Complex energy networks optimization: Part II - Software application to a case study

COMPLEX ENERGY NETWORKS OPTIMIZATION: PART II – SOFTWARE APPLICATION TO A CASE STUDY

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ABSTRACT

In order to increase the exploitation of the renewable energy sources, the diffusion of the distributed generation systems is grown, leading to an increase in the complexity of the electrical, thermal, cooling and fuel energy distribution networks. With the main purpose of improving the overall energy conversion efficiency and reducing the greenhouse gas emissions associated to fossil fuel based production systems, the design and the management of these complex energy grids play a key role.

In this context, an in-house developed software, called COMBO, presented and validated in the Part I of this study, has been applied to a case study in order to define the optimal scheduling of each generation system connected to a complex energy network. The software is based on a non-heuristic technique which considers all the possible combination of solutions, elaborating the optimal scheduling for each energy system by minimizing an objective function based on the evaluation of the total energy production cost and energy systems environmental impact.

In particular, the software COMBO is applied to a case study represented by an existing small-scale complex energy network, with the main objective of optimizing the energy production mix and the complex energy networks yearly operation depending on the energy demand of the users. The electrical, thermal and cooling needs of the users are satisfied with a centralized energy production, by means of internal combustion engines, natural gas boilers, heat pumps, compression and absorption chillers. The optimal energy systems operation evaluated by the software COMBO will be compared to a Reference Case, representative of the current energy systems set-up, in order to highlight the environmental and economic benefits achievable with the proposed strategy.

Keywords: scheduling optimization; non-heuristic algorithm; complex energy networks; cogeneration; residential sector.

NOMENCLATURE

C	cost [€]
COP	coefficient of performance [-]
EER	energy efficiency ratio [-]
ITER	iteration [-]
OF	objective function [€]
P	power [kW]
TOL	tolerance value [-]

Acronyms

AB	Auxiliary Boilers
AC	Absorption Chiller
CC	Compression Chiller
CHP	Combined Heat and Power
DG	Distributed generation
DHW	Domestic Hot Water
GA	Genetic Algorithm
HP	Heat Pump
ICE	Internal Combustion Engine
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
OF	Objective Function
SH	Space Heating

Greek symbols

λ	fuel [-]
η	efficiency [-]
ξ	specific cost [€/kW]

Subscripts and Superscripts

c	cooling
E	electricity
EM	electromechanical
F	fictitious
M	maintenance
mec	mechanical
NP	non-produced energy
pur	purchased
th	thermal

INTRODUCTION

With the growing diffusion of the distributed generation systems, as a consequence of the stringent constraints imposed by European and national legislations related to the environmental issues [1], the energy networks are becoming increasingly complex, both from the energy distribution and network management viewpoints [2, 3]. In particular, as it regards the residential sector, it has been estimated that cities are responsible for 67 % of the World's energy demand and are the major contributors of CO_2 emissions, producing more than 70 % of the global emissions [4]. Furthermore, it is expected that the world population who lives in the cities will increase in the next years, from the current percentage of 55 % to a percentage equal to 66% in 2050. As a consequence, urban areas will have a crucial role in the climate change contrast [5]. For these reasons, governments and researchers promote energy policy initiatives focused on the increase in the sustainability of urban areas. In this context, in order to further improve the energy conversion efficiency and to reduce the fossil fuel consumption and the pollutant emissions, the distribution of electrical, thermal and cooling energies, as well as the distribution of fuel, can be seen as strictly interconnected, giving rise to the so-called complex energy networks [6, 7].

One of the main challenges for these complex energy grids is represented by the optimization of the energy systems operation (*i.e.* the definition of optimal management criteria, which result in the energy systems optimal scheduling during the whole year of operation) [8-10]. Indeed, the determination of ideal systems set-up, as well as the control and operation of the integrated network, is not easy. With this purpose, several optimization algorithms can be applied, such as genetic algorithm (GA) [11, 12], particle swarm optimization [13] and firefly algorithm [14] – as it concerns heuristic models – or Linear Programming, Mixed Integer Linear Programming (MILP) [15-17] and Mixed Integer Non Linear Programming (MINLP) models [18, 19], as it regards exact methods. Considering the energy networks, genetic algorithms and MILP based models are the most widely used for the scheduling optimization problems. Furthermore, MINLP models are considered as an interesting way, but further efforts have to be made in order to maintain the nonlinear complexity of the problem and an admissible computation time (the temporal horizon is usually one year of operation).

In this context, a novel software called COMBO, based on a non-heuristic algorithm and able to solve the non-linear problem of systems load allocation, has been developed by the Authors and presented in the Part I of this study [20]. In detail, the software COMBO – evaluating a very high number of energy systems loads combinations (potentially all the combinations) – determines the optimal scheduling for a given set of energy systems, on the basis of an iterative procedure. The objective function of this software consists in the minimization of the total cost of energy production, including both economic and environmental aspects.

The main aim of the Part II of this study is represented by the application of the developed software to a case study, consisting of an existing residential neighborhood. The electrical, thermal and cooling energy required by the users is produced by means of internal combustion engines (operating as combined heat and power units), natural gas boilers, a heat pump, compression and absorption chillers. The software application allowed to define the optimal scheduling of the energy systems for a whole year of operation, minimizing the total energy production costs. The obtained results have been compared to a Reference Case, representing a common strategy in terms of set-up and operation for the existing energy distribution network which includes heat distribution (*i.e.* district heating network). The comparison allowed to demonstrate the benefits – from energy, environmental and economic viewpoints – achievable with the proposed strategy and with the application of the developed software.

