ENTREPRENEURSHIP AND SUSTAINABILITY CENTER
University of Essex
International Centre for Entrepreneurship Research
ESSEX BUSINESS SCHOOL

ENTREPRENEURSHIP AND SUSTAINABILITY ISSUES
ISSN 2345-0282 (online) http://jssidoi.org/jesi/aims-and-scope-of-research/

SUSTAINABLE DISTRICT DEVELOPMENT: A CASE OF THERMOECONOMIC OPTIMIZATION OF AN ENERGY HUB

Alessandra Cuneo[1], Mario L. Ferrari[2], AlbertoTraverso[3], Aristide F. Massardo[4]

[1,2,3,4] University of Genoa
DIME – Thermo-chemical Power Group (TPG) Via Montallegro,1
16145 Genova, Italy

E-mail: alessandra.cuneo@edu.unige.it

Received 10 September 2014; accepted 20 November 2014

Abstract. Sustainable distric development requires innovative energy use solutions. The aim of this paper is to illustrate the operation of a real energy hub that can satisfy both thermal and electrical demands of a generic user. In particular, a specific case study developed around the smart grid of the University Campus of Savona (Italy), which just completed in 2014, is analysed. The grid includes different cogenerative prime movers and a storage system to manage the thermal load demand. Through a time-dependent thermo-economic hierarchical approach developed by the Authors, the work aims at optimizing the management strategy of the different prime movers to satisfy the energy demand, taking into proper account both the energetic and economic aspects. The analysis was carried out considering two different layouts, with and without a conventional stratified thermal storage, to evaluate the impact of this component in the management of the district.

Keywords: sustainable development, energy, smart grid, cogeneration, thermoeconomic optimization, thermal storage

Reference to this paper should be made as follows: Cuneo, A.; Ferrari, M.L.; Traverso, A.; Massardo, A.F. 2014. Sustainable district development: a case of thermoeconomic optimization of an energy hub, *Entrepreneurship and Sustainability Issues* 2(2): 74–85.
DOI: http://dx.doi.org/10.9770/jesi.2014.2.2(3)

JEL Classifications: R11, 04, 031, M1, Q4

Nomenclature

P power [kW]
C Cost [€]
c Specific cost [€/kWh]
E Electricity flow [kWh]
F Fuel consumption [kg]
Q Heat flow [kWh]

Subscripts

el electrical
th thermal
var variable
virt virtual
acq acquired

Acronyms

mgt MicroGasTurbine
ice InternalCombustionEngine

1. Introduction

According to the strategy for Climate Action, implemented by the European Commission in 2008, the Member States will reduce their collective greenhouse gas emissions by at least 20% and boost the share of renewable energy to 20% of total consumption by 2020 (UNEP 2012). In addition, the European Union has set an indicative objective to reduce its primary energy consumption by 20% compared with the projected 2020 energy consumption (EC, The "20-20-20" targets 2010). Issues related to implementation of targets set are widely discussed in scientific literature (Stańczyk 2011; Białoskórski 2012; Lankauskienė, Tvaronavičienė 2012; Balkienė 2013; Miškinis *et al.* 2013; Vosylius *et al.* 2013; Dzemyda, Raudeliūnienė 2014; Tvaronavičienė 2014; Korsakienė, Tvaronavičienė 2014; Laužikas, Mokšeckienė 2013; Baublys *et al.* 2014; Tvaronavičienė *et al.* 2014; Vasiliūnaitė 2014).

Sustainable districts‘ development oriented to set targets requres innovative solutions in energy sector. We believe, that in this context a primary role is played by the Distributed Generation (DG), which refers to the electrical and thermal generation located near to the place of use, exploiting available renewable sources. One of the best way to exploit the emerging potential of DG is to take a system approach which views generation and associated loads as a whole concept called "microgrid". The major benefits can be divided into two categories: economic and operational (El-khattam 2004). From an economic point of view, distributed generation provides power support when load increases during peak demand periods, thus reducing interruption that may lead to system outages. It also reduces the risk of investment, due to the flexibility of its capacity and installation placement. Distributed generation cuts operational costs when installed close to the customer load because it avoids upgrading or setting up a new transmission and distribution network, thereby providing a cost saving. From the operational point of view, distributed generation warranties the reliability and stability of supply and reduces power losses.

These main aspects increase the interest of researchers on distributed polygeneration grids at both industrial and academic levels. Specifically, the Thermochemical Power Group (TPG) of the University of Genoa is involved in a four years European Collaborative project called E-HUB (Energy-HUB for residential and commercial districts and transport). An E-hub is similar to an energy station in which some different forms of energy are used in order to satisfy the energy demand of the district. Both consumers and suppliers of energy should be connected to this E-hub by means of bi-directional energy grids (low and/or high temperature heat grid, cold grid for cooling, electrical grid, gas grid). The main aim of the hub is to distribute the energy in the smart way over the consumers. The "smartness" is also in the management system, where control strategies aiming at the optimization of technical, economic and environmental issues are typically implemented.

