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Market analysis of CHP solutions applied in commercial applications

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Abstract:

The following deliverable is focusing on the market analysis for the Comsos Mini FC-CHP systems. The work is showing benefits and drawbacks of specific markets, defined in accordance with the consortium. For specific market segments, like hospitals, hotels and supermarkets, a detailed analysis on load profiles and market size has been developed. Furthermore, for the supermarket sector, a detailed techno-economic model (developed in D5.2) has been applied to verify the benefit of installing a FC system in this sector. Results show interesting technical and economic benefit of these installations in the presented segments. Furthermore, an analysis on different geographical regions has been conducted to define the best regions where the installation of SOFC-CHP systems should start, because of positive boundaries conditions.

Keyword list:

Market analysis, SOFC systems, geographical areas, hotels, supermarkets, hospitals

Index

1. Summary

The presented work deals with the analysis of several market areas for the installation of the SOFC-CHP system, in the framework of the COMSOS project. The consortium agreed on the following commercial sectors to be investigated:

- Hotels
- Supermarkets
- Office buildings
- Sport centers
- Hospitals
- Shopping centres

Furthermore, some key drivers such as spark spread, incentives and grid reliability, have been analyzed.
The 'best' countries for each segment have been defined and listed.
According to the spark spread (difference between electricity and natural gas price), best countries for a NG-fed CHP installation are Spain, Belgium, Slovakia, Latvia, Italy and UK. Italy, together with Germany, is also one of the few countries in Europe were a clear supporting scheme for CHP systems (not depending on the technology) is also available. If the SAIDI (System Average Interruption Duration Index) is analyzed, less efficient countries (and thus most suitable for a reliable SOFC-CHP installation) are found to be Latvia, Malta, Croatia, Romania and Slovenia, while the most reliable countries – in terms of SAIDI – are Denmark, Germany, Luxembourg, The Netherlands and Switzerland. These countries will not opt for a SOFC-CHP system because of grid reliability problems. Similar, but not equal, results are found when analyzing the second important parameter in terms of grid reliability, which is the SAIFI (System Average Interruption Frequency Index). In terms of SAIFI, the less reliable countries are found to be Latvia, Malta. Romania and Poland. As can be seen, EU Eastern Countries are found to be less reliable in terms of grid stability. Anyway, analyzing the SAIFI index, more modern countries like Spain, Italy, Portugal and Greece show indexed which are not as low as East Europe but anyway far from the Northern EU countries, where the grid is found to be more reliable.
The second level analysis has been performed analyzing the specific segments and thus the market potential for each of them. This analysis is performed by searching for the number of 'sites' for each country. Analyzing the retail sector, US are found to be very interesting as a market, together with Italy, UK, Spain and Sweden. For what concerning the hotels, countries with the highest number of accommodation facilities are Italy, Germany, Spain, UK and France (where the more touristic capital cities and cities are found). In case of medical sector (hospitals), the largest markets are Germany, Lithuania, Bulgaria, Austria and Belgium. The analysis has been extended to the shopping centers (malls) and best countries are UK, France, Italy, Germany, Spain and The Netherlands. Finally, looking at the data centers, US has – as well-known – the largest

investment in data center worldwide, together with China, Japan and Australia. Looking at Europe, largest data centers investments are found to be in Germany, UK and The Netherlands.

Looking at all the possible parameters and sector for SOFC-CHP installations, the following conclusions are discussed:

- Italy and Germany and found to be among the most interesting markets for SOFC-CHP installations. They both have a specific supporting schemes and Italy shows a quite high spark spread, with a high electricity cost and a relatively low natural gas cost. Furthermore, analyzing the market segments, they both shows a large number (among the highest in Europe) of retail shops (Italy), hotels (Italy and Germany), hospitals (Germany), shopping centers (Italy and Germany) and data centers (Germany).
- UK is similar to Italy and Germany in terms of spark spread and market size in different sectors but the dedicated CHP incentives has been stopped in the last years, making this country less attractive than before.
- Eastern EU countries seem an interesting opportunity because of the lower grid reliability. Furthermore, spark spread shows interesting values in Slovakia and Latvia.
- On the contrary, there are other countries in which both energy price scenario and market size make the SOFC-CHP installation more difficult, like Sweden, Finland and Denmark.

This document will analyze in detail the possible markets for the SOFC-CHP system installation. Furthermore, a dedicated case study for supermarket is provided in Appendix (chapter 8).

2. Drivers and barriers for the installation of SOFC-CHP systems in the commercial sector

2.1 Spark spread

The spark spread is here defined as the differente between the Electricity price and the NG price , both expressed in €/kWh. Analyzing these data from the Eurostat website [1], [2], seven ranges are available for the electricity consumption (IA, IB, IC, ID, IE, IF, IG) and six ranges for the NG consumption (I1, I2, I3, I4, I5, I6). These ranges are strongly affecting the energy prices, which are here analyzed without any taxes and levies.

The available ranges for electricity and NG have been coupled to identify some possible commercial installation based on their energy consumption:

- Extra Small: IA + I1
- Small: IB + I2
- Medium: IC + I3
- Large: ID + I4
- Extra Large: IE + I5
- Extra Extra Large: IF + I6

The commercial sector would fall in the central rages, between Small and Large; furthermore, mixed scenarios are also possible (e.g. IB + I4). The trend of the spark spread in the EU countries for the 6 proposed case studies in shown in Figure 1.

When analysing a NG-fed cogeneration installation, which is fed by NG (consumption=cost) and produce electricity (production=saving), the higher is the spark spread, the better will be the economic performance of the investment: countries with cheap NG and expensive electricity are the best place for an SOFC installation. As can be seen from the figure below, the higher spark is always linked to the smallest applications. This means that smaller commercial activities would have higher specific savings compare to large plants. On the contrary, it should be underlined that too small commercial activities are usually not willing to invest a high amount of money in new technology. Larger activities, even if with a smaller specific savings, are usually more attracted by new investment since they are focusing not only on direct economic savings but also on branding, image, greening the brand, etc. For this reason, the best-case study is usually found in the S-M case studies.

Analysing the geographical distribution of the spark spread it can be noticed that some countries show better conditions for the installation of the system. If we focus in the XS-S-M case studies and we list the top 10 countries for spark spread (from higher to lower), we can define countries which are present in all the 3 lists and are:

- Spain
- Belgium
- Slovakia
- Latvia
- Italy
- United Kingdom

Other countries like Czechia, Croatia, Bulgaria and Germany are found in only 2 out of 3 top 10 list of spark spread. Finally, countries like Netherlands, Luxembourg, Portugal and Estonia are found only in 1 out of 3. This behaviour means that the spark spread geographical trend in the different analyzed case studies is not always linear and the trend can vary depending on the energy consumptions. The Netherlands, for example, is found only in the top 10 list of XS case: this means that spark spread is quite interesting for extra small size plants while the conditions get worst for larger systems.

The detailed spark spread values for the six categories can be found in Table 1.

Table 1. Spark spread values for the six energy consumption case studies and different EU countries.