METHODOLOGY

In this section the methodology and the hypothesis at the basis of the analysis will be presented. In detail, the software COMBO will be briefly introduced (a detailed description along with its validation is given in [20]), the case study and the reference case will be presented and the assumptions related to the energy systems and the economic analysis will be discussed.

Software COMBO

In order to optimize the operation of a complex energy network, the software COMBO has been developed by the University of Bologna. The realized software allows to evaluate the optimal load allocation among the various energy systems of a given network – characterized by electrical, thermal, cooling energy and fuel distribution – by minimizing an objective function based on the total cost of energy production. In Figure 1 a schematic flow chart of the software is presented. In detail, as can be noted from the figure, the input section of the software mainly consists in the definition of:

- energy demand of the users (electrical, thermal, mechanical – if present – and cooling power required by the users connected to the grid at each time step);
- prime movers (number, typology, size and main characteristics, such as the electrical, mechanical and thermal design power output, off-design behavior, electrical and thermal design efficiency, etc.);
- heating and cooling systems (number, typology, size, performance parameters, etc.);
- renewable source generators (typology, performances, peak power, etc.);
- tariff scenario (cost of the fuel, cost of purchased and sold electricity, etc.);
- internal parameters of the algorithm (iteration number, tolerance value, virtual machines performance parameters, etc.).

On the other hand, the output section of the software consists in the definition of the optimal load of each generation system composing the complex energy network and the associated total cost of energy production.

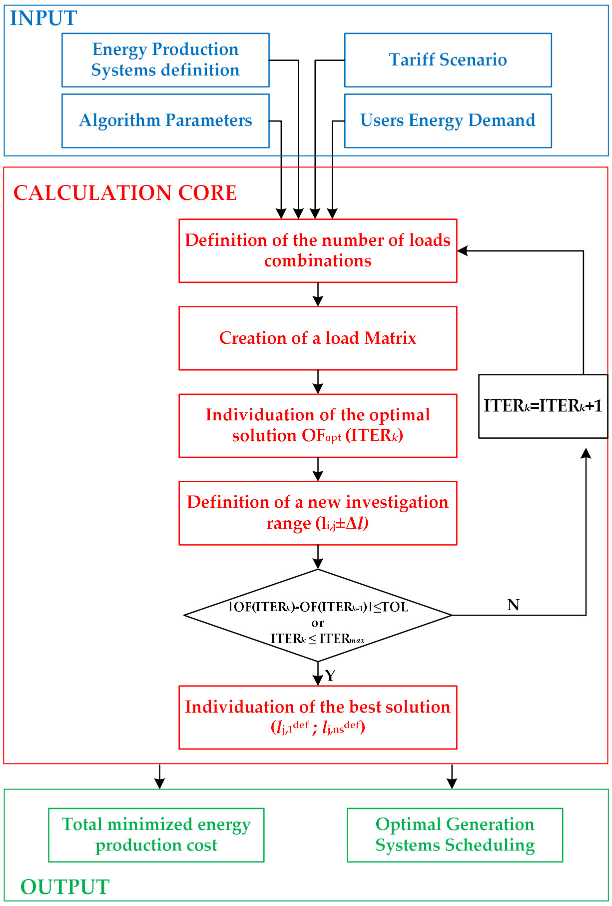

Figure 1 – Schematic flow chart of the software.

As can be noted from Figure 1, the calculation core of the software is based on an iterative process which is aimed at creating and investigating all the possible combinations between the energy systems loads, in order to find out the optimal solution minimizing the objective function.

In more detail, starting from the first iteration, the software defines the total number of possible load combinations on the basis of both (*i*) the number of energy systems composing the network and (*ii*) the total number of load combinations between them (which depends on the minimum and maximum load value that each unit can assumed). Then the software generates a load matrix, in which all the previously defined combinations are listed, and evaluates each one of them on the basis of an objective function, in order to identify the optimal combination. With the main purpose of obtaining a more accurate solution, once the optimal solution of the k^{th} iteration has been identified, at the k^{th}+1 iteration the developed algorithm defines a new solution range (namely a new matrix of loads) to investigate the solutions range around the optimal one identified in the previous iteration.

This iterative procedure ends if all the iterations – whose number has been defined as a parameter of the algorithm – have been processed and evaluated, or if the absolute value of the difference between the optimal objective functions of the k^{th} iteration and of the k^{th} -1 iteration is lower than a given tolerance value.

As already said, the research of the optimal solution consists in finding the load combination that minimizes an objective function (OF). In particular, the OF of COMBO software is defined as follows:

$$OF = C_\lambda + C_M + C_E + C_F \qquad (1)$$

where:

- C_λ indicates the costs of the fuel;
- C_E represents the costs due to the purchase of electricity from the national electric grid;
- C_M is the term which takes into account the maintenance costs of each energy system;
- C_F denotes the *fictitious costs* which have been defined in order to include also the environmental aspects in addition to the economic ones.

Before entering into the detail of the *fictitious costs*, it must be highlighted that, due to the combinatorial nature of the developed algorithm, there is the possibility that some of the evaluated solutions are characterized by an energy scrap between production and users demand (surplus or lack). To this respect, the definition of the *fictitious costs* (C_F) has been made with the main aim to avoid the energy non-production (namely to guarantee the users energy demand fulfillment). Therefore, the mechanical, thermal and cooling energy surplus are not defined within the *fictitious costs*, but are accounted with the terms C_E, C_λ and C_M of the Eq.1. In more detail, depending on the nature of the energy surplus – such as from the employment of prime movers, auxiliary boilers, heat pump, compressor chillers, etc. – it will be evaluated as an increase in the fuel introduced or as an increase in the electricity purchase for the energy system operation and, at the same time, it will results also in an increase in the maintenance cost. As example, if the energy surplus is due to the auxiliary boiler operation, it will be accounted as an increase in the fuel used to feed it. This method allows to avoid that the small quantities of energy surplus, which can occur due to the combinatorial nature of the algorithm, will considerably affect the objective function if evaluated with multiplier factors.