Under such conditions storing energy will become beneficial, because those who can store energy can generate flexibility and make use of market opportunities. An important difference between electrical and thermal energy is that heat can be stored more easily and efficiently. So, thermal storage will be one of the first candidates to support smart grids. Heat pumps, CHPs and other devices convert electrical power into heat or vice versa and can do this when the market conditions are best (Ferrari *et al.* 2014).

Aim of this paper is to study the best management of the energy hub installed in Savona Campus with studying in particular the better operational strategy of the e-hub if a thermal storage is installed. So the same simulation was carried out considering with or without this component.

2. E-hub description

The facilities installed are based on different technologies with the aim to produce both electrical and thermal energy: the poly-generation smart grid analyzed here is based on the one installed at the TPG laboratory of the University of Genoa (Ferrari *et al.* 2012).

T

he test rig considered in this work (Fig.1) is based on the following technology (both electrical and thermal energy):

- a 100 kW_{el} recuperated micro gas turbine (T100 PHS Series): nominal electrical efficiency of 30% and thermal efficiency of 47%;

- 20 kW_{el} internal combustion engine (TANDEM T20-A): nominal electrical efficiency of 29% and thermal efficiency of 68%;
- 5000 l storage tank.

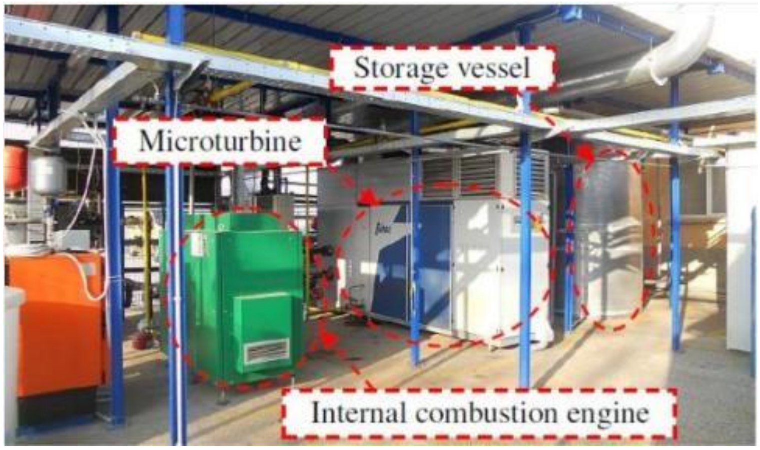

Fig.1. Test rig

Since the test rig is real installed in a University Campus and from the next winter it will contribute to satisfy the load demand of the Campus, the aim of this paper is to find the best operational strategy of the prime movers taking into account only the variable cost and not the economic parameters (like NPV or PBP) because there is no investment for the machine.

3. ECoMP description

ECoMP (Economic Cogeneration Modular Program) is an original software developed by the Thermochemical Power Group (TPG), at the University of Genoa, aiming at thermo-economic time-dependent analyses and optimization of energy systems, including off-design conditions (Rivarolo *et al.* 2013). Recently, a standard component interface (NeWECoMP) has been added to the software, allowing for the implementation of the most complex plant lay-outs with a user-friendly interface.

ECoMP is characterized by a modular approach and a standard component interface. It maintains the flexibility and the extendibility of the library components (46 modules are available at the moment), allowing users to add new components without modifying the core of the software (Yokoyama and Oseb 2012). Each component is described by three subroutines, which define mass and energy flows, off-design performance curves, variable and capital costs. Thanks to its modular approach, ECoMP allows to analyze various plant solutions, searching for the optimal dimensioning and/or for the best strategy of management from the thermo-economic point of view.

The Figure 2 shows how, given as an input the economic environment and the electrical and thermal loads, taking into account the connection to the power grid, the desired plant optimisation is obtained.

The choice of the design conditions and optimal management is carried out by pursuing a very clear goal: minimize the total cost calculated over the considered period. For the definition of the total cost, two items must be considered:
- Fixed cost
- Variable cost

The first considers the capital cost of each component and it is a function of size, the second one takes into account the consumption of energy and fuel and depends on the chosen operational strategy.