	Spark Spread					
	XS: IA+I1	S: IB+I2	M: IC+I3	L: ID+I4	XL: IE+I5	XXL: IF+I6
European Union	0.1008	0.0686	0.0534	0.0485	0.042	0.037
Euro area	0.1054	0.0659	0.0526	0.0461	0.0385	0.0328
Belgium	0.1366	0.0855	0.0596	0.0503	0.0384	0.0363
Bulgaria	0.075	0.0634	0.0556	0.0523	0.0449	n.a.
Czechia	0.1437	0.1011	0.0456	0.038	0.0395	n.a.
Denmark	0.0607	0.0504	0.0363	0.0357	0.0301	n.a.
Germany	0.0929	0.0628	0.0505	0.0425	0.0287	n.a.
Estonia	0.0812	0.0615	0.0513	0.0375	0.0356	n.a.
Spain	0.1877	0.0972	0.0752	0.0632	0.0546	0.0521
France	0.077	0.0506	0.0354	0.0322	0.032	0.0259
Croatia	0.0827	0.0687	0.0589	0.0499	n.a.	n.a.
Italy	0.0993	0.065	0.0608	0.0565	0.0516	0.0434
Latvia	0.1049	0.0695	0.0521	0.0426	n.a.	n.a.
Lithuania	0.0766	0.0531	0.042	0.0359	n.a.	n.a.
Luxembourg	0.0845	0.0566	0.0426	0.038	n.a.	n.a.
Hungary	0.078	0.0605	0.0467	0.0409	0.0356	0.0408
Netherlands	0.0902	0.0453	0.0389	0.0387	0.0339	0.0327
Austria	0.0789	0.059	0.0442	0.0387	0.0334	0.0287
Poland	0.0817	0.0573	0.0352	0.0317	0.0309	n.a.
Portugal	0.076	0.0578	0.0515	0.0501	0.0404	0.032
Romania	0.0615	0.0542	0.0453	0.043	0.041	0.0436
Slovenia	0.0663	0.0489	0.0402	0.0362	n.a.	n.a.
Slovakia	0.1255	0.0642	0.0524	0.0454	0.0399	0.0364
Finland	0.0369	0.0329	0.0204	0.0296	0.021	n.a.
Sweden	0.0826	0.0311	0.0281	0.0228	0.0125	n.a.
United Kingdom	0.0939	0.0931	0.0743	0.0806	0.0757	0.07
Serbia	0.0465	0.0412	0.0285	0.0243	0.0214	0.0263
Turkey	0.0449	0.0457	0.0416	0.0396	0.0352	0.035
Ukraine	0.0319	0.0341	0.0327	0.0339	0.0298	0.0303

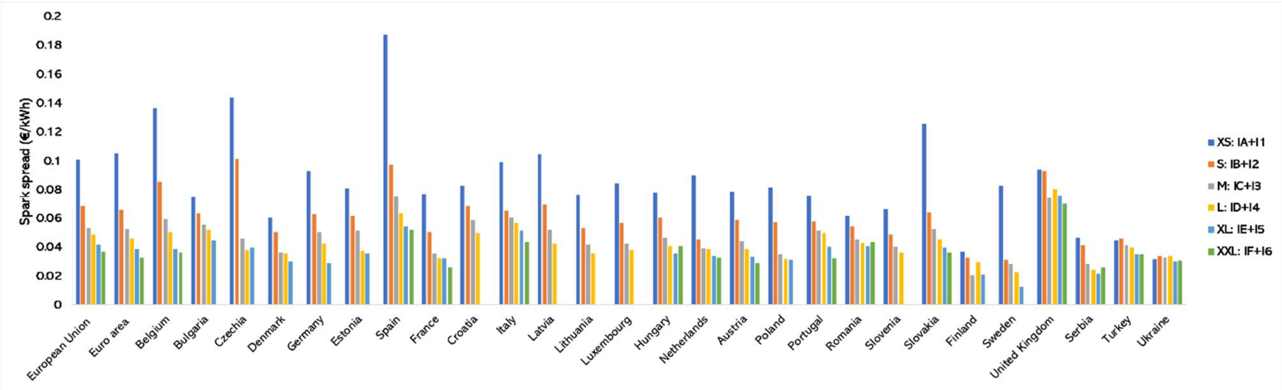

Figure 1. Spark spread distribution for different energy consumption categories and countries.

2.2 CHP-dedicated supporting schemes

The second driver which could help the diffusion of SOFC-based CHP systems in specific countries is the availability of dedicated CHP incentives or, even better, fuel cell ones. When available, such incentives could help the economic balance of the installation. Some examples are provided below.

In Germany a dedicated 'CHP Act' is available since 2012 and has been updated in 2016. The owners of CHP systems obtain bonuses for the electricity generated via their cogeneration plants. Through this act, the government aims to enhance future prospects for the growth as well as development of cogeneration systems. To date, the country's CHP plants obtained funding support for cogeneration involving a capacity of up to 50 kilowatt (kW) and a time period of 10 years. Larger cogeneration plants with more than 30,000 full load hours also obtained funding. In the new 2016 CHP Act, the eligibility period for cogeneration involving a capacity of over 50kW and with 30,000 full load hours remained unchanged; this is not the case with mini-CHP with capacity up to 50kW where the eligibility period by full load hours has been altered to 60,000 full load hours. Promotion under the CHP Act is carried out by bonuses, which are limited in time and payable in addition to the market-based electricity price. Newly constructed, modernised and upgraded CHP plants are entitled to funding. Additional bonus incentives are granted for CHP plants subject to the conditions of the Greenhouse Gas Emission Trading Law (TEHG). In addition, CHP plant owners who replace their existing CHP plant based on coal or lignite, receive a subsidy bonus of 0.6 cents / kWh over the entire funding period. In order to minimize the administrative burden of micro-cogeneration units, owners of CHP in the power range of up to 2 kW can receive their CHP surcharge payments as a flat one-time payment. This corresponds to a subsidy of 2,400 euros per kilowatt. So far, micro-CHP systems received KWKG allowance of 1.623, – Euro per kW.

Due to the current decline in prices reflected in the development of the usual price diagram, existing CHP plants may no longer be able to operate economically in the municipal sector. Therefore, a supplementary funding was introduced into the new CHP Act to accommodate existing cogeneration systems in the municipal sector with more than 2 MW electrical cogeneration power if they are no longer supported by the previous

CHP Act. The promotion of 1.5 cents / kWh for existing plants applies only for CHP plants which are operated with gaseous fuels and includes a maximum funding duration above 16,000 full load hours.[1]

In Italy a supporting scheme is also available, called 'Certificati bianchi' (white certificates)[2]. The scheme is related to all the interventions which increase the energy efficiency of the building, and thus not only CHP systems. Furthermore, to obtain this incentive, CHP systems should reach the label of CAR[3] (High Efficiency Cogeneration) which is calculated based on the yearly Primary Energy Saving (and heat should be really used for a real purpose, and not wasted). If the CHP system is labelled as CAR, different benefits are available:

- Priority on the electricity dispatching on the grid respect to conventional energy production systems;
- Reduction in the taxes paid on the NG fed to the CHP system;
- Opportunity of performing on-site energy exchange (for systems up to 200 kW)
- Simplified conditions for the connection to the electrical grid;
- Electricity produced and injected into the grid can be subsidized with White certificates.

PES should be at least 10% compared to conventional technologies (grid and boiler). Limits (minimum values) on the global efficiency (electrical + thermal) are also available in the ministerial decree and is equal to 75% for fuel cells. If the limit is not reached, only a portion of the electricity produced is subsidized.

Maximum power installed should be 50 kW for micro-CHP and 1 MW for mini-CHP.

The methodology to evaluate the number of certificates (CB) given for a certain system (which satisfies the minimum limits) is shown below. In case the minimum limits are not satisfies a more complicated method is available.

The Primary Energy Saving (PES) should be first calculated by knowing the CHP electrical efficiency (CHPEη), the CHP thermal efficiency (CHPHη), the reference boiler efficiency (RefHη) and the reference grid efficiency (RefEη):

$$PES = \left(1 - \frac{1}{\frac{CHPH\eta}{RefH\eta} + \frac{CHPE\eta}{RefE\eta}}\right) * 100\%$$

If the PES is equal or higher than 10%, the saving (RISP) can then be evaluated starting from the electrical (Echp) and thermal (Hchp) energy produced, the reference efficiencies (ηE,RIF and ηT,RIF) and the fuel consumption for the CHP (Fchp):

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[1] https://www.power-technology.com/comment/getting-grips-germanys-chp-regulations/
https://www.bhkw-infozentrum.de/rechtliche-rahmenbedingungen-bhkw-kwk/chp-act-2016-summary-of-regulations-within-the-new-chp-act.html

[2] https://www.gse.it/servizi-per-te/efficienza-energetica/certificati-bianchi

[3] https://www.gse.it/servizi-per-te/efficienza-energetica/cogenerazione-ad-alto-rendimento

$$RISP = \frac{E_{chp}}{\eta_E RIF} + \frac{H_{chp}}{\eta_T RIF} - F_{chp}$$

Finally, the number of certificates (CB) is proportional to the savings with a factor K, which is an harmonization factor depending on the unit power:

$$CB = RISP * 0{,}086 * K$$

The certificates can the be exhanched on a dedicated market. Current value is oscillating between 258 and 280 €/CB (260€ average on May 14th, 2019).

