulated steel tank and a water pit storage. An insulated steel tank has lower thermal losses and is mostly used for small sizes (up to 5000 m^3). A pit heat storage is instead substantially cheaper per cubic meter of water (approximately 25% of a steel tank) and for this reason is used for larger sizes. The task 45 of the international energy agency (IEA) on seasonal pit heat storages [46] presents different case studies for thermal storage solutions with an estimation of the annual losses of the storage systems. In the considered systems, annual losses are found to be of the order of 30 % of the overall storage capacity. In order to convert these annual losses into hourly losses (as necessary for our model), 5000 hours of operation have been assumed per year. This is of course a very simplified model that roughly corresponds to the yearly losses identified in Task 45.

Lithium-ion batteries have reached high penetration levels into the portable consumer electronics markets and are rapidly diffusing into hybrid and electric vehicle applications. They have also high potential regarding grid storage modulation. The biggest barrier to their diffusion in this sector is the high cost while the high efficiency (η = 0.8) and the absence of particular territory constraints are definitely advantages [43–49].

Table 2 shows a summary of the costs of the three considered technologies and their values used into the analysis [43–49].

2.4. The model PV-STOth

A model has been developed in order to describe the interactions between PV, large heat pumps and seasonal thermal storage. It is directly inspired by EnergyPLAN, implementing priorities with equations of the same type, but it is restricted to the technologies directly related to the present case study. On the other hand, with respect to EnergyPLAN the model adds a few variables that allow to manage the storage with a higher flexibility. In particular, the model gives the possibility to set few parameters that EnergyPLAN does not consider and that permit to handle the thermal storage system with higher flexibility: (i) an initial content of the thermal storage system, (ii) a parameter for thermal storage losses, and (iii) the charging and discharging power of the thermal storage system.

2.4.1. Assumptions and CHP modelling

The inputs of the PV-STPth model, the terminology, units and descriptions for each input are shown in Table 3. The main inputs are hourly electricity demand, hourly heat demand of the district heating and hourly PV production followed by the absolute variables like capacities and overall annual production, the costs and economic variables and the CO_2 emissions factors. The main outputs are the hourly shares of power supplied by large heat pumps (generically called heat pumps below), boilers, thermal storage and the contribution of the grid. The used time step for the simulation is the hour. As a consequence, at each hour, the content of the storage is updated in relationship to the excess of electricity production.

The model is based on three main blocks, managing in sequence thermal demand, excess electricity and electricity demand. Each block is accurately described in a dedicated subsection (see below), but a general summary of the underlying prioritization strategy is provide here. The first block carries out the analysis of the DH thermal demand. The latter is covered, in order of priority, by thermal storage, heat pumps and boilers. This determines a "lower bound" (minimum value) for

Table 2: Summary of the parameters' costs of the new considered technologies. For the heat pumps, the investment cost unit is €/kW–el [43–49].

	Units	Heat Pumps	Thermal Storage	Batteries
type		CO_2	Pit heat storage	Lithium-ion
C_{inv}	€/kW_{HP} or €/kWh_{STO}	3430	0.76	500
lifetime	years	25	20	10
O&M	%	2	0.7	0

Table 3: Main inputs and outputs of the developed model, terminology and values [43–49].

	Variables				
	Types	***Abbreviation***	***Description***	***Units***	***Values***
input	distributions	$d_{D,DH}(t)$	heat demand of the DH network	kW per hour	—
		$d_{D,el}(t)$	electricity demand	kW per hour	—
		$d_{p,PV}(t)$	PV electricity production	kW per hour	—
	absolute variables	$E_{D,DH}$	Total heat demand within the DH	kWh	30247193
		$E_{D,el}$	Total electricity demand	kWh	70091797
		C_{PV}	PV capacity	kW	variable
		C_{HPs}	HPs capacity	kW	variable
		COP	COP of the HPs	—	3
		C_{boil}	Boilers capacity	kW	10000
		C_{STO}	Thermal storage capacity	kWh	variable
		$I_{STO,DH}$	Initial content storage	kWh	variable
		$P_{STO,DH}$	Loading power of the storage	kW	$C_{HPs,\ th}$
		$L_{STO,DH}$	Thermal storage annual losses	%	30
	Costs and economic variables	c_{grid}	cost of buying electricity from the grid	€/kWh	0.16
		$c_{grid,exported}$	value of exported electricity	€/kWh	0.06
		c_{gas}	cost of buying natural gas	€/kWh	0.103
		$c_{inv,PV}$	Investment cost per unit	€/kW	2000
		L_{PV}	Lifetime	years	20
		$O\&M_{PV}$	Operation and manteinance costs (%of the Inv. cost)	%	2
		$c_{inv,HPs}$	Investment cost per unit	€/kW	3430
		L_{HPs}	Lifetime	years	25
		$O\&M_{HPs}$	Operation and manteinance costs (%of the Inv. cost)	%	2
		$c_{inv,STO}$	Investment cost per unit	€/kWh	0.76
		L_{STO}	Lifetime	years	20
		$O\&M_{STO}$	Operation and manteinance costs (%of the Inv. cost)	%	0.7
		i	interest rate	%	3
	CO_2 emissions	e_{grid}	specific emissions of the electricity imported from the grid	t_{CO2}/kWh	0.483
		e_{gas}	specific emissions related to the combustion of a unit of natural gas	t_{CO2}/kWh	0.202
output	technical variables	$d_{P,HPs}(t)$	distribution of heat production of HPs	kW per hour	
		$d_{P,Boil}(t)$	distribution of heat production of boilers	kW per hour	
		$d_{P,grid}(t)$	distribution electricity imported from the grid	kW per hour	
		$d_{P,STO}(t)$	distribution of heat contribution from the thermal storage	kW per hour	
		$d_{STO,history}(t)$	distribution of heat content of the thermal storage	kW per hour	
	Economic and environmental output	TOTAL_ANNUAL _EMISSIONS	Total annual CO_2 emissions	kt	
		TOTAL_ANNUAL _COSTS	Total annual costs	k€	