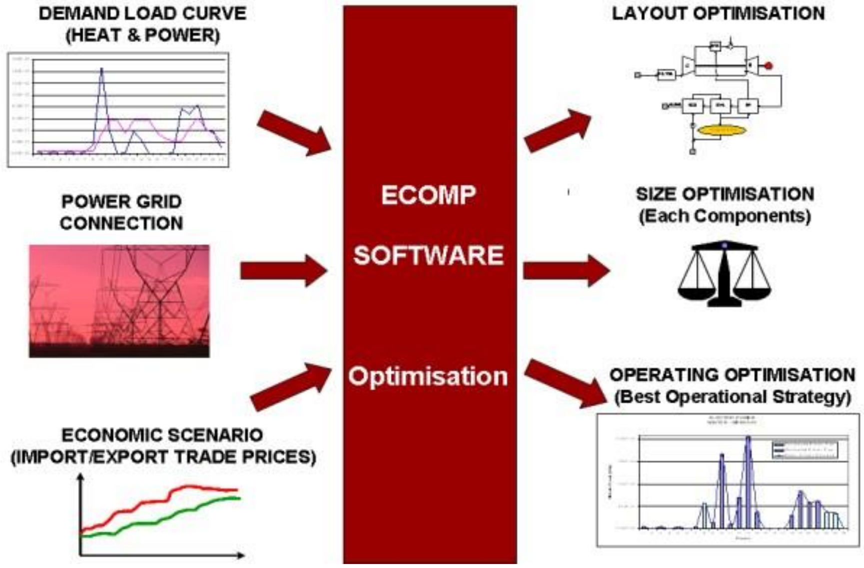

Fig.2. General structure of ECoMP

First of all, the software loads the input data, which are stored in specific matrices and report information about ambient temperature, user electrical demand, user thermal demand, etc.. Secondly, it calculates the component fixed costs, using internal cost functions. Finally, it calculates the variable costs basing on the decided operational strategy and the prime movers off-design performance curves. The revenues, obtained from the sale of electrical or thermal energy to the network, are considered as negative costs and then lower the objective function to be minimized. The input file of requested energy must be completed in a timely manner, and it contents information about the operation/non operation days. The operating days are divided into a number of periods: one of the most important features of ECoMP is the possibility of performing analysis for whatever number of periods, depending on the plant under analysis; moreover, it is possible to choose the number of seconds which a single period is made of.

ECoMP software uses built-in cost equations, which evaluate the capital cost of the single components of the plant based on installed power (gas turbines, internal combustion engines, boilers, fuel cells, solar panels, etc.) or volume (thermal storage), or other relevant parameters. The cost functions for different modules were developed and updated thanks to the contribution of industrial partners over the last few years, from literature data and from commercial offers collected during the Energy-Hub construction (Turbec SpA... 2012; asJagen, SpA..2013).

In order to improve the reliability of the simulation results, the off-design curves of the prime movers installed in the plant have been implemented in the software. These curves have been extracted from experimental tests. The curves refer to the internal combustion engine TANDEM T20, as well as to the micro gas turbines Turbec T100. The curves are plotted as a function of the electrical power, taking into account three different indicators: thermal power produced by the mover (black line), electrical efficiency (blue line) and fuel consumption (red line). All the values are compared to the nominal ones, as shown in Figure 3 (Ferrari 2014).

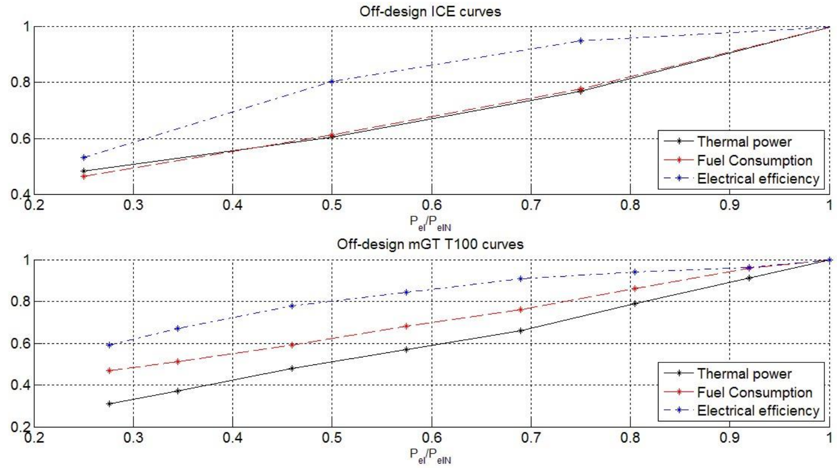

Fig.3. Performance curves for prime movers

Two different optimization levels can be investigated by ECoMP: a low and a high level. At the low level, the size of the components is considered fixed (therefore, capital costs are fixed) and the software employs a genetic algorithm in order to determine the best operational strategy. The choice of the use of a genetic algorithm to solve this kind of problem and the advantages/disadvantaged respect to other technique/programme is well described in (Carroll 1996).

In this case, the software aims to minimize the objective function (Eq. 1), which represents the hourly (or less) variable costs, as follows:

$$C_{\mathrm{var}} = F_i \cdot \sum_{i=1}^{N} c_{fuel,i} + c_{el} \cdot E_{acq} + c_{virt} \cdot \left(F_{virt} + E_{virt} + Q_{virt}^{*} \right) \quad (1)$$

Variable costs are made up of the following terms: (i) fuel consumption costs, (ii) electrical energy costs, and (iii) ‘‘virtual costs’’. The electrical energy costs term represents the product of the electrical energy purchased from the external grid and the specific cost of electricity: when the electricity produced by the plant is not sufficient to satisfy the electrical load, which is one of the problem constraints, electricity is purchased from the external grid. It is important to underline that “virtual flows” represent energy exchanges between the plant and the external environment, necessary to satisfy the optimization constraints (i.e. load demands). Since these amounts of energy cannot be produced by the plant, penalty costs are associated with virtual flows. Since the term c_{virt} assumes a high value (two orders of magnitude higher than the other specific cost terms), the optimization process is forced to find an operational strategy which minimizes virtual flows.

