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Energy Analysis in an Italian Opera House

By Massimo Mitolo, Michel Noussan, Enrico Pons,
Davide Porte, and Michele Tartaglia

THE REFURBISHMENT OF HISTORIC BUILDINGS IS A COMPLEX TASK in which the goal of obtaining a more energy-efficient building can conflict with the peculiar characteristics of the building's environment and its intended use. In this article, the authors address this problem for a very specific type of building: a historic opera house located in northern Italy. The results of energy consumption monitoring and spot measurements on selected loads were used as a basis to propose energy-savings strategies.

The objective of this article is to highlight the difficulties in refurbishing historic buildings, particularly regarding the building envelope, in lieu

HIGHLIGHTING THE DIFFICULTIES IN REFURBISHING HISTORIC BUILDINGS USING ENERGY-SAVINGS STRATEGIES

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of proposing a new methodology for measurements or a new strategy for energy savings. It is documented that energy savings are obtainable with relatively small investments and low-impact construction work.

Energy-Efficiency Goals and Problems

Energy efficiency in buildings is a primary objective for energy policy at regional, national, and international levels, as energy consumption of buildings comprises 20–40% of total energy use [1]. Energy efficiency is also a primary goal of building owners and managers as remarkable monetary savings can be achieved through its implementation [2]. In existing buildings, different energy-saving strategies need to be compared and evaluated to determine the best combination of economic performance, energy-consumption minimization, and the optimal comfort of users [3]. The problem of energy savings for historic buildings becomes challenging as the number and effectiveness of possible energy-efficiency measures may be reduced and not always possible without compromises [4].

Energy savings becomes even more critical when the building has uncommon characteristics, such as the large historic opera house discussed in this article. Possible energy-efficiency measures may involve the building envelope and/or technological installations. In historic buildings, solutions involving the building envelope are rather problematic, as some strategies for energy efficiency can be implemented in electrical and thermal systems. In particular, it is possible to improve the efficiency of electric transformers and motors [5], [6], [12], install and properly manage multigeneration systems [7], [8], or promote the connection to district heating (DH) networks, if available [9], [10]. In this study, the authors describe the opera house building and report the results of energy monitoring and spot measurements, which are used as a base to propose possible energy-efficiency measures.

Building Description

The opera house of this study is the Teatro Regio di Torino, located in Turin, Italy. It was built in 1740, partially destroyed by a fire in 1936, and reconstructed in 1973. Its facade, which was untouched by the fire, is a UNESCO World Heritage Site. The building is nine floors, from level –12.5 m to level +32.1 m. Its total surface is around 60,000 m^2, while its volume is approximately 190,000 m^3. The opera house hosts two halls: an opera theater of 1,600 seats and a smaller theater of 400 seats, mainly used for concerts, dances, and conferences.

In addition to the two halls, the building also contains several offices and artisan shops. The following spaces are considered for energy consumption analysis:

- foyer
- practice rooms
- employee cafeteria
- artisan shops.

Due to the building's historical characteristics and its inclusion as a UNESCO World Heritage Site, possible energy-efficiency measures are necessarily limited. The opera season runs from October to July, while the concert season usually starts in September. In the month of August, no performances are scheduled, but offices may be open and maintenance work performed.

Measurement Results

Analyzing the building's energy consumption was the first step in evaluating and choosing the best energy-efficiency measures. The opera house receives energy via two energy vectors: natural gas and electricity. Natural gas is mainly used for heating, while electricity is used for lighting, cooling, ventilation, circulation pumps, the kitchen, and all other electric loads. Monthly natural gas consumption for 2012 and 2013 is reported in Figure 1.