heat pump electricity consumptions. Once this is known, the second block can perform the excess electricity analysis, by comparing PV production to the sum of residential electricity demand and heat pump electricity consumptions. Whenever PV production exceeds this quantity, provided the thermal storage is not full, heat pumps are further exploited to load the latter. The last block can finally complete the electricity demand analysis, where the overall electricity demand (including the additional heat pump consumptions) is covered, in order of priority, by PV and electric grid.

As far as the CHP units are concerned, some clarifications are useful. From the general point of view of the energy balance, they have been included through the EnergyPLAN reference scenario. Here they are assumed to operate with a fixed constant profile during each single month. This assumption is justified by the small variance of the real observed data, which is of the order of 10% in a typical winter month. Indeed, these units operate at constant load to optimize their performance and duration, a specific choice of the case of Bressanone. For this reason, even if having a flexible operation of these units could improve the overall energy balance of the system, they are not included in the PV-STOth and in the optimization tool of this paper. In a future study it would be interesting to analyze the energy balance of the system if the CHP cogeneration plants could operate in a more flexible way.

2.4.2. Thermal demand analysis

Starting with the thermal demand analysis, Figure 4, the content of the thermal storage is initialize to the value of the initial content of the storage, Eq. (1):

$$\text{Content}_{\text{STO}_{\text{available}}}(0) = I_{STO,\,DH} \tag{1}$$

The thermal storage has priority in satisfying the need of heat power within the district heating network. The quantity of heat power, taken from the storage, used to cover the demand $(d^1_{P,STO}(t))$ is equal to the minimum between the heat power demand, the content available in the storage and the loading power of the storage, Eq (2):

$$d^1_{P,\,STO}(t) = \min(d_{D,DH}(t), \text{Content}_{\text{STO}_{\text{available}}}(t), P_{STO,DH}) \tag{2}$$

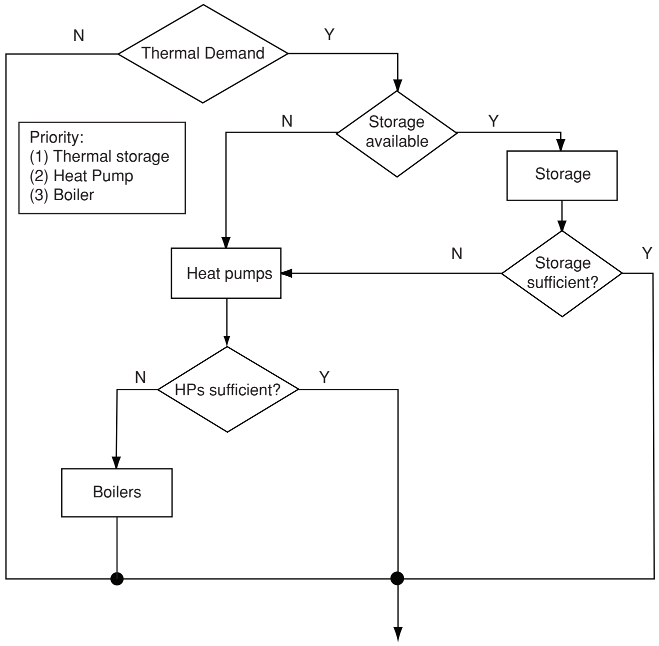

Figure 4: Thermal demand analysis.

The available storage content is now the difference between the old content of the storage and the heat used to satisfy the demand, Eq (3). The storage content is updated after the previous possible discharge within the same time step:

$$\text{Content}_{\text{STO}_{\text{available}}}(\text{t}) = \max(0, \text{Content}_{\text{STO}_{\text{available}}}(t) - d^1_{P,STO}(t)) \tag{3}$$

The residual quantity of heat power demand that hasnot been satisfied yet ($P^1_{RES}(t)$, $P^2_{RES}(t)$, $P^3_{RES}(t)$) is covered by heat pumps and if their capacity is not enough by boilers Eq. (4,5,6,7,8):

$$P^1_{RES}(t) = \max(0,\, d_{D,DH}(t) - d^1_{P,STO}(t)) \tag{4}$$

$$d^1_{P,HPS}(t) = \min(P^1_{RES}(t),\, C_{HPs} \cdot COP) \tag{5}$$

$$P^2_{RES}(t) = \max\left(0,\, P^1_{RES}(t) - d^1_{P,HPs}(t)\right) \tag{6}$$

$$d_{p.boil}(t) = \min\left(P^2_{RES}(t),\, C_{boil}\right) \tag{7}$$

$$P^3_{RES}(t) = \max\left(0,\, P^2_{RES}(t) - d_{p.boil}(t)\right) \tag{8}$$

2.4.3. Excess electricity analysis

The excess electricity analysis presents only one priority: heat pumps cover the share of excess electricity production generating heat that is stored in the thermal storage. The theoretical scheme is shown in Figure 5.