The results of the optimisation process and some additional input data are passed to the economic subroutine for the investment analysis, which is carried out considering a variety of economic scenario parameters (e.g.: construction time, inflation, escalation rates, plant life, financial interests, etc.).

4. Main inputs for the thermo-economic analysis

As mentioned before, a large number of inputs, most of them related to the site where the plant is installed, must be considered in the thermo-economic optimization approach. This section details the main plant data considered for the analysis. The simulation was carried out for three hours considering five minutes as time step.

a) Electricity and thermal load curves: they represent the main optimization problem constraint. The software receives the time dependent electrical/thermal load demands as input, which must be satisfied in each period of the year using electricity produced by the generators or by purchasing electricity from the National grid.

For this study Fig. 4 and 5 represent the thermal and electrical demand considered.

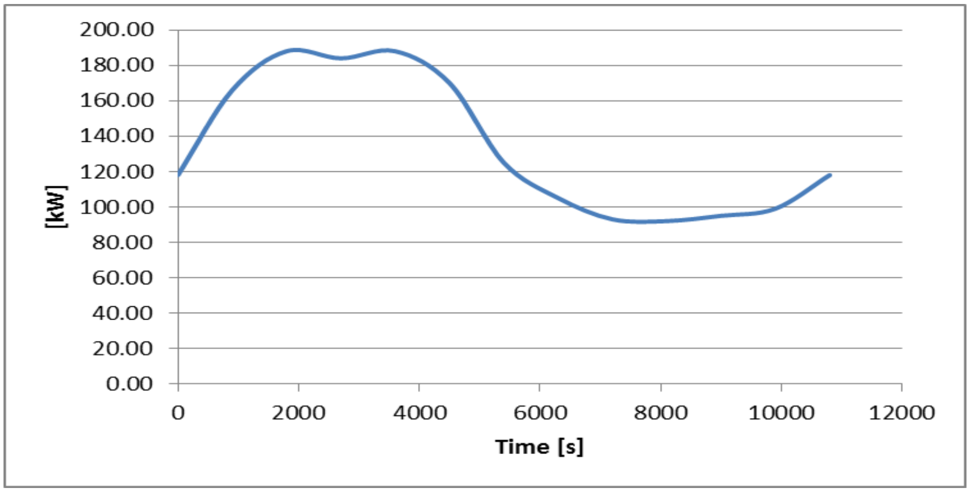

Fig.4. Thermal demand profile

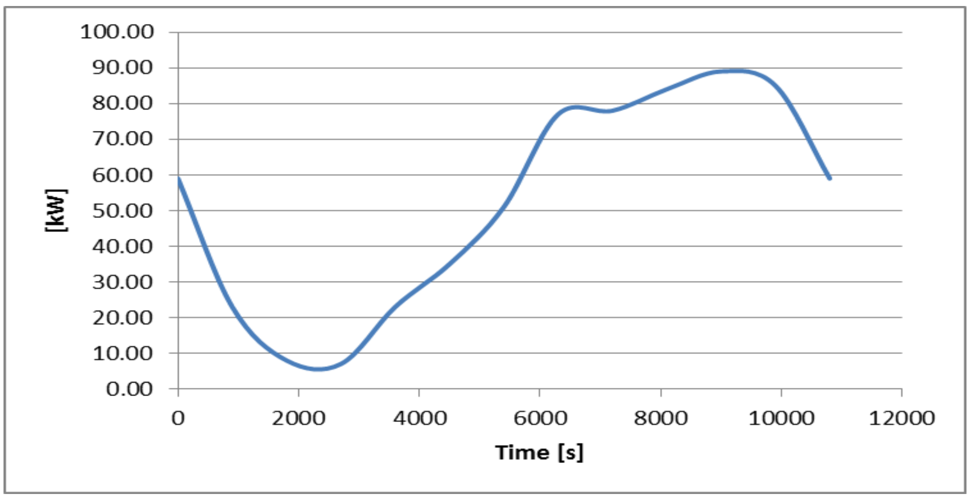

Fig.5. Electrical demand profile

It is important to underline that electrical and thermal demand are conflicting. This creates a problem for the management of the plant, especially in the first case without the thermal storage, since there is no flexibility in the thermal demand.

b) Operating costs: they have been evaluated starting from statistic data available from Eurostat (Cassa Depositi e Prestiti 2013; Market Analysis 2014). Italian case study has been taken into consideration and global values are summarized in Table 1.

