Energy Consumption in an Italian Opera House: Analysis and Possible Reduction

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***Abstract*—The refurbishment of historic buildings is a complex task where the goal of obtaining a more energy efficient building often conflicts with the peculiar characteristics of the built environment, and its final destination. In this paper, 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 are herein used as a basis to propose energy saving strategies.**

I. Introduction

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]. It is also a primary goal for building owners and managers, as through energy efficiency remarkable monetary savings can be achieved [2].

In existing buildings, different energy saving strategies need to be compared and evaluated to determine the best combination between economic performance, energy consumption minimization and optimal comfort of the users [3].

The problem becomes challenging for historic buildings, as the possible energy efficiency measures that can be implemented may be reduced in number and effectiveness, and are not always possible without compromises [4].

The problem becomes even critical when the building has uncommon characteristics, such as the large historic opera house considered in this work.

Possible energy efficiency measures may involve the building envelope and/or technological installations. In historic buildings the former solution is rather problematic, whereas some measures can be implemented in the electrical and thermal systems. In particular, it is possible to improve the efficiency of electric transformers and motors [5], [6], install and properly manage multi-generation systems [7], [8], or promote the connection to district heating networks, if available [9], [10].

This work is organized as follows: the opera house building is described, the results of energy monitoring and spot measurements are reported as a base to propose possible energy efficiency measures.

II. Building description

The opera house object of this study is *Teatro Regio di Torino*, located in Turin, Italy. It was built in 1740, partially destroyed by a fire in 1936 and restructured in 1973. Its facade, which was not destroyed by the fire, is one of the UNESCO World Heritage Sites.

The building is made of 9 floors, from level $-12.5\,m$ to level $+32.1\,m$. The total surface of the building is around $60,000\,m^2$ while its volume is approximately $190,000\,m^3$.

Two theaters are hosted in the opera house. An opera theater with around 1,600 seats and a smaller theater, mainly used for concerts, dance and conferences, with around 400 seats.

Besides the two theaters, several offices and artisan shops are also present in the building. In particular, the following spaces are considered for energy consumption analysis:

- foyer;
- practice rooms;
- employee's cafeteria;
- artisan shops.

Due to the historical characteristics of the building and its inclusion in the UNESCO World Heritage Sites, the possible energy efficiency measures are necessarily limited.

The opera season usually runs from October to July, while the concerts season usually starts in September. In the month of August no performances are scheduled but offices may be open, and maintenance works are carried out.

III. Measurements results

The analysis of the building energy consumption was the first step to evaluate and choose the best energy efficiency measures. The opera house in question receives energy via two energy vectors: natural gas and electricity. Natural gas is mainly used for heating purposes, while electricity is used for lighting, cooling, ventilation, circulation pumps, for the kitchen and for all other electric loads.

The monthly natural gas consumptions were available for 2012 and 2013 and are reported in Fig. 1.

As to electric energy, the opera house has two points of delivery: one in LV at $380V$ and one in MV at $22kV$. The end-user MV/LV substation is equipped with three transformers

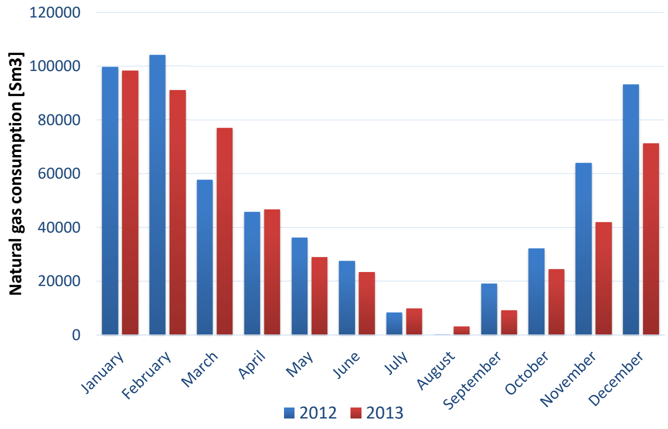

Fig. 1. Monthly natural gas consumption.