The excess electricity production ($d_{el,ex}(t)$) is given by the difference between the production by PV, the

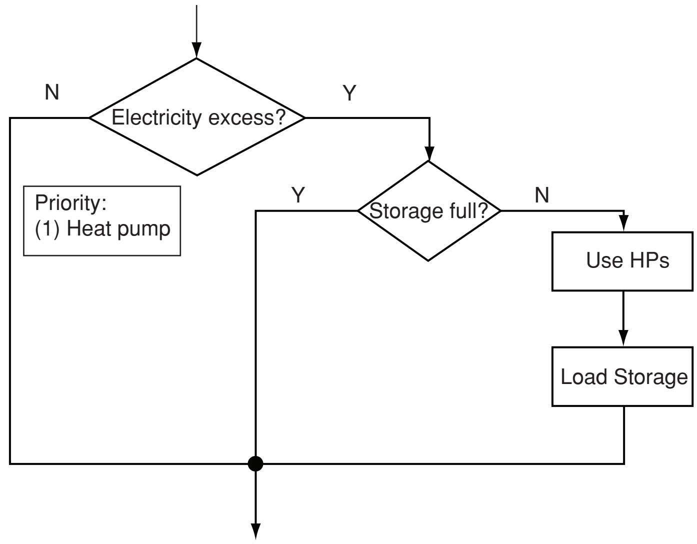

Figure 5: Excess electricity analysis.

electricity demand and the necessary quantity requested by the heat pumps to cover the thermal load (calculated through COP), Eq. (9). There is no transmission limit to the grid:

$$d_{el,ex}(t) = \max\left(0, d_{P,PV}(t) - d_{D,el}(t) - \frac{d^1_{P,HPs}(t)}{coP}\right) \tag{9}$$

The electricity supply that the heat pumps can use in order to produce heat to load the storage is given by the minimum between the excess electricity available and the minimum between the capacity of the heat pumps available yet, the available capacity of the thermal storage and the loading power of the storage (using COP to properly convert from thermal to electric and vice versa), Eq. (10):

$$d^2_{P,HPs,el}(t) = \min\left(d_{el,ex}(t), \frac{\min\left(C_{HPs}COP - d^1_{P,HPs}(t), C_{STO} - Content_{STO_{available}}(t), P_{STO,DH}\right)}{COP}\right) \tag{10}$$

Indeed, if the storage is full (capacity limit), or it cannot be loaded fast enough (loading power limit), or the heat pumps were already exploited at maximum during this time step (HP capacity limit), or there is not excess electricity, then no additional use of heat pumps is feasible. The consequent heat production by the heat pumps is obtained multiplying the value of the COP with the one found at the Eq. (10). The thermal storage is loaded by an equal share, Eq. (12):

$$d^2_{P,HPs}(t) = \mathrm{d}^2_{P,HPs,el}(t) \cdot COP \tag{11}$$

$$d^2_{P,STO}(t) = d^2_{P,HPs}(t) \tag{12}$$

The remaining excess electricity is given by the difference between the total excess electricity and the quantity used by the heat pumps. It could be different from zero if the remaining exploitable capacity of the heat pumps (also taking into account the current storage level) is not enough to cover all the excess, Eq. (13):

$$d_{el,ex,RES}(t) = \max\left(\mathrm{O}, d_{el,ex}(t) - d^2_{P,HPs,el}(t)\right) \tag{13}$$

It is now necessary to update the content of the storage with the quantity produced by the heat pumps, Eq. (14). It is necessary also to consider the losses of the storage.

$$\begin{aligned} &\mathrm{Content}_{\mathrm{STO}_{\mathrm{available}}}(\mathrm{t}+1) = \\ &\min\left(C_{STO,} d^2_{P,STO}(t) + \mathrm{Content}_{\mathrm{STO}_{\mathrm{available}}}(\mathrm{t})\right) - \\ &\left(1 - \frac{L_{STO,DH}}{5000}\right) \end{aligned} \tag{14}$$

The overall production by the heat pumps is obtained adding the first and the second contributions, Eq. (15):

$$d_{P,HPs}(t) = d^2_{P,HPs}(t) + d^1_{P,HPs}(t) \tag{15}$$

2.4.4. Electricity demand analysis

The electricity demand analysis, theoretical scheme shown in Figure 6, presents as priorities: PV and the grid to cover the electricity demand. The value of the

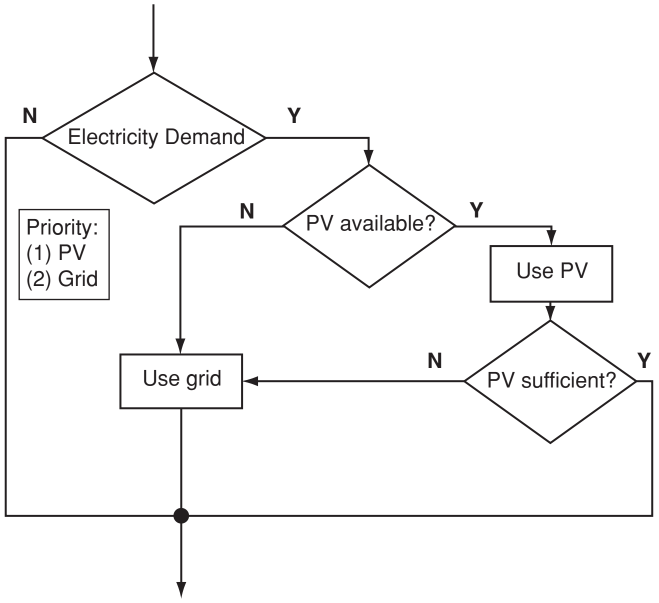

Figure 6: Electricity demand analysis.