Table 1. Energy cost

Electricity cost [€/kWh]	0.2
Electricity price [€/kWh]	0.1
Thermal energy [€/kWh]	0.1
Gas [€/kg]	0.25

It has to be said the distinction between Electricity cost and Electricity price is due to different value in terms of money associated to energy bought from the grid or sold back to. Value of thermal energy has been evaluated by considering a 90% efficiency boiler.

5. Simulation and results

WITHOUT STORAGE

The first test simulated with ECoMP was without a thermal storage; in this way the system is forced to satisfy the heat demand in a timely manner, without exception.

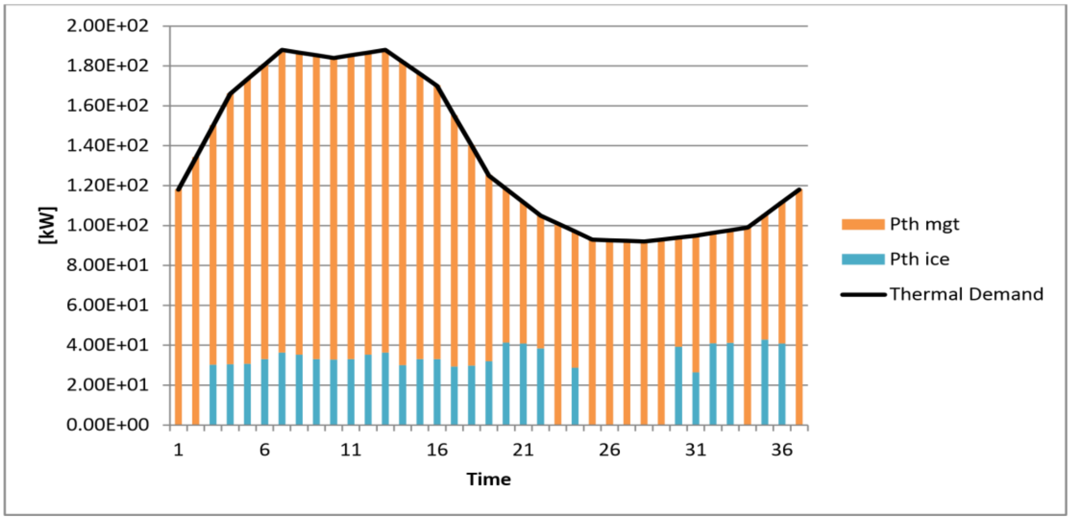

Fig.6. Thermal generation/consumption without thermal storage

Figure 7 shows the results for electricity production/consumption. It can be immediately seen how the request (black curve) and production (orange and blue line) have different trends and are not related each other. This behaviour is due to the constraints regarding the heat commodity imposed during the test (i.e. no thermal demand flexibility). The plant is, in fact, in the position of having to meet a given heat load without having the possibility to store thermal energy; electricity production, on the other hand, has the ability to interact with the grid network.

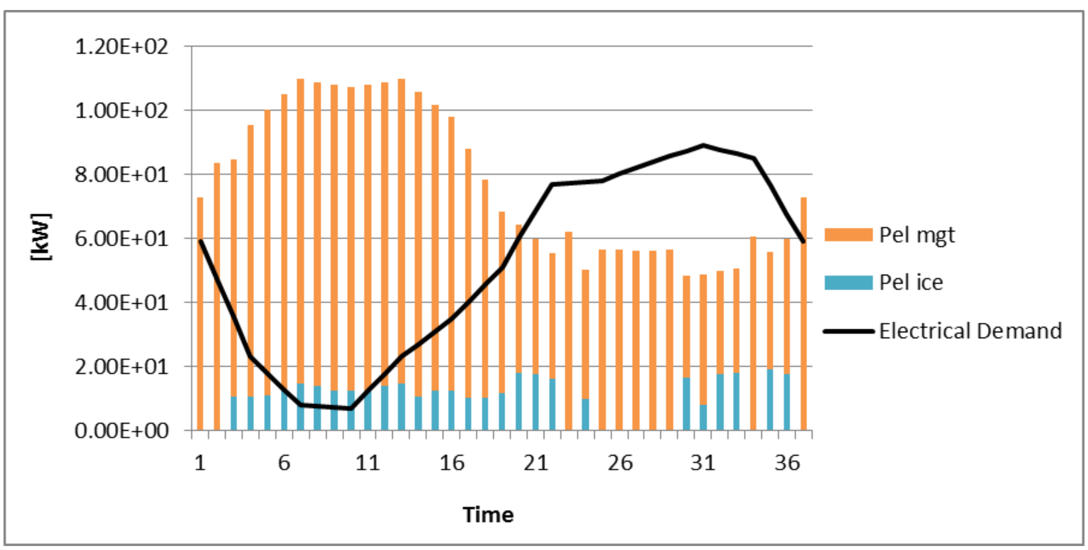

Fig.7. Electrical generation/consumption without thermal storage

Analysing the power levels of CHP (Combined Heat and Power) generators, it can be observed that the production of the microturbine is always higher than the internal combustion engine; this is due both to the choice made by the control system (i.e. ECoMP optimiser) and the different size of the two machines. Secondly, the microturbine is maintained almost constantly close to the nominal working point, while most of the adjustments are assigned to the internal combustion engine. Table 2 summarizes the energetic parameters of the plant.