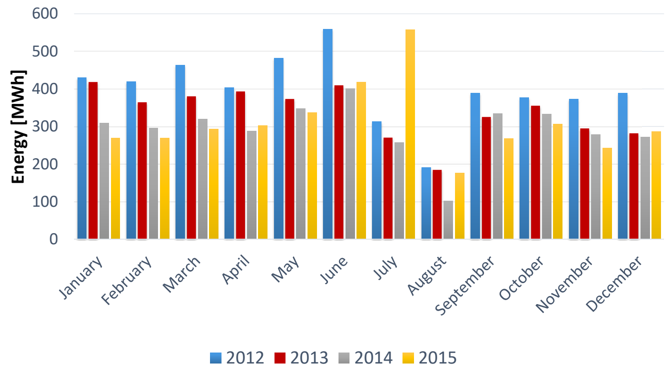

Fig. 2. Monthly electricity consumption.

with a rated power of 1600 kVA each. Through the electrical bills it was possible to obtain the monthly consumptions of electricity for the years 2012 through 2015, which are reported in Fig. 2.

It was also possible to estimate the yearly natural gas consumption for the years 2014 and 2015. The natural gas volume consumptions have then been used to estimate a heat consumption of the building (by using an average annual boiler efficiency of 90%): Table I reports the summary for each energy carrier, expressed in GWh. Considering the primary energy requirements, the total energy consumption is equivalent to around 1100 toe for the year 2013, of which around 60% are provided by electricity and around 40% are provided by natural gas. The estimated CO_2 emissions related to the energy supply for the same year are around 2400 t. The primary energy factors and the 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.

Among building services, HVAC systems energy usage is particularly significant. In addition, 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

TABLE I

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

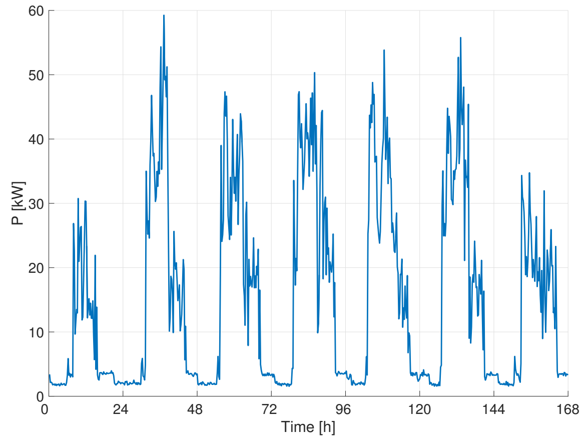

Fig. 3. Cafeteria electricity consumption, central week of June.

unit of the HVAC system. For the measurement of voltages 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 (in the range from 20 A to 300 A) were also used to measure the phase currents. The power values have been saved with a time step of 15 minutes. The results of these measurements are presented hereafter.

A. Cafeteria

The measurements in the cafeteria were taken in the month of June 2016. In Fig. 3 the average power measured in each 15 minutes interval is presented for the time frame from June 13th to June 19th 2016. Other measured data for other weeks were similar, and confirmed that the opera program does not affect the cafeteria consumption.

Besides the average power, the network analyzer also provided, for each time interval, maximum and minimum power peeks, which helped better understand the load behavior. The cumulative monthly distributions for the minimum, average and maximum power absorbed by the cafeteria are presented in Fig. 4. The peak power absorbed by the cafeteria is around 100 kW while the base load is approximately 2 kW. The energy consumption in the month of June was approximately 9 MWh.

