Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2451 – 2459

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Design optimization of a distributed energy system through cost and exergy assessments

Marialaura Di Somma*[,a], Bing Yan[c], Nicola Bianco[b], Giorgio Graditi[a], Peter B. Luh[c], Luigi Mongibello[a], Vincenzo Naso[b]

[a]*ENEA – Italian National Agency for New Technologies, Energy and Sustainable Economic Development, CR Portici, 80055 Portici, Italy*

[b]*Dipartimento di Ingegneria Industriale (DII), Università degli studi Federico II, P.le Tecchio, Napoli 80125, Italy*

[c]*Department of Electrical and Computer Engineering, University of Connecticut, Storrs, CT 06269, USA*

Abstract

In recent years, Distributed Energy Systems (DESs) have been recognized as a good option for sustainable development of future energy systems. With growing environmental concerns, design optimization of DESs through economic assessments only is not sufficient. To achieve long-run sustainability of energy supply, the key idea of this paper is to investigate exergy assessments in DES design optimization to attain rational use of energy resources while considering energy qualities of supply and demand. By using low-temperature sources for low-quality thermal demand, the waste of high-quality energy can be reduced, and the overall exergy efficiency can be increased. Based on a pre-established superstructure, the aim is to determine numbers and sizes of energy devices in the DES and the corresponding operation strategies. A multi-objective linear problem is formulated to reduce the total annual cost and increase the overall exergy efficiency. The Pareto frontier is found to provide different design options for planners based on economic and sustainability priorities, through minimizing a weighted-sum of the total annual cost and primary exergy input, by using branch-and-cut. Numerical results demonstrate that different optimized DES configurations can be found according to the two objectives. Moreover, results also show that the total annual cost and primary exergy input are reduced by 20% - 30% as compared with conventional energy supply systems.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Distributed Energy System; Design optimization; Annual cost; Exergy efficiency; Multi-objective linear problem.

1. Introduction

In recent years, depletion of fossil energy resources and global warming problems have prompted worldwide awareness about sustainability of energy supply. Distributed Energy Systems (DESs) have been recognized as a good option for sustainable development of future energy systems [1, 2]. A DES may consists of small-scale technologies including renewable ones and storage units, providing electric and thermal energy close to end-users [1]. To achieve the expected potentials of DESs, it is necessary to

* Corresponding author. Tel.: +39 0817723204; fax: +39 0817723344.
E-mail address: marialaura.disomma@enea.it.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.706

determine the system configuration rationally by selecting the appropriate energy devices, identifying their numbers and sizes, and the corresponding operation strategies, to match energy requirements of a specific end-user [2]. Design optimization of a DES is therefore essential for future energy planning, and inherently involves multiple and conflicting objectives [3, 4]. For instance, the interest of DES developers in achieving a system configuration with lowest costs might conflict with the interest of energy legislations, such as the EU ones, for sustainability concerns on reducing the waste of fossil energy resources and environmental impacts [4, 5]. In such a context, a multi-objective approach helps identify balancing solutions between economic and sustainability priorities to promote participation in the decision-making process and facilitate collective decisions [3].

According to [5], application of exergy principles in energy supply systems can achieve rational use of energy resources by taking into account the different energy quality levels of energy supply and building demand. In the literature, exergy has been linked to sustainability of energy supply since it clearly identifies the efficiency in energy resource use, and the importance of including exergy in energy legislations was discussed [5, 6]. DESs provide a great opportunity to demonstrate the effectiveness of exergy analysis in designing sustainable energy systems since multiple energy resources with different quality levels can be used to satisfy various user demand with different quality levels. By using low exergy sources, e.g., solar thermal or waste heat of power generation, for low-quality thermal demand, the waste of high-quality energy can be reduced, thereby increasing the overall exergy efficiency of DESs.

In previous works, exergy was investigated in DES operation through a multi-objective approach [7, 8]. With fixed DES configurations, optimized operation strategies were established by considering energy costs and exergy efficiency. As regards DES design optimization, most studies focused on minimizing the total annual cost as a crucial objective for DES developers [2, 9 - 13]. Also, before optimizing the design, "superstructures" were pre-established with energy devices chosen among the most commonly used ones in practical DESs. To identify the size of an energy device, several sizes were pre-fixed as possible choices to be selected through binary decision variables [2, 9 - 11]. However, how to select these sizes among the almost infinite possible solutions available in the market is difficult. Conversely, the size of an energy device was a continuous decision variable within the entire available size range, with efficiencies as well as specific capital and operation and maintenance (O&M) costs assumed constant in the entire size range [12, 13], while neglecting their variations with the sizes, which is significant for certain devices.

