Optimization of Distributed Trigeneration Systems Integrated with Heating and Cooling Micro-grids

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ABSTRACT

The article deals with the influence of the amortization period in the optimization of a distributed urban district heating and cooling trigeneration system. The model, presented in detail in [1], is based on a Mixed Integer Linear Program (MILP) and includes a set of micro-cogeneration gas turbines for producing electricity and thermal energy and a set of absorption chillers, driven by cogenerated heat, for producing cooling energy. Micro-gas turbines and absorption chillers can be used instead of purchasing electricity from the grid, producing thermal energy by boilers and cooling energy by compression chillers. Moreover, various building can be connected each other through a district heating and cooling network (DHC network). The optimization specifies the kind, the number and the location of cogeneration equipment and absorption machines, the size and the position of district heating and cooling pipelines as well as the optimal operation of each component. The objective function takes into account investment cost of micro-gas turbine, absorption chillers and DHC network, maintenance costs, operation costs and any income from the sale of electricity.

The aim of the article is to obtain the optimal solution varying the amortization period of machines and networks, for understanding the influence of capital costs on the annual total cost, the optimal system configuration and operation.

Key Words: Trigeneration, Mixed Integer Linear Program, micro-gas turbines, absorption chillers, District Heating and Cooling

INTRODUCTION

Distributed cogeneration and trigeneration systems allow achievement of primary energy savings utilizing wasted heat from power generation, and so can play an important role in reducing primary energy consumption [2-achieved, unless an appropriate choice of the system components and a viable operation strategy are adopted [5-11].

It is well known that trigeneration or CHCP (combined heating cooling and power) systems allow obtaining simultaneously electric power, hot and cold energy vectors, typically by means of cogeneration systems combined with absorption chillers. In this solution the cooling energy is produced through the heat obtained by the cogenerators, extending their operation time, obtaining a better exploitation of the primary energy sources and, generally, also reducing all of the polluting emissions [2].

Both energetic and environmental advantages can increase if district heating and cooling micro-grids are used to connect a set of buildings, because tri-generation units operation can be -15]. On the other hand, cost rises with the size (length and tube diameter) of the pipelines. Moreover, heating and cooling grids of various kilometers in length are hard to build in areas with high density of buildings.

From the economic point of view, the model has to be optimized to guarantee that the investment is most profitable. In industrial plants, where the energy demand is fairly constant, a system optimization can be carried out on an annual basis, but in a residential and commercial or service buildings, where the energy demand is highly time dependent, an optimization on an hourly basis is recommended.

Thus, this article presents a mixed integer linear programming (MILP) model to solve the optimal layout and operation of a problem that deals with trigeneration systems [15-19] integrated with district heating and cooling network [20]. For each potential application, we consider a trigeneration system to produce electricity, thermal and cooling energy, and such system can be eventually connected to other users. The optimization has to determine which is the best configuration and operation in terms of economic benefits. The base case is the conventional solution, which means buying all electricity from the grid, producing all thermal energy by boiler and all cooling energy by electrically driven chiller compressor.

The objective function takes into account investment costs, operation costs, maintenance costs and the income from electricity sale. The proposed model allows one to simulate all the days of the year, but taking each day into account would take a long time to solve the model. So that, only some typical days are considered for representing the whole year. In this article six typical -four hours have been considered [5].

In previous research work, simpler systems operating in different boundary conditions have been studied. Thus, models dealing with distributed cogeneration systems integrated with district heating network have been introduced in [6, 7], a comparison between different support policies and the option of integrating renewable energy sources was discussed in [8], while the model of trigeneration systems and of district heating and cooling network was introduced in [1].

The aim of this article is to obtain the optimal solution varying the amortization period of machines and networks, in order to understand the influence of capital costs on the annual total cost, the optimal system configuration and operation. Therefore, the decision variables involved have to describe the number of machines to be installed in each building, the number, size and position of pipelines inside of district heating-cooling network and the magnitude of each energy flow in all time intervals.

The model has been applied to a real case study composed by six municipal users, each with a distinct energy profile, located in a town in northeastern Italy. In this case the energy demands of each user are known. But in new buildings, the demands are unknown, so prior to the application of the suggested methodology, the demands need to be estimated.

COMPONENT MODELS

In this section, the components of the trigeneration system are modeled through piece-wise linear equations. In formulating the underlying models, each user can satisfy its energy demand by the base or conventional solution (electricity from the grid, thermal energy by boiler and cooling energy by compression chiller) or can be served by a trigeneration local unit, installed by the user. Micro-gas turbines have been chosen as cogenerators because they fit well office building applications (low noise, reduced maintenance, fully automated operations). Next, in order to apply a MILP algorithm for the optimization of the whole system, machine performance and energy balances have to be expressed by linear equations [5, 15, 16, 19].

In this article the influence of the environment temperature in the performance of cogenerators and of absorption chillers is taken into account. In fact, as it's well known, higher ambient air temperature penalize machine performance and, in some situations, it could compromise the investment.

While the energy balances are inherently linear with respect to the energy flows, the machine performance curves are generally not linear, so that a linearization, introducing some approximations, is necessary. In order to reduce approximation errors, the introduction of multi-linear or piece-wise linear correlations is possible. On the other hand, such correlations increase the complexity of the model and the optimal solution can be harder to reach.

Commercial microturbines are normally equipped with a heat exchanger which cool the exhaust gases with water. The heated water can be used to directly satisfy thermal demand or to drive absorption chillers. The thermal energy that can be transferred from exhaust gases to hot water depends on the inlet water temperature. The lower the water temperature is, the greater the amount of exhaust gas thermal energy that can be recovered. When the water is sent to the user, to satisfy their thermal demands, the temperature is required to be greater than 70°C, while when hot water drives an absorption chiller its temperature is required to be greater than 85°C. To represent the cogenerated thermal energy is then necessary to linearize real curves based on machine load (affected by environmental temperature) and on water temperature.