Combined Heat and Power Incentives are also available in United Kingdom. It includes:

- A Climate Change Levy (CCL) Exemption: CHP systems are exempt from the main rates of CCL on: the fuel they utilise (assuming they meet a power efficiency threshold of 20% otherwise this exemption is scaled back) and the direct and self-supplies of the power output generated (assuming the QI is met, otherwise the qualifying power output (QPO) is scaled back)[4].
- Carbon Price Support Tax Exemption: the Government introduced an exemption from the CPF for fuels that are used in CHPs to generate Good Quality electricity for self-supply or use 'on site'.
- The Enhanced Capital Allowances scheme allows businesses to write-off 100% of their investment in those energy saving technologies that are listed in the Energy Technology Criteria List against the taxable profits of the period during which they make the investment (but fuel cells are not yet included in the list).

The Feed-in Tariff (FiT) was introduced by the UK Government in order to support renewable electricity generating technologies installed up to 5 MWe in capacity. On 18 December 2018 legislation was laid before government which closes the FIT scheme to new applicants from 1 April 2019, barring some exceptions.

The FiT scheme includes a pilot which provides support to domestic scale micro CHP installations. Micro CHP units are normally fuelled by natural gas and must have an installed capacity of 2 kWe or less. To be eligible for support from FiTs, qualifying micro CHP units must be installed and certified in accordance with the Microgeneration Certification Scheme (MCS). Any other technology and scale of project must be accredited through a process based on the existing Renewable Obligation process, known as the RO-FIT process. Note that the FiT micro CHP pilot will support up to 30,000 installations, with a review to start once 12,000 installations are complete.

A database is available online to detect the status of CHP systems development in UK[5]. Different sectors are available (Figure 2):

[4] https://www.gov.uk/guidance/combined-heat-and-power-incentives

[5] https://chptools.decc.gov.uk/developmentmap

- Large Industrial
- Small Industrial
- Domestic
- Commercial Offices
- Government Buildings
- Education
- Health
- District Heating

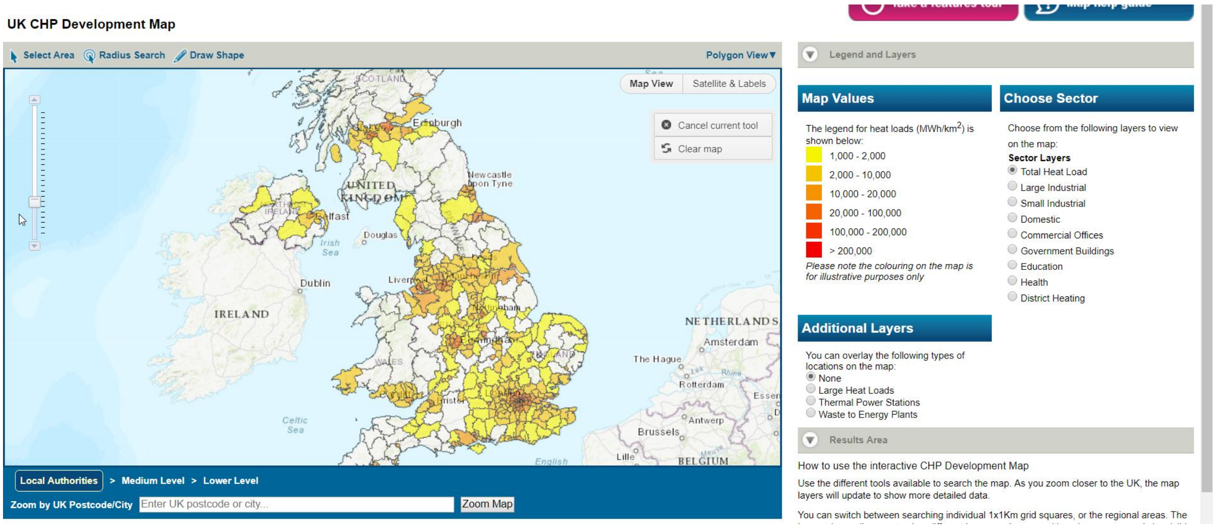


Figure 2. Total CHP installations in UK.

By analyzing the share among the different sectors (Figure 3), it is pointed out that the domestic sector seems dominating the installations, together with the industrial ones. When commercial sectors are plotted (commercial offices, health and small industrial) it is clearly visible that the amount of power produced is very low. Furthermore, in another available database from the UK government[6] a list of the installed CHPs is also available. Since, for the Comsos size, the key competitors are internal combustion engines, the total number of reciprocating engines has been analyzed and is shown in Table 2 and **Error! Reference source not found.**. Average system size is ranging between 1 and 10 MW and the dominant categories are Transport, commerce and administration together with other industrials.

[6] https://chptools.decc.gov.uk/chp/public

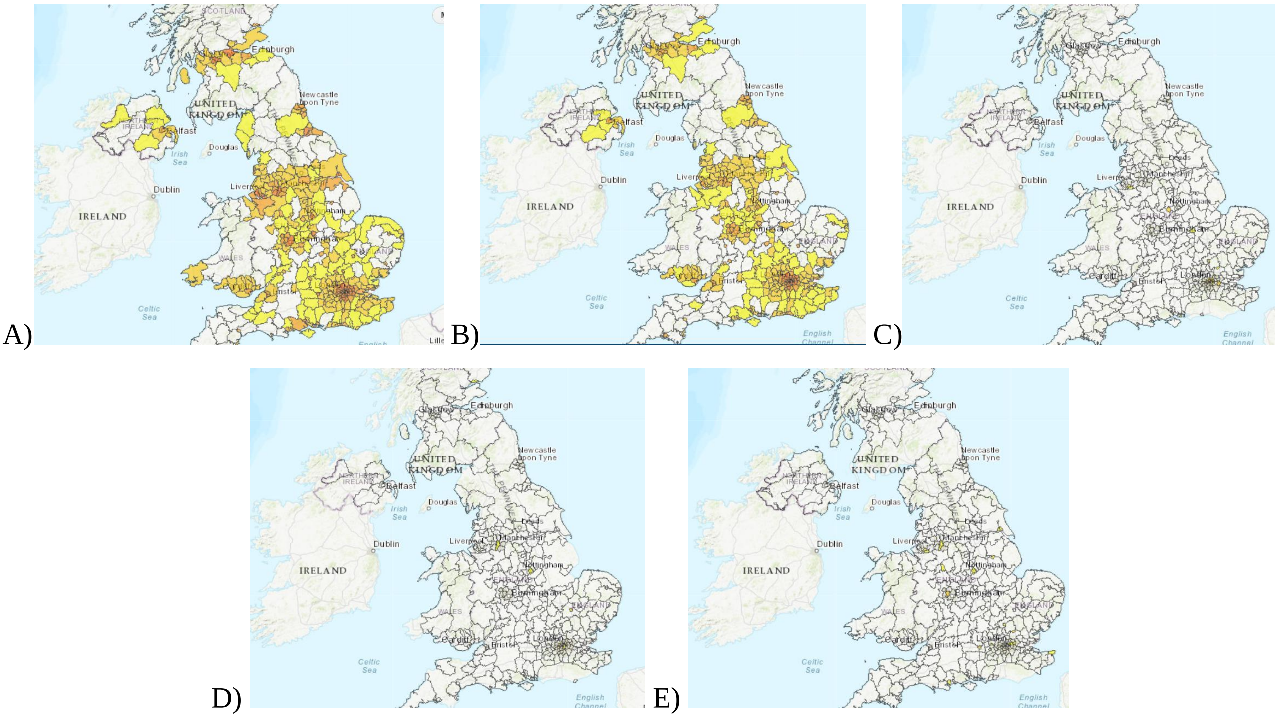


Figure 3. Details on different sectors development for CHP installations. A) Total; B) Domestic; C) Commercial Offices; D) Health; E) Small industrial

Table 2. Number of reciprocating engines CHP in UK. [7]

Sector	Total power installed (kW)	Number of plants
Chemicals	20’490	8
Iron steel & non ferrous metals	8’739	2
Transport, commerce and administration etc	93’778	69
Extraction, mining & agglom. of solid fuels	9’600	1
Metal machinery & equipment	9’302	2
Other industrial branches	73’233	28
Food drink & tobacco	35’433	7
Paper, publishing and printing	2’289	2
Other	66’135	58

The potential interest of new CHP solutions for the medium-large size market is thus interesting, especially in countries – like UK – where the CHP development is followed constantly, and incentives have been always issued. Currently, there is not a dedicated incentive for commercial size (only domestic, and this is probably the reason for the large diffusion shown in Figure 3) but fuel cells are mentioned among the possible technologies. A push towards a cleaner and more efficient energy production system will be required.