If we consider that the cafeteria consumption is approximately constant during all the year, except for the month of August, we can extrapolate from the energy consumption of the month of June a yearly energy consumption of about 100 MWh. This value is approximately only $2.1\% \div 2.8\%$ of the total electricity consumption of the Opera House: the demand

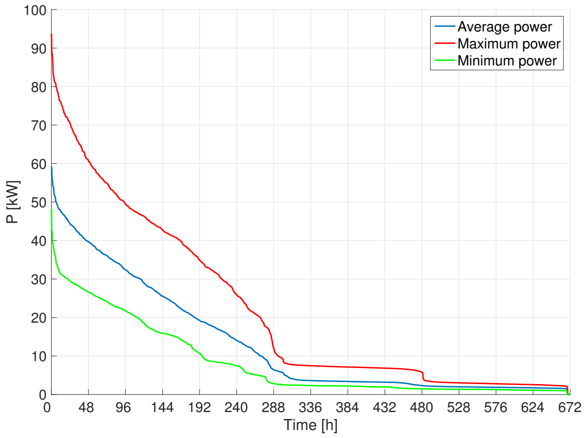

Fig. 4. Cafeteria electricity consumption, cumulative distribution.

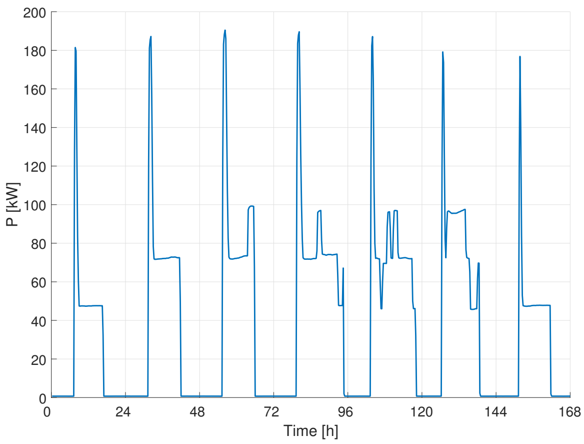

Fig. 5. Refrigerating unit electricity consumption, July 18th to July 24th 2016.

reduction measures should therefore focus mainly on other electric loads.

B. HVAC refrigerating unit

The Opera house includes four HVAC refrigerating units of 180 kW each. Measurements were performed from the month of July to the month of September 2016 on one of those four units, and, based on the indications provided by the system operator, the total consumption was accordingly estimated.

In Fig. 5 the consumption for a typical summer week (when the opera house is still open) is presented and the cumulative consumption distribution is reported for the period July 16th - September 13th (Fig. 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 programmed: they absorb the full power in the morning when they are started; then they are regulated at fixed steps to maintain the temperature set-point inside the building during the rest of the day. In this

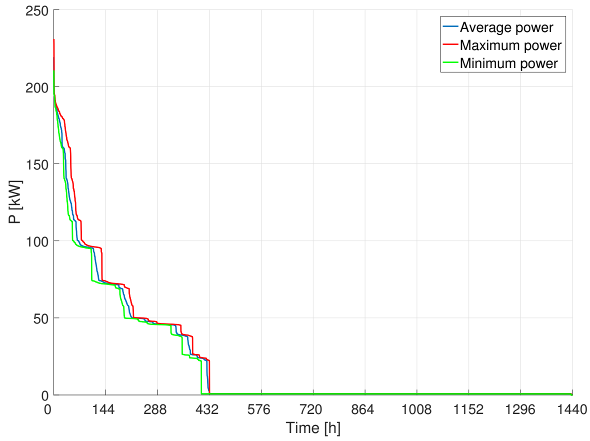

Fig. 6. Refrigerating unit electricity consumption, cumulative distribution.

case, as the refrigerating units are operated at constant power for long periods, the cumulative distributions of the maximum, minimum and average power inside the 15 minutes intervals are approximately equivalent.

The peak power absorbed by one refrigerating unit is around 200 kW, but for most of the operating time the consumption is in the range $50 \div 70$ kW. The daily energy consumption of a single refrigerating unit ranges between 500 and 1,000 kWh. The consumption is strongly dependent on the opera house program.

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

IV. Proposed Efficiency Measures

Based on the above energy consumption analysis, different energy efficiency measures are proposed. These measures can be focused on the reduction of the electricity, heating and cooling demand of the building, or on the increase of the conversion efficiency in order to reduce the 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 higher COP.