imported electricity ($d_{P,grid}(t)$) is given by the sum between the electricity demand and the share used by the heat pumps deducted by the PV production, Eq. (16):

$$d_{P,grid}(t) = \max\left(\text{o}, d_{D,el}(t) + \frac{d_{P,HPs}(t)}{COP} - d_{P,PV}(t) \right) \quad (16)$$

In a well-balanced system, the storage content at the end of the year must be identical to that at the beginning of the year. Indeed simulations are based on a "standard" year, which is assumed to repeat identically in time. This periodicity is required to ensure the correct energy balance: a higher content at the end of the year would correspond to wasted energy, while a lower content would correspond to generating energy from nothing. In this model, periodicity can be ensured adjusting the initial storage content. The matching value can be automatically calculated with a single (properly designed) trial simulation. Within this approach, the performance analysis of a given configuration hence requires to run the model twice.

2.4.5. CO_2 emissions analysis

It is now possible to evaluate the annual CO_2 emissions of the system and perform the economic analysis. In order to estimate the annual CO_2 emissions, the inputs are e_{grid} (the average emissions of a unit of electricity imported from the grid) and e_{gas} (the average emissions of the combustion of a unit of natural gas).

The total annual CO_2 emissions, Eq. (19), are given by the sum between the emissions originated by the imported electricity, Eq. (17), and the ones produced by consuming gas through the use of boilers, Eq. (18):

$$CO_{2grid} = e_{grid} \Delta t \sum_t d_{P,grid}(t) \quad (17)$$

$$CO_{2gas} = e_{gas} \Delta t \sum_t d_{P,boil}(t) \quad (18)$$

$$CO_{2tot} = CO_{2grid} + CO_{2gas} + CO_{2energyPLAN} \quad (19)$$

The $CO_{2energyPLAN}$ contribution is the quantity of CO_2 emissions calculated through EnergyPLAN that are produced by the remaining whole system.

2.4.6. Costs analysis

As previously mentioned, the developed model PV-STOth follows the EnergyPLAN approach, using the same formula for the actualization of the investment costs that are thus converted in annual costs. The total annual costs, Eq. (29) are given by the sum of different contributions: C_{gas} is the cost of the natural gas used by boilers, Eq. (20), C_{grid} is the cost of the electricity imported from the grid (21), $C_{grid,exported}$ is the income for selling excess electricity to the grid, Eq. (22), $C_{PV,annual,invc}$ is the investment cost of PV amortized during its lifetime, Eq. (23), $C_{PV,annual,O\&M}$ is the annual operation and maintenance cost of PV, Eq. (24), $C_{HPs,annual,invC}$ is the investment cost of HPs amortized during their lifetime, Eq. (25), $C_{HPs,annual,O\&M}$ is the annual operation and maintenance cost of HPs, Eq. (26), $C_{STO,annuual,invC}$ is the investment cost of storage amortized during its lifetime, Eq. (27), $C_{STO,annual,O\&M}$ is the annual operation and maintenance cost of the storage, Eq. (28).

$$C_{gas} = c_{gas} \Delta t \sum_t d_{P,boil}(t) \quad (20)$$

$$C_{grid} = c_{grid} \Delta t \sum_t d_{P,grid}(t) \quad (21)$$

$$C_{grid,exported} = c_{grid,exported} \Delta t \sum_t d_{el,ex,RES}(t) \quad (22)$$

$$C_{PV,AnnualinvC} = C_{inv,PV} \cdot C_{PV} \cdot \frac{i}{1-(1+i)^{-L_{PV}}} \tag{23}$$

$$C_{PV,AnnualinvC} = C_{inv,PV} \cdot C_{PV} \cdot O\,\&\,M_{PV} \tag{24}$$

$$C_{HPs,Annual,invC} = C_{inv,HPs} \cdot C_{HPs} \cdot \frac{i}{1-(1+i)^{-L_{HPs}}} \tag{25}$$

$$C_{HPs,Annual,O\&M} = C_{inv,HPs} \cdot C_{HPs} \cdot O\,\&\,M_{HP.} \tag{26}$$

$$C_{STO,Annual,invC} = C_{inv,STO} \cdot C_{STO} \cdot \frac{i}{1-(1+i)^{-L_{STO}}} \tag{27}$$

$$C_{STO,Annual,O\&M} = C_{inv,STO} \cdot C_{STO} \cdot O\,\&\,M_{STO} \tag{28}$$

$$\begin{aligned} &C_{Tot,annual} = C_{gas} + C_{grid} - \\ &C_{grid,exported} + C_{PV,Annual,invC} + \\ &C_{PV,Annual,O\&M} + C_{HPs,Annual,invC} + \\ &C_{HPs,Annual,O\&M} + C_{STO,Annual,invC} + \\ &C_{STO,Annual,O\&M} + C_{\_energyPLAN} \end{aligned} \tag{29}$$

The $C_{EnergyPLAN}$ is the value of the total annual costs calculated through EnergyPLAN that are produced by the remaining whole energy system.