Table 2. Energetic Results

Electricity Consumed [kWh]	1.92E+03
Electricity Production [kWh]	2.86E+03
Electricity sold to the grid [kWh]	1.35E+03
Electricity bought from the grid [kWh]	4.06E+02
Fuel Consumption [kg]	7.81E+01

WITH STORAGE

The second analysis was performed including the use of thermal storage. In this case, the system can exploit one additional degree of freedom, thanks to the flexibility on the thermal demand/load; the model, in fact, is no longer required to meet the heat demand in a timely manner, without exception, but it can depart from that request within the limits of the storage.

Analyzing the curves of the request and production it can be seen that the two curves have nearly the same trends for quite all the time; this behaviour does not differ from that recorded in the previous simulation without storage. During the peak of the thermal demand, where the electrical load is very low, the storage help to satisfy the request keeping off the internal combustion engine and at the maximum power the micro-gas turbine.

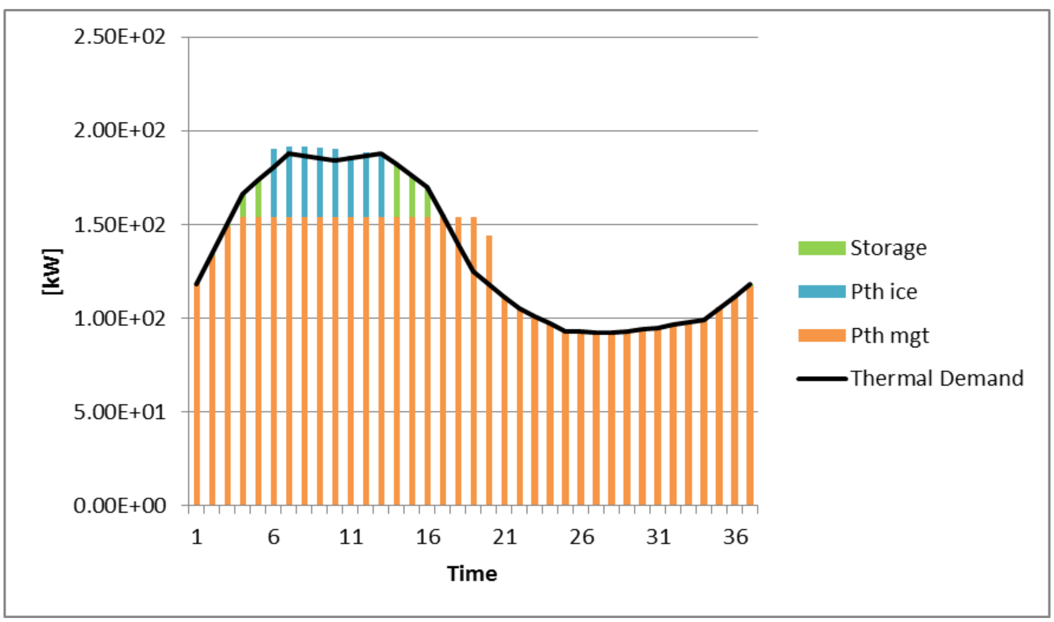

Fig. 8. Thermal generation/consumption with thermal storage

In Figure 9 it is possible to see how the request and the production have different trends, as the thermal demand dominates, despite the additional flexibility introduced by the thermal storage. The flow of energy exchanged with the grid network indicates intense exchanges where the production deviates from the demand. This condition occurs in two periods during the simulation, in particular:

- At the beginning, when production definitely overmatches, this configuration is characterized by a large sale of electricity (it reaches a maximum power of almost 100 kW)
- Subsequently, since the storage is almost fill, the thermal demand is covered exactly by the mGT taking switch off the ICE. This configuration is clearly biased in favour of an underproduction compensated by a large purchase of electricity (indicated by the purple curve). Also in this case the network balances the mismatch, providing a maximum power of about 39 kW.