In addition, two alternative solutions are proposed for the reduction of the total primary energy consumption of the building:

- installation of a Combined Heat and Power (CHP) system;
- connection to the city district heating (DH) network.

TABLE II
TRANSFORMERS 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	2.00	6.00	13,000

TABLE III
ELECTRIC MOTORS CHARACTERISTICS

	n	P [kW]	V [V]	I [A]	$cos\phi$	η [%]
Water pump	7	30.0	400	55.5	0.85	91.8
Water pump	3	37.0	400	66.8	0.86	93.0
Fan HVAC	1	18.5	400	39.0	0.79	86.7
Fan HVAC	1	11.0	400	22.0	0.86	83.9
Fan HVAC	1	22.0	400	40.2	0.85	92.9
Fan HVAC	1	15.0	400	31.5	0.80	85.9
Fan HVAC	2	37.0	400	71.5	0.87	85.9
Fan HVAC	1	15.0	400	31.5	0.80	85.9
Fan HVAC	1	18.5	400	39.0	0.80	85.6
Fan HVAC	1	18.5	400	36.0	0.87	85.3
Fan HVAC	1	9.2	400	17.6	0.85	88.8
Fan HVAC	1	30.0	400	61.0	0.84	84.5
Fan HVAC	1	11.0	400	23.5	0.82	82.4

A. Replacement of transformers

The first option that can be considered for the reduction of the electricity demand is the replacement of the MV/LV transformers with more efficient models.

The opera house uses three MV/LV transformers (T1, T2, T3) with rated power of 1,600 kVA each, with nominal voltages 22 kV/400 V. One of the three transformers is a backup, while two are normally operating. 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 (Table II) [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.

The replacement of the transformers with new models complying with the above requirements would lead to an annual saving of about 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 however have a very long payback period.

B. Replacement of electric motors

A second option for the reduction of electricity demand, is the replacement of 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 III), and their characteristics were extracted from the data-sheets.

The existing motor efficiencies were in general lower than those prescribed by Standard EN 60034-30-1 [6]. The replacement of all the electric motors listed in Table III with new ones, with efficiency class *IE3*, would lead to an annual saving of about 120 MWh (approximately 3% of the total opera house electricity consumption), with a payback period of only 3 years.

C. Replacement of refrigerating units

From the energy consumption measurements, the HVAC refrigerating units appeared to have a high share of the total electricity consumption. The replacement of the existing refrigerating units is a viable solution to reduce the electricity demand of the opera house.

The current refrigerating units have an average COP of about 4.16, calculated from the performance monitoring. Modern refrigerating units can reach average COPs up to 6 or 7.

The replacement of all four existing refrigerating units with models with higher COPs would lead to potential annual savings from 60 MWh to 75 MWh.

D. Alternative generation possibilities

To decrease the primary energy consumption, the evaluation of possible alternative solutions for the generation of heat and power was considered, and a comparison between the installation of a CHP system (natural gas engine) and the connection to the city of Turin district heating (DH) was performed. The comparison was based by using national primary energy factors for electricity, and local primary energy factor for the heat provided by the DH system.

The installation of a CHP system for buildings with high thermal and electricity consumption can be a worthwhile energy efficiency measure.

The technical and economic feasibility of this measure should be evaluated through a detailed analysis of thermal and electrical load. A CHP system is in fact a good choice if thermal and electric loads present similar hourly profiles, and have a base load that is present for at least 3,000 - 4,000 hours per year.

In the current situation, the thermal needs of the opera house are covered by three boilers with a rated power of $1,750kW$ each, while all the electric energy is provided by the national power grid. The cumulative distributions for thermal end electric energy for the years 2012 and 2013 are reported in Fig. 7. It can be observed that the thermal and electric base loads, of around 500 kW, are present for more than 4,500 hours.

Typical daily load profiles for the four seasons are reported in Fig. 8. As it can be seen, thermal and electric profiles present different values, but a similar trend.

