Effect of different economic support policies on the optimal synthesis and operation of a distributed energy supply system with renewable energy sources for an industrial area

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A R T I C L E I N F O

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A B S T R A C T

Economic support policies are widely adopted in European countries in order to promote a more efficient energy usage and the growth of renewable energy technologies. On one hand these schemes allow us to reduce the overall pollutant emissions and the total cost from the point of view of the energy systems, but on the other hand their social impact in terms of economic investment needs to be evaluated. The aim of this paper is to compare the social cost of the application of each incentive with the correspondent CO_2 emission reduction and overall energy saving. A Mixed Integer Linear Programming optimization procedure is used to evaluate the effect of different economic support policies on the optimal configuration and operation of a distributed energy supply system of an industrial area located in the north-east of Italy. The minimized objective function is the total annual cost for owning, operating and maintaining the whole energy system. The expectation is that a proper mix of renewable energy technologies and cogeneration systems will be included in the optimal solution, depending on the amount and nature of the supporting policies, highlighting the incentives that promote a real environmental benefit.

1. Introduction

Distributed energy generation is a cost-effective alternative to the conventional supply of heat and electricity, especially for industrial users [1]. The integration of renewable energy sources (RES) into the system allows users to achieve higher economic and energy savings [2]. Considering that industrial users are characterized by quite predictable energy demands throughout the year, the adoption of such smart solutions leads to improving the energy efficiency of the system and thus to reducing primary energy consumptions and polluting emissions.

However, industrial stakeholders generally make their decisions looking for the minimum cost solutions, while environmental issues such as the greenhouse effect and the availability of energy resources should be evaluated as much as the economic aspect of the problem [3]. To promote a more efficient energy usage and the growth of renewable energy technologies economic support policies are widely adopted in European countries.

The objective of this paper is to evaluate the effect of different economic support policies on the optimal configuration of the energy supply systems and to compare the pollutant emission reduction and energy saving achieved by each incentive with its economic cost for society. The objective function to be minimized represents the total annual cost for purchasing, operating and maintaining the whole system, considering also the cost reduction for industrial stakeholders associated to the support scheme. The evaluation is carried on using as reference the distributed energy system designed to supply electricity and heat to nine factories belonging to the PonteRosso Industrial Area (San Vito al Tagliamento – Italy). Due to the complexity of the system, the minimum cost solutions have to be obtained adopting the configuration and the operation (including dispatch strategy) that result from the simultaneous optimization of the whole energy supply system [4,5].

Various subsidies related to the adoption of energy saving technologies are analysed: the capital cost reduction for cogenerators and solar thermal (ST) modules, special tariffs for electricity produced by biofuel cogeneration and photovoltaic (PV) panels, grants for fuel consumption and CO_2 emission saving (detailed references to the support policies implemented are given in chapter 3). The expectation is that a mix of cogeneration and renewable energies will be included in the optimal solution, depending on the amount and nature of the support policies adopted. Therefore, the

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Nomenclature

BOI	boiler	H_{boi}	boiler heat (kW h)
CCHP	combined cooling heat and power	HS	heat storage
c_{ep}	purchased electricity price (€/kW h)	H_{st}	solar thermal field heat (kW h)
c_{es}	sold electricity price (€/kW h)	i	interest rate
c_{fuel}	fuel price (€/kW h)	I	support policy (€)
CHP	combined heat and power	ICE	internal combustion engine
C_{inv}	annual investment (€/y)	Inv	total investment (€)
C_{man}	maintenance cost (€)	MILP	Mixed Integer Linear Programming
CO_2	carbon dioxide	n	life span (y)
C_{ope}	annual operating cost (€/y)	PV	photovoltaic
C_{tot}	total annual cost (€/y)	RES	renewable energy sources
DHN	district heating network	rf	capital recovery factor (y^{-1})
E_{cog}	cogenerated electricity (kW h)	S_{boi}	boiler size (kW)
E_p	purchased electricity (kW h)	S_{cog}	cogenerator size (kW)
E_{pv}	photovoltaic electricity (kW h)	SP	support policy (€)
E_s	sold electricity (kW h)	ST	solar thermal
EU	European union	t	time interval
F	fuel consumption (kW h)	TC	Traditional Case
H_{cog}	cogenerated heat (kW h)	j	component

incentives that promote real environmental benefit at an acceptable cost are highlighted.

The algorithm used to solve the system optimization comes from long research work in the field of low-impact generation systems and is the result of the evolution of previous Mixed Integer Linear Program (MILP) models, developed by the authors in other recent studies. An example of this kind of model for the optimal power generation and energy management for off-grid systems is also described by Dai and Mesbahi in [6].

First a MILP model was used by the authors to optimize the configuration and operation of cogeneration (CHP) and trigeneration (CCHP) systems for tertiary service buildings in [7–9]. That original model, with appropriate changes and introducing the thermal inertia of the district heating network (DHN), was then adapted to the PonteRosso Industrial Area [10]. A solar district heating system including a heat water storage (HS) was added in [11], while [12] describes a multi-objective optimization of the energy system, at the same time minimizing the total annual cost and the CO_2 emissions. All the users' configurations need to be optimized simultaneously due to the heat flowing through the various components of the system and the utilities themselves. This is one of the reasons why the MILP model developed in the study is optimized by considering the whole energy supply system as one indivisible entity. However, it is not difficult to find in literature cases where cogeneration systems of various concepts are designed and optimized to serve a single user [13–15]. An example of optimization model for industrial district heating networks is developed by Chinese et al. [16], while Lozano et al. [17] presents the thermoeconomic cost analysis of central solar heating plants combined with seasonal storage.