The Capstone C60 micro gas turbine is considered here as the cogenerator [22]. Figure 1 shows machine performance curves evaluated at ISO conditions. It can be noted they are fairly linear. Figure 2 shows the influence of environmental temperature on the machine performance at full load. Note the increase of environment temperature penalizes the electric performance, while thermal efficiency raises.

Maya Yazaki WFC—stage absorption machine and it is driven by

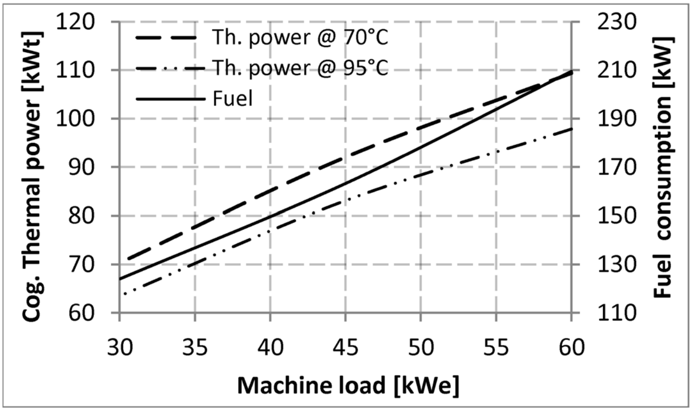


Figure 1: Cogenerated thermal energy and fuel consumption vs. machine load—Capstone C60

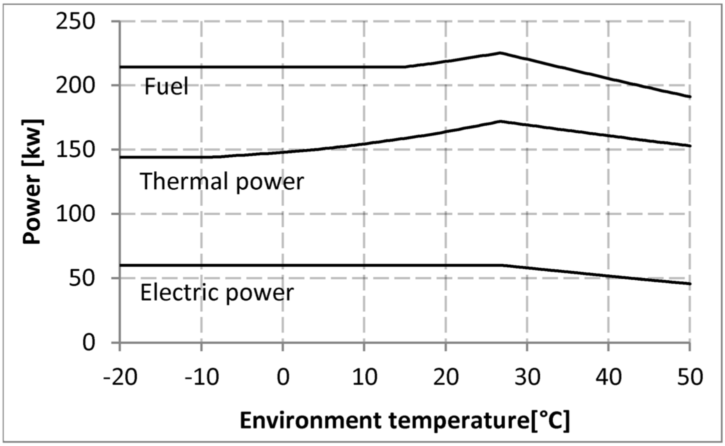


Figure 2: Influence of ambient air temperature in the gas turbine performance at full load

hot water supplied by a microgas turbine [23]. Absorption machines can work at partial load until 10% without losing their performance as seen in Figure 3. Absorption chillers need also a cooling tower, the efficiency of which depends on ambient air temperature. In this article cooling tower has not been modeled. But the investment cost of the absorption machine includes the cooling tower cost. The effect of cooling tower efficiency on absorption machine performance is included in the model too.

Boilers and compression chillers are also described in the model and constants efficiency have been introduced (□b=90%, EER=3) as average values.

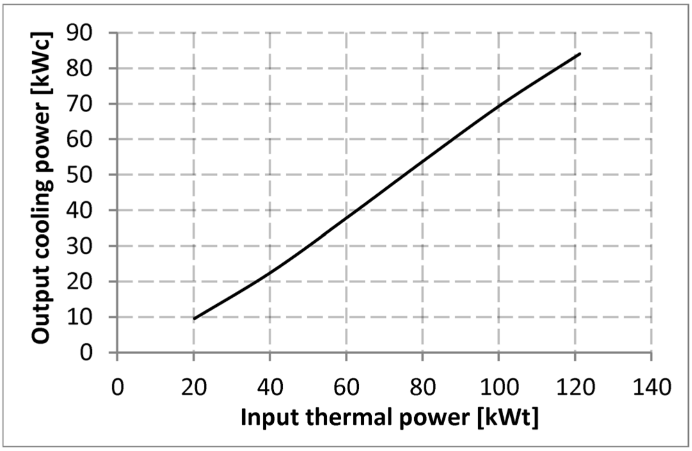


Figure 3. Output cooling power vs. input thermal power—Maya Yazaky WFC-SC20

The linear relations between fuel consumption (electricity or gas) and machine outputs (electricity, thermal energy, cooling energy) of the modeled machines are stated below.

Microturbine

Cogenerated thermal energy vs. electric energy and hot water temperature:

$$qcog_{m,i,g,j,k} = Kt1_{m,i} \cdot pel_{m,g,i,j,k} + Kt2_{m,i} \cdot th_{m,g,i,j,k} + Kt3_{m,i} \cdot y_{m,g,i,j,k} \quad [kJt] \qquad (1)$$

Where *Kt*s are the linearization coefficients and *y* is a binary variable expressing the on-off condition of the machine.

Natural gas consumption vs. electric energy:

$$Fchp_{m,g,i,j,k} = \frac{3.600}{Hi} \cdot Wt1_{m,i} \cdot pel_{m,g,i,j,k} + \frac{3.600}{Hi} \cdot Wt2_{m,i} \cdot y_{m,g,i,j,k} \; [m^3] \qquad (2)$$

Absorption chiller

Cooling energy vs. input thermal energy and hot water temperature:

$$Ha1_{i,m} \cdot qcoga_{m,g,i,j,k} + Ha2_{i,m} \cdot tha_{m,g,i,j,k} + Ha3_{i,m} \cdot w_{m,g,i,j,k} \qquad (3)$$

Boiler

Natural gas consumption vs. thermal energy:

$$Fboi_{m,g,i,k} = \frac{3.600}{Hi \cdot \eta b} \cdot ptin_{m,g,i,k} \; [m^3] \qquad (4)$$

Compression chiller

Electric energy consumed vs. produced cooling energy:

$$pfrg_{m,g,i,k} = EER \cdot R1 \cdot qfrg_{m,g,i,k} + EER \cdot R2 \cdot dp_{m,g,i,k} \quad [kJf] \qquad (5)$$

With R1=0,75 and R2=0,185

Linear regression of all real curves carries out linearization coefficients of each relation. As mentioned before, an approximation is introduced and a piece-wise multilinear interpolation can be done to reduce the errors, raising the complexity of the model. In the case study presented in this article, linear relations without multilinear interpolations introduce maximum approximation error of 5%. The linear regression have to be done for each time interval taking into account the related environment temperature. Table 1 shows the linear coefficients evaluated at 20°C.