In this paper, exergy assessments are investigated in DES design optimization through a multi-objective approach. Based on a pre-established superstructure with multiple energy devices, a multi-objective linear problem is formulated to determine numbers and sizes of energy devices with the corresponding operation strategies on the Pareto frontier, thereby providing different design options for planners based on economic and sustainability priorities. In modeling energy devices, the entire size range available in the market as well as the variations of efficiencies, specific capital and O&M costs with sizes are taken into account. The economic objective is formulated as the total annual cost (total annualized investment cost, total annual O&M and energy cost) to be minimized. The exergetic objective is to maximize the overall exergy efficiency of the DES. With given energy demand, the total exergy required to meet the demand is known, and the exergetic objective is formulated as the total annual primary exergy input to be minimized. The Pareto frontier is found by minimizing a weighted sum of the two objectives, by using branch-and-cut. Numerical results show that different optimized DES configurations are found according to the two objectives. The Pareto frontier provides good balancing solutions for planners based on economic and sustainability priorities. The optimized DES configurations allow to reduce the total annual cost and primary exergy input by 20% - 30% as compared with conventional energy supply systems (CESs), where grid power is used for the electricity demand, natural gas boilers for domestic hot water (DHW) and space heating (SH) demand, and electric chillers for space cooling demand (SC).

2. Problem formulation and solution methodology

The DES superstructure consisting of the energy devices considered in the design optimization problem is shown in Fig. 1. Electricity demand and electricity required by heat pumps can be satisfied by grid power and Combined Heat and Power (CHP) systems. SC demand can be satisfied by CHPs, natural gas and biomass boilers through absorption chillers, heat pumps and thermal storage, whereas SH demand by CHPs, natural gas and biomass boilers, and thermal storage. DHW demand can be satisfied by CHPs, natural gas and biomass boilers, solar thermal collectors and thermal storage.

2.1. Decision variables

The decision variables include: existence, numbers, and sizes of energy devices; operation status (on/off) and energy rates provided by energy devices; capacities of thermal storage devices; heat rates input and output to/from thermal storage devices; electricity rate bought from the power grid. Existence and operation status of energy devices are binary. Numbers of energy devices are also determined through binary decision variables to be explained later. All the other decision variables are continuous.

2.2. Economic objective

The economic objective is to minimize the total annual cost of the DES, C_{TOT}, formulated as the sum of the total annualized investment cost, and the total annual O&M and energy costs:

$$C_{TOT} = C_{INV} + C_{O\&M} + C_{FUEL} + C_{PUR}^{GRID}, \tag{1}$$

where C_{INV} is the annualized investment cost of all energy devices of the DES, $C_{O\&M}$ is the total annual O&M cost of all energy devices, C_{FUEL} is the total annual cost of consumed fuels, and C_{PUR}^{GRID} is the annual cost of purchasing electricity from the power grid.

The annualized investment cost of energy devices is obtained through the capital recovery factor [2, 9 - 13], and the annual O&M cost of energy devices depends on the DES operation:

$$C_{INV} = \sum_i \sum_{k_i}^{K_i} CRF_i \left(C_{c,i} S_{i,k_i} \right), \; CRF_i = r(1+r)^{N_i} / \left[(1+r)^{N_i} - 1 \right], \quad C_{O\&M} = \sum_i \sum_{k_i}^{K_i} \sum_d \sum_{hr} OM_i R_{i,k_i,d,hr} D_t, \tag{2}$$

where CRF_i is the capital recovery factor of technology i; k_i is the energy device associated with technology