2. Optimization model

Several recent studies on the design and operation of energy supply systems are available in literature [18–23]. There can be many different systems including various options: centralized and decentralized machines, cogeneration and trigeneration units, renewable sources, DHN, etc.

Linearizing the performance curves of the cogenerators (the relationships between input and output streams), the MILP model is still a valid way to represent the system analysed [24,25]. In fact the other constraint equations of the model are linear: energy and cost balances are inherently linear while solar modules and boilers can be regarded as components with constant efficiency. Also the heat losses of the HS and the DHN are obtained as a fixed fraction of the hourly thermal energy stored in the respective component. In [26] a complete explanation of the MILP model developed in the paper can be found. The model is consistent with the algorithmic approach presented by Frangopoulos et al. in [27].

The first step towards optimizing an energy supply system is to define a superstructure: a representation of the system itself that encompass every single machine and component which might appear in the final optimal configuration.

The superstructure of the case study is represented in Fig. 1. The supply system has to provide the heating and electric energy needed by a set of industrial users. The energy demands are known in advance and considered constant in each time interval. The electricity can be produced by CHP units, both distributed (placed in the site of each user) and centralized, by a central solar PV plant or can be purchased from the external grid. The required heating energy can be produced by CHP units, by conventional boilers or by a centralized ST field. Looking at the superstructure, a general user may include only a CHP and a boiler while in the central unit a cogenerator, a boiler, the HS, the ST modules and the PV panels may be installed. The users are connected together and to the central unit through a DHN of predefined layout and design. As the DHN connects the factories, the heat produced by central and distributed units can be self-consumed, exchanged between the users or sent to the HS.

A system that includes a ST field and a HS connected to a DHN is called a solar district heating system. Practical examples of such a configuration can be found in central and northern European countries and are designed to supply heating energy both to residential and industrial buildings, allowing a solar fraction of 50% [28]. The main advantage of those systems is the possibility of storing the energy in the form of hot water and using it when needed. Another characteristic is usually a low specific investment cost, mainly because of the large scale of the plant.

The MILP model developed in the paper is quite flexible and the equations can be adapted to different case studies simply by varying component performance parameters and energy vector prices.

2.1. Objective function

The aim of the model is to minimize the total annual cost for owning, operating and maintaining the whole energy supply system. The objective function C_{tot} is linear and its expression is:

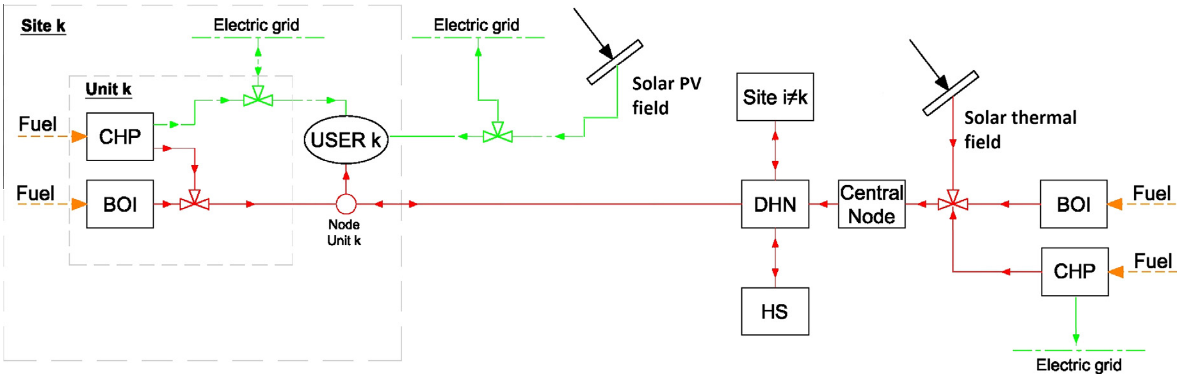

Fig. 1. Superstructure of the energy supply system described by the optimization model.

$$C_{tot} = C_{inv} + C_{ope} + C_{man} - I \quad (1)$$

The term I represents the social cost related to the adoption of a general support policy and is obtained by multiplying the value of the incentive by the amount of resource produced, sold or saved. The total annual investment C_{inv} is the sum of the investment cost of each component $Inv(j)$ multiplied by the respective capital recovery factor $rf(j)$. The capital recovery factor is calculated with Eq. (3) and depends on the life span n of each component j and on the interest rate $i = 0.07$.

$$C_{inv} = \sum_{j} rf(j) \cdot Inv(j) \quad (2)$$

$$rf(j) = \frac{i \cdot (1+i)^{n(j)}}{(1+i)^{n(j)} - 1} \quad (3)$$

The whole year is represented by 2016 time intervals t.