The opera house has two points of delivery for electric energy: one in low voltage (LV) at 380 V and one in medium voltage (MV) at 22 kV. The end-user MV/LV substation is equipped with three transformers with a rated power of 1,600 kVA each. Through the study of electric bills, the building's monthly consumption from 2012 through 2015 was determined, shown in Figure 2. It was also possible to estimate yearly natural gas consumption for 2014

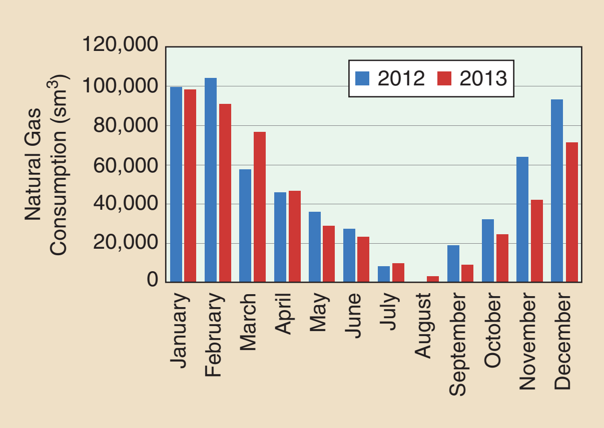

FIGURE 1. Monthly natural gas consumption.

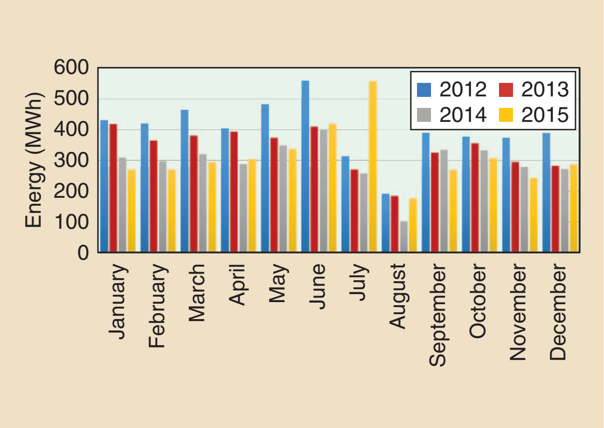

FIGURE 2. Monthly electricity consumption.

and 2015, which was then used to estimate the buidling's heat consumption (by using an average annual boiler efficiency of 90%).

Table 1 summarizes each energy carrier, expressed in gigawatt hours. Considering the primary energy requirements, the total energy consumption is equivalent to around 1,100 toe for the year 2013. Around 60% of energy requirements are served by electricity and around 40% are served by natural gas. The estimated carbon dioxide (CO_2) emissions related to the energy supply for the same year are around 2,400 t. The primary energy factors and specific emission factors related to the electrical supply have been calculated by considering the actual parameters of the Italian network for each hour of operation.

No other data were available from the energy manager of the opera house. With such a limited amount of information, it is hard to make proper decisions and plan investments for energy savings. For these reasons, spot measurements were planned and carried out on specific sections of the electrical installation. Among building services, the energy usage of heating, ventilation, and air-conditioning (HVAC) systems is particularly significant. The kitchen, which serves the cafeteria, is all electric. For these reasons, specific measurements were carried out with a network analyzer on the switchboard feeding the cafeteria and on a refrigerating unit of the HVAC system. For measuring voltage, a direct connection was possible, as the voltage channels of the testing equipment are insulated up to 600 V rms. Three ac clamp-on probes (ranging from 20 to 300 A) were also used to measure the phase currents. The power values were saved with a time step of 15 min. The results of these measurements will be presented next.

Cafeteria

The measurements in the cafeteria were taken in June 2016. In Figure 3, the average power measured in each 15-min interval is presented for the time frame 13–19 June 2016. Other measured data for other weeks were similar and confirmed that the opera program does not affect the cafeteria consumption.

Besides average power, the network analyzer also provided, for each time interval, maximum and minimum power peaks, which helped to better understand the load behavior. The cumulative monthly distributions for the minimum, average, and maximum power absorbed by the cafeteria are presented in Figure 4. The peak power absorbed by the cafeteria is around 100 kW, while the base load is approximately 2 kW. The energy consumption in June was approximately 9 MWh. By considering that the cafeteria consumption is approximately constant throughout the year, except for the month of August, it can be extrapolated based on the energy consumption recorded during the month of June that the yearly energy consumption is roughly 100 MWh. This value ranges approximately from 2.1 to 2.8% of the opera house's total electricity consumption. The demand reduction measures should, therefore, focus mainly on other electrical loads.