As a consequence, the *fictitious costs* (C_F in Eq.1) only account for the energy non-production and are evaluated by the software COMBO with the following equation:

$$C_F = C_{th,NP} + C_{c,NP} + C_{mec,NP} \qquad (2)$$

where the thermal, cooling and, if present, the mechanical non produced energy amounts are indicated respectively with the terms $C_{th,NP}$, $C_{c,NP}$ and $C_{mec,NP}$. In particular, to evaluate these quantities, three virtual machines – a heat pump, a compressor chiller and an electric engine – have been defined and supposed to be powered by the electrical national grid. These systems do not concur for the energy production for the users energy needs fulfillment, but they are defined, as algorithm input parameters, with the only purpose of categorizing the fictitious costs. Furthermore, it has been assumed that these machines are characterized by lower performance parameters in terms of electrical efficiency, COP and EER respectively for the electric engine, the heat pump and the compressor chiller.

In more detail, by considering the specific cost of the electricity purchase for the virtual machine powering $\xi_{E,pur}$, the fictitious costs related to the non-production can be further explicated. In particular, the cost of the thermal non-production $C_{th,NP}$ is evaluated with the following equation:

$$C_{th,NP} = \frac{Q_{th,NP}}{COP^*} \cdot \xi_{E,pur} \tag{3}$$

in which the term $Q_{th,NP}$ represents the non-produced thermal power and COP^* is the Coefficient of Performance of the virtual heat pump.

The cost of cooling non-production $C_{th,NP}$, instead, is determined as:

$$C_{c,NP} = \frac{P_{c,NP}}{EER^*} \cdot \xi_{E,pur} \tag{4}$$

being $P_{c,NP}$ the non-produced cooling power and EER^* the Energy Efficiency Ration of the virtual compressor chiller.

At least, the mechanical non-production cost $C_{mec,NP}$ is calculated as follows:

$$C_{mec,NP} = \frac{P_{mec,NP}}{\eta^*_{EM}} \cdot \xi_{E,pur} \tag{5}$$

where η^*_{EM} is the electromechanical efficiency of the virtual electric engine and $P_{mec,NP}$ represents the mechanical power non-produced.

In summary, the *fictitious costs* represent an additional cost which is accounted in the objective function with the aim to contribute to the minimization of the total cost of energy production by avoiding the non-fulfillment of the users energy demand.

Furthermore, it has to be highlighted that the electricity non-production is accounted within the term C_E of Eq.1. More in detail, this quantity is calculated with the following equation:

$$C_E = P_{EL,NP} \cdot \xi_{E,pur} \tag{6}$$

where the term $P_{EL,NP}$ represents the non-produced electrical energy while the term $\xi_{E,pur}$, according to the previously equations, indicates the specific cost of the electricity purchase.

A more detailed description of the calculation core of the software is given in the Part I of this work [20], along with its validation.

Case Study

The software COMBO has been applied to a Case Study which consists of a residential neighborhood network, presented in Figure 2.

In detail, the considered Case Study is a small-medium network located in the North of Italy, with a centralized energy generation station and composed by a total of 17 users, 13 of which are residential users (for a total of 960 residential units) and 4 of which are tertiary users (in particular a supermarket, one day hospital structure and two schools) [7].

In order to analyze the energy network operation with an yearly time horizon, the typical days representative of each season have been considered. To this respect, to identify the partition of each period, two main characteristics have been considered: (*i*) the seasonal average temperature and (*ii*) the users energy needs.

By analyzing the users energy needs (see Table 1) it can be noted that the spring and fall season are characterized by the demand for electricity and for domestic hot water (DHW), which are not affected by the seasonality. On the other hand, the request of thermal energy for space heating (SH) occurs only during wintertime.

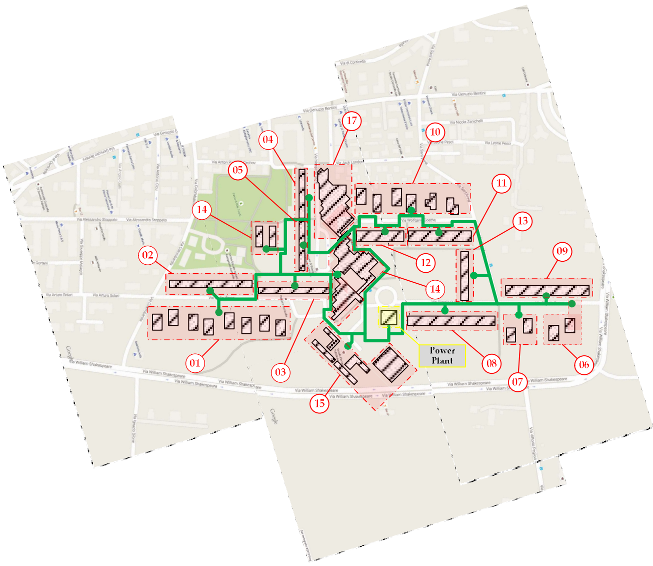

Figure 2 – Complex energy network scheme [7].