The annual operating cost of the energy supply system C_{ope} is the sum of the fuel and the net electricity costs. It is obtained by the expression:

$$C_{ope} = \sum_{t} (c_{fuel} \cdot F(t) + c_{ep} \cdot E_p(t) - c_{es} \cdot E_s(t)) \quad (4)$$

c_{fuel}, c_{ep} and c_{es} are the prices of natural gas, purchased electricity and sold electricity. $F(t)$, $E_p(t)$ and $E_s(t)$ represent the total fuel consumed and the total purchased and sold electricity.

The maintenance cost C_{man} of a generic machine j is proportional to the energy produced (heat or electricity) by the machine itself.

2.2. Decision variables

The decision variables of the MILP model (binary and continuous) are:

- the existence (0/1) and size of each component (CHPs, boilers, HS, PV and ST fields);
- the operation status (0/1) of each component in each time interval;
- the quantity of electricity from the PV modules to the users, and electricity purchased and sold from/to the electric grid;
- the quantity of heating energy from the HS and the ST plant to the users;
- the heating flows from and to the DHN and the HS;
- the levels of the energy stored in the DHN and in the HS.

The binary variables describe the existence and the on/off status of each machine, while all other variables are continuous. The binary variables can be set to force or exclude in advance the existence of a certain component. For instance, as the heat demand of user 2 is zero, no boilers need to be installed there. Thus the binary variable related to the existence of the boiler of user 2 is pre-set to be equal to zero ($ex\_boi(2) = 0$).

2.3. Model constraints

Equality component constraints describe the links between input (fuel), product (electricity) and sub-product (heat), while inequality constraints define load and size limits of the components.

The output energy of the PV and ST fields is related to the area of the respective solar modules. The energy output per surface unit of the two solar plants is obtained through environmental monitoring available from other research studies [29]. The panel orientation and the tilt angle are therefore fixed in advance.

The equality constraint of the HS relates its energy load to the input/output flows considering the thermal losses through the storage surface. The stored energy is obtained by multiplying the temperature of the medium (water) by the volume of liquid contained in the HS. As all the relationships of the model have to be linear, volume and temperature cannot both be decision variables. Thus volume is variable and temperature is supposed constant. The assumption corresponds to the hypothesis of a perfect stratification of the fluid inside the HS. Hence, the water in the storage is always available at the temperature level required by the DHN. The quantity of energy stored in each time interval is a decision variable and its value at the first and last time interval of the year must be the same, therefore the energy stored at the beginning of the year is determined by the optimization procedure.

The constraints that describe the operation of the DHN are similar to those of the HS as the DHN is also considered a storage medium. As in the HS, the heat loss along the pipelines is also a fixed percentage of the energy stored in each time interval.

Additional constraints concern the energy balance of each node of the superstructure and the possible direction of energy flows. Energy balances are very important equality constraints and represent the heating and electric behaviour of the system. For each time interval and for each node, they ensure that the input energy is equal to the output. Moreover, a set of equality and inequality constraints has to be added in order to guarantee that a user cannot purchase and sell electricity and cannot receive and release heat in the same time interval. Other inequality constraints are introduced to assure a correct electricity and heat transfer between users, DHN and the electric grid.

3. Economic support policies

Focusing on the European scenario, since the late 1980s various economic support policies have been introduced by the member states that stimulate the development of renewable energy technologies and that contribute to increase the heat and electric production efficiency of the energy conversion systems. As the great majority of these renewable support schemes have been developed on a national basis, in the past decade the European Commission has started to discuss the implementation of cooperation mechanisms aiming at harmonizing the fragmented national legislations. However the Commission, in its official communication [30], stated that, due to different approaches of the member states regarding renewable energies, the harmonisation seems very difficult to achieve in the short term. Thus, in this context, an effort has to be made to identify the most effective support schemes in terms of social impact, in order to meet both economic and environmental targets.

A wide range of direct support schemes for RES technologies are used in the European Union (EU). These can be broadly classified as quota and price mechanisms. Quotas set a certain level of renewable production and let the market establish the price. Price mechanisms guarantee a certain level of support to renewable producers and allow this price to determine the level of development [31]. This paper focuses on feed-in tariff, feed-in premium, tradable certificates (green and white) and non-refundable subsidies (discount on capital cost), as they are the most widely spread mechanisms across the EU.

The MILP model of the energy supply system is optimized by introducing six different support policies related to the adoption of RES and to the energy saving linked to the utilization of efficient cogeneration units. The following cases, corresponding to the adoption of six incentives, are analysed:

– Case 1: Feed in Tariff for PV energy. It is a price-based mechanism providing a fixed incentive of 0.205 € for each kW h of PV energy sold to the national grid. This support policy is the most common in the EU as it is adopted in 21 countries [31].
– Case 2: Feed in Premium for PV energy. It is a price-based mechanism providing an incentive (premium) of 0.14 € for each kW h of PV energy generated, no matter what the final use. The electric energy produced by the PV modules may be either self-consumed or sold to the grid at market price. This support scheme is used in the Czech Republic, Denmark, Estonia, Italy, Slovenia, Spain and The Netherlands [31].
– Case 3: Green Papers. It is a quota-based mechanism which obliges suppliers to produce a defined volume of their electricity from renewable sources, presenting the papers (or titles) as proof. If a supplier manages to obtain more titles than required, the difference can be sold to other suppliers generating a profit. As the individual seller cannot modify the market equilibrium price, the scheme corresponds to a price based mechanism granted to the seller. An incentive of 0.1001 € is recognised for each kW h of electricity produced by cogeneration units powered by biofuels. This support policy is implemented in Belgium, Italy, Poland, Romania, Sweden and United Kingdom [31].
– Case 4: White Papers. It is a quota-based mechanism that works exactly like the Green Papers. An incentive of 113.7 € is recognised for each ton of oil equivalent saved as a result of cogeneration, ST and PV productions. This support scheme is used in Denmark, France, United Kingdom, Italy and The Netherlands [32].
– Case 5: It is a mechanism providing 25% capital cost reduction on the purchase of efficient CHP units, in the form of non-refundable subsidies [33].
– Case 6: It is a mechanism providing 50% capital cost reduction on the purchase of ST collectors, in the form of non-refundable subsidies [33].