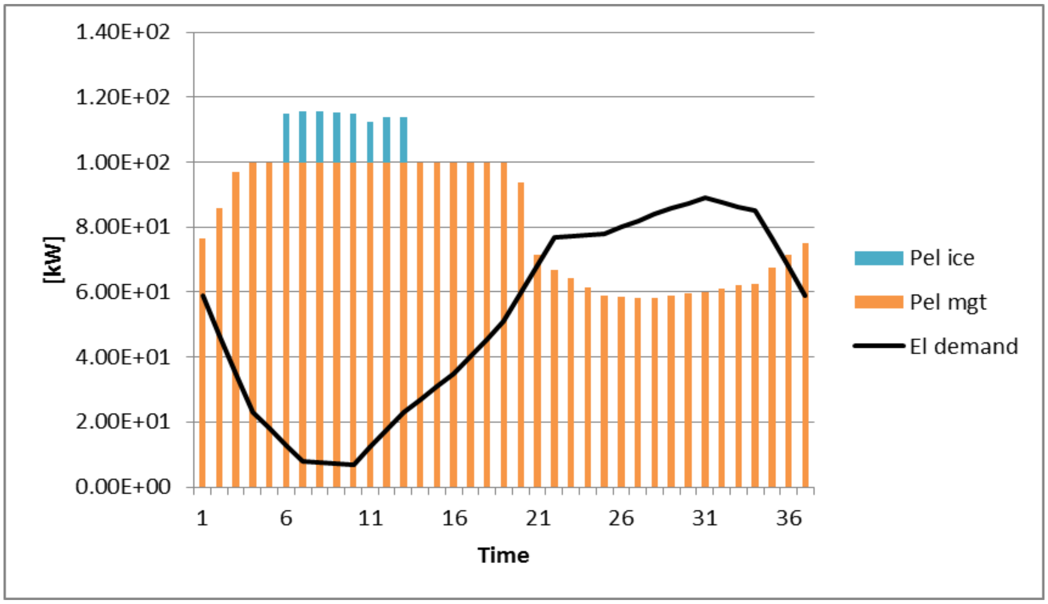

Fig.9. Electrical generation/consumption with thermal storage

Table 3 summarized the energetic parameters of the plant.

Table 3. Energetic Results

Electricity Consumed [kWh]	1.92E+03
Electricity Production [kWh]	3.14E+03
Electricity sold to the grid [kWh]	1.52E+03
Electricity bought from the grid [kWh]	2.96E+02
Fuel Consumption [kg]	7.30E+01

It is possible to notice that the use of a thermal storage in the management of a smart grid brings an improvement in the energetic consumption of the plant. In fact, with respect to the solution without a thermal storage, the electricity produced by the prime movers is higher, this caused a reduction of the electricity bought from the grid and an increase of revenues from the electricity sold to the grid (Figure 10).

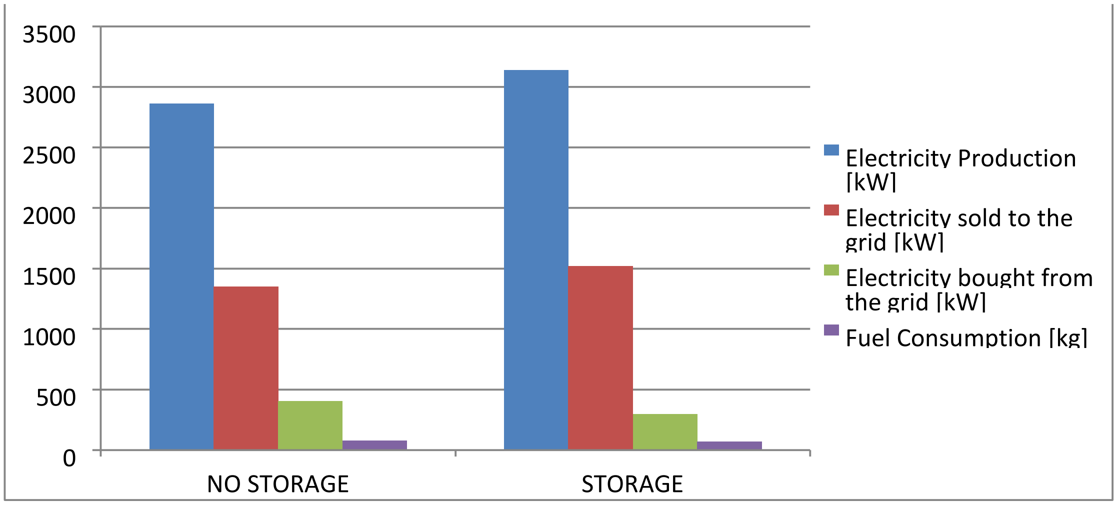

Fig.10. Energetic Comparison

Based on the operating cost in Table 4, it is possible to evaluate the variable cost for both configuration evaluating the economic improvement if the thermal storage.

Table 4. Economic results

	Without thermal storage	**With thermal storage**
Revenues [€]	633.70	650
Costs [€]	81.20	78.73
Profit [€]	522.5	571.97

Considering how the machine work in both case (Figure 11), the use of thermal storage have an important impact in the management of the mGT because it works for a longer time in nominal condition, with an important reduction of the time in off design. This is very significant since when the mGT operates outside of its nominal conditions, average efficiency decreases and the impact of maintenance costs on the energy produced increases. On the other hand, the ICE, in the configuration with thermal storage, never works in nominal condition and it is switch off for a longer time.