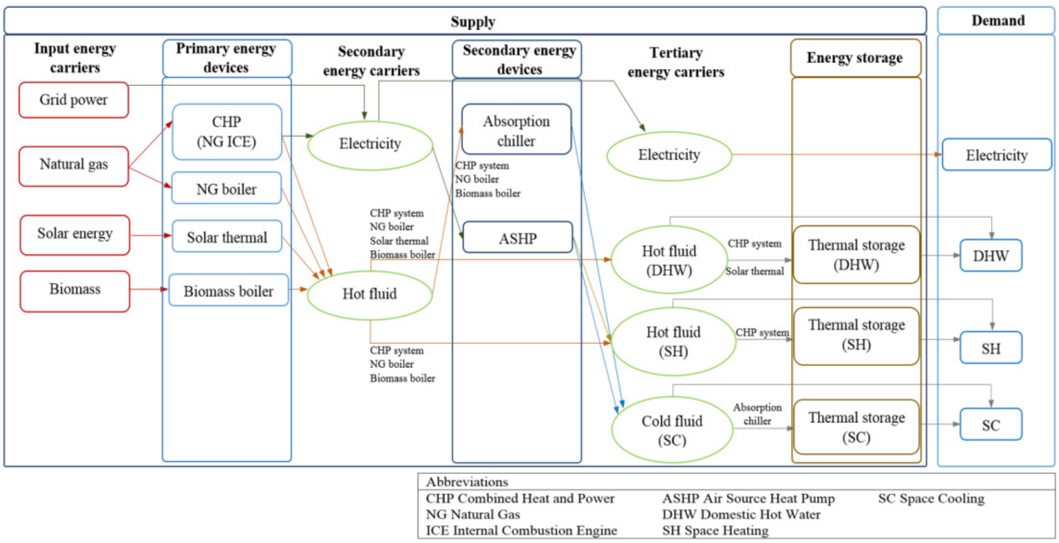

Fig. 1. Superstructure representation of the design optimization problem of the DES.

i, where K_i is its maximum number; S_{i,k_i} is the designed size of device k_i; $C_{c,i}$ is the specific capital cost; r is the interest rate; N_i is the lifetime in years; OM_i is the O&M cost; $R_{i,k_i,d,hr}$ is the energy rate provided by the device k_i at hour hr of day d; and D_t is the time interval length (1 hour).

The total annual costs of the consumed fuels and purchased grid power are formulated as:

$$C_{FUEL} = \sum_i \sum_{k_i}^{K_i} \sum_d \sum_{hr} P_{fuel,i} \left(R_{i,k_i d,hr} / \left(\eta_i LHV_{fuel} \right) \right) D_t,\ i \in \{NGICE, NGboiler, Bioboiler\}, \quad C_{PUR}^{GRID} = \sum_d \sum_{hr} P_{e,hr} E_{d,hr}^{GRID} D_t\ , \tag{3}$$

where η_i is the energy efficiency (thermal or electrical); $P_{fuel,i}$ and LHV_{fuel} are the price and lower heat value of the corresponding fuel (i.e., natural gas and biomass fuels), respectively; $P_{e,hr}$ is the time-of-day unit price of electricity from the power grid; and $E_{d,hr}^{GRID}$ is the electricity rate taken from the grid.

2.3. Exergetic objective

The exergetic objective is to maximize the overall exergy efficiency of the DES, as the ratio of the total annual exergy output (exergy required to meet the given user demand), Ex_{out}, to the total annual primary exergy input, Ex_{in}. With given energy demand, the total exergy required to meet the demand is known, and the overall exergy efficiency can be increased by reducing the total primary exergy input. At the supply side, the input energy carriers are grid power, natural gas, biomass and solar energy. Therefore, the exergetic objective is formulated as the total annual primary exergy input to be minimized as:

$$Ex_{in} = \sum_j \sum_d \sum_{hr} Ex_{j,d,hr} D_t\ , \tag{4}$$

where $Ex_{j,d,hr}$ is the exergy rate input to the DES related to the energy carrier j.

Electricity from the power grid is an energy carrier provided by power generation plants, and the exergy input rate to the DES depends on the exergy efficiency of the plants, ε_{gen} [7]:

$$Ex_{e,d,hr} = E_{d,hr}^{GRID} / \varepsilon_{gen},\ \forall d, \forall hr\ , \tag{5}$$

The exergy input rates of natural gas and biomass depend on their specific chemical exergy:

$$\begin{gathered} Ex_{fuel,d,hr} = \sum_i \sum_{k_i}^{K_i} \sum_{fuel} ex_{fuel} \left(R_{i,k_i,d,hr} / \left(\eta_i LHV_{fuel} \right) \right),\ ex_{fuel} = \varsigma_{fuel} LHV_{fuel}, \\ fuel \in \{natural\ gas, biomass\},\ i \in \{NGICE, NGboiler, Bioboiler\},\ \forall d, \forall hr \end{gathered}\ , \tag{6}$$

where ex_{fuel} is the specific chemical exergy of the fuel, and ς_{fuel} is the exergy factor [14].