[7] https://chptools.decc.gov.uk/chp/public

On the contrary, existing supporting schemes for CHP systems in Germany and Italy, makes these two countries a good starting market for the technology.

2.3 Reliability of the electrical grid

The third important factor which could influence the best market for CHP installations is also the quality of the electrical grid, in terms of number of failures and duration. This parameter is important especially for specific segments like hospitals, commercial centers and supermarkets.

For analyzing this behavior among different countries, two parameters have been selected [3]:

- SAIDI System Average Interruption Duration Index (min)
- SAIFI System Average Interruption Frequence Index (number of interruptions)

Figure 4 shows the SAIDI for different EU values and shows in which countries the duration of grid failure is higher. The most sensitive countries seem to be Latvia, Malta, Croatia, Romania, and Slovenia. On the contrary, the best countries are Denmark, Germany, Luxembourg, The Netherlands and Switzerland.

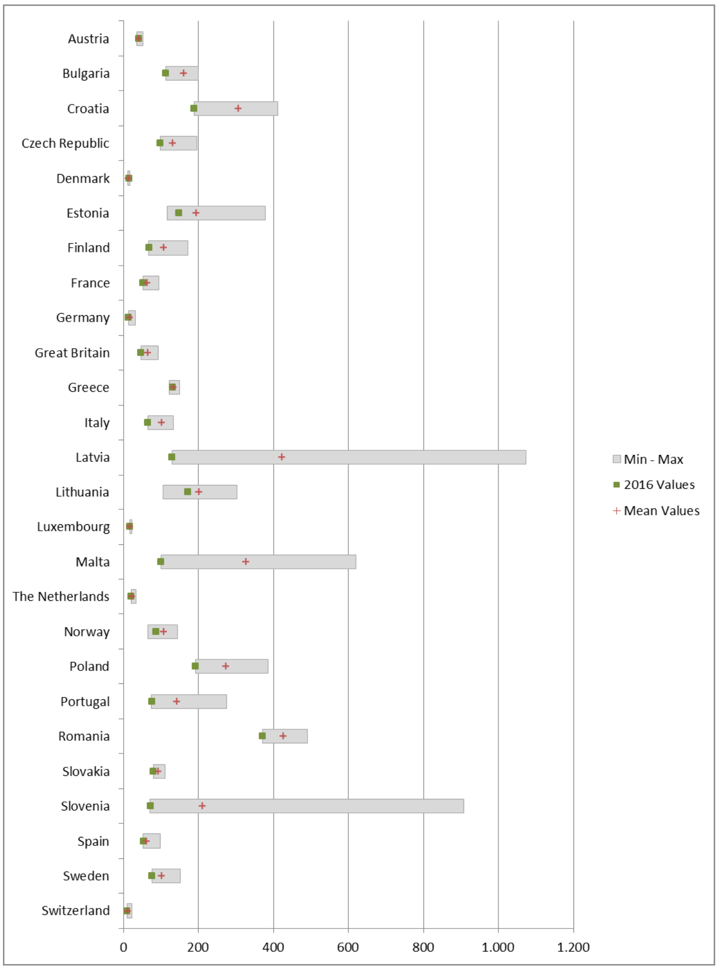


Figure 4. Electricity-unplanned SAIDI, including exceptional events (minutes per customer)

If we then look at the frequency (SAIF) in terms of number of events (Figure 5) the picture is partially changed. Worst country (which means favorable conditions for SOFC-CHP installation) are Latvia, Malta, Romania, Poland and Croatia, but also Spain, Italy, Portugal and Greece are in a 'not-optimal' condition.

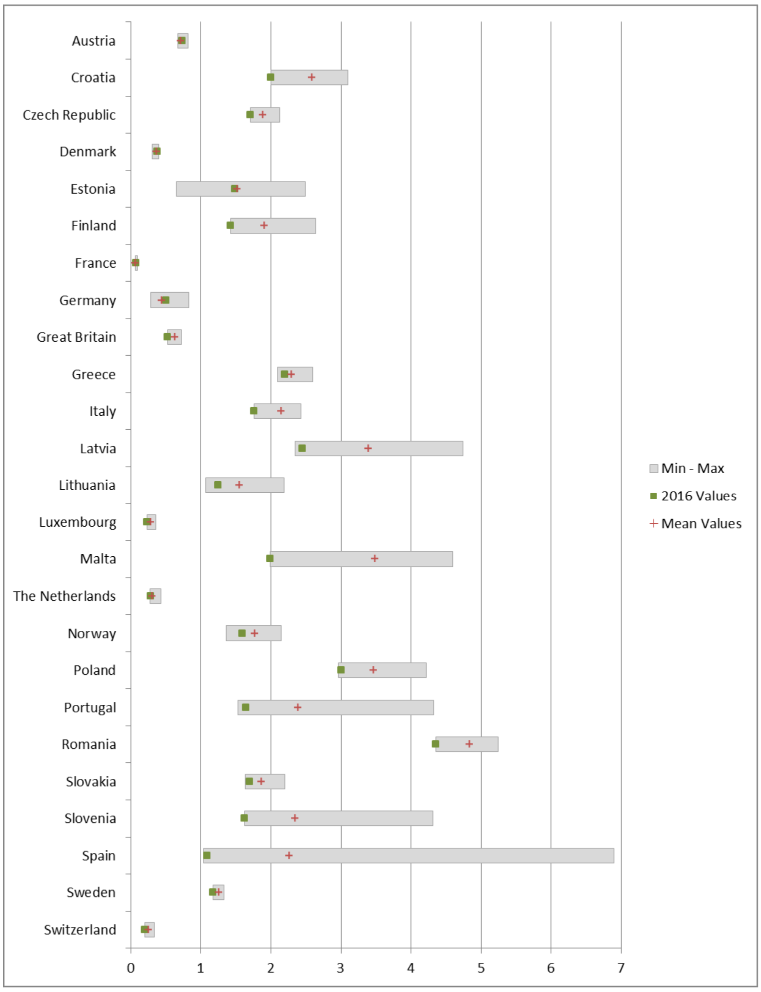


Figure 5. Electricity-unplanned SAIFI, including exceptional events (interruptions per customer).

3. Retail sector

Supermarkets are good candidates for SOFC installations because of their electrical load behavior. It is indeed possible to divide a generic supermarket electrical load in two main sub-categories, one that is dependent on the opening time and external conditions and one that is constant during time. With the first term we could recollect for example lights, instrumentation, and other services that are usually switched on only in certain periods of the day, that usually match with the opening time of the supermarket. On the other hand, there is an electrical load quite constant during the year, which is also one of the highest expenditures in the overall consumption, and it is the refrigeration system. The refrigeration system needs energy for the whole day, even if the supermarket is closed, and usually the changes in loads are mainly due to variations of the external ambient temperature. Nowadays supermarkets h24 are also a growing trend so in the future it would be possible to have flatter electricity profile also for the other loads.

Concerning electrical load, supermarkets are thus an optimal sector for SOFC installation since a base load is always requested, as will be shown in detail in the next sub-chapters.