HVAC Refrigerating Unit

The opera house includes four HVAC refrigerating units of 180 kW each. Measurements were taken from July to September 2016 on one unit, and the total consumption was estimated based on the indications provided by the system operator. Figure 5 presents the consumption for a typical

Table 1. Energy consumption (GWh)

Year	Natural Gas	Heat	Electricity
2012	5.64	5.08	4.79
2013	5.03	4.53	4.05
2014	5.17	4.65	3.54
2015	4.32	3.89	3.72

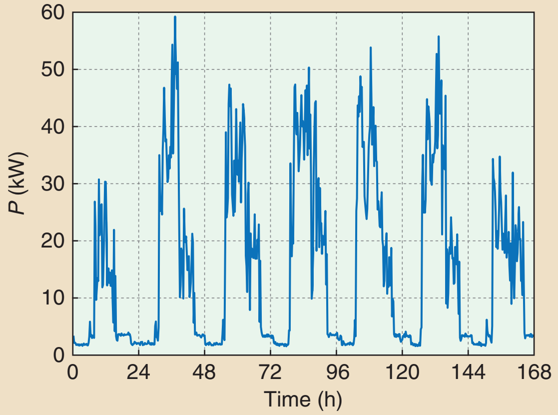

FIGURE 3. Cafeteria electricity consumption during the central week of June.

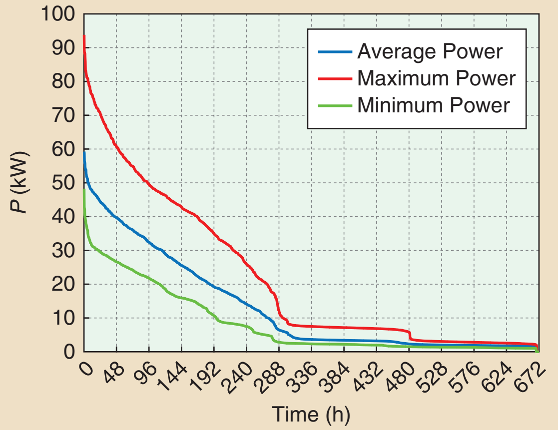

FIGURE 4. The cumulative distribution of the cafeteria electricity consumption.

summer week (when the opera house is still open), and the cumulative consumption distribution is reported for 16 July–13 September (Figure 6). For a large number of hours, the consumed power was zero, as the opera house was closed in August.

The refrigerating units are manually programed; they absorb full power in the morning when they are started, and then they are regulated at fixed steps to maintain the temperature set point inside the building for the rest of the day. In this case, as the refrigerating units operated at constant power for long periods, the cumulative distributions of the maximum, minimum, and average power inside the 15 min intervals were approximately equivalent. The peak power absorbed by one refrigerating unit is around 200 kW, but for most of the operating time, consumption ranged from 50 to 70 kW. The daily energy consumption of a single refrigerating unit is between 500 and 1,000 kWh. Consumption is strongly dependent on what is going on at the opera house.

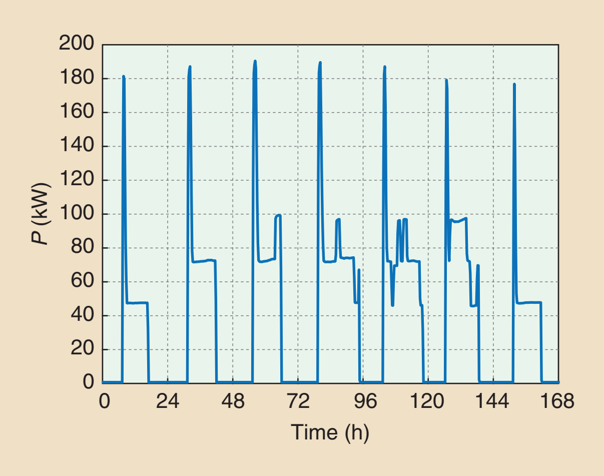

FIGURE 5. Refrigerating unit electricity consumption, 18–24 July 2016.