Thermal energy output of solar thermal collectors at the corresponding temperature level is considered as the primary energy source [7]. The exergy input rate to solar thermal collectors, $Ex_{ST,d,hr}$, is defined as:

$$Ex_{ST,d,hr} = R_{ST,d,hr} \left(1 - T_{0,d,hr} / T_{coll}^{out} \right),\ \forall d, \forall hr\ , \tag{7}$$

where $T_{0,d,hr}$ and T_{coll}^{out} are the reference temperature (hourly ambient temperature), and the temperature of the heat transfer fluid at the exit of the collector field (assumed constant), respectively.

2.4. Constraints

Three main categories of constraints are established: design constraints, energy balances and operation constraints. As for design constraints, the designed size of the energy device k_i has to be within the minimum and maximum sizes of the related technology $S_i^{\min}$ and $S_i^{\max}$ available in the market:

$$S_i^{\min} x_{i,k_i} \le S_{i,k_i} \le S_i^{\max} x_{i,k_i},\ \forall i,\ k_i \le K_i\ , \tag{8}$$

where x_{i,k_i} is a binary decision variable, which is equal to 1 if the device k_i is implemented in the DES configuration. For the solar collector array, the designed area has to be lower than the available one. In the design optimization problem, the entire size range available in the market as well as the variations of efficiencies, specific capital and O&M costs with sizes are taken into account. These characteristics are usually piecewise linear functions of the size, which is a continuous decision variable, thereby making the problem nonlinear. To avoid this, the key idea is to divide the entire size range of an energy device into several small ranges, so that these characteristics can be assumed constant in each size range. Consider CHP with a gas-fired internal combustion engine (ICE) as an example. The designed size of CHP in the range l is limited by its minimum and maximum values $S_l^{CHP\min}$ and $S_l^{CHP\max}$ in this range:

$$S_l^{CHP\min} x_{k_{CHP},l}^{CHP} \le S_{k_{CHP},l}^{CHP} \le S_l^{CHP\max} x_{k_{CHP},l}^{CHP},\ \sum_l x_{k_{CHP},l}^{CHP} \le 1,\ \forall l,\ k_{CHP} \le K_{CHP}\ , \tag{9}$$

where $S_{k_{CHP},l}^{CHP}$ and $x_{k_{CHP},l}^{CHP}$ are defined similarly as in Eq (8) in the range l. Also, the summation of binary decision variables $x_{k_{CHP},l}^{CHP}$ over l has to be smaller than or equal to 1, ensuring that at most one range is selected.

To satisfy the given user demand, electricity, DHW, SH and SC energy balances are formulated based on the DES superstructure shown in Fig. 1. As for operation constraints, the energy rate provided by each energy device is limited by its minimum part load and the capacity. Still considering the CHP example, the electricity rate, $R_{k_{CHP},d,hr}$ is limited by its minimum and maximum values $R_{k_{CHP}}^{\min}$ and $R_{k_{CHP}}^{\max}$ if the device is on:

$$R_{k_{CHP}}^{\min} x_{k_{CHP},d,hr} \le R_{k_{CHP},d,hr} \le R_{k_{CHP}}^{\max} x_{k_{CHP},d,hr},\ R_{k_{CHP}}^{\min} = r^{CHP} \sum_l S_{k_{CHP},l}^{CHP},\ R_{k_{CHP}}^{\max} = \sum_l S_{k_{CHP},l}^{CHP},\ k_{CHP} \le K_{CHP},\ \forall d, \forall hr\ , \tag{10}$$

where $x_{k_{CHP},d,hr}$ is the on/off status of CHP, and r^{CHP} is the minimum part load (expressed in percentage of the designed size). The product of one continuous decision variable and one binary decision variable is linearized in a standard way. Beyond ICE, CHPs also involve heat recovery units for thermal purposes. The heat rate recovered by CHPs is subdivided among the heating coils for DHW and SH demand, and absorption chillers for SC as modeled in [7]. CHP ramp-rate constraints are also included to limit power generation between two successive time-steps. The natural gas and biomass boilers can be used to meet DHW and SH demand, and SC through absorption chillers. As regards solar thermal collectors, the heat rate provided is related to the designed area through the hourly solar irradiance and the thermal efficiency. For the operation of thermal storage devices, the amount of energy stored at the beginning of each time interval equals the non-dissipated energy stored at the beginning of the previous time interval (based on the storage loss fraction), plus the net energy flow (heat input rate to the storage minus heat output rate from the storage) [2, 7].