The investment costs of microgas turbines and of absorption chillers are shown in Table 2. Installation costs of microgas turbines and

Table 1: Linear coefficients evaluated at 20°C

Kt1	Kt2	Kt3	Wt1	Wt2	Ha1	Ha2	Ha3
1,25	-0,39	70,51	2,90	53,43	0,87	0,61	-64,18

absorption chillers are supposed to decrease with the total number of machine installed inside the same unit. Investment costs of boilers and compression chillers have not been taken into consideration, because in this case users are already equipped with these boilers and chillers. In other situation, e.g. new buildings, these investment costs have generally to be considered. The costs of district heating and cooling network are listed in Table 3.

The prices of electricity and gas can change over time. The values adopted for the simulation are reported in Table 4. These values are referred to Italian situation and could be different in other country where different taxation policy can be applied.

In the specific case different prices have been assumed for gas supplying micro-gas turbines and boilers, because of the different taxation level between the cogeneration gas and gas for heating purpose in the tertiary sector.

Table 2: Capital and maintenance costs of micro gas turbines (MTG) and absorption chillers (ABS)

Typology of cost	MTG	ABS	
1st machine capital cost	120.000	26.250	[€]
2nd machine capital cost	90.000	21.000	[€]
3rd machine capital cost	80.000	19.500	[€]
4th machine capital cost	75.000	19.000	[€]
Maintenance cost (G1, G2)	0,01	0,01	[€/kWh]

Table 3: Costs of district heating and cooling network

Fixed cost of excavation (Cfix)	180	[€/m]
Cost proportional to diameter (F1)	0,1798	[€/m^2]
Cost of spread out pipelines (F2)	93,61	[€/m]

Table 4: Prices of electricity and gas

Electric energy purchase cost (*Cbuy*)	0.170	[€/kWh]
Sold electric energy price range (*Csel*)	0.044÷0.106	[€/kWh]
Integration boiler fuel cost (*Cfboi*)	0.59	[€/m^3]
µTG fuel cost (*Cfchp*)	0.39	[€/m^3]

OPTIMIZATION MODEL

To perform the study, a mixed integer linear programming (MILP) model was used for optimizing the distributed trigeneration system. The model has been developed to find the synthesis and optimal operation of energy systems evaluating different investment options that satisfy electric, heat and cooling demands of the users at the lowest cost.

The problem cannot be solved separately for each building and its related trigeneration unit, because each of them is connected with the district heating and cooling network through a node, where thermal and cooling energy can be potentially exchanged with any other node of the network. Figure 4 shows a scheme of the user lay-out with the CHCP units and its connections to the user, with the electric grid and with the district heating and cooling network. In each building up to 4 microturbines (MTG) and up to four (4) absorption chillers (ABS) can be chosen by the optimization procedure. These limitations take into account the size of the machines considered and the maximum load required by users.

In the following numerical application, microturbines Capstone C60, introduced in the previous section, are taken into account, but the underlying MILP model would still apply if different CHP technology (for instance, Internal Combustion Engine) and/or different machine size were considered in the optimization.

As seen in Figure 4, each absorption chiller is directly connected to the heat recovery circuit of the corresponding microturbine and it is constrained to be operated using cogenerated heat, so that a specific absorption chiller cannot be adopted if the related microturbine does not exist, inside the optimal solution.

Each node of the district heating and cooling network can exchange energy with all the others, if the corresponding grid lines exist inside the optimal solution. In addition, a boiler (BOI) and a compression chiller (REFC) are always present inside the CHCP units, to integrate the energy demand.

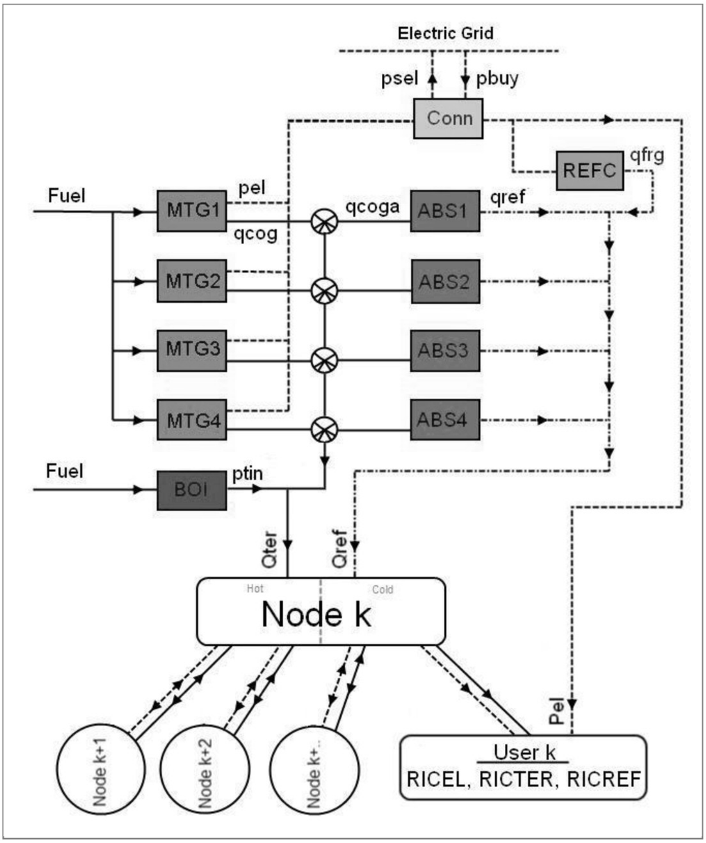


Figure 4: Scheme of single user with trigeneration system and connection to district heating-cooling network

A set of binary variables is introduced into the model in order to express the choice of adopting, or not, each microturbine or absorption chiller, as well as each pipeline of district and cooling network. Therefore optimal lay-out of the distributed trigeneration system is obtained optimizing the problem, not being fixed in advanced. Other binary variables are introduced to represent on/off status of each machine installed, while continuous variables represent the operation level of machines and energy flows through each pipeline.