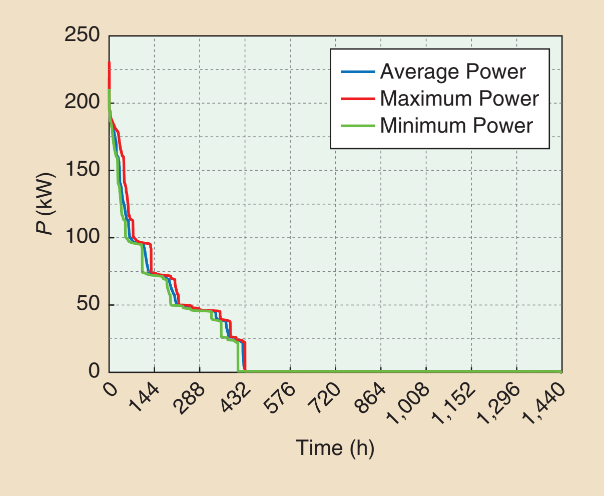

FIGURE 6. The cumulative distribution of refrigerating unit electricity consumption.

Table 2. Transformer characteristics

Transformer	A (kVA)	P_0 (W)	I_0 (%)	Z_{kT} (%)	P_{kT} (W)
T1	1,600	2,110	0.18	5.89	11,886
T2	1,600	2,086	0.19	5.82	12,269
T3	1,600	2,063	0.18	5.88	12,522
EN 50588-1	1,600	1,265	2	6	13,000

Based on the measurements for a single refrigerating unit and the data provided by the HVAC system manager, it was possible to estimate a total energy consumption for the summer of approximately 180 MWh. The total opera house electricity consumption for the same period is around 1,550 MWh. The refrigerating units represent a share of approximately 11.6% in the summer period (May to September).

Proposed Energy-Efficiency Measures

Based on the prior energy-consumption analysis, different energy-efficiency measures are proposed, which focus on electricity reduction, heating and cooling demands, or the increase of conversion efficiency to reduce primary energy consumption. The main choices for energy-demand reduction are

- replacement of transformers and motors with higher efficiency ones
- control of electric motors with variable speed drives
- installation of chillers with a higher coefficient of performance (COP).

Two alternative solutions are proposed for reducing the total primary energy consumption of the building:

- installing a combined heat and ower (CHP) system
- connecting to the city DH network.

Replacement of Transformers

The first option for reducing electricity demand is replacing the MV/LV transformers with more efficient models. The opera house uses three MV/LV transformers (T1, T2, T3) with a rated power of 1,600 kVA each with nominal voltages of 22 kV/400 V. One of the three transformers is a backup, while two operate normally. The main characteristics of the transformers have been extracted from the acceptance tests documentation and can be compared with the requirements provided by Standard EN 50588-1 in Table 2 [5].

The parameters of the existing transformers are acceptable, except for the no-load losses, which are higher than the value recommended by current standards. Replacing the transformers with new models complying with these requirements would lead to an annual savings of roughly 7 MWh. Due to the high cost of transformers and the relatively small losses reduction (0.2% of the total electricity consumption), this investment would have a very long payback period.

Replacement of Electric Motors

A second option is replacing electric motors with higher efficiency models [6]. The main electric motors with higher rated power and number of working hours during the year were identified (Table 3) and their characteristics extracted from data sheets. The existing motor efficiencies were generally lower than those prescribed by Standard EN 60034-30-1 [6]. The replacement of all the electric motors listed in Table 3 with new ones, with efficiency class IE3, would lead to an annual savings of roughly 120 MWh (approximately 3% of the total opera house electricity consumption), with a payback period of only three years.

Replacement of Refrigerating Units

From the energy consumption measurements, the HVAC refrigerating units appeared to have a high share of total electricity consumption. Replacing the existing refrigerating units is a viable solution to reduce electricity demands. The current refrigerating units have an average COP of approximately 4.16, calculated from performance monitoring. Modern refrigerating units can reach average COPs of up to six or seven. Replacing all four existing refrigerating units with models with higher COPs would lead to potential annual savings of 60–75 MWh.

Alternative Generation Possibilities

To decrease primary energy consumption, alternative solutions for generating heat and power were evaluated, and a comparison between the installation of a CHP system (natural gas engine) and the connection to the city of Turin DH was performed. The comparison was made by using national primary energy factors for electricity, and local primary energy factors for the heat provided by the DH system.