In all cases the surplus electricity produced can still be sold to the national grid at reference market price.

4. Case study

The energy supply system of nine users of the "PonteRosso" industrial area (San Vito al Tagliamento – Italy) is analysed. The region presents the typical climate of a continental European country with an average yearly solar radiation of about 1200 kW h/m^2 [34].

A district heating network of fixed length and layout connects all the users. The energy demands of the utilities, coming from local audits, are met by a centralized cogenerator and various distributed cogeneration units of smaller size. Traditional boilers are also an option and each user can exchange electricity with the external grid. The optimization model has therefore to consider a first trade-off between centralized and distributed solutions: if heat is produced and used locally investment in pipelines and heat dissipations may be avoided, but, on the other hand, a single centralized cogenerator entails a lower investment and a higher efficiency than many small decentralized conversion units of comparable total capacity [35]. The addition of PV and ST modules to the structure of the system allow us to investigate the effects produced by the usage of renewable energy technologies on the optimal solution.

The electricity from the PV modules can either be self-consumed or sold to the national grid. The ST plant is coupled with a heat energy storage, creating a solar district heating system. This kind of configuration is considered an intelligent way of meeting the heating needs in cases of lack of solar energy, that is during the night and the winter season (for the north hemisphere), especially in northern European countries. Schmidt et al. present in [36] a solar heating plant with seasonal storage for a German household, while a hybrid dynamic model with RES for a green building is optimized in [37].

A complete description of the case study is presented in [12], thus only the additions and updates are reported below.

Fig. 2 shows the aggregated energy load duration curves of the nine factories and Table 1 the electric and heating consumptions of each user.

Table 2 shows the energy vector prices considered in the model. The prices are consistent with the current European market. Electricity prices are assumed constant independent the hour of the day.

Table 3 shows the cost and life span of the components used in the application [35]. Prices of CHPs and boilers are made up of a fixed part and a variable part proportional to the size. Maintenance costs of cogenerators and boilers are respectively 0.017 and 0.001 € per kW h produced (electricity and heat respectively) and they include the manpower cost too [35].

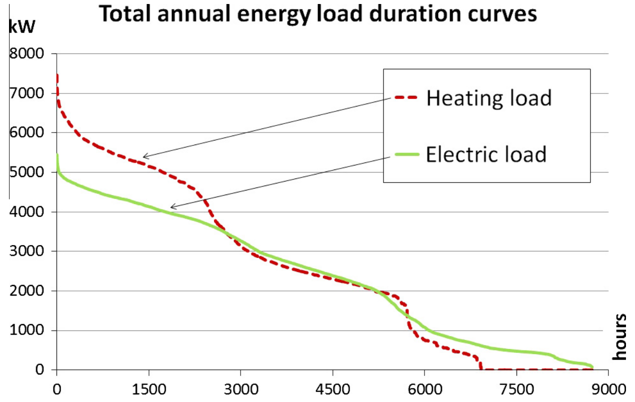

Fig. 2. Total energy load duration curves.

Table 1
Users' energy consumptions [MW h].

User	Electric demand	Heating demand
1	1169	434
2	1718	–
3	1553	950
4	1582	1650
5	2936	864
6	57	120
7	2631	3667
8	3679	13438
9	4891	62
Total	20216	21184

Table 2
Energy prices.

	PRICE (€/kW h)
Electricity purchased	0.12
Electricity sold	0.085
Natural gas	0.05
Palm oil	0.083

Table 3
Components' cost and life span.

	Cost	Life span
ICE	130 k€ + 730 €/kW	15
Boiler	6.3 k€ + 18 €/kW	15
DHN	4500 k€	40
HS	160 €/m^3	40
PV module	350 €/m^2	15
ST collector	250 €/m^2	15

All boilers have an efficiency of 80%. The cost of the HS varies between 120 and 180 €/m^3 [36], mainly depending on its characteristics such as type and size. An average cost of 160 €/m^3 is considered.

Thermal losses of the HS are 0.2% of the energy stored in each time interval, while those of the DHN are 1%.

An emission of 0.202 $kgCO_2$ per kW h is considered for the combustion of natural gas [38] and 0.529 $kgCO_2$/kW h for the greenhouse emissions related to the 2010 global electricity generation [39]. The emission factor for the combustion of palm oil is equal to zero. A certain value associated to the palm oil life cycle assessment may be considered, but this option would entail increasing the carbon intensity of the natural gas including also the CO_2 emissions related to its production.