Table 1 – Typology of users energy need as a function of the season.

Type of energy need	Spring	Summer	Autumn	Winter
Electricity	✓	✓	✓	✓
Thermal energy (SH)	×	×	×	✓
Thermal energy (DHW)	✓	✓	✓	✓
Cooling energy	×	✓	×	×

Therefore, it can be reasonably assumed that the curves of the electrical and thermal energy demand are coincident for the spring and the fall seasons. Thus, three typical days have been considered for the annual analysis, representative of wintertime, summertime and mid-season. The following seasonal partition during the year has been assumed:

- winter: 183 days;
- mid-season: 90 days;
- summer: 92 days.

Furthermore, for the three representative days, the hourly profiles of the total electrical, thermal and cooling energy demand of the network are presented respectively in Figure 3, Figure 4 and Figure 5 [7]. To this respect, it should be highlighted that the electrical and cooling needs profiles represent the real demands of the users, while, as it regards the thermal need, also the thermal dissipations through the distribution network (that is a district heating network) have been included.

In detail, Figure 3 shows that the trends of the electrical demand are quite similar for wintertime, mid-season and summertime, since they account for the lighting, cold and/or hot appliances, computer side, etc., which are not so influenced by the seasonality. In particular, it can be observed that the hourly electrical demand is characterized by a minimum value, which occurs around 5 a.m. and by two peaks of request which occur around 9 a.m. and 9 p.m. respectively. Overall, the minimum value is equal to about 520 kW (during wintertime) and the maximum value is equal to 1˙479 kW (during middle season).

As it regards the thermal needs (see Figure 4), the behavior is quite similar during the mid-season and summertime, since only the domestic hot water request is considered. During these seasons, the thermal demand varies from a minimum value equal to 68 kW and 80 kW to a maximum value equal to 803 kW and 836 kW, respectively during summertime and mid-season. During wintertime, instead, the demand is higher due to the thermal energy demand for space heating, which ranges from a minimum value equal to 300 kW to a maximum value equal to about 11 MW. The minimum request occurs during the night (at 1 a.m.) for all the three typical days, while the maximum thermal need is registered at 9 a.m..

Finally, as it concerns the cooling demand shown in Figure 5, it is obviously presented only during summertime, since it accounts only the air conditioning needs. As can be noted from the figure, this request varies from a minimum value equal to 875 kW (occurring at 5 a.m.) to a maximum value equal to 2˙115 kW (occurring at 8 p.m.).

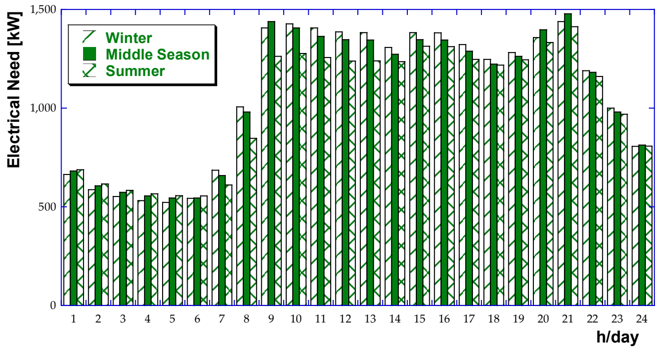

Figure 3 – Hourly electrical needs of the total users for the three typical days.

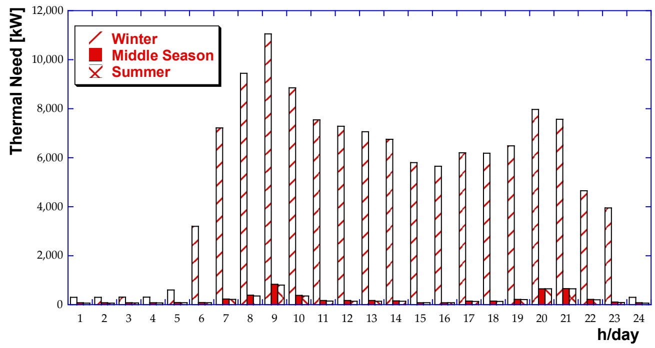

Figure 4 – Hourly thermal needs of the network for the three typical days.

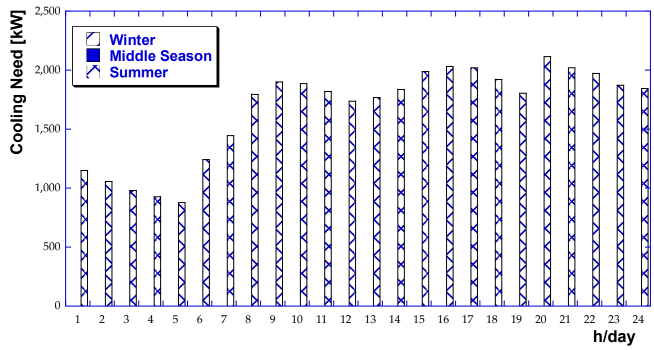

Figure 5 – Hourly cooling needs of the total users for the three typical days.

Energy Systems Assumptions

In order to fulfill the users' energy needs, the energy production systems considered for the case study are two internal combustion engines (operating as combined heat and power units), natural gas auxiliary boilers, a heat pump, compression and absorption chillers. The main design parameters of these energy systems are listed in Table 2.