2.5. Deterministic and optimization approach

Two different approaches have been chosen to inspect the possible RES high penetration scenarios on the considered area.

A deterministic approach has been chosen for a first analysis of different extreme solutions. The PV scenario with incremental increase of PV capacity has been compared with a *PV + electric storage* scenario, implemented with the EnergyPLAN software and a *PV + thermal storage* scenario, evaluated through the model PV-STOth. By inserting manually the data in EnergyPLAN, it is possible to inspect for each configuration the output parameters of CO_2 emissions and total annual costs. The two scenarios *PV+electric storage* and *PV+thermal storage* describe extreme cases where PV capacity – and hence all the PV generated excess electricity production (EEP_{PV}) – is the only driver to set the others parameters (capacity of the virtual pump C_P, capacity of the virtual turbine C_t, capacity of the electric storage $C_{STO,el,}$ capacity of the heat pumps $C_{HPs,}$ capacity of the thermal storage $C_{STO,th}$ and initial content of the thermal storage $I_{STO,DH}$). For this reason, this approach is useful to analyze the extreme cases. In the *PV+electric storage* the capacity of the storage is sized to cover all the excess electricity production, therefore not even a single kWh of electricity is wasted or sold to the grid (see [19] for a similar approach). This scenario has been implemented in EnergyPLAN. For this reason the electric storage parameters that have been considered are: capacity of the virtual pump C_P, capacity of the virtual turbine C_t, capacity of the electric storage $C_{STO,el}$. Indeed EnergyPLAN models all the types of electric storage as a virtual pumped hydro storage system where the charging capacity is the virtual capacity of the pump and the discharging capacity is the virtual capacity of the turbine. In this scenario Lithium-ion batteries have been considered as electric storage. Their characteristics are shown in Table 2.

In the *PV+thermal storage* scenario the maximum of the excess electricity production allows for the estimation of the heat pump's size. This latter value permits to estimate the capacity and the initial content of the thermal storage with the same strategy used for the electric storage. In other words, the capacity of the thermal storage is sized to cover all the heat generated by the heat pumps.

In order to inspect the best mix of technologies for the *PV+thermal storage* scenario, an optimization algorithm has been implemented [50, 51]. Indeed, the optimization approach permits to inspect not only few extreme configurations but also among all the solutions choose the best one in terms of CO_2 emissions and total annual costs. The problem is, thus, characterized by two objectives that have to be minimized. The two objectives are the minimization of the annual CO_2 emissions of the system and the minimization of the total annual costs. The problem is 1a multi objective problem (MOO).

The choice of the optimization model has fallen upon an evolutionary algorithm (EA). An EA is a meta-heuristic optimization algorithm that is inspired by the

Table 4: Increase of PV capacity and consequent increase of capacity of the electric and thermal storage.

		Electric storage			Thermal storage		
C_{PV}	EEP_{PV} [GWh/year]	C_p [kW]	C_t [kW]	$C_{STO,el}$ [kWh]	C_{HPs} [kW]	$C_{STO,DH}$ [kWh]	$V_{STO,DH}$ [m^3]
0	0	0	0	0	0	0	0
10	0.06	2043	3866	8431	2161	8200	131
20	2.17	9386	10240	58406	9504	416554	6665
30	8.40	17452	13400	122826	17512	10991626	175866

principle of natural selection. A heuristic optimization algorithms is particularly suited for finding solutions in a fast and easy way [20]. Multi-objective evolutionary algorithms (MOEA) [52–53] are a version of EAs for MOO problems. Figure 7 shows how this optimization model works interacting with the developed model (see [19] for a similar approach with EnergyPLAN). The model starts generating a number of random solution that compose the initial population. Each individual, within the evolutionary algorithm, corresponds to a given configuration in terms of the capacity of PV, heat pumps and thermal storage and by the initial content of the storage itself. In order to evaluate each individual or solution the model PV-STOth is launched with the input variables of the considered individual. The outputs of the model PV-STOth, CO_2 emissions and total annual costs are used to evaluate each individual.

There is a constraint in the optimization model that permits to select only solutions with a surplus, Eq. (29), lower than the 1% of the storage capacity. Eq. (30) shows this constraint (in EnergyPLAN the year is considered a leap year and is hence composed by 8784 hours):

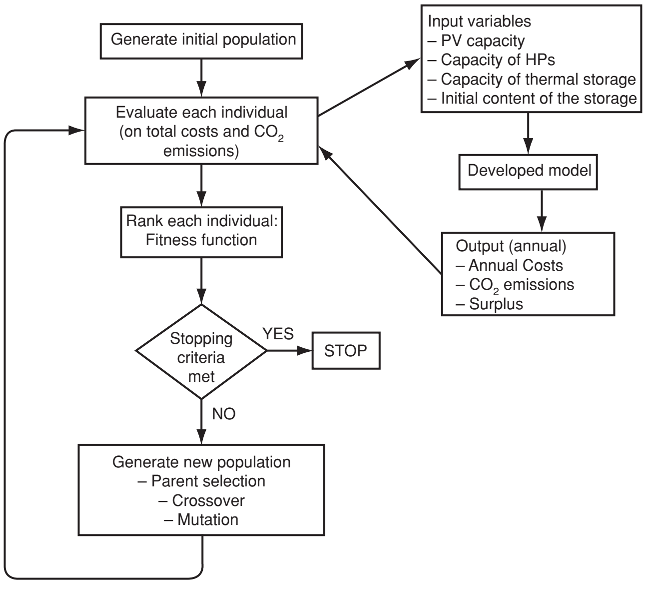

Figure 7: MOEA's Flow chart.