A PV field is added to the system. The collectors have the same orientation and inclination as the ST ones. The nominal cell efficiency of the PV modules is 16% while the average efficiency of the ST panels is 42% [29].

5. Results and discussion

The algebraic model of the energy supply system is optimized by the commercial software FICO Xpress [40]. It counts 153000 variables and 230000 constraints and the calculations are automatically interrupted when an acceptable gap of 0.2% is reached. The solutions have been obtained for six cases introducing different support policies and for the following two additional configurations:

- Traditional Case (TC): only boilers may be installed, the electricity is purchased from the grid, the central unit is not present and there is no DHN, no HS and no ST or FV fields;
- Case 0: is the reference case when all the machines and components may be installed, but no incentives are applied.

Table 4 shows the results of the model optimizations for the all cases analysed. The upper section of the table shows the optimal sizes of cogenerators, boilers, ST field, PV field and HS, while the lower section presents the energy and economic flows of the whole system.

The CO_2 saved cost is the ratio between the support policy cost and the CO_2 emission difference with respect to Case 0. The Energy Saving is calculated in relation to the Traditional Case (TC). The fuel consumed is considered a primary energy, while the primary energy impact of the electricity available from the grid is obtained taking into account an average conversion efficiency equal to 44%.

In Case 0 (without a subsidy) the optimal solution consists of a centralized boiler, two CHP units for a total installed electric power of 1.5 MW, a heat storage of about 1000 m^3 and a ST field of 9300 m^2. It can be seen that this configuration already produces an operating cost reduction of 1000 k€ per year compared with the Traditional Case, thus the additional investment on CHP systems and ST collectors has a payback time of 8.5 years.

For Cases 1 and 2 (when the PV modules are incentivized) the optimal configuration is very close to that of Case 0, except for the installation of a PV field of the maximum allowed size. In particular, Case 1 supports the sale of PV electricity to the grid, while Case 2 promotes the PV electricity production. In the second case the self-consumed PV energy is equal to 8500 MW per year (58% of the total production), therefore the quantity of purchased electricity decreases and the payback period is less than 6 years. Another consequence of a higher self-consumption of PV energy is a decrease of the total installed cogeneration power, so that the reduced quantity of available heat is compensated for the increase of the ST field size. The unitary costs of both the CO_2 saved and the Energy Saving are lower in Case 2.

Supporting the biofuel cogeneration (Case 3), the total installed cogeneration power increases by 19% with regard to Case 0 and consequently the heat and power production increase too. The cogenerated electricity sold is higher, but the Energy Saving is limited because palm oil is regarded as a fuel consumed by the system, as well as the natural gas. A very good performance is obtained considering the CO_2 emissions: since the environmental impact related to the combustion of the biofuel is zero, the cost of the CO_2 saved is the lowest of all the cases (176 €/Ton). Poorer results concerning the CO_2 emissions may be obtained in the case of also adding the life cycle impact of the palm oil into the evaluation.

Incentivizing the reduction of equivalent oil consumption (Case 4), various interesting improvements are obtained compared to the optimal solution of Case 0. In particular, all the components that positively affect the energy saving of the system present a size increase: CHP units +5%, ST collector +7%, HS tank +13%, PV field +7400 m^2. 79% of the electricity produced by cogenerators and PV modules is self-consumed and the quantity of purchased electricity is reduced by 12%. The social cost of the support policy is the lowest of the all cases (253 k€) and the unitary cost of the Energy Saving is also the lowest (only 9 €/MW h).

Introducing a subsidy to the CHP systems (Case 5) the total installed cogeneration power increases by 21% compared with Case 0, but the cogenerated electricity increases only by 7%, meaning that the additional installed power is only partially exploited. Besides that, the energy and the environmental benefits are negligible.

When a 50% capital cost reduction on ST collectors is applied (Case 6), the 4% decrease of total installed cogeneration power is compensated by an increase of the ST field size (+8%). The consequence is an increase in the size of the HS (+11%) and a very high increase in heat dissipations (+30%). As a result, both the CO_2 saved

Table 4
Optimization results.