In addition, in order to highlight the economic and environmental benefits obtainable with the proposed energy generation mix (which is quite unusual for the existing

networks), a Reference Case has been defined by considering the energy production systems and operation on the basis of the most common configuration for energy distribution networks.
In particular, this Reference Case includes – with reference to Table 2 – the ICE #1, the natural gas auxiliary boilers and the compression chillers. As it regards the systems operation during the year, for the Reference Case the internal combustion engine is assumed to be completely shut down during middle season and summertime (when thermal energy is required only for domestic hot water), while it is in operation at the design load from 9 a.m. to 8 p.m. during wintertime. All the remaining thermal energy needs are fulfilled by the natural gas auxiliary boilers. The electrical needs, instead, are partially covered by the ICE during wintertime and by electricity purchase for the remaining amount in wintertime and for the whole needs during summertime and middle season. To this respect, it has to be highlighted that the micro-cogenerative approach of this work is based on the minimization (or avoidance) of the electricity sale for the stability and frequency of the national electric grid.

Finally, the cooling needs are completely fulfilled via compression chillers and by the electricity purchase from the national electric grid.

Table 2 – Design parameters of the energy production systems included in the Case Study.

Internal Combustion Engine (ICE) #1		
Manufacturer	Jenbacher	
Model	JMS 420	
Fuel Type	Natural Gas	
Design Electric Power	[kW]	1˙415
Design Thermal Power	[kW]	1˙493
Design Electrical Efficiency	[-]	0.419
Design Thermal Efficiency	[-]	0.442
Internal Combustion Engine (ICE) #2		
Manufacturer	EMD	
Model	EMD45	
Fuel Type	Natural Gas	
Design Electric Power	[kW]	45
Design Thermal Power	[kW]	63
Design Electrical Efficiency	[-]	0.325
Design Thermal Efficiency	[-]	0.455
Auxiliary Boilers (AB)		
Design Thermal Power	[kW]	11˙600
Design Thermal Efficiency	[-]	0.80
Heat Pump (HP)		
Design Thermal Power	[kW]	20˙000
COP	[-]	4
Compressor Chillers (CC)		
Design Cooling Power	[kW]	2˙200
EER	[-]	4
Absorption Chillers (AC)		
Design Cooling Power	[kW]	2˙000
EER	[-]	0.67

Economic Analysis Assumptions

For the sake of completeness, the complex energy network operations have been also analyzed from the economic viewpoint. To this purpose, the economic analysis has been carried out by evaluating the real cost of energy production, namely without considering the fictitious costs included in the objective function of the software. To this respect, the fuel cost, the electricity purchase cost and the maintenance costs have been taken into account in the annual analysis. With respect to the maintenance costs of each energy system, the values assumed for the analysis are listed in Table 3.

Furthermore, the cost of the fuel (*i.e.* natural gas) has been assumed equal to 0.075 €/kWh. The assumed cost of the electricity purchase from the national grid, instead, is different during the day depending on the time frame: a value equal to 0.250 €/kWh has been assumed from 9 a.m. to 8 p.m. and a value equal to 0.125 €/kWh has been assumed from 9 p.m. to 8 a.m..

Table 3 – Maintenance costs assumed for the analysis.

Maintenance Costs		
Internal Combustion Engines	[€/kWh$_e$]	0.020
Auxiliary Boilers	[€/kWh$_t$]	0.005
Heat Pump	[€/kWh$_t$]	0.010
Compressor Chillers	[€/kWh$_c$]	0.006
Absorption Chillers	[€/kWh$_c$]	0.002

RESULTS AND DISCUSSION

In this section, the hourly-based energy and economic results, obtained for the Case Study and divided into the three typical days, will be presented and discussed. Furthermore, a comparison with the Reference Case in terms of energy and economic annual results will be presented.

Energy results

The hourly-based energy results, obtained for the three considered typical days by the application of the software COMBO, are presented in Figure 6, Figure 7 and Figure 8, respectively as it concerns the electrical, thermal and cooling energy.

In detail, Figure 6 – for each typical day and for each hour of the day – shows, on one hand, the total electrical energy needs of the network (composed by the users electrical need, the heat pump electrical need and the compression chillers electrical need) and, on the other hand, the electrical energy fulfillment mix. As it can be seen from the figure, during wintertime the internal combustion engines cover around 40 % of request (with a maximum value equal to 95 % of the total electrical needs at 6 a.m.), being in operation for the whole day excepting for 4 a.m., when the minimum electrical request occurs and it is entirely covered by electricity purchase. The behavior registered during summertime shows a higher ICE production during the day (covering between 33 % and 93 % of the total electrical need), while a complete shut down during the night. Instead, during middle season, only the smaller CHP unit (ICE #2 in Table 1) is in operation, due to the lower total electrical needs: indeed, as it will be better clarified discussing the thermal and cooling needs results, the heat pump gives a small contribute while the compression chillers are shut down (no cooling request occurs during middle season). As a consequence, the large part of electrical need is fulfilled by electricity purchase.