Based on these premises, the installation of a CHP system tailored on these heat and power profiles seems to be a viable option. Two possibilities have been explored, based on two different models of internal combustion engines, fed with natural gas, with the characteristics presented in Table IV. The

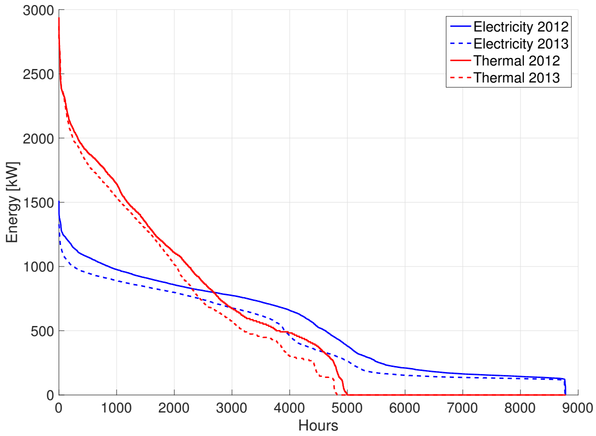

Fig. 7. Cumulative distributions of electric and thermal loads.

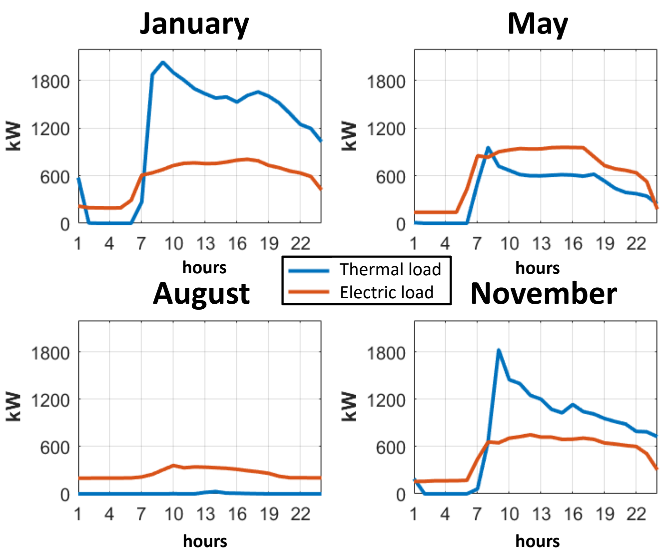

Fig. 8. Typical daily load profiles.

TABLE IV
CHP CHARACTERISTICS

Model	A	B
P_{fuel} $[kW]$	785	1320
P_{el} $[kW]$	300	527
P_{th} $[kW]$	400	626

operation of the CHP engines has been performed on an hourly basis, considering the year 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 $g_{[CO2]}/kWh$ (data provided by the DH owner).

The DH system is mainly supplied by three natural gas combined cycle (NGCC) units, which are operating in cogeneration

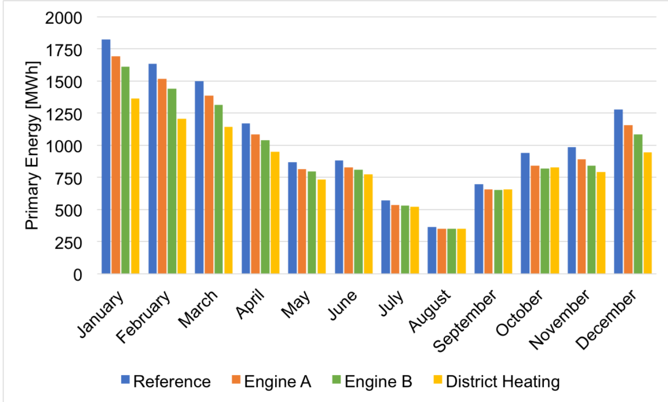

Fig. 9. Monthly Primary Energy Consumption.