The primary energy factor of the electricity supplied by the Italian power grid was calculated by considering the actual generation of power plants with an hourly time resolution. The methodology is discussed in [13], where some performance indicators are presented for electricity generation in Italy within a larger timeframe. In this article, the primary energy factors for electricity are used, limited to 2013, from which the alternative generation scenarios are calculated. The values of the primary energy factor for electricity consumption are reported in Figure 7 and include electricity losses on the power grid, i.e., the ratio is calculated by considering the electricity supplied to the final user at MV (with reference losses of 4%).

Figure 7 shows the wide range of primary energy variability associated with electricity generation, which is strictly dependent on the electricity sources mix for each hour. Usual approaches are based on average annual data, which causes a significant approximation of the actual variability of this indicator. The installation of a CHP system for buildings with high thermal and electricity consumption can be a worthwhile energy-efficiency measure, and its technical and economic

Table 3. Electric motors characteristics

	n	P (kW)	V (V)	I (A)	cosφ	η (%)
Water pump	7	30	400	55.5	0.85	91.8
Water pump	3	37	400	66.8	0.86	93
Fan HVAC	1	18.5	400	39	0.79	86.7
Fan HVAC	1	11	400	22	0.86	83.9
Fan HVAC	1	22	400	40.2	0.85	92.9
Fan HVAC	1	15	400	31.5	0.80	85.9
Fan HVAC	2	37	400	71.5	0.87	85.9
Fan HVAC	1	15	400	31.5	0.80	85.9
Fan HVAC	1	18.5	400	39	0.80	85.6
Fan HVAC	1	18.5	400	36	0.87	85.3
Fan HVAC	1	9.2	400	17.6	0.85	88.8
Fan HVAC	1	30	400	61	0.84	84.5
Fan HVAC	1	11	400	23.5	0.82	82.4

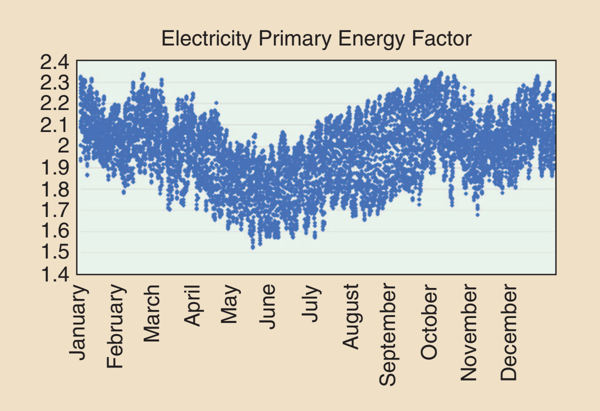

FIGURE 7. The primary energy factor of electricity in Italy in 2013 (elaboration from [13]).

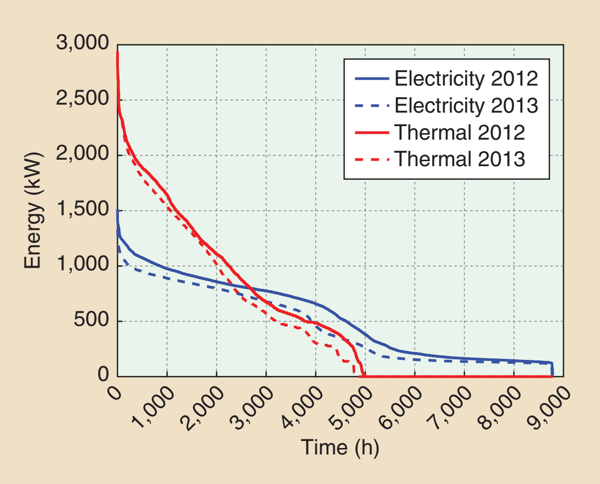

FIGURE 8. Cumulative distributions of electric and thermal loads.