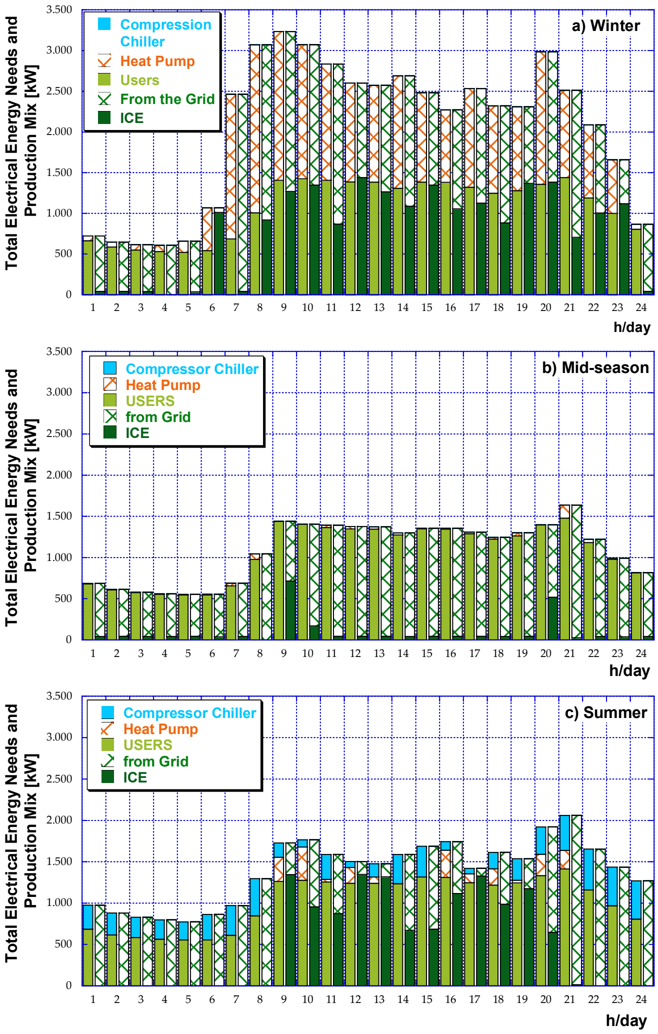

Figure 6 – Hourly total electrical energy needs along with the energy production mix for (a) winter, (b) mid-season and (c) summer.

Furthermore, in Figure 7 the thermal energy production mix is presented.

In this case, indeed, during wintertime and middle season the total thermal needs coincide with the users' thermal needs. Thus, for the sake of simplicity, the total thermal needs are not reported in Figure 7a and in Figure 7b. On the other hand, for summertime, the thermal energy production mix is shown in Figure 7c along with the total thermal needs (composed by the users' thermal needs plus the absorption chillers thermal input).

As it regards the wintertime (see Figure 7a), it can be observed that the users' thermal need is mainly satisfied by the heat pump (used to cover about 76 % on average), followed by the ICEs (covering around 17 %) and finally by the auxiliary boilers (about 7 %). A different behavior can be noted in middle season (see Figure 7b), where the thermal demand is met for the larger part by the ICE (51 % on average). This result is due to the second internal combustion engine (ICE #2), which – thanks to the low rated power – can be operated at high efficiency also with a small thermal request. In any case, the heat pump contribution remains high also in middle season, covering about 44 % of the thermal needs. The auxiliary boilers, instead, fulfill only about 5 % of the thermal energy need.

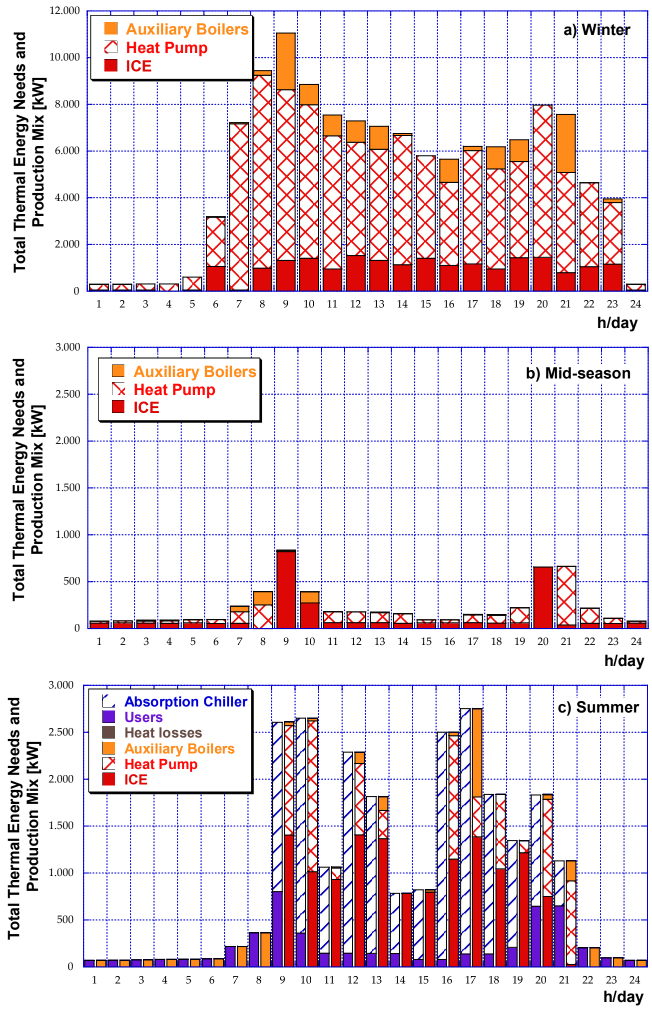

Figure 7 – Hourly total thermal energy needs along with the energy production mix for (a) winter, (b) mid-season and (c) summer.

As it regards the summertime (see Figure 7c), during the night (from 10 p.m. to 8 a.m.) the total thermal need is completely fulfilled by the natural gas auxiliary boilers, while during the day the needs are covered by the ICE for around 61 % on average and by the heat pump for 32 % on average. Finally, it must be highlighted that – during few hours of summertime – a small amount of thermal dissipations through the chimney is registered. However, the heat losses are always lower than 1.5 % of the produced thermal energy and, consequently, can be neglected.