2.5. Optimization method

With the exergetic objective function formulated in Eq. (4) and the economic one formulated in Eq. (1), the problem has two objective functions to be minimized. To solve this multi-objective optimization problem, a single objective function is formulated as a weighted sum of the total annual cost, C_{TOT}, and the total annual primary exergy input, Ex_{in}, to be minimized:

$$F_{obj} = c\omega C_{TOT} + (1-\omega) Ex_{in}\ , \tag{11}$$

where constant c is a scaling factor, chosen such that $c\, C_{TOT}$ and Ex_{in} have the same order of magnitude. The Pareto frontier is found by varying the weight ω in the interval 0 – 1. The solution that minimizes the total annual cost can be found when $\omega = 1$, whereas the one that minimizes the total annual primary exergy input (i.e., maximizes the overall exergy efficiency) when $\omega = 0$. The problem formulated above is linear, and involves both discrete and continuous variables, so this is to be solved by branch-and-cut, which is powerful for mixed-integer linear optimization problems, and easy to code by using commercial solvers.

3. Numerical testing

Numerical testing is presented below, where a hypothetic cluster of 30 buildings located in Torino (Italy) is chosen as the targeted end-user. The method developed in Section 2 is implemented by using IBM ILOG CPLEX Optimization Studio Version 12.6, a popular and powerful solver where branch-and-cut is implemented with flexibility and high-performance.

3.1. Input data

Each building has a surface area of 5000 m^2, and a shape factor S/V of 0.5 m^{-1}. The hourly energy rate demand for electricity, DHW, SH, and SC for four representative days per season are used as input data, based on [15, 16]. To compute the annual energy requirements, the year is assumed to include 90, 92, 91, and 92 days in the cold, cold-mid, hot-mid, and hot seasons, respectively. Table 1 shows the peak and average energy rate demand of the end-user for the four representative season days as well as the annual energy requirements. The average hourly solar irradiance profiles (on a south-oriented and 35° tilted surface) have been assumed for each representative season day [17]. The technical and economic information of energy devices are summarized in Table 2 [18, 19]. The unit price of grid power is assumed as 0.15 €/kWh, and the unit prices of natural gas and biomass (wood pellet) are assumed as 0.477 €/Nm^3, and 120 €/ton, respectively. The exergy efficiency of power generation plants is assumed as 0.40, based on the fossil fuel energy mix for electricity production and on the average efficiency of fossil fuel-fired electricity production in Italy [20]. The exergy factors of natural gas and biomass are assumed as 1.04 and 1.16 [14], respectively. A 5% interest rate is assumed to evaluate the total annualized investment cost.

3.2. Pareto frontier

The optimization problem is solved within few hours with a mixed integer gap lower than 0.15% on a PC with 2.60GHz (2 processors) Intel(R) Xeon(R) E5 CPU and 32G RAM. The Pareto frontier is shown in Fig. 2a. The point marked with *a* is obtained under exergetic optimization (ω = 0), and the point marked with *b* is obtained under economic optimization (ω = 1). The points between these two extreme points are found by subdividing the weight interval into 10 equally-spaced points. Each point on the Pareto frontier corresponds to a different optimized configuration of the DES. Fig. 2b shows the percentages of reduction in the total annual cost and increase in the total annual primary exergy input obtained by varying the weight ω from 0 to 1 with a 0.1 increase.

3.3. Optimized DES configurations

The optimized configurations of the DES (numbers, sizes and total installed capacities of energy devices), and the economic and exergetic performances for points *a* and *b* on the Pareto frontier are shown in Table 3. For the illustration purpose, the point marked with *c* in Fig. 2a (obtained for ω = 0.2) is also selected as an attractive economic/exergetic balancing solution. Under exergetic optimization, the total capacity of CHP is the largest among the three configurations. This highlights its importance for the exergetic objective, due to the possibility of waste heat recovery for thermal purposes, thereby promoting efficient use of the energy resource. As ω increases, the total capacity reduces, reaching the minimum under

Table 1. Peak and average energy rate demand (MW) in the representative season days and annual energy requirements of the building cluster (MWh).

Season	Electricity			DHW			SH			SC		
	Peak	Average	Annual	Peak	Average	Annual	Peak	Average	Annual	Peak	Average	Annual
Cold	0.86	0.52	1114	1.30	0.25	544.3	5.50	2.88	6227	0	0	0
Cold-mid	0.86	0.52	1139	1.30	0.25	556.4	3.22	1.53	3378	0	0	0
Hot-mid	0.86	0.52	1126	1.30	0.25	550.3	0	0	0	0	0	0
Hot	0.86	0.52	1139	1.30	0.25	556.4	0	0	0	4.47	1.47	3235

Table 2. Technical and economic information of energy devices.