The situation is different for what concerns the heat load. Heat loads of the supermarket are much more dependent on the external conditions and thus less predictable. For instance, the HVAC (Heating, Ventilation and Air Conditioning) system works in a different way depending on the season, and the power needed by the system is linked with the external temperature and to the number of people inside the supermarket (customers). The HVAC system is usually the most important of the heat loads, but also the loads from bakery and DHW could be relevant in the balance. Heat load is usually, as will be shown later, not constant and there is not availability of a continuous base load. A daily or even seasonal heat storage would help to increase the thermal energy use. Another possible way to exploit even more the fuel cells could be the use of an absorption-chiller that could use the heat generated by the fuel cell and convert it into cold energy. The absorption-chiller could be used continuously during the year to help the refrigeration system or could be used as an HVAC system during the summer, so the heat produced by the fuel cells is not wasted.

3.1 Energy consumption

The Energy Intensity (EI) – which is the ratio between the energy consumed in an arch of time (usually in a year, expressed in kWh per year) and the area of the supermarket (m^2) – is dependent by several variables:

- Area of the supermarket
- Ratio between refrigerated products and all products
- Geographic Location (temperatures and ambient conditions)
- Energy Legislation
- Sales Volume
- Number of people working in the supermarket and number of clients
- Others

Among these variables, the most studied in literature are without any doubt the first three, and especially the area, because it seems it has the major impact on the EI. From the analysis of several literature works, the following graph has been derived. Input data for the figure are shown in the table below.

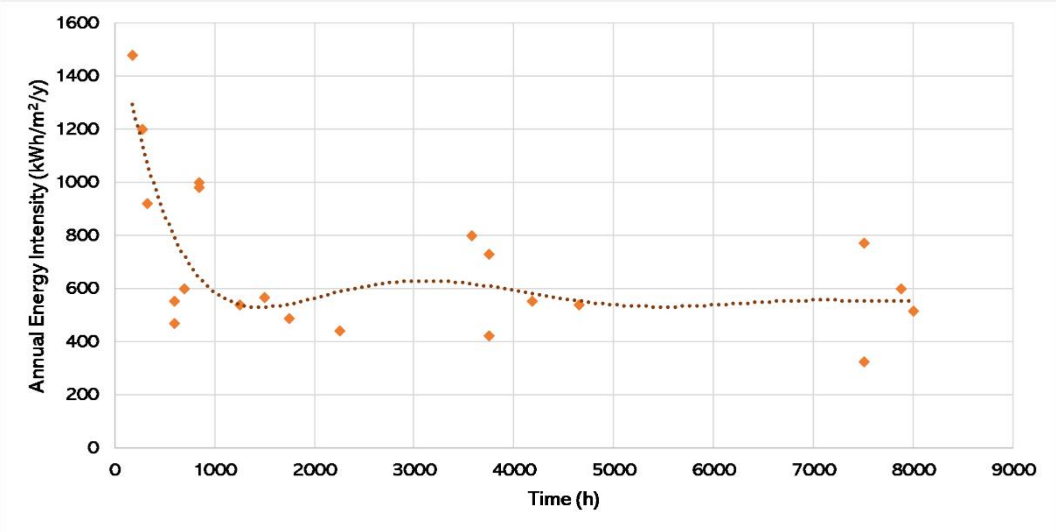


Figure 6. Energy intensity vs Area [4]–[11].

It should be also underlined that the range of area of a certain type of retail shop is not the same for each country and can vary widely. The table below shows the average supermarket and hypermarket area in different countries.

Table 3. Average value of Area of Supermarkets and Hypermarkets.

Country	Average surface of Supermarkets area $[m^2]$	Average surface of Hypermarkets area $[m^2]$
Brazil	680	3500
China	510	6800
France	1500	6000
Japan	1120	8250
USA	4000	11500

As can be seen by the graph above the curve decreases as the area increases until it reaches a plateau. The EI is much higher in the small shops and then is constant once it reaches a certain value of area (asymptotic trend). The main reason of this phenomenon is the diversity of product sold between groceries stores and hypermarkets. In the first category the major part of products is food, which needs a considerable amount of energy to be refrigerated; on the other hand, as the store becomes bigger, it diversifies the products and the part of non-refrigerated items increases. Also, for bigger shops the energy system is more controlled and designed better than in groceries store, where the owner usually does not invest money in long term energy saving. The same behavior can be found in a work conducted by Tassou et al. [10]. In this work 6578 supermarket in UK were studied and - using a regression approach - several equations are extrapolated to define the behavior of energy consumption in supermarkets depending on some input variables (Figure 7).

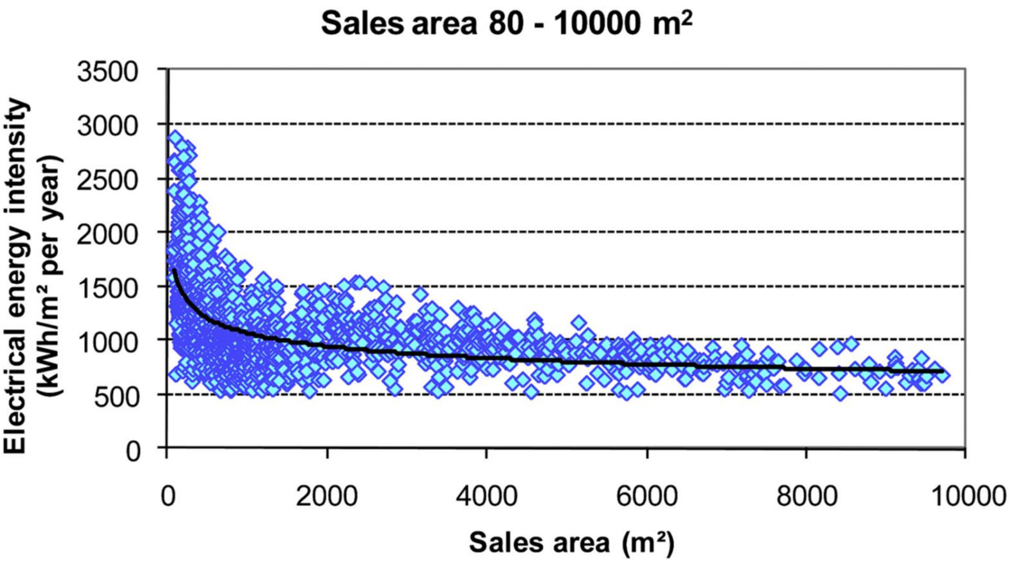


Figure 7. Energy intensity vs Area in UK [10].

Looking at the vertical axis, anyway, it can be noticed that EI values in the Tassou et al. study are higher than the one collected is this work. This difference can be justified by the fact that the second graph refers just for the sales area and not the total area of the supermarket, like the first one. The difference between sales area and total area is that the sales area refers only to the area where accessible to the customers, while the total area is the complete area of the building. Because of the lighting, instrumentation and HVAC system, the sales area has a higher energy intensity than the whole area, in which there can be spaces that do not require so much energy, like parking and warehouses of non-alimentary products.

As a general comment, the smallest is the supermarket, the larger will be the specific energy consumption and thus the benefits from a SOFC-CHP installation. On the contrary, too small shops could be (if not included in a larger retail chain) unwilling to invest an high amount of money for renewing the energy system.

Electricity and gas are the main energy sources for a supermarket. These two energy vectors are used for several applications that vary from store to store, but more than 50% of electricity and gas is used for:

- Refrigeration
- Lighting
- HVAC system

Among these three refrigeration is the most dominant, with usually 1/3 of the overall consumption. The same behavior can be found also for other cases in literature , for example the work of Tassou et al. [10] or in the analysis of Giovanni Piano from Carrefour [9].