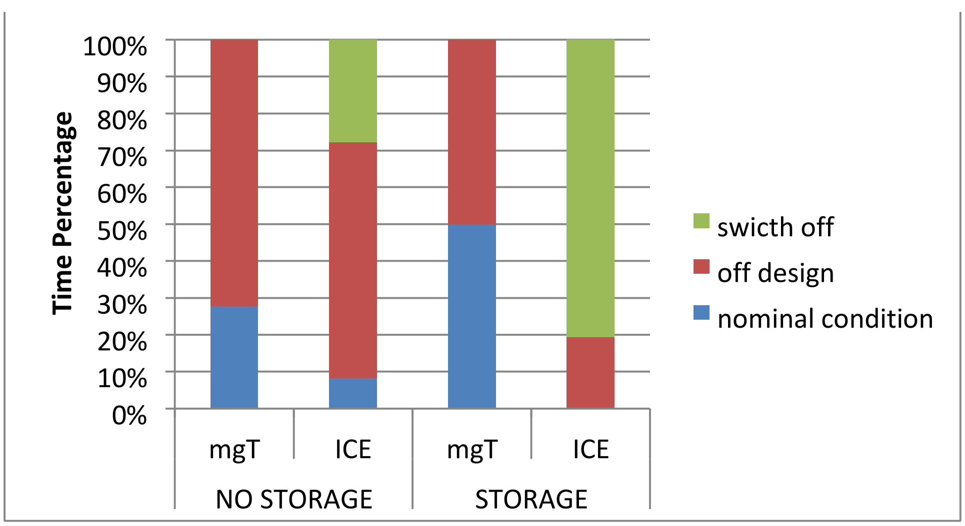

Fig.11. Comparison of time percentage of the prime movers with and without thermal storage

Conclusions

In this paper the Energy Hub installed in the Savona Campus of the University of Genoa, Italy, to satisfy the thermal and electrical demands was analysed via a thermo-economic approach, employing the software ECoMP. In particular the impact of thermal storage was investigated. From the results, it can be inferred that the thermal storage has a considerable impact in the system behaviour. The use of a thermal storage to management better the thermal demand, have an improvement not only in the energetic results but also in the economic one with a reduction of about 4% in the variable costs. So, it can be concluded that a relatively simple device, as a conventional water stratified thermal storage, can have a significant positive impact on system performance, provided that proper control algorithms are employed. Implementation of suggeted innovative solution contributes to sutainable development of district and facilitates meating goals set by the EU.

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Alessandra CUNEO (Ph.d student). Alessandra Cuneo was born in Genoa in 1989. She obtained her Master Degree in Environmental Engineering: Sustainable Development and Risk Management at University of Genoa in 2015. She started to work at TPG with a scholarship in 2013 and she carried out research about distribution generation, smart poly-generation grid and renewable energy collaborating in the E-HUB project. She started her PhD in 2014 with a research project about design under uncertainty and its application to different energy systems.

Mario L.FERRARI (Researcher). Mario Luigi Ferrari was born in Novi Ligure (AL) in 1978. He obtained his Degree in Mechanical Engineering with honours at the University of Genoa in 2003. He obtained the Ph.D. in Mechanical Engineering at the University of Genoa in 2006. He has worked as an Associate Researcher in the Dipartimento di Macchine, Sistemi Energetici e Trasporti of the University of Genoa, and as a Researcher at Rolls-Royce Fuel Cell Systems Ltd, under the Marie-Curie program. At the moment he is a permanent Researcher in the Dipartimento di Ingegneria meccanica, energetica, gestionale e dei trasporti, where he is studying the transient behaviour of SOFC hybrid cycles and the optimization of smart grids based on both fossil fuel and renewable energy systems (the TPG laboratory of Savona).

Alberto TRAVERSO (Associate professor). Alberto Traverso is Associate Professor of Energy Systems for Mechanical Engineering. He obtained the Ph.D. in 2004 with the thesis "TRANSEO: A New Simulation Tool for the Transient Analysis of Innovative Energy Systems". His main field of expertise is the time-dependent analysis of energy systems, including fuel cell hybrid cycles. He is also responsible of WTEMP software development for thermoeconomic analysis of innovative energy systems. He is part of the steering committee at TPG for the Rolls-Royce Fuel Cell Systems Ltd UTC.

Aristide F. MASSARDO (Professor). Aristide Massardo obtained his Degree in Mechanical Engineering with honours at the University of Genoa, Italy, in 1978. After several years working for international companies in the field of energy and power plants in 1984 he entered the University of Genoa as a researcher. Now he is Full Professor of Energy Systems at the Department of Mechanical Engineering). Prof. Massardo established the Thermochemical Power Group at DIMSET in 1998, and he is at the moment the University of Genoa co-ordinator for several international projects. He was also responsible for administering many grants from Italian Space Agency, National Research Council of Italy, MURST, ENEL, and other private companies. He is now the Dean of the Polytechnic School of Engineering and Architecture.