	TC	CASE 0	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
Cogenerators (kW)								
Central Unit	–	0	0	0	0	0	0	0
Unit 1	–	0	0	0	0	0	0	0
Unit 2	–	0	0	0	0	0	0	0
Unit 3	–	0	0	0	0	0	0	0
Unit 4	–	0	0	0	0	0	0	0
Unit 5	–	0	0	0	0	0	0	0
Unit 6	–	0	0	0	0	0	0	0
Unit 7	–	0	0	0	0	0	458	0
Unit 8	–	657	652	623	794	733	647	645
Unit 9	–	881	871	831	1102	885	850	840
Boilers (kW)								
Central Unit	–	1947	0	0	0	0	1135	758
Unit 1	561	0	0	0	0	0	0	0
Unit 2	–	–	–	–	–	–	–	–
Unit 3	891	0	0	0	0	0	0	0
Unit 4	996	0	0	0	0	0	0	0
Unit 5	749	0	0	0	0	0	0	0
Unit 6	189	0	0	0	0	0	0	0
Unit 7	1556	0	0	0	0	0	0	0
Unit 8	3720	0	1964	1997	1538	1895	0	1291
Unit 9	92	0	0	0	0	0	0	0
ST field (m^2)	–	9321	9291	9739	9034	10028	9280	10152
PV field (m^2)	–	0	70640	70640	0	7390	0	0
Heat storage (m^3)	–	1043	1045	1122	1065	1201	1069	1171
Cogenerated electricity (MW h)	–	6721	6690	6326	8019	6773	7261	6329
Purchased electricity (MW h)	20217	15022	15027	7373	14566	13224	13882	15319
Sold electricity (MW h)	–	1526	21716	13670	2368	1894	926	1431
Cogenerated electricity sold (MW h)	–	1526	1500	1937	2368	1692	926	1431
PV electricity produced (MW h)	–	0	20217	20217	0	2115	0	0
PV electricity sold (MW h)	–	0	20217	11762	0	203	0	0
Cogenerated heat (MW h)	–	8627	8614	8214	9666	8550	9835	8197
Heat from boilers (MW h)	21528	1722	1753	1824	1062	1384	669	1668
Heat from ST field (MW h)	–	12259	12220	12809	11882	13189	12205	13352
Total dissipated heat (MW h)	343	1424	1402	1663	1425	1937	1524	2033
Total investment (k€)	208	8421	33127	33202	8607	11267	8381	7350
Support policy cost (k€/y)	–	–	4144	2830	803	253	454	1269
Annual investment (k€/y)	23	762	3475	3483	783	1074	758	644
Operating cost (k€/y)	3793	2830	−1314	828	3537	2561	2791	2812
Objective function (k€/y)	**3816**	**3592**	**2162**	**1480**	**3517**	**3382**	**3549**	**3457**
Obj. fun. reduction vs. TC (%)	–	5.8	43.3	61.2	7.8	11.4	7.0	9.4
PBP respect to TC (year)	–	8.5	6.4	5.7	7.9	7.4	8.2	7.3
CO_2 emissions (Ton/y)	15437	10879	863	874	6317	9714	10769	10858
CO_2 saved cost (€/Ton)	–	–	414	283	176	217	4127	60429
Energy Saving vs. TC (MW h)	–	21366	67259	67274	22277	26739	21804	21545
Energy Saving cost (€/MW h)	–	–	62	42	36	9	21	59

The bold numbers represent the values of the objective functions of the optimized models, i.e. minimum total annual cost of the different energy systems analysed.

and the Energy Saving are zero compared with Case 0. Finally, the CO_2 saved cost and the Energy Saving cost are even worse than the ones of Case 5 because of a higher support policy cost.

For a clear comparison, tons and costs of the CO_2 saved and amounts and costs of the Energy Saving for Cases 1 to 6 are shown in Fig. 3, left and right respectively.

Taking previous considerations into account, the most attractive support policies are shown to be the ones of Case 2 (Feed in Premium for PV production), Case 3 (cogeneration with biofuel) and Case 4 (support of tons of oil equivalent saved). The high value of saved CO_2 in Case 2 corresponds to the installation of a PV field of the maximum size and a quite high support policy cost (note that Case 1 is even less attractive than Case 2, in all respects). Therefore, excluding Case 2, a sensitivity analysis of Cases 3 and 4 is performed by increasing the amount of the incentive with the aim of evaluating further possible economic and environmental benefits. Figs. 4 and 5 show the quantities and the costs of saved CO_2 and Energy Saving for Case 3 and 4, varying the amount of the respective incentives.

Fig. 4 shows that the very high improvements obtained by increasing the incentive of the Case 3 by 25% and 50% correspond to a very high increase of the unitary costs to sustain these benefits.

Fig. 5 shows the effect of increasing the incentive of the Case 4 from 10% to 50%. It can be inferred that a minimum value of the CO_2 saved cost is expected when the incentive is increased by about 30%, while looking at the Energy Saving, the benefit increases but its unit cost increases too. It can be easily inferred that all results and considerations depend, to some extent, on the data used for energy vector prices and for the heat and electricity demands of each user. Nevertheless, a sensitivity analysis of an energy supply system of a similar kind [41] shows that the optimal structure of the system is not affected by a 15% variation of gas and electricity prices, when they both vary in a parallel manner.

Considering the possible variation of energy demands, further analyses have been performed.

Table 5 compares the main economic and energy parameters of Case 0 (without incentives) when electric and heating demands are both decreased (column 2) and increased (column 4) of 10%. The third and fifth columns represent the results obtained setting the sizes of machines and components at the values shown in Table 4 and varying the energy consumptions. Thus the structure is fixed and only the operation is optimized; the variations (Δ%) are calculated compared to the simultaneous optimization of structure and operation.

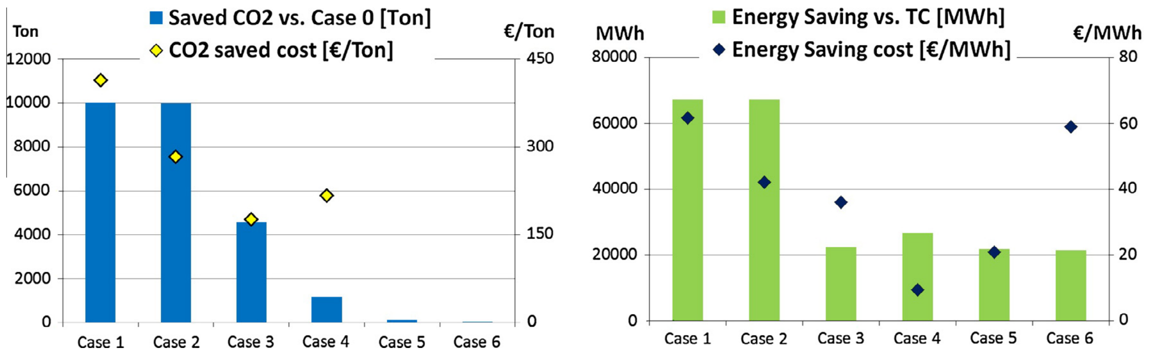

Fig. 3. Saved CO_2 (left) and Energy Saving (right) of the optimized cases.