Energy device	Size range (kW)	Specific capital cost	O&M costs (€/kWh)	Efficiency		Lifetime
				Electrical	Thermal	
CHP gas-fired ICE	20-5000	1495-840 €/kW	0.020-0.008	0.28-0.41	0.68-0.40	20
NG boiler	10-2000	100 €/kW	0.0014		0.9	15
Biomass boiler	10-2000	400 €/kW	0.0027		0.85	15
Solar Thermal (ST)	-	200 €/m^2	0.0057		0.6	15
Air-source heat pump	10-6000	460 €/kW	0.0025		COP=3.0-3.5	20
Absorption chiller	10-5000	510-230 €/kW	0.0020		COP=0.8	20
Thermal storage	-	20 €/kWh	0.0012		loss fraction=0.05	20

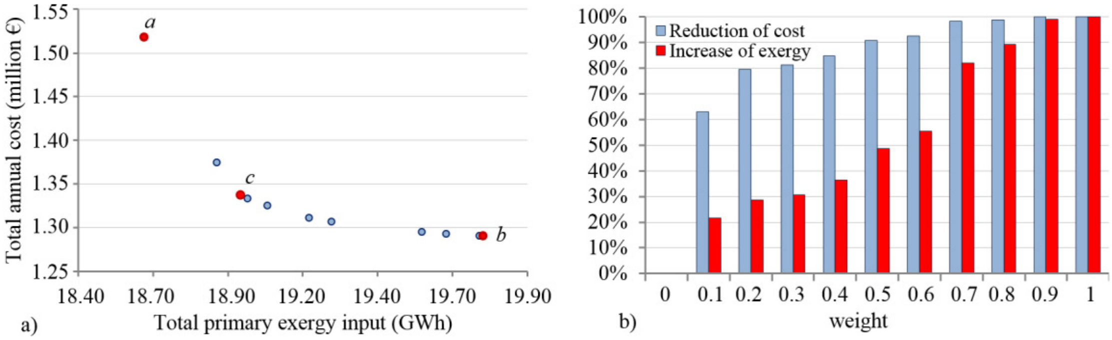

Fig. 2. a) Pareto frontier; b) Percentages of reduction in annual cost and increase in annual primary exergy input for ω varying from 0 to 1 with a 0.1 increase.

economic optimization, due to its high investment cost. Conversely, the total capacity of natural gas boiler is maximum under economic optimization, due to the low investment and O&M costs. The natural gas boiler is not chosen at point *c*, under a higher weight of the exergetic objective, highlighting that natural gas, as high-quality energy, should not be used for low-quality thermal demand. The choice of one natural gas boiler of 345 kW under exergetic optimization is due to the large sizes of the two CHPs, characterized by high minimum part loads, below of which they cannot operate.

The biomass boiler is not chosen in any configuration. Under exergetic optimization, although both wood and natural gas are high-quality energy, the efficiency of the biomass boiler is lower than that of the gas-fired boiler. The biomass boiler is also inconvenient for the economic objective due to the high investment cost. The area of the solar thermal array is maximum and the same for points *a* and *c*, under a higher weight of the exergetic objective, highlighting the convenience of solar thermal for the exergetic objective, due to low exergy of the thermal energy output from the collectors. Also the total capacities of heat pump and absorption chiller reach the maximum under exergetic optimization, highlighting their convenience for the exergetic purpose, due to the high conversion efficiency and the possibility of waste heat recovery for the SC demand, respectively. When ω increases, the total capacities reduce in order to reduce the total annual cost.

The capacity of the DHW thermal storage is maximum and the same for points *a* and *c*, since it is related to the thermal energy provided by the solar thermal plant. The capacity of the SH thermal storage is maximum under exergetic optimization, due to large amount of exhaust gas from CHPs. Conversely, the capacity of the SC thermal storage is minimum and the same for points *a* and *c*, whereas it strongly increases under economic optimization. By increasing the storage capacity, the size of the absorption chiller can be strongly reduced, thereby reducing the total investment costs.

In Table 3, the total annual cost and primary exergy input are also reported for an optimized CES system, where grid power is used for the electricity demand, natural gas boilers for DHW and SH demand, and

Table 3. Optimized solutions resulting from the analysis of the Pareto Frontier.