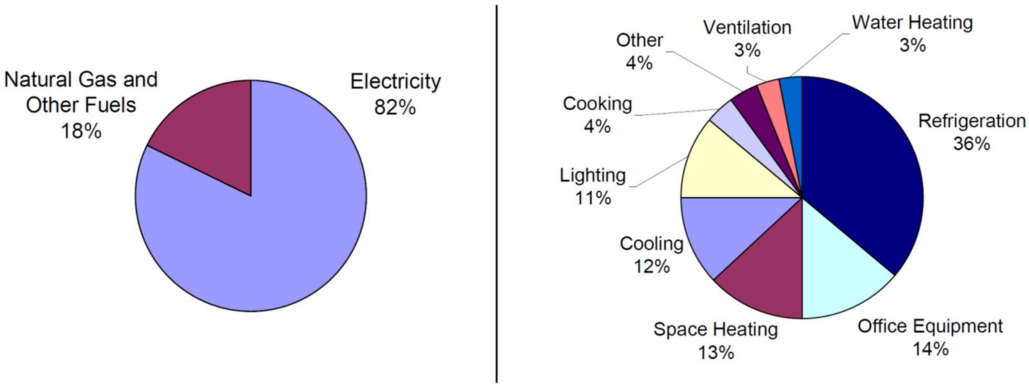


Figure 8. On the left the energy consumption by fuel type, on the right by end user [7].

3.2 Load profiles

The total consumption profile of a supermarket is subjected to several variables, like seasons, hour of the day, temperature, area of the supermarket, but its daily and hourly shape is usually similar between different shops and countries. In a typical day the shape is characterized by a baseline load that increases until a peak located in the middle of the day (and it usually coincides with noon) and then decreases to reach again the baseline load at the end of the day, as shown in Figure 9 [12]. The major part of the baseline load is the refrigeration, while the variable load is usually divided into the equipment that are turned on just when the customers and the workers are in (for example lighting, instrumentation, HVAC system, bakery and so on). Since SOFCs work at a higher efficiency and longer lifetime in constant operating point, even if modulation is feasible, it would be better to set the size of the fuel cell close to the baseline load of the supermarket.

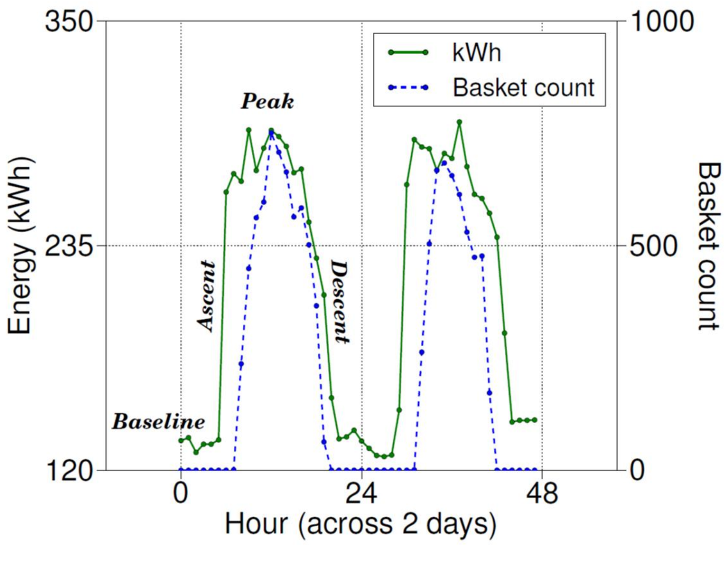


Figure 9. Energy load profile and Basket Count [12].

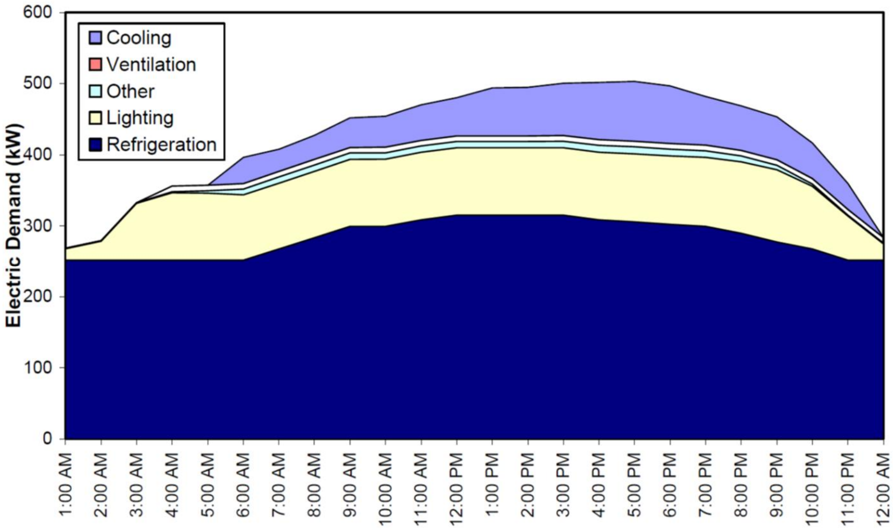


Figure 10. Energy load profile with the distribution of loads [7].

It is also important to consider how the average demand of electricity and heat varies along the year and between night-time and day-time. The main difference is between summer and winter for the heat load. In fact, even if there is an increase of the electric load in summer months because of the cooling request (around 30% more with the respect to the winter), the difference for the heat is larger, because in the summer the load is almost zero. Day-time demand (7:00-24:00 h), both of electricity and heat, is higher than night-time demand for two main reasons: lower shopping activity, or no shopping activity at all (if the supermarket is closed during night-time) and lower night-time temperatures that lead to lower refrigeration power consumption. Other loads that contribute to this difference are the demand of air conditioning in the summer months that usually operates only during opening hours and internal lighting. In Figure 11 two examples of electric consumption distribution along the year are shown, in Figure 12 the heat consumption [13].

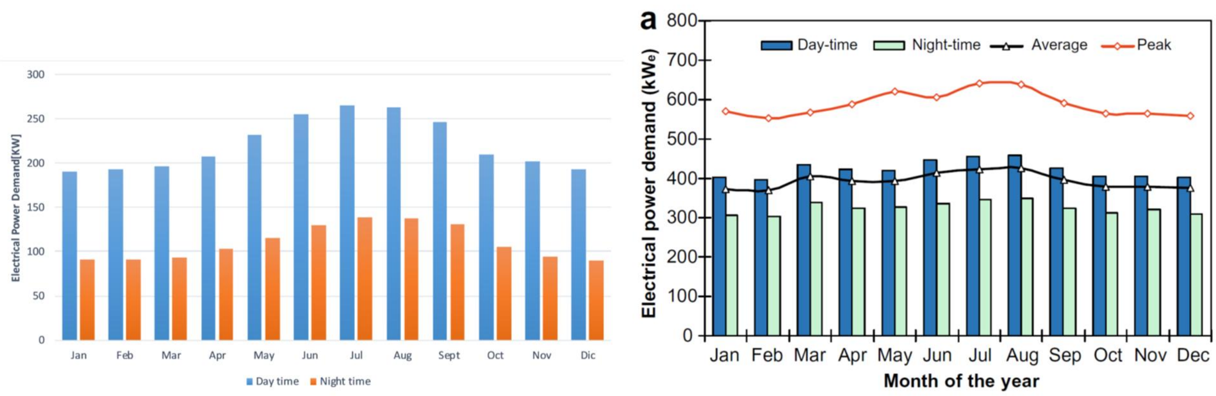


Figure 11. Variation of electric consumption in a year, day-time and night-time. On the left: electric consumption in Baltimore (US) [4]. *On the right: electric consumption in South of England (UK)* [13].

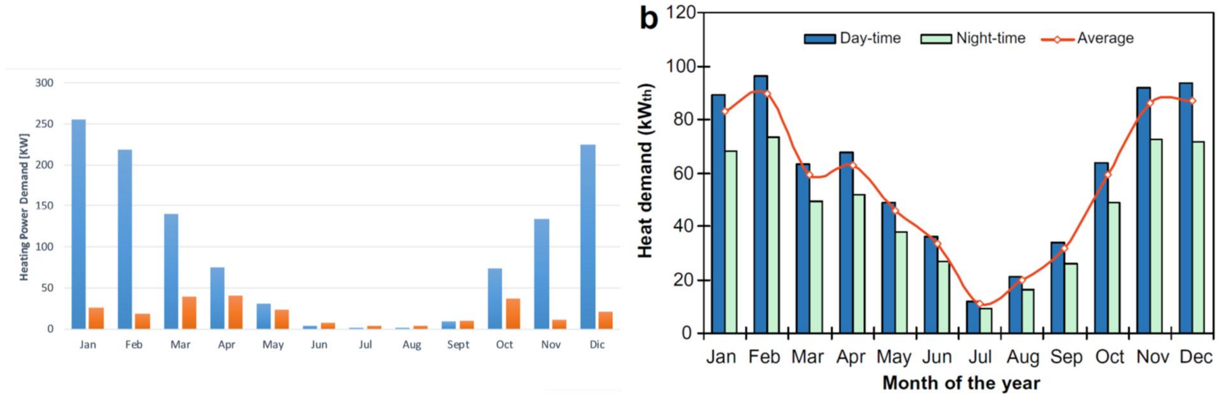


Figure 12. Variation of heat consumption in a year, day-time and night-time. On the left: heat consumption in Baltimore (US) [4]. *On the right: heat consumption in South of England (UK)* [13].