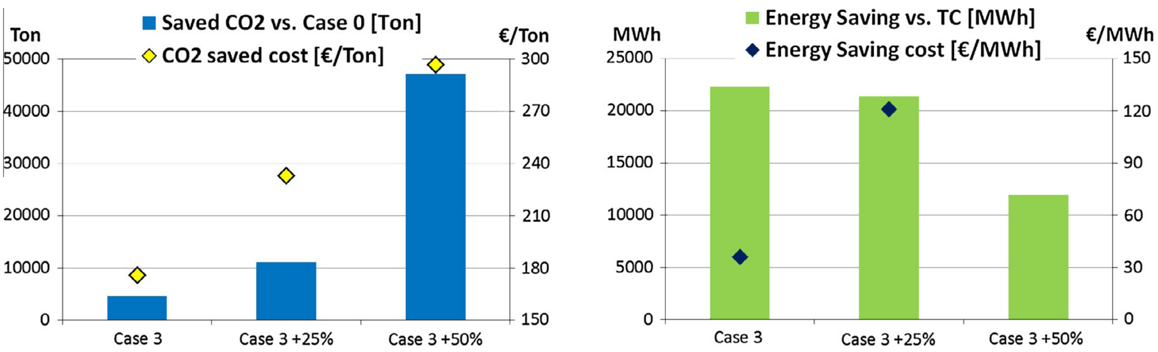

Fig. 4. Sensitivity analysis of saved CO_2 (left) and Energy Saving (right) of Case 3.

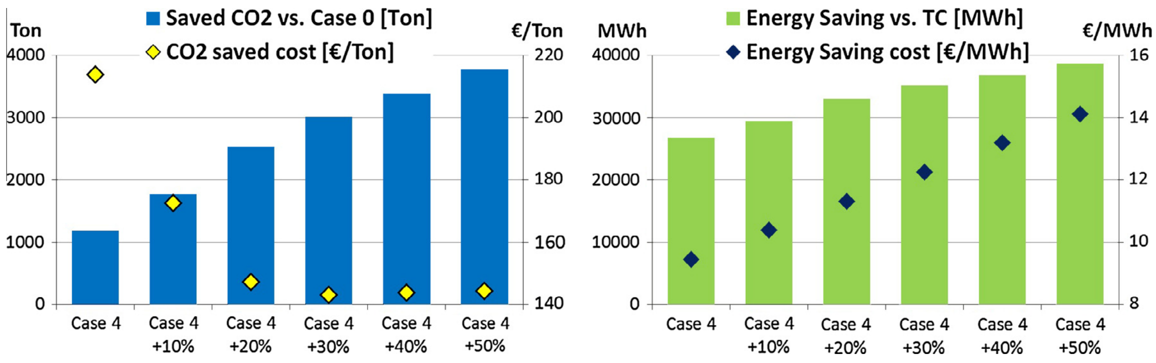

Fig. 5. Sensitivity analysis of saved CO_2 (left) and Energy Saving (right) of Case 4.

Table 5
Case 0 decreasing and increasing the energy demands of 10%.

	Case 0	−10%	Δ%	Set sizes	Δ%	+10%	Δ%	Set sizes	Δ%
C_{tot} (k€/y)	3592	3271	−8.9	3279	0.2	3914	9.0	3928	0.4
CO_2 (Ton/y)	10879	9864	−9.3	9686	−1.8	11977	10.1	12210	1.9
E_{cog} (MW h)	6721	5771	−14.1	5997	3.9	7392	10.0	7427	0.5
E_p (MW h)	15022	13653	−9.1	13595	−0.4	16519	10.0	16303	−1.3
E_s (MW h)	1526	1229	−19.5	1397	13.7	1672	9.6	1491	−10.8
H_{cog} (MW h)	8568	7766	−9.4	7857	1.2	9310	8.7	9547	2.5
H_{boi} (MW h)	1722	1574	−8.6	995	−36.8	2104	22.2	2841	35.0
H_{st} (MW h)	12259	10987	−10.4	12220	11.2	13429	9.5	12220	−9.0
S_{cog_8} (kW)	657	565	−14.0	638	12.9	705	7.3	638	−9.5
S_{cog_9} (kW)	881	753	−14.5	872	15.8	956	8.5	872	−8.8
S_{boi_cu} (kW)	1947	1795	−7.8	1984	10.5	2265	16.3	1984	−12.4

Analysing Table 5 the first observation is that the structure of the system never changes even when varying the energy demands: the optimization selects a boiler and two CHP units. Moreover the variations of energy parameters and component sizes are proportional to the change of energy consumption and they are always very close to ±10%. It can be also noted that increasing the demand

Table 6
Case 4 decreasing and increasing the energy demands of 10%.