$$Surplus = \text{Content}_{\text{STO}_{\text{available}}}(8784) - \text{Content}_{\text{STO}_{\text{available}}}(0) \tag{29}$$

$$Surplus \leq C_{STO}\ 0.01 \tag{30}$$

The MOEA allows for the evaluation of the best solutions through the Pareto front. It is composed by all the non-dominated solutions that are characterized by the fact that no one of the objectives can be improved without degrading some of the other objective values.

3. Results

3.1. Deterministic approach

The results of the deterministic approach are presented in Figure 8. The use of electric and thermal storage enables to save more CO_2 emissions compared to the "PV" scenario, but with a high cost increase that corresponds to the growing PV installed power. In this way, a deterministic approach to estimate the possibility to save excess electricity production has been developed. The considered cases are the extreme ones and do not considered intermediate possibility. A solution in which a part of the excess electricity production is stored and a part is sold to the grid could be cost-effective compared to these ones, where all the overproduction is stored.

3.2. Optimization approach

The results of the optimization approach are presented in Figure 9, where it is possible to see the results of the MOEA's optimization analysis and the Pareto front of the best solutions. Figure 9 shows also the comparison with the reference scenario and the results obtained with the deterministic approach.

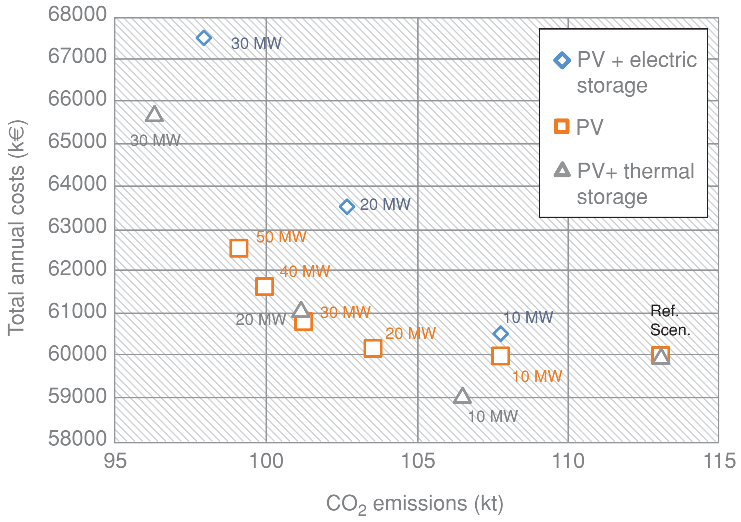

Figure 8: Comparison between the *PV scenario, PV+electric storage* scenario and *PV+thermal storage* scenario.

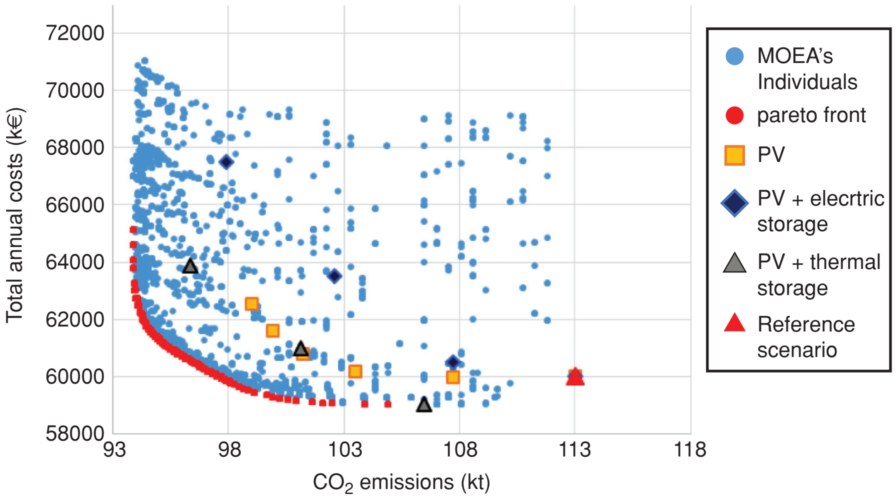

Figure 9: Multi objective evolutionary algorithm results and comparison with reference scenario and results of the deterministic approach.

The identified Pareto front permits to highlight that there are solutions that dominate the reference scenario. Only one solution found with the deterministic approach for the *PV+thermal storage* scenario belongs to the Pareto front. After this solution, all the others are intermediate solutions that present a part of the excess electricity production that is sold to the grid and the other part that it is stored into the thermal storage.