The following decision variables (integer and continuous) are determined by the optimization model through objective function minimization:

- Number of micro gas turbines and absorption machines to be installed in each building;
- Number, size and position of pipelines inside of district heating-cooling network;
- Hourly operation of installed machines;
- Hourly management of energetic flows in each building and through each pipeline;
- Hourly electric energy sold to or bought from electric grid;

The objective function is expressed as:

$$\begin{aligned}
&\boldsymbol{min} \quad \boldsymbol{C_{tot}} = \\
&\quad \textstyle\sum_{j,k} fa \cdot (Ccogen_j \cdot X_{j,k} + Cass_j \cdot Z_{j,k}) + \\
&\quad \textstyle\sum_{k,v|k \neq v} far \cdot l_{k,v} \cdot \left[rt_{k,v} \cdot Cfix + F1 \cdot \left(DHc_{k,v} + DHf_{k,v}\right) \right. \\
&\qquad\qquad\qquad\qquad\qquad\qquad \left. + F2 \cdot \left(rc_{k,v} + rf_{k,v}\right)\right] + \\
&\quad \textstyle\sum_{m,g,i,k} Pbuy_{m,g,i,k} \cdot Cbuy - \\
&\quad \textstyle\sum_{m,g,i,k} Psel_{m,g,i,k} \cdot Csel_{m,i} + \\
&\quad \textstyle\sum_{m,g,i,j,k} Fchp_{m,g,i,j,k} \cdot Cfchp + \\
&\quad \textstyle\sum_{m,g,i,j,k} Fboi_{m,g,i,j,k} \cdot Cfboi + \\
&\quad \textstyle\sum_{m,g,j,k} G1 \cdot Pel_{m,g,i,j,k} + G2 \cdot Qref_{m,g,i,j,k} \;\; [€]
\end{aligned} \qquad (6)$$

Ctot is the Total Annual cost and includes respectively investment costs of machines and network, purchasing electricity cost, income from the sale of electricity, cost of fuel used in microgas turbines and boilers, and machine maintenance costs. This objective function is linear with respect to independent variables described before and it has to be optimized subjected to constraints that express machine performance (See COMPONENT MODELS section above) and energy balances. Other constraints are introduced to take into account the functional parameters of CHCP units and the connection between machine, etc. Energy balances (electric, thermal and cooling) ensure that for each time interval and for each node the amount of input energy is equal to output, as described below:

1.Electric balance: Electricity purchased from the grid and produced by microturbines has to be equal to the sum of electricity required by users, sold to the grid and sent to compression chiller.

$$pbuy_{m,g,i,k} = RICEL_{m,g,i,k} - \sum_j \ pel_{m,g,i,j,k} + pfrg_{m,g,i,k} + psel_{m,g,i,k} \qquad (7)$$

2. Thermal balance: The total amount of heat produced by cogenerators, produced by boiler and received from the thermal grid has to be equal to the sum of heat sent to the user, to absorption machines, to the grid and dissipated.

$$ptin_{m,g,i,k} = RICTER_{m,g,i,k} - \sum_j \ qcog_{m,g,i,j,k} + \sum_j \ qcoga_{m,g,i,j,k} + pdiss_{m,g,i,k} + \sum_v \left(Qc_{m,g,i,k,v} - Qc_{m,g,i,v,k} \cdot \left(1 - pc_{k,v}\right)\right) \qquad (8)$$

3. Cooling balance: The total amount of cooling energy produced by compression chiller, by absorption chillers and received from the grid has to be equal to the sum of cooling energy required from the user, sent to the grid and dissipated.

$$qfrg_{m,g,i,k} = RICREF_{m,g,i,k} - \sum_j \ qref_{m,g,i,j,k} + pdissr_{m,g,i,k} + \sum_v \left(Qf_{m,g,i,k,v} - Qf_{m,g,i,v,k} \cdot \left(1 - pf_{k,v}\right)\right) \qquad (9)$$

Thermal and cooling energy received from the grid are reduced by loss coefficients proportional to the length of pipelines passed through, as follows.

$$pc_{k,v} = \frac{\delta c \cdot l_{k,v}}{1000} \qquad (10)$$

$$pf_{k,v} = \frac{\delta f \cdot l_{k,v}}{1000} \qquad (11)$$

A more detailed model, in a previous paper [1], has been solved implementing it in the commercial software X-Press® through the programming language called Mosel, that converts algebraic relations, like those presented above, into the MILP standard form.

Once the optimal solution has been obtained, the impact on primary energy consumption has been evaluated by the calculation of the Primary Energy Saving (PES) index and the saved Tons of Oil Equivalent (TOE), according to [24].

$$PES = 100 - \frac{E_c}{\frac{E_e}{\eta_{es} \cdot p} + \frac{E_{t,civ}}{\eta_{t,civ}} + \frac{E_{t,ind}}{\eta_{t,ind}}} \cdot 100 \qquad (12)$$

$$TOE = \Delta Ep \cdot ft = \left(\frac{E_e}{\eta_{es} \cdot p} + \frac{E_{t,civ}}{\eta_{t,civ}} + \frac{E_{t,ind}}{\eta_{t,ind}} - E_c \right) \cdot ft \qquad (13)$$

The optimization model described above has been applied to a tertiary sector real case, made up by six public buildings located in a small town of north-east Italy. The location of the buildings is schematically represented in Figure 5, which shows also the path and the length of all possible pipelines, agreeing with existing streets, their curves and corners.