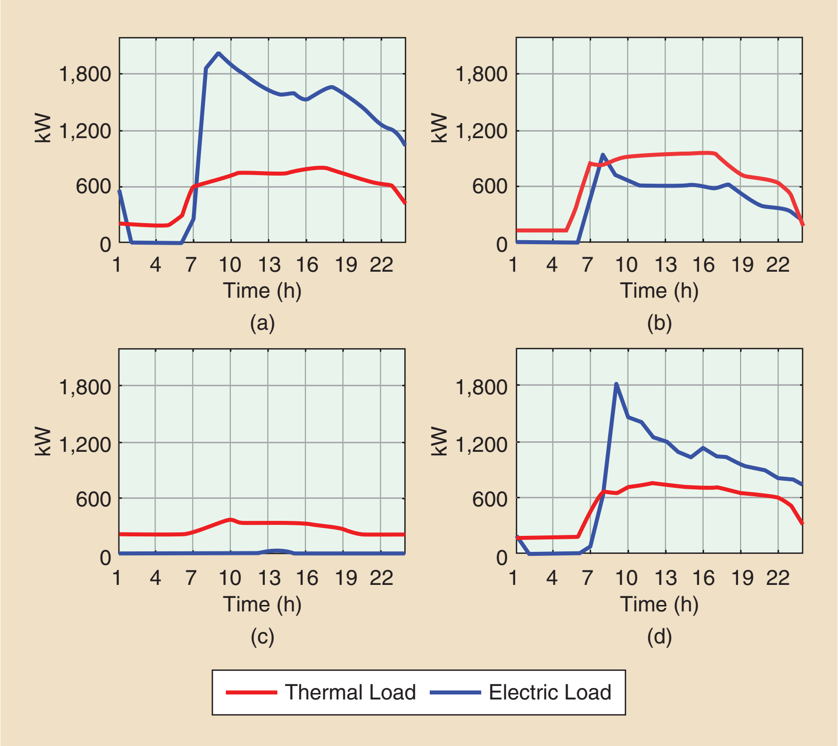

FIGURE 9. The typical daily load profiles for (a) January, (b) May, (c) August, and (d) November.

Table 4. CHP characteristics

Model	A	B
P_{fuel} (kW)	785	1,320
P_{el} (kW)	300	527
P_{th} (kW)	400	626

Table 5. Simulations results

	Reference Value	CHP (A)	CHP (B)	DH
Primary energy (GWh)	12.7	11.8	11.3	10.3
CO_2 emissions (t)	2,355	2,200	2,125	1,881
Engine equivalent hours	—	4,400	3,990	—

feasibility should be evaluated through a detailed analysis of thermal and electrical load. A CHP system is a good choice if thermal and electrical loads present similar hourly profiles and have a base load present for at least 3,000–4,000 h per year.

In the current situation, the thermal needs of the opera house are covered by three boilers with a rated power of 1,750 kW each, while all of the electric energy is provided by the national power grid. The cumulative distributions for thermal and electric energy for 2012 and 2013 are reported in Figure 8. The thermal and electric base loads of around 500 kW are present for more than 4,500 h. Typical daily load profiles for the four seasons are reported in Figure 9. As shown, thermal and electric profiles present different values but a similar trend.

Based on these premises, the installation of a CHP system tailored to these heat and power profiles is a viable option. Two possibilities have been explored, based on two different models of internal combustion engines, fed with natural gas; the characteristics are shown in Table 4, where P_{fuel} is the power input of the engine, P_{el} the power output, and P_{th} the heat output. The operation of the CHP engines has been performed on an hourly basis, as of 2013.

As for the connection to the DH network, the primary energy and CO_2 emissions of the heat supplied by the network were calculated using a primary energy factor of 0.626 kWh[p]/kWh[th] and an emissions factor of 120 g[CO_2]/kWh. This data was provided by the DH owner. The DH system is primarily supplied by three natural gas combined cycle units, which are operating in cogeneration with a very high electrical efficiency. Due to the allocation of primary energy consumption and emissions to both heat and power, the heat supplied by the DH system has a much lower impact on both primary energy and CO_2 emissions than the heat from natural gas boilers.

Table 5 shows the annual comparison of the previously described scenarios. The comparison considers both the heat and electrical power demands of the opera house. Figure 10 reports the monthly primary energy consumption, which compares to the reference scenario (current operation, already considering the additional electricity savings).