Today, most of supermarkets are still fully dependent on the grid both for electricity and NG supply. The primary supply for the electricity is the grid, and in case of failures there is a UPS device that fulfills the need of electricity for the time of the failure. For the heat needs, there is a boiler fed by the NG from the grid. Anyway, the number of CHP systems (usually based on gas engines) installed directly in loco, that could cover both electricity and heat loads, or at least a part of them, is increasing. In a study conducted by Spyrou et al. [11], a sample of 123 supermarkets were studied and the authors analyzed those without CHP (89) and those with a CHP (34). The typical scheme of energy supply and its distribution for a typical supermarket is shown below in Figure 13 [13].

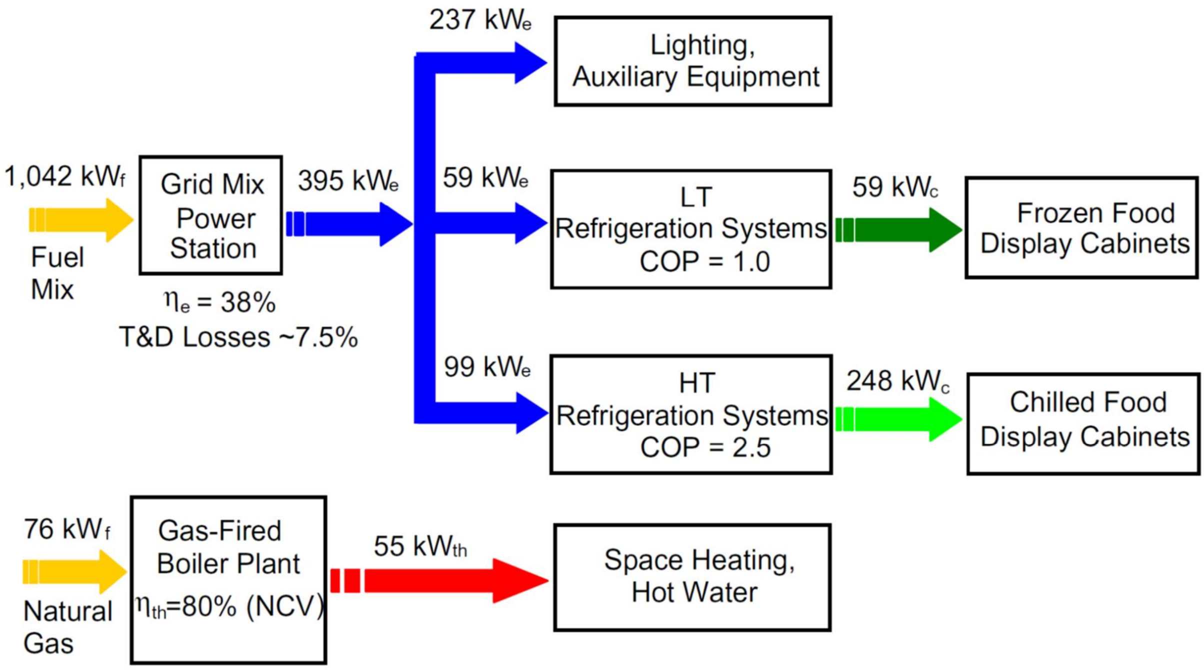


Figure 13. Flow diagram for conventional power, refrigeration and heating in a supermarket [13].

Market Potential

The market potential for SOFC installations in the supermarket sector for the countries analyzed is presented here. For each country the best size to maximize the savings was chosen, and then multiplied for the number of supermarkets that fulfill the criteria used in this study (area higher than 1000 m^2). The results will be the potential power that can be installed in that country.

Table 4. Market potential evaluation.

Country	Size (kW)	Number of supermarkets	Potential Market (kW)	LCOE (c€/kWh)	Reference
US	120	31’450	3774	16.56	[14]
Italy	180	4’955	891.9	23.38	[15]
UK	360	3’679	1324.4	23.82	[16]
Sweden	60	7’858	471.5	24.49	[17]
Spain	120	2’416	289.9	23.82	[18]

The best size to be installed (second column) varies a lot between the countries, from 60 kW in Sweden to 360 kW in UK, as discussed previously. The best size is dependent on several variables, but mainly on the energy price and the energy consumption of a certain location that. For countries like US and UK, the market potential is respectively 3.7 and 1.3 GW and for Italy almost 1 GW. These results refer only to supermarket with an area higher than 1000 m^2, so the market can be even larger if the whole supermarket sector is considered. Even considering this part of the market, the potential of business is significant and can lead to a first entry of SOFC based CHP system.

4. Hotels

The second section is related to the study of the hotels sector. The reason for analysing this market is because the consumption of electricity is again continuous 24/7 and quite constant, as will be discussed in the next sections. Inside an hotel, the electricity is the primary energy source and it is used for HVAC system, lighting, lifting and for all the equipment, while NG is used mostly for heating and cooking purposes.

An hotel, from an architectural point of view, is a combination of three different areas, each one with different purposes and design:

- The guest room area that includes individual spaces (rooms, bathrooms) characterized by variable energy loads depending on the number of customers;

- The public area including reception, bars, restaurants, swimming pool with a high exchange of heat so with a higher consumption of energy;
- The service area with kitchen, offices, staff facilities that also have a constant energy load due to, mainly, ventilation and cooling or heating.

Therefore, the energy load of a hotel is characterized by a constant load due to ventilation, lighting, heating or refrigeration of common areas and by a variable load depending on external temperature, location, number of customers, class, size, type of services and amenities like swimming pool, spa, restaurants.

Looking at Figure 14, countries with the highest domestic and chains hotels are France, Italy, UK, Italy, Germany and Spain, where also the most touristic capital cities are found. The same trend is confirmed also from another report, as shown in Figure 15.

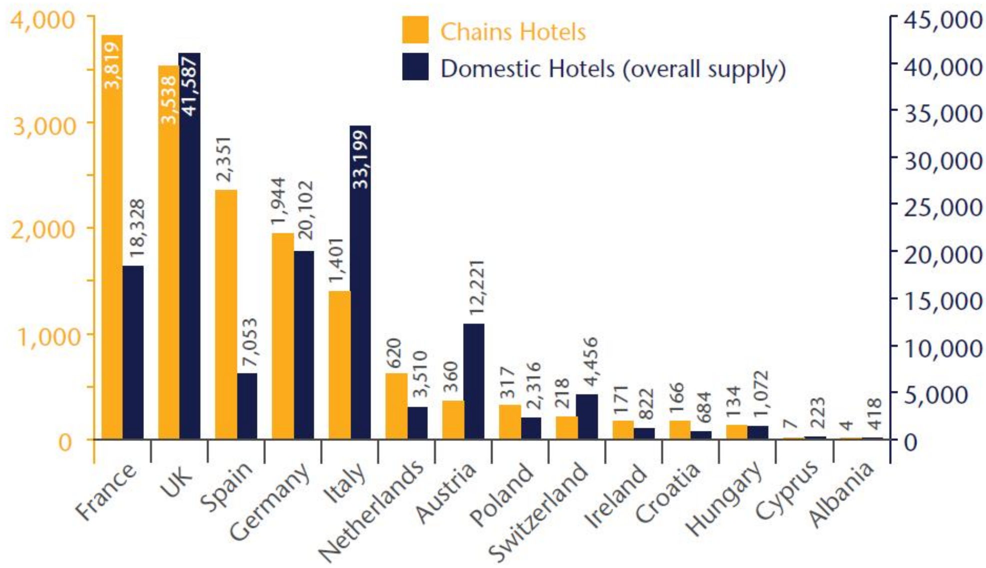


Figure 14.Domestic and chains hotels in EU countries. [19]