The heterogeneous choice of the considered buildings, with a variety of energy demands, allow that the achieved results be not affected by a specific user profile. A similar mix of users is expected to be easily recognized in a lot of other small and medium size towns in Europe.

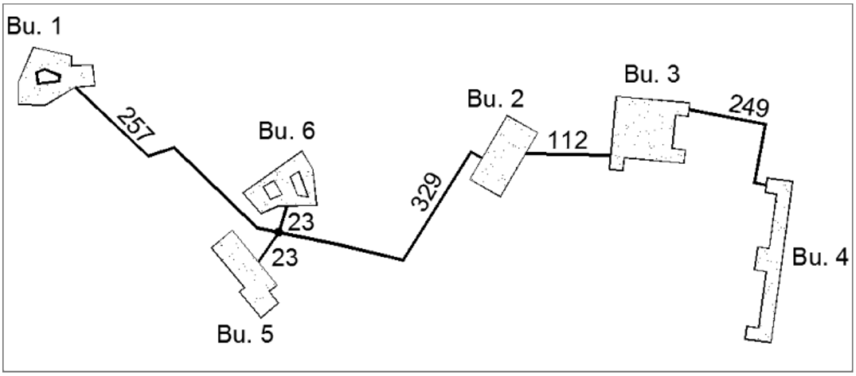


Figure 5: Plan of buildings, possible path and length of district heating-cooling network: 1-Town Hall 2-Theatre 3-Library 4-Primary school 5-Retirement Home 6-Ex-monastery

Table 5 shows the yearly energy demand of the users, supplied by current owners. In the model, hourly energy demands have been introduced in order to simulate precisely the energy requirement of each user [6]. To reduce the overall number of variables, the whole year can be modeled by taking into account a small number of "typical days." In this way the energy demand of the whole year is adequately approximated by repeating a proper number of times each typical day. In this case study, 6 typical days with hourly variation of energy demands have been considered. This assumption seems to be the right compromise, in fact assuming 24 typical days the conventional energy costs vary less than 2.5% and the optimal global synthesis doesn't change at all. Hence the suggestion is to find the synthesis assuming 6 typical days and to refine the solution assuming a greater number of typical days. This allows to significantly reduce the total time required to find the optimal solution.

At the present time, all the considered buildings adopt the conventional solution to satisfy their energy demands. All the electricity is purchased from the external electric grid, the thermal energy is produced by natural gas boilers present in each unit and the cooling energy is produced through conventional electrical chillers present in each unit too. In this situation only electric energy and gas have to be supplied to the buildings, incurring a cost equal to 1.180.000 €/Year.

The Theatre is located in the centre of the area and it is the highest energy consumer. See Table 5. It should be noted that cooling energy is not required by the Primary School, as it is closed in summer.

Table 5: Energy demands of users

	Energy demand [kWh]		
	Electricicty	Thermal	Cooling
1-Town Hall	376.444	748.523	162.199
2-Theatre	925.820	1.140.784	501.040
3-Library	534.870	634.935	123.110
4-Primary School	79.868	1.057.543	0
5-Retirement Home	531.164	800.116	189.799
6-Municipal Archive	89.821	464.299	86.189
Total	2.537.987	4.846.200	1.062.337

RESULTS

The results of the optimization presented below have been carried out solving the model through a commercial software X-Press®. Once energy demands of each user are known, jointly with other boundary conditions like prices of electric energy and gas, distances between buildings and performance curves of considered machines, the optimal solutions is mainly affected by the component capital costs. This influence can be evaluated keeping constant the price of each component and varying the recovery factor (eq. 14). It depends from both interest rate (assumed equal to 5%) and investment life time.

$$f_{(n)} = \frac{int \cdot (1+int)^n}{(1+int)^n - 1} \qquad (14)$$

Two different capital recovery factor have been assumed for machines (*fa*) and pipelines (*far*) taking into account that the latter have a double life span compared to the former (microgas turbines and network). In Table 6, four cases, with life times (na) of 2, 4, 6 and 10 years have been considered for microgas turbines and absorption chillers, while networks life times are twice such as much.

Table 6: Results of optimizations carried out varying life time of investment

Case	na	fa	far	Inv. Cost k€		Operation cost k€	Objective func. k€
				Machines	Networks		
1	2	0,538	0,282	146,3	18,3	1.090,1	1.173,9
2	4	0,282	0,155	854,3	251,2	725,0	1.005,0
3	6	0,197	0,113	1.222,5	259,5	632,2	902,4
4	10	0,130	0,080	1.222,5	260,0	632,8	812,0

Table 6 shows, the trend of investment cost, operation cost and objective function by varying the capital recovery factor for the four cases. Note that high values of recovery factor limit the investment, so that the operation costs and the objective functions are similar to conventional energy cost. With a lower recovery factor, or higher life span of machines and networks, the investment increases while operation costs and objective function decrease. In fact, low recovery factors make more convenient to invest in trigeneration and in district heating and cooling systems, in order to achieve reduction of annual cost and primary energy. In cases 3 and 4 the objective function value changes even if the configuration and the machines management are the same because the investment cost is spread over several years through the capital recovery factor.

It should be noted also that case 3 and 4 have the same investment costs but the operational costs are little greater in case number 4, contrary to what would be expected. It happens because, the GAP considered in the branch and bound algorithm was equal to 0,1%, so that the optimal lay out and operation of these two cases fall within the GAP. In fact, if the capital recovery factors of the case 4 are applied to the optimal solution find in case 3, the resulting objective function is lower by 0,08% only than one reported in Table 6.