Optimized solutions		Point *a*	Point *c*	Point *b*	CES
CHP	Number - Sizes - Total (kW_{el})	2 - 1006/2130 - 3136	2 - 453/1103 - 1556	2 - 300/1007 - 1307	
NG boiler	Number – Sizes, Total (kW_{th})	1 - 345 - 345	0	2 - 260/807 – 1067	
Biomass boiler	Number - Sizes - Total (kW_{th})	0	0	0	
Solar Thermal	Area (m^2)	1485	1485	0	
Heat pump	Number - Sizes - Total (kW_{th})	2 - 360/5732 - 6092	2 - 995/2563 - 3558	2 - 402/2466 - 2868	
Absorption chiller	Number - Sizes - Total (kW_{th})	2 - 300/1298 - 1589	1 - 1450 - 1450	1 - 1000 – 1000	
DHW storage	Total capacity (kWh_{th})	2746	2746	2063	
SH storage	Total capacity (kWh_{th})	2268	1382	1450	
SC storage	Total capacity (kWh_{th})	948	948	2406	
Total annual cost (million €)		1.517	1.374	1.290	1.913
Total annual primary exergy input (GWh)		18.620	18.864	19.753	27.641

electric chillers for SC demand (same configurations attained under economic and exergetic optimization). As compared with CES, the total annual cost and primary exergy input of the DES are both reduced by 33% under economic and exergetic optimization. Moreover, as compared with CES, the total annual cost of the DES under exergetic optimization is reduced by 21%, whereas the total annual primary exergy input under the economic optimization is reduced by 28%.

3.4. Operation strategies of optimized DES configurations under economic and exergetic optimization

For each optimized configuration, different operation strategies of energy devices are found. For the illustration purpose, Fig. 3 shows the operation strategies of the DES (electricity and thermal energy provided by energy devices) in the four representative season days at points *a* and *b* of the Pareto frontier for a) electricity, b) DHW and c) SH/SC demand. As shown in Fig. 3a, grid power is generally lower than the electricity provided by CHPs, highlighting that CHP is convenient for both objectives. The contrary occurs in the hot mid-season day under exergetic optimization. In this day, only electricity and DHW demand need to be satisfied, and solar thermal is preferred instead of waste heat from CHPs to meet the demand as shown in Fig. 3b. The integration of the natural gas boiler is due to the large sizes of the CHPs, as discussed earlier. Conversely, waste heat from CHPs is mostly used under economic optimization. In Fig. 3c for SH and SC, heat pumps are mostly used under both exergetic and economic optimization. For SC, the absorption chiller is used more under exergetic optimization than under economic one. Moreover, both Fig.s 3b and c show that to meet the DHW and SH demand, natural gas boilers are more used under economic optimization than under exergetic one.

4. Conclusions

In this paper, exergy assessments are investigated in DES design optimization for sustainable development of energy supply systems. Based on a pre-established superstructure, a multi-objective linear problem is formulated to determine numbers and sizes of energy devices with the corresponding operation strategies through cost and exergy assessments. The Pareto frontier is found through minimizing a weighted sum of the total annual cost and primary exergy input by using branch-and-cut. Numerical results demonstrate that different optimized DES configurations are found according to the two objectives, and the Pareto frontier provides good balancing solutions for planners based on economic and sustainability priorities. The optimized DES configurations allow to reduce the total annual cost and primary exergy input by 20% - 30% as compared with CES. Although there are no exergy requirements (as a methodology or an indicator) yet in current energy legislations, results underline that exergy assessments may allow to meet the main goal of energy legislations in sustainability of energy supply.

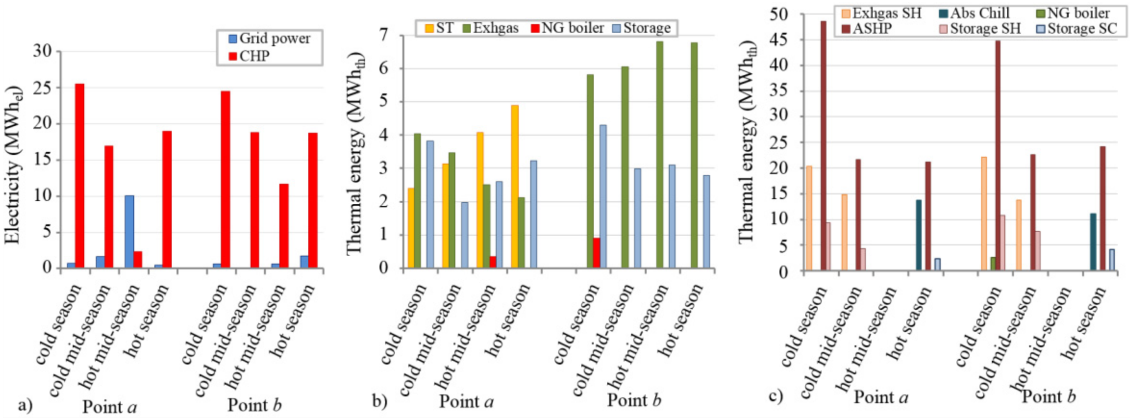

Fig. 3. Operation strategies of the DES in the four season days at points *a* and *b* of the Pareto frontier for a) Electricity, b) DHW, c) SH/SC demand