Finally, the energy production mix to fulfill the cooling demand is presented in Figure 8 for the summertime typical day (no cooling needs occur during wintertime and middle season).

As can be observed from the figure, the larger part of the users' cooling need is covered by the compression chillers, which fulfill 100 % of the users' needs during the night (from 10 p.m. to 8 a.m.) and 47 % on average during the daily hours. The remaining amount of cooling need is obviously covered by the absorption chillers (for 53 % on average during the daily hours, not operating during the night).

Economic results

The economic results are presented in Figure 9, in terms of hourly total cost of energy production as a function of the considered typical day, for the Case Study in comparison with the Reference Case (red line in figure). The results for the case study are presented highlighting the different contribution of the maintenance costs, the fuel cost and the electricity purchase costs.

Relating to the Case Study, during wintertime (Figure 9a) the major contribution to the total cost of energy production is given by the electricity purchase, ranging from a minimum value equal to 3 % to a maximum value equal to around 96 % (and covering about 49 % on average of the daily cost). The second contribution to the total cost of energy production is due to the fuel cost, with an average value slightly lower than 39 %. No fuel costs are registered at 4 a.m., when all the users' energy needs are satisfied via electricity purchase, while a maximum value equal to around 79 % is obtained at 6 a.m.. Finally, the maintenance costs contribute to the total cost of energy production for an amount ranging from 3 % to 19 % (with a daily average contribution equal to around 12 %). As it regards the mid-season (Figure 9b), instead, the resulting total energy production cost is almost entirely due to the purchase of electrical energy from the grid, which accounts for 89 % of the total daily cost. Furthermore, the fuel costs represent only 9 % of the total daily cost and the remaining percentage is due to the maintenance costs.

Finally, during summertime, a different behavior – with respect to wintertime and middle season – can be seen for the economic results (see Figure 9c). In particular, the major contribution to the total cost of energy production is given by the fuel costs (covering around 53 % of the daily cost, with a minimum value equal to 4 % and a maximum value equal to 84 %), followed by the electricity purchase cost (which contributes for 39 % of the daily cost, with a minimum value equal to 6 % at 5 p.m. and a maximum value equal to 90 % at 1 a.m.). As for the wintertime and middle season typical days, the smaller contribution is given by the maintenance costs, which during summertime covers 8 % of the daily cost of energy production.

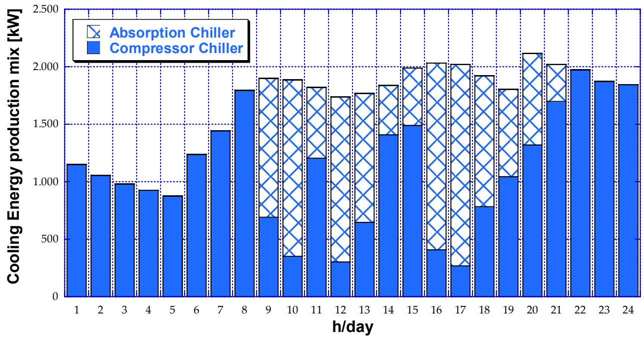

Figure 8 – Hourly cooling energy production mix for the typical day representative of summertime.

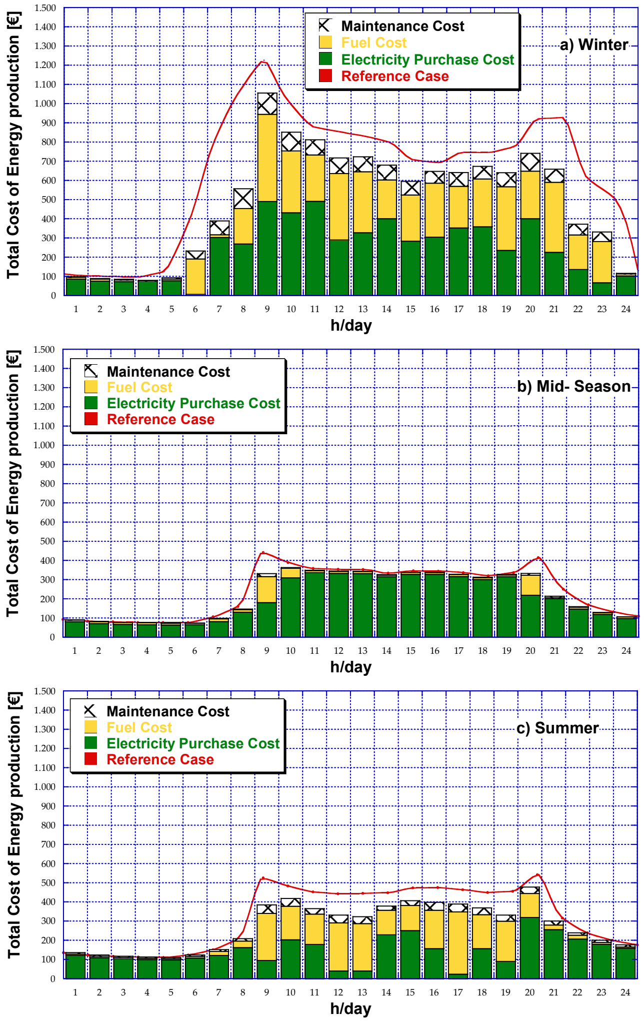

Figure 9 – Hourly total cost of energy production for (a) winter, (b) mid-season and (c) summer.