Regarding the CHP units, the results show that Engine B has a larger impact on reducing both primary energy and CO_2 emissions. Since the CHP operates with a heat-driven logic (i.e., avoids heat dissipation), Engine A has a higher number of equivalent hours of operation, which generally relates to a better exploitation of the economic investment. Thanks to the high-efficiency heat production of the Turin DH system, however, this last solution is preferable to CHP units (primary energy savings of 19.3% instead of 11.2% and a CO_2 emission reduction of 20.1% instead of 9.8% with respect to the reference scenario with savings).

The DH network connection would have no impact on the environment, while the installation of a CHP unit would increase the emissions of oxides of nitrogen, CO, and other

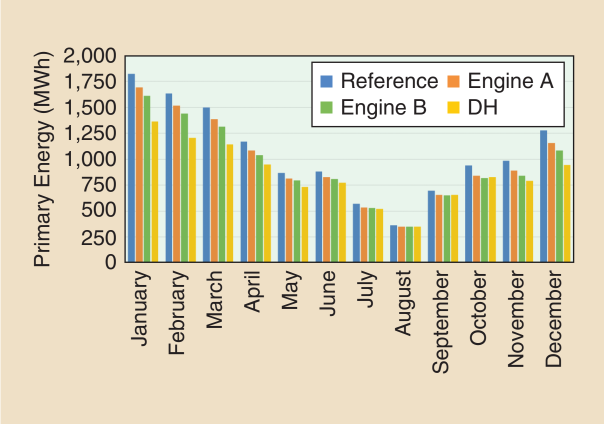

FIGURE 10. Monthly primary energy consumption.

pollutants in the central area of the city. Considering the building's usage, the installation of a CHP unit would also require mitigation strategies to limit noise emissions. However, the current development of the DH network does not allow a direct connection to the grid, so an extension of the pipes should be planned. This extension could also allow for the connection of other historical buildings that have similar issues in lowering their primary energy consumption. A detailed analysis must compare the estimated investment and the operation and maintenance costs of different solutions against current costs for the energy supply.

Conclusions

In this article based on [11], the results of the continuous monitoring of energy consumption and spot measurements on selected loads have been presented for the Teatro Regio di Torino, a historical opera house located in Turin, Italy. Measurements and monitoring results have been used to propose energy-saving strategies from two perspectives: a reduction in energy demand and of the total primary energy consumption.

The experimental results show that the cafeteria's share of energy consumption is a small percentage of the total yearly consumption. During the summer, the HVAC refrigerating units represent an important load of approximately 12% of total consumption. Different demand reduction strategies have been proposed. The most promising appeared to be the replacement of electric motors, which would lead to a savings of roughly 120 MWh per year, with an investment characterized by a very short payback period. For reducing total primary energy consumption, the optimal solution might be connecting to the city's DH network. This solution could lead to a 19% reduction in primary energy consumption. The connection to the DH would require an extension of the existing network to reach the city center, however. Other historical buildings with similar issues could be connected to the DH network, thanks to this expansion.

It is worth stressing that, for historic buildings, it is particularly challenging to obtain detailed data on heat and electricity consumption. Thus, it is crucial to accurately select the main loads to be monitored via spot measurements. Even in buildings with hard restrictions on possible energy-saving measures, important savings can be still achieved with simple and low-impact measures, such as replacing electric motors with high-efficiency motors.

Author Information

Massimo Mitolo (mitolo@ieee.org) is with Irvine Valley College, California. ***Michel Noussan*** and ***Enrico Pons*** are with Politecnico di Torino, Italy. ***Davide Porte*** is with Teenconsulting, Belgium. ***Michele Tartaglia*** is with Politecnico di Torino, Italy. Mitolo and Tartaglia are Senior Members of the IEEE. This article first appeared as "Energy Analysis in an Italian Opera House and Energy Savings Strategies" at the 2017 IEEE International Conference on Environment and Electrical Engineering/IEEE Industrial and Commercial Power Systems Europe. This article was reviewed by the IAS Energy Systems Committee.

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