Acknowledgement

Authors thank ENEA for funding this study within the Italian Research Program *"Ricerca di Sistema Elettrico – PAR 2015*, "Area: Efficienza energetica e risparmio di energia negli usi finali elettrici ed interazione con altri vettori energetici".

References

[1] Kari A, Arto S. Distributed energy generation and sustainable development. *Renew Sustain Energy Rev* 2006;**10**:539–58.

[2] Ren H, Gao W. A MILP model for integrated plan and evaluation of distributed energy systems. *Appl En* 2010;**87**(3):1001-1014.

[3] Ren H, Zhou W, Nakagami KI, Gao W, Wu Q. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. *Appl En* 2010;**87**(12):3642-3651.

[4] Alarcon-Rodriguez A, Ault G, Galloway G. Multi-objective planning of distributed energy resources: A review of the state-of-the-art. *Renew Sustain Energy Rev* 2010;**14**:1353–66.

[5] ECBCS - Annex 49 - *Low Exergy Systems for High Performance Buildings and Communities*, homepage. Available <http://www.ecbcs.org/annexes/annex49.htm>.

[6] Dincer I, Rosen M. *Exergy-Energy, Environment and Sustainable Development*. 1st Ed., Elsevier Publication, Oxford, UK, (2007).

[7] Di Somma M, Yan B, Bianco N, Luh PB, Graditi G, Mongibello L, Naso V. Operation optimization of a distributed energy system considering energy costs and exergy efficiency. *Energ Convers Manage* 2015;**103**:739-751.

[8] Yan B, Di Somma M, Bianco N, Luh PB, Graditi G, Mongibello L, Naso V. Exergy-based operation optimization of a distributed energy system through the energy-supply chain. *Appl Therm Eng* 2016;**101**:741-751.

[9] Mehleri ED, Sarimveis H, Markatos NC, Papageorgiou LG. A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level. *Energy* 2012;**44**:396-104.

[10] Hawkes AD, Leach MA. Modelling high level system design and unit commitment for a microgrid. *Appl En* 2009;**86**(7):253-1265.

[11] Omu A, Choudhary R, Boies A. Distributed energy resource system optimisation using mixed integer linear programming. *Energy Policy* 2013:**61**, 249-266.

[12] Zhou Z, Zhang J, Liu P, Li Z, Georgiadis MC, Pistikopoulos EN. A two-stage stochastic programming model for the optimal design of distributed energy systems. *Appl En* 2013;**103**:135-144.

[13] Zhou Z, Liu P, Li Z, Ni W. An engineering approach to the optimal design of distributed energy systems in China. *Appl Therm Eng* 2013;**53**:387-96.

[14] Kotas YJ. *The exergy method for thermal plant analysis*. reprint ed. Malabar, FL: Krieger; 1995.

[15] Mongibello L, Bianco N, Caliano M, Graditi G. Influence of heat dumping on the operation of residential micro-CHP systems. *Appl En* 2015;**160**:206-220.

[16] Barbieri ES, Melino F, Morini M. Influence of the thermal energy storage on the profitability of micro CHP systems for residential building applications. *Appl En* 2012;**97**:714–22.

[17] *ASHRAE International Weather files for Energy Calculations* (IWEC weather files). Users manual and CD-ROM, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA, 2001.

[18] Darrow, K., Tidball, R., Wang, J., & Hampson, A. 2015. *Catalog of CHP technologies*. Available: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf.

[19] *Technology Data for Energy Plants*. Energinet.dk (2012). Available: http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology_data_for_energy_plants.pdf.

[20] Trudeau N, Francoeur M. *Energy Efficiency indicators for Public Electricity Production from fossil fuels*. OECD/IEA, 2008.

Biography

Marialaura Di Somma received the Ph. D degree in Mechanical Systems Engineering from the Università di Napoli Federico II, Italy, in 2016. She is a research associate at ENEA RC Portici, Italy. Her research interests include design and operation optimization of distributed energy systems through multi-objective criteria.