Furthermore, from Figure 9 it can be observed that the hourly based total costs of energy production obtained for the Reference Case are always greater or – at least – equal to the ones obtained for the Case Study. In more detail, for all the considered typical days, the total costs of energy production of the Reference Case are almost coincident to the ones of the Case Study during the night, while a difference is registered during the daily hours. This difference is more evident during wintertime and summertime, due to a lower fuel consumption for the Case Study with respect to the Reference Case. Indeed, while in the Reference Case the thermal energy needs are fulfilled only by the employment of ICE and auxiliary boilers, in the Case Study also a heat pump is considered. In particular, a large employment of the heat pump occurs during wintertime and summertime allowing a decrease in the fuel consumption and, thus, also in the related cost. During middle season, instead, the heat pump operation is limited and, as a consequence, the economic results for the Case Study and for the Reference Case are similar.

Annual evaluation

The energy and economic annual results – obtained by modelling 183 days as wintertime typical day, 90 days as middle season typical day and 92 days as summertime typical days – are summarized in Table 3, both for the Reference Case and for the Case Study.

In particular, the Case Study annual results show that the fuel consumption is reduced for more than 50 % with respect to the Reference Case: this result, as previously mentioned is due to the heat pump operation (17˙371 MWh/y), with the consequent important decrease in the auxiliary boilers employment (3˙493 MWh/y instead of 20˙568 MWh/y). As it regards the electrical energy, an increase in the purchase from the national grid is registered for the Case Study, but the electrical energy sold to the network results completely nullified.

Table 3 – Yearly evaluation results.

Parameter	Ref. Case	Case Study
Electricity sold to the grid [kWh/y]	128˙704	0
Electricity Purchase [kWh/y]	7˙323˙344	9˙465˙904
Electrical Energy from ICE [kWh/y]	3˙107˙340	4˙909˙482
Fuel Energy [kWh/y]	33˙125˙985	15˙040˙816
Thermal Energy from ICEs* [kWh/y]	3˙277˙910	5˙866˙237
Thermal Energy from AB [kWh/y]	20˙567˙919	3˙493˙436
Thermal Energy from HP [kWh/y]	-	17˙371˙238
Cooling Energy from CC [kWh/y]	3˙680˙686	2˙463˙601
Cooling Energy from AC [kWh/y]	-	1˙217˙084
Total cost of energy production [€/y]	3˙996˙511	3˙261˙979

* ICE #1 and ICE #2 for the Case Study; only ICE #1 for the Reference Case (see Table 1).

Finally, as a consequence of the energy results, the annual total costs of energy production are lower for the Case Study (decreased for a value equal to around 18 %), demonstrating the economic and energy benefits resulting from the proposed strategy and the application of the developed software.

CONCLUSIONS

In the last years, an increase in the complexity of the electrical, thermal and cooling energy and fuel distribution networks has been seen, as a consequence of the increased penetration of renewable sources generators. With the purpose of further improving the energy conversion efficiency and of reducing the pollutant emissions, the optimal management of these complex energy grids is a fundamental aspect.

In the Part II of this study, the software COMBO – developed for the optimization of the loads allocation of a number of energy systems composing a network and presented in detail in the Part I – has been applied to a Case Study, consisting in a residential neighborhood located in the North of Italy. The electrical, thermal and cooling needs of the users are fulfilled by means of internal combustion engines (operating as CHP units), natural gas auxiliary boilers, a heat pump, compression and absorption chillers. Furthermore, the carried out annual energy and economic analysis accounts for three typical days representative of wintertime, mid-season and summertime. In addition, a Reference Case has been defined considering the energy production systems and operation of the most common configuration for energy distribution networks, with the aim to evaluate the energy and economic advantages achievable with the proposed (and quite unusual) energy generation mix. In detail, the Reference Case includes one internal combustion engine, natural gas auxiliary boilers and compression chillers.

The optimized electrical production mix resulting from the application of the software COMBO shows that, during wintertime the internal combustion engines is in operation for almost the whole day (covering around 40 % of request), while during summertime is completely shut down in the nighttime. As it regards mid-season, the larger contribute is given by the electricity purchase. Relating to the optimized thermal production mix, a large use of the heat pump is registered during wintertime and mid-season, where only a percentage between 5 % and 7 % is satisfied by means of the auxiliary boilers. On the other hand, the major contribution to the thermal needs fulfillment during the summer is due to the auxiliary boilers employment during the night and mainly to the ICEs during the day. Relating to the optimized cooling production mix, the results show that the major contribution is given by the compression chillers with respect to the absorption chillers (operating only in the daily hours).

Furthermore, the annual energy results show that the fuel consumption is reduced for more than 50 % with respect to the Reference Case, thanks to the heat pump operation (17˙371 MWh/y), with the consequent significant decrease in the auxiliary boilers employment (3˙493 MWh/y instead of 20˙568

MWh/y). Moreover, even if an increase in the electricity purchase from the national grid is registered for the Case Study, the electrical energy sold to the network results completely nullified, with consequent benefits in terms of grid stability.

Relating to the economic evaluation, the results highlight that the total costs of energy production (sum of fuel, electricity purchase and maintenance costs) of the Reference Case are – for all the considered typical days – almost coincident to the ones of the Case Study during the night, while a difference is registered during the central hours of the day. This difference, remarkable especially during wintertime and summertime, is mainly due to the lower fuel consumption of the Case Study with respect to the Reference Case and attributable to the heat pump operation. As a consequence of the fuel consumption reduction, along with the electricity fluxes variation, the annual total costs of energy production result about 18 % lower for the Case Study compared to the Reference Case. In conclusion, the comparison allowed to demonstrate the benefits – from energy and economic viewpoints – achievable with the proposed strategy and with the application of the developed software.

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