TABLE V
SIMULATIONS RESULTS

	Reference	CHP (A)	CHP (B)	DH
Primary Energy [GWh]	12.7	11.8	11.3	10.3
CO_2 Emissions [t]	2355	2200	2125	1881
Engine equiv. hours	-	4400	3990	-

with a really high electrical efficiency. For this reason, due to the allocation of primary energy consumption and emissions to both heat and power, the heat supplied by the DH system has much lower impact both for primary energy and CO_2 emissions than the use of natural gas boilers.

Table V shows the annual comparison of the different scenarios described above, while the monthly *Primary Energy Consumption* is reported in Fig. 9, compared to the reference scenario (current operation, already considering the additional electricity savings).

Considering the CHP units, the results show that the Engine B has a larger impact in the reduction of both Primary Energy and CO_2 Emissions. However, since the CHP is operated with a heat-driven logic (i.e. avoid heat dissipation), Engine A has a higher number of equivalent hours of operation, which is generally related to a better exploitation of the economic investment.

However, thanks to the high efficiency of the heat production of the DH system of Turin, this last solution is preferable to CHP units (primary energy savings of 19.3% instead of 11.2% and CO_2 emissions reduction of 20.1% instead of 9.8% with respect to the reference scenario with savings).

In addition, the DH network connection would have no impact on the environment, while the installation of a CHP unit would increase the emissions of NO_X, CO and other pollutants in the central area of the city. Considering the building usage, the installation of a CHP would also require mitigation strategies to limit noise emission.

A detailed analysis must compare the estimated investment and O&M costs of the different solutions, with the current costs for the energy supply.

V. Conclusion

In this paper the results of the continuous monitoring of energy consumption, and of 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 as a basis to propose energy saving strategies from two perspectives: a reduction in energy demand and a reduction of the total primary energy consumption.

The experimental results show that the cafeteria has a share of energy consumption of a few percentage of the total yearly consumption. The HVAC refrigerating units, instead, represent in summer an important load, of approximately 12% of the 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 saving of about 120 MWh per year, with an investment characterized by a very short payback period.

As far as the reduction of the total primary energy consumption, the optimal solution might be the connection to the District Heating network of the city. This solution, in fact, could lead to a reduction of 19% of the present primary energy consumption.

References

[1] L. Perez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy and buildings*, vol. 40, no. 3, pp. 394–398, 2008.

[2] M. Jarre, S. Macagno, and M. Noussan, "Energy consumption data as a decision-making tool for energy efficient interventions in pa: The case-study of turin," *Energy Procedia*, vol. 111, pp. 1050 – 1059, 2017, 8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, Italy. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1876610217303016

[3] P. Penna, A. Prada, F. Cappelletti, and A. Gasparella, "Multi-objectives optimization of energy efficiency measures in existing buildings," *Energy and Buildings*, vol. 95, pp. 57–69, 2015.

[4] C. S. P. López and F. Frontini, "Energy efficiency and renewable solar energy integration in heritage historic buildings," *Energy Procedia*, vol. 48, pp. 1493–1502, 2014.

[5] *Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV Part 1: General requirements*. Standard CEI EN 50588-1, 2016.

[6] *Rotating electrical machines Part 30-1: Efficiency classes of line operated AC motors (IE code)*. Standard CEI EN 60034-30-1, 2015.

[7] A. Canova, C. Cavallero, F. Freschi, L. Giaccone, M. Repetto, and M. Tartaglia, "Optimal energy management," *IEEE Industry Applications Magazine*, vol. 15, no. 2, pp. 62–65, 2009.

[8] P. Mancarella, "{MES} (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1 – 17, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360544213008931

[9] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, and B. V. Mathiesen, "4th generation district heating (4gdh): Integrating smart thermal grids into future sustainable energy systems," *Energy*, vol. 68, pp. 1 – 11, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360544214002369

[10] B. Morvaj, R. Evins, and J. Carmeliet, "Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout," *Energy*, vol. 116, Part 1, pp. 619 – 636, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360544216314207