Figure 6 shows the different optimal system configurations ob-

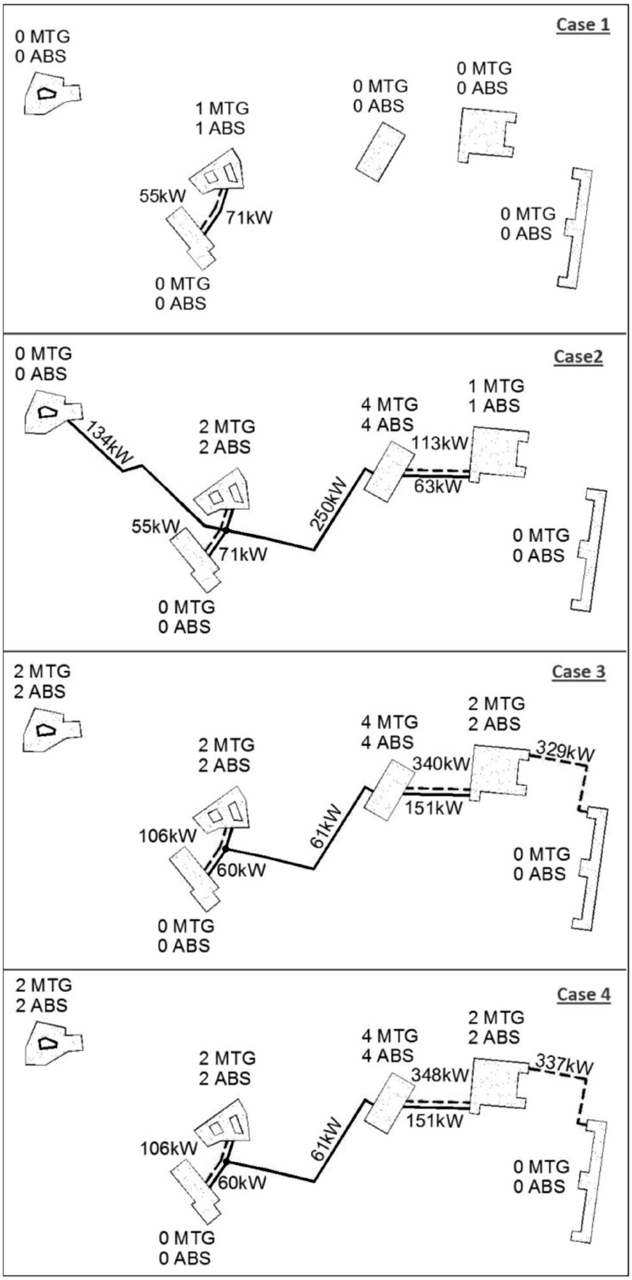


Figure 6: Optimal configuration of four case studies

tained for the Case 4 by varying the capital recovery factor. The different optimization results show also that Cases 3 and 4 have only small differences in the pipelines size that connect building 3 and 4.

A non-significant test has been performed assuming a greater number of years as machines life time, (the same results might be obtained reducing prices of machines and networks) and the optimal solution is the same obtained in Cases 3 and 4. This optimal solution has to be considered as a limit and further installations of machines and/or pipelines would not decrease the operation cost. This can be explained considering that the cost of electricity produced by microturbines, when the cogenerated heat is totally dissipated, is higher than the cost of electricity purchased from the grid. When the cogenerated heat is difficult to be allocated to the users, further investments in CHCP systems are not profitable even for very low capital recovery factor.

The total annual cost (objective function) is the parameter used to choose the best economic solution but it is not exhaustive because it does not take into consideration the investment risk. A parameter commonly used to evaluate investment is the payback period that is the time necessary to recuperate the initial cost of investment. Figure 7 shows net present value (NPV) of the different optimal solutions obtained by varying the investment life times. Line representing solution obtained assuming 6 and 10 years as investment life time is the same because, as seen above, optimal solution obtained in the case 3 and 4 have to be regarded as the same optimum.

It can be noted also that payback periods of all solutions are included between two and three years. Focusing on NPV related to 4 years and 6-10 years, the NPV of the latter solution is greater than the former by about 15.5%, against a major investment equal to 34%. Thus, the optimal solution obtained assuming 6 or 10 years is more convenient than the one obtained assuming 4 years, but is more risky.

The optimal solution obtained solving the MILP model contains not only the optimal configuration, but also the optimal operation of each machine installed and the flows through each pipeline. Figures 8, 9 and 10 show optimal management of electric, thermal and cooling energy in a typical day, related to building n° 3 (library).

Note in Figure 9, related to building n°3, that some hours are characterized by thermal energy received and sent to the grid at the same time. By analyzing the outcomes, it emerges that thermal energy is received from building n°2 and sent to building n°4 which has no

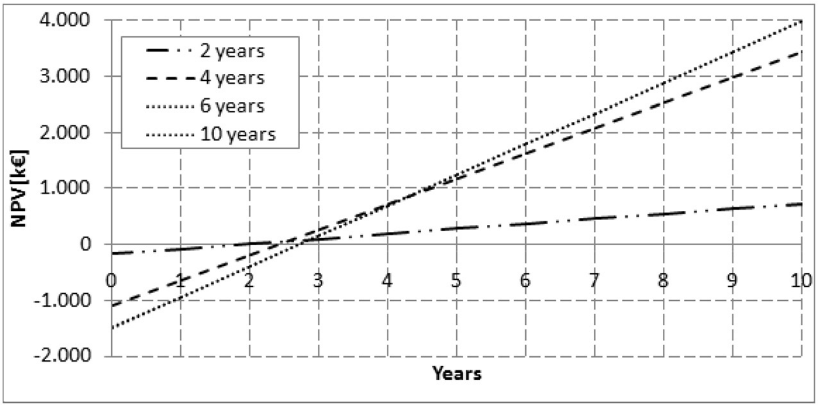


Figure 7: NPV vs. years of optimal solutions obtained assuming different life span