A solution on the Pareto front has been analyzed deeper, Figure 10. The point P1 is the point on the Pareto front that is closest to the total annual costs of the reference scenario. It doesn't increase the total annual

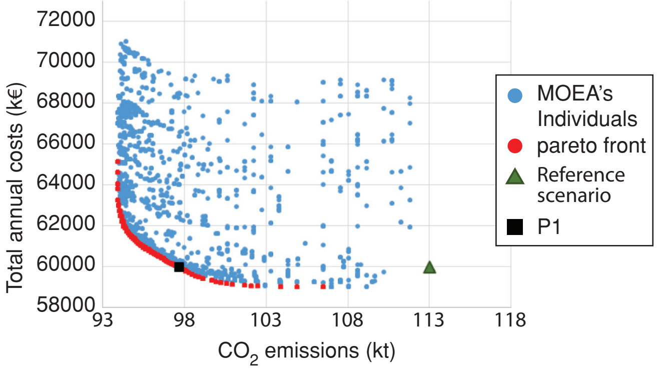

Figure 10: Multi objective evolutionary algorithm results and comparison with the reference scenario and the P1 solution.

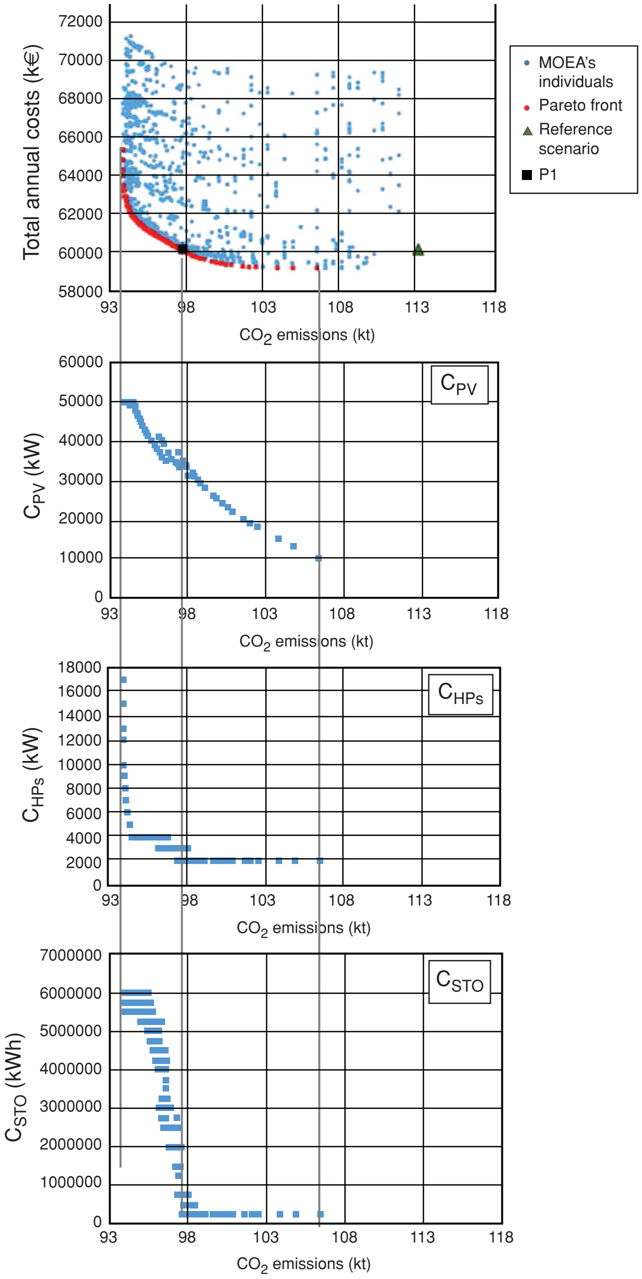

Figure 11: Analysis of the solutions on the Pareto front.

cost and allows for a significant reduction of the CO_2 emissions (about 15%). The P1 solution is characterized by a PV capacity of 35 MW, a HPs capacity of 3 MWel, a thermal storage capacity of 750 MWh and an initial content of the storage equal to zero.

Figure 11 shows the trend of the capacity of PV, heat pumps and thermal storage of the solutions on the Pareto front. Until 30 MW of PV installed power, a large capacity of the heat pumps and of the thermal storage is not required. After 30 MW of PV installed capacity the excess electricity production greatly increases and the capacities of the heat pumps and of the thermal storage consequently rise.

Figure 12 shows the trend of the electricity consumption and production and the trend of the thermal storage content for two different weeks of the year, one in spring and one in summer. In spring the seasonal thermal storage content is very low and if the PV production is not relevant during the central hours of the day there is no heat available in the storage to cover the demand during the other hours. For this reason the *grid+PV* curve differs from the *electricity demand* one because the heat pumps require additional electricity to cover the thermal load. The *electricity demand* curve does not include HPs electricity demand while the *grid+PV* curve consider this share. On the other hand, in summer, the thermal storage content is very high and is able to cover the heat demand.

4. Conclusions

The municipality of Bressanone-Brixen was selected as case study as it has joined the Covenant of Mayors in 2013 and baseline information is available in the Bressanone Sustainable Energy Action Plan. Moreover, this municipality can be considered well representative of several cities in the Alpine region, recently addressed by a specific EU strategy. Thanks to this, it has been possible to create the reference model and to validate it into the EnergyPLAN software, comparing the obtained total annual emissions with the value given by the SEAP.

A model to describe the interactions between PV, large CO_2 heat pumps and seasonal pit thermal storage has been developed. It is directly inspired by EnergyPLAN, implementing priorities with equations of the same type and following the same calculations for the estimation of the CO_2 emissions and total annual costs, but it takes into account only the mentioned technologies. On the other hand, with respect to EnergyPLAN the model adds a few variables that allow to manage the storage with a higher flexibility. In particular, the model gives the possibility to set (i) an initial content of the thermal storage system, (ii) a parameter for thermal storage losses, and (iii) the charging and discharging power of the thermal storage system.