	Case 4	−10%	Δ%	Set sizes	Δ%	+10%	Δ%	Set sizes	Δ%
C_{tot} (k€/y)	3382	3081	−8.9	3096	0.5	3679	8.8	3692	0.4
SP (k€/y)	253	225	−11.1	236	4.9	278	9.9	264	−5.0
CO_2 (Ton/y)	9714	8795	−9.5	8538	−2.9	10667	9.8	10967	2.8
CO_2 saved cost (€/Ton)	44	44	0.0	44	0.0	44	0.0	44	0.0
E_{cog} (MW h)	6773	6073	−10.3	6332	4.3	7788	15.0	7749	−0.5
E_p (MW h)	13224	11852	−10.4	11693	−1.3	14382	8.8	14409	0.2
E_{pv} (MW h)	2115	1874	−11.4	2092	11.6	2276	7.6	2092	−8.1
E_s (MW h)	1894	1603	−15.4	1921	19.8	2208	16.6	2011	−8.9
H_{cog} (MW h)	8550	7940	−7.1	8058	1.5	9551	11.7	9652	1.1
H_{boi} (MW h)	1384	1144	−17.3	690	−39.7	1540	11.3	2236	45.2
H_{st} (MW h)	13189	11522	−12.6	12804	11.1	14080	6.8	12804	−9.1
S_{cog_8} (kW)	733	621	−15.3	711	14.5	787	7.4	711	−9.7
S_{cog_9} (kW)	885	842	−4.9	949	12.7	1057	19.4	949	−10.2
S_{boi_8} (kW)	1895	1820	−4.0	2073	13.9	1992	5.1	2073	4.1

by 10% has a positive effect on the total cost, which is only 9% higher. On the other hand, decreasing the demand by 10% has a negative effect on the objective function because it decreases only by 8.9%. When sizes are set and only the operation is optimized, the objective function (total cost of the system) increases by less than 0.5%. In both cases, the non-optimal sizes of the components are compensated for increasing or decreasing the quantity of electricity sold and the heat produced by the boiler, while the CO_2 emission variations (positive or negative) are directly related to the ST field size: when it is bigger than the optimal size, the CO_2 emissions are lower than in the global optimal solution and vice versa.

A similar analysis has also been carried on for Case 4 (White Papers) and the results are shown in Table 6.

As happened in Case 0, the first observation looking at Table 6 is that the structure of the system never changes even when varying the energy demands: the optimization selects a boiler and two CHP units. Similar comments may be also developed concerning the simultaneous optimization of structure and operation. The main difference is that a PV field is also present as a result of the considered incentive. Also in this Case 4, when sizes are set and only the operation is optimized, the total cost of the system increases by less than 0.5%.

Specifically, when the energy demand is decreased by 10% and thus the sizes of the ST and PV fields are oversized compared to the optimized case, the CO_2 emission variation is negative (the CO_2 emissions decrease), therefore the Support Policy increases (meaning a higher subsidy for good performance) and the objective function (the total cost of the system calculated with Eq. (1)) decreases. Conversely, when the energy demand is increased by 10% the CO_2 emissions are higher due to undersized ST and PV fields, so the amount of the incentive is lower and the objective function increases.

It is important to note that the variation of the energy demands does not affect the cost of the CO_2 saved (calculated compared to the Traditional Case – TC), even if the CO_2 emissions and the amount of the incentive change.

6. Conclusion

This paper presents the evaluation of different support policies, aimed at improving energy efficiency and the usage of renewable energy resources in the industrial sector.

A mixed integer linear optimization model has been used to evaluate the effect of the different economic support policies on the configuration and operation of the distributed energy supply system for an industrial area, allowing the minimum cost for the owners of the plants. The results show that, if photovoltaic production is not supported, the PV modules are not installed, while the solar thermal collectors are affordable (on the basis of the considered economic data of energy vectors and components) and they are included in the optimal solutions, even without any incentive. The actual profitability of investing on this solution has to be evaluated taking into account a payback period greater than 8 years.

When PV production is incentivized a PV field of the maximum available size is installed. The payback period decreases to around 6 years, but the cost for the society of the energy benefits obtained is quite high.

Supporting the capital cost reduction of CHP systems and ST collectors result in an economic advantage for the owner of the plants, but no environmental benefit is obtained.

Fair environmental benefits are achievable through incentivizing production of energy by cogeneration from biofuel. However, the hypothesis of considering the CO_2 emission factor of the biofuel combustion as zero may be questionable.

Incentivizing the reduction of primary energy consumption (in terms of tons of oil equivalent) various interesting improvements in the optimal energy supply system are obtained. In particular, all the components that positively affect the energy saving of the system present a size increase in comparison with the non-incentivized case. The social cost of the support policy is the lowest of all the analysed cases and the unit cost of the Energy Saving is also the lowest. The sensitivity analysis suggests that a minimum value of the environmental benefit costs may be reached by increasing the amount of the incentive in the range 115–140 € per ton of oil equivalent saved. With reference to possible variations of the energy demands, variations of ±10% do not affect the unit cost of the CO_2 saved, even if the CO_2 emissions and the amount of the incentive change.

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