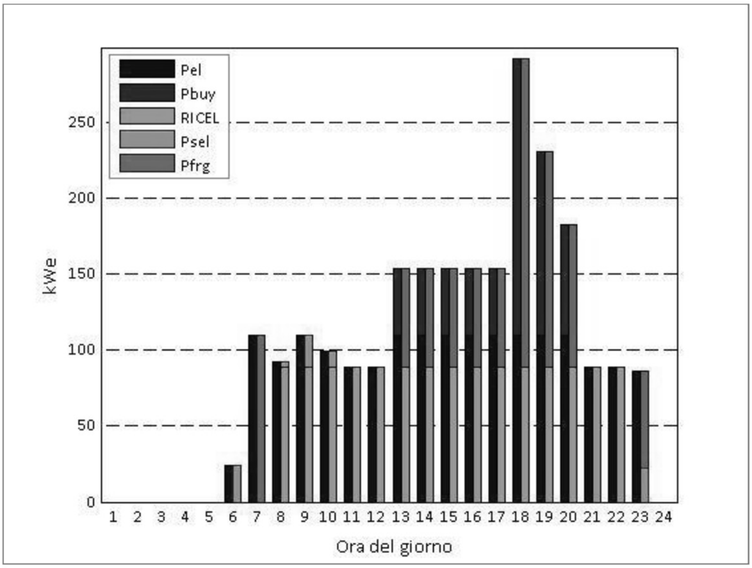


Figure 8: NPV vs. years of optimal solutions obtained assuming different life span

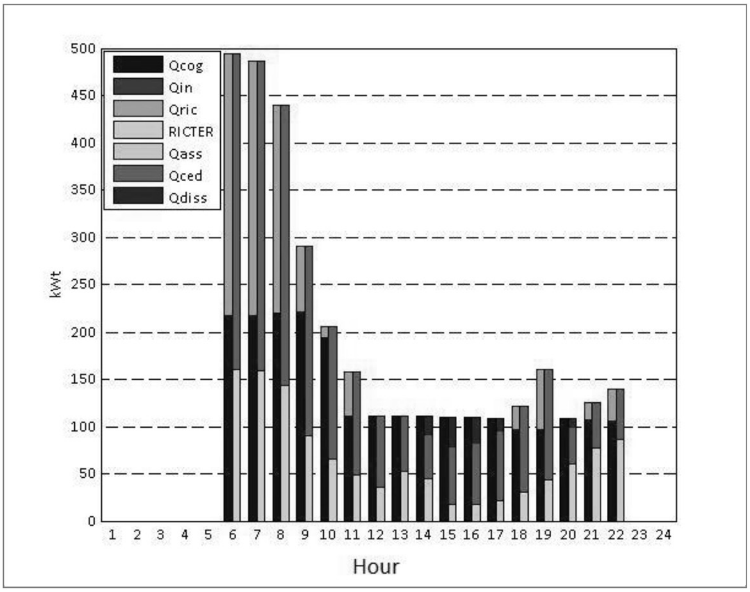


Figure 8: Optimal management of thermal energy, building n°3, mid-season typical day

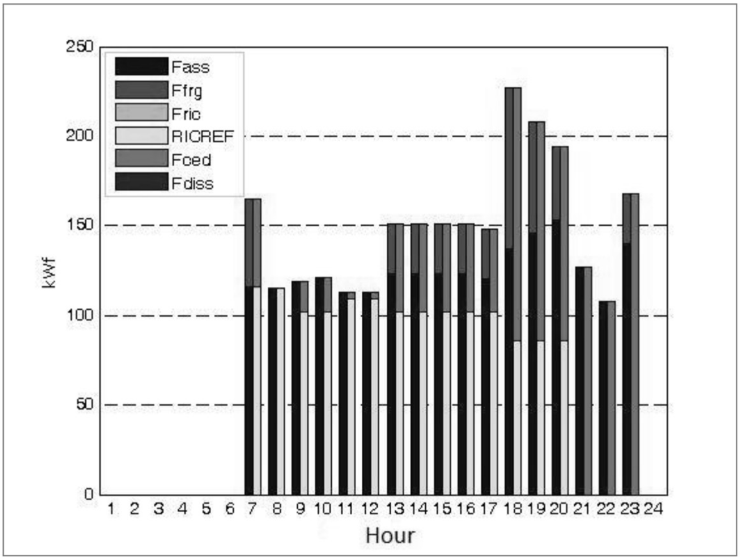


Figure 9: Optimal management of cooling energy, building n°3, summer typical day

cogenerators inside. The same does not happen for cooling energy, reported in Figure 10, because the school does not have cooling demand.

CONCLUSIONS

The optimal solution of the problem dealing with distributed trigeneration systems integrated with district heating and cooling microgrids can be obtained with a commercial software on the basis of the proposed MILP model.

As expected, by reducing the capital recovery factor, the number of microgas turbines and absorption chillers in the optimal solution increase. At the same time, the district heating and cooling microgrids are extended to connect more buildings and their whole investment costs also increase.

By reducing the capital recovery factor, or by increasing the life time of components, the grow of the whole trigeneration and DHC systems reaches a limit of diminished returns. In this situation further investments in system components are not profitable because the cost of electricity produced by microturbines is higher than the cost of electricity purchased from the grid when the cogenerated heat cannot be easily allocated to the users.

This result could be overturned if the electrical efficiency of microturbines were close to that of the big centralized power plant used to feed the electrical grid, but this hypothesis is not realistic nowadays. Therefore the useful allocation of cogenerated heat is a critical issue for profitability of trigeneration systems.