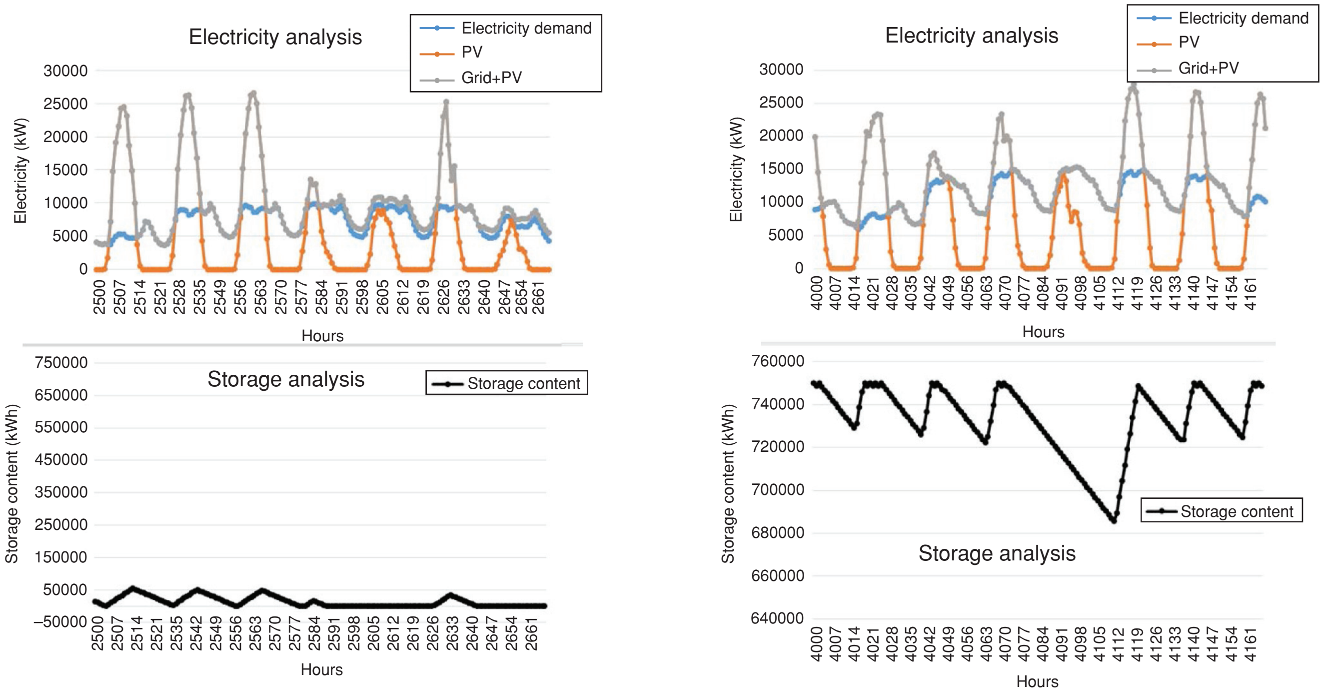

Figure 12: P1 solution analysis in a spring (from the hour 2500 to 2668) and summer week (from the hour 4000 to 4168).

A deterministic approach has been used to compare different peak shaving solutions: thermal (analysed with the created model) and electric storage (inspected with EnergyPLAN). The two scenarios have been created varying only the installed capacity of PV and calculating the size of the other variables (like capacity of the heat pumps, thermal storage, virtual capacity of the pump and of the turbine and capacity of the batteries) in order to cover the entire excess electricity production without exchanges to the grid. For this reason the two scenarios describe the extreme cases. The results have shown that, with these types of assumptions, the most cost-effective mean to perform peak shaving is given by the heat pumps coupled to seasonal thermal energy storage. However, the volume required by the storage to cover all the excess electricity production increases extremely fast beyond a certain PV capacity and the total annual costs rise correspondingly. For this reason, it is advised to inspect the intermediate solutions between storing all the excess electricity production and selling it to the grid.

A Multi-Objective Evolutionary Algorithm has been used to study the best intermediate solutions of the *PV + thermal storage* scenario, finding out the Pareto front of best technology mix. A solution on the Pareto front (P1) has been chosen as solution that permits to save more annual CO_2 emissions without increasing the annual costs of the energy system compared to the reference scenario. A future development can focus on the extension of the optimization analysis not only on the considered sources but also on a more flexible operation of the existing cogeneration power plants that have a high potential in the integration of renewable energy sources.

It is worth recalling that the current analysis relies on a few requisites and assumptions. In particular, the proposed energy configuration relies on the existence or on the feasibility of a DH network and on the availability of a reasonable solar fraction for PV. Moreover, the installation of a seasonal storage require favorable conditions in terms of ground availability and costs, an aspect which was not investigated in detail for the present case study. Finally, the energy source and the temperature levels used by heat pumps should be properly analyzed for a full feasibility study. The overall energy balance proposed here, however, is already sufficient to clearly highlight the interest of hybrid electric-thermal applications, showing that extending the analysis of storage solutions beyond the purely electric sector can be highly beneficial.

5. Acknowledgements

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