The procedure applied in this article allows us to highlight the more profitable system configurations and operations to reduce the total cost of energy demand (electrical, heating and cooling). In the real case to which the model has been applied, the installation of one trigeneration group and the connection between two buildings (case 1) costs 164 k€ and allows to save 90 k€/years, so that the payback period is lower than 2 years. In the more complete optimal solution (case 4) 10 trigeneration groups are installed and six pipelines are lied down. It costs 1.480 k€ and allows to halved the yearly operation cost. The annual saving is 550k€ and the payback period is lower than 3 years.

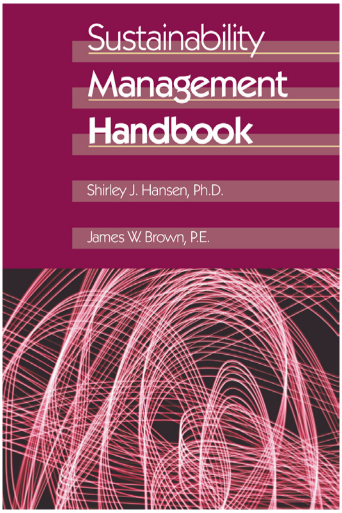
The results show that the integration of more buildings through district heating and cooling microgrids reduce cost and primary energy consumption, when the optimal solution arrived here is adopted. In fact, microgrids allow to useful allocate more thermal and cooling energy making more profitable the operation of the trigeneration systems.

NOMENCLATURE

$Cass$	Absorption chiller capital cost [€]
$Cbuy$	Electrical energy purchase cost [€/kWh]
$Ccogen$	μTG capital cost [€]
$Cfboi$	Integration boiler fuel cost [€/m^3]
$Cfchp$	μTG fuel cost [€/m^3]
$Cfix$	Fixed cost of district heating/cooling network dig [€/m]
$Csel$	Sold electrical energy price [€/kWh]
$Ctot$	Total annual cost [€/year]
DHc	District heating pipeline heat flow [kW]
DHf	District cooling pipeline heat flow [kW]
dp	Binary variable related to compression chiller
Ec	Total μTG energy consumption [kWh]
Ee	Total μTG produced electric energy [kWh]
EER	Compression chiller energy efficiency ratio
Et	Total μTG produced thermal energy [kWh]
$F1, F2$	District heating/cooling network coefficients
fa/far	Capital recovery factor
$Fass$	Cooling energy produced by ABS [kWh]
$Fboi$	Boiler fuel consumption [kWh]
$Fchp$	μTG fuel consumption [kWh]
$Ffrg$	Cooling energy produced by REFC [kWh]
$Fced$	Cooling energy sent to the grid [kWh]
$Fdiss$	Dissipated cooling energy [kWh]
$Fric$	Cooling energy received by the grid [kWh]
ft	Conversion factor [0,086 TOE/MWh]
g	Generic day index
$G1, G2$	Maintenance coefficient [€/kWh]
$Ha1, Ha2, Ha3$	Performance curve linearization coefficients of absorption chiller
Hi	Lower heating value
i	Generic hour index
int	Interest rate
j	Generic trigeneration unit index

SUSTAINABILITY MANAGEMENT HANDBOOK

Shirley J. Hansen, Ph.D., and James W. Brown, P.E.



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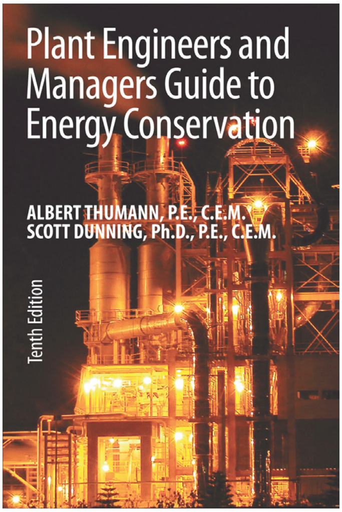

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k	Generic node index
Kt1, Kt2, Kt3	Performance curve linearization coefficients of μTG
l	Distance between two nodes [m]
m	Generic month index
n, na, nar	Investment life time
p	Electric grid loss coefficient (= 0,957)
pbuy	Purchased electrical energy [kWh]
pc, pf	District heating/cooling pipeline thermal losses [kWh]
pfrg	Compression chiller produced cooling energy [kWh]
pdiss	Dissipated thermal energy [kWh]
pdissr	Dissipated cooling energy [kWh]
pel	μTG produced electrical energy [kWh]
PES	Primary energy saving
pfrg	Compression chiller electrical Energy consumption [kWh]
psel	Sold electrical energy [kWh]
ptin	Integration boiler thermal energy [kWh]
qass	Absorption chiller input thermal energy [kWh]
Qc, Qf	Thermal energy transferred throw district heating/cooling pipeline [kWh]
Qced	Thermal energy sent to the grid [kWh]
qcog	Cogenerated thermal energy [kWh]
qcoga	Input absorption chiller thermal energy [kWh]
Qdiss	Dissipated thermal energy [kWh]
qfrg	Compression chiller produced cooling energy [kWh]
Qric	Thernal energy received by the grid [kWh]
Qin	Thermal energy produced by boiler [kWh]
qref	Absorption chiller produced cooling energy [kWh]
qter	Node input thermal energy [kWh]
R1,R2	Performance curve linearization coefficients of compression chiller
rc, rf	Binary variables related to heating/cooling pipelines
rt	Binary variable related to generic pipeline
RICEL	Electric energy demand [kWh]
RICREF	Cooling energy demand [kWh]
RICTER	Thermal energy demand [kWh]
TOE	Tons of equivalent oil
th	Temperature of hot water produced by μTG [°C]
tha	Temperature of absorption chiller hot water input [°C]
w, Z	Binary variables related to absorption chiller
X, y	Binary variables related to μTG
δ_c, δ_f	Percentage thermal losses along the district heating/

	cooling pipeline per unit length [km^{-1}]
Δep	Saved energy [MWh]
ηb	Boiler efficiency
ηes	Power generation mean electric efficiency
ηt	Thermal plants mean efficiency

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