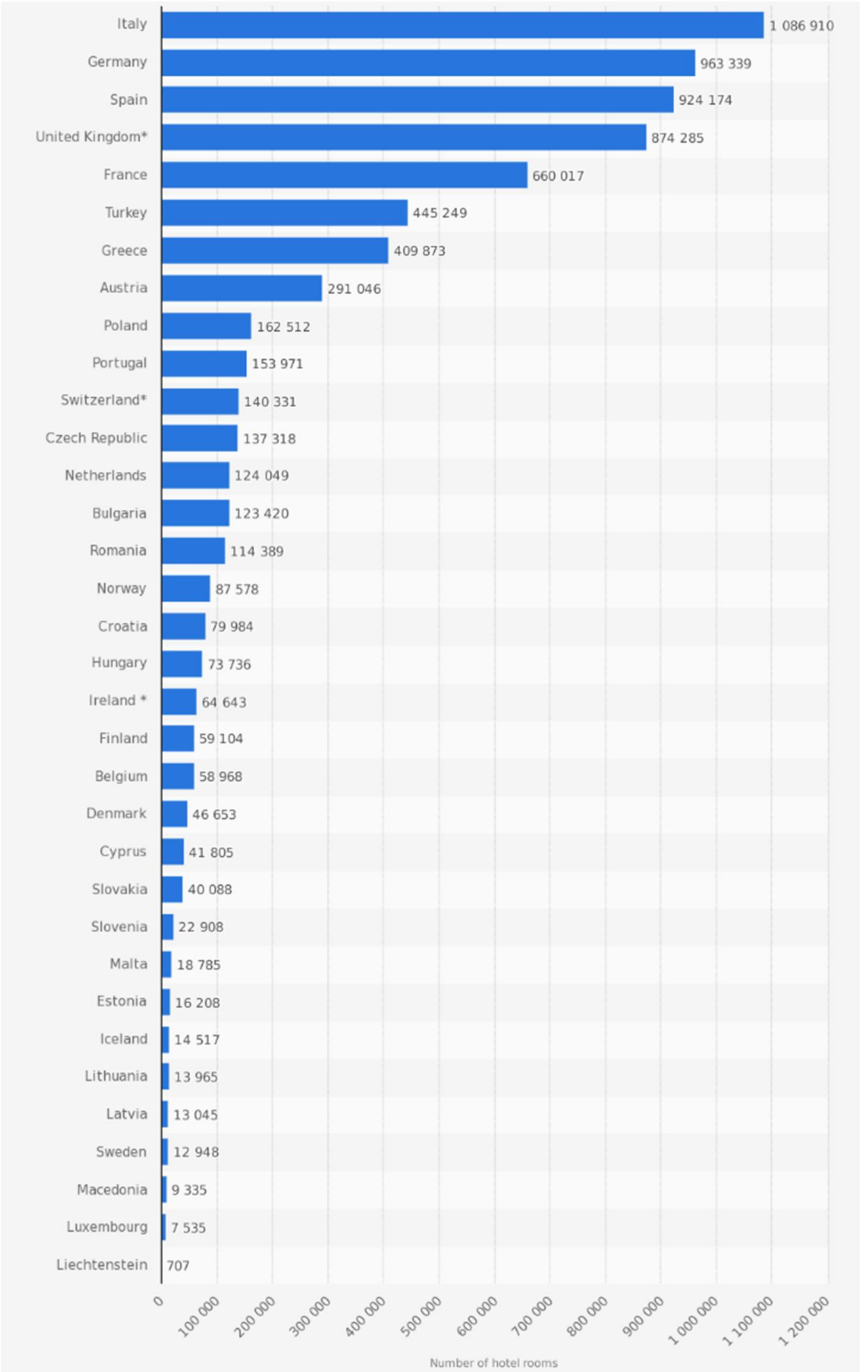


Figure 15. Number of bedrooms in hotels and similar accommodation in EU, 2017, by country. [20]

4.1 Energy consumption

Table 5 shows the list of countries analyzed with relative number of hotels and values of EI in kWh/m^2.

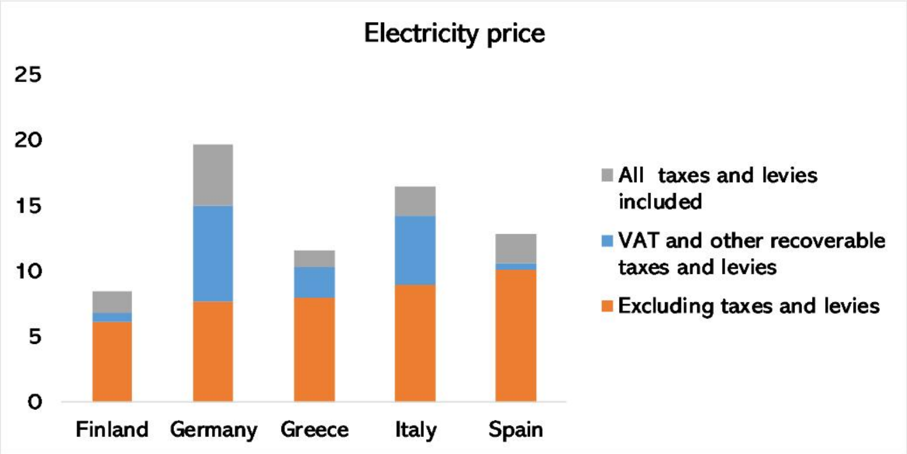
Table 5. Value of the energy intensities for the chosen countries.

State	Hotel	EI [kWh/m²]	References
Finland	787	278	[21]
Germany	32’749	268	[21]
Greece	9’772	273	[21], [22]
Italy	30’379	230	[21], [23]
Spain	19’630	177	[21]
Singapore	29	427	[24]
USA - Baltimore	1	260	[4]
USA - Boulder	1	212	[4]
USA - Minneapolis	1	235	[4]
USA - Seattle	1	210	[4]

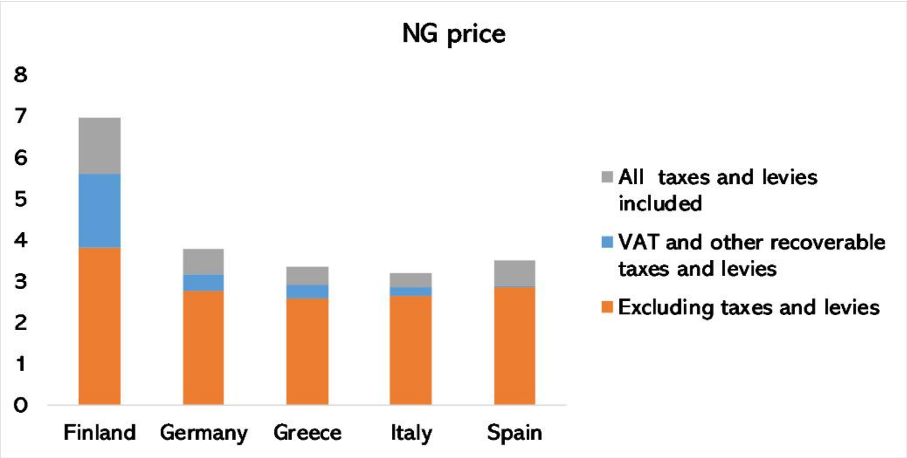
In Europe the selected countries are Finland, Germany, Greece, Italy and Spain. Electricity and gas prices were taken from the website of Eurostat [25] in which is possible to select country, fuel, consumer, consumption level and unit. Concerning the share of consumption, as can be seen in the figures below, the energy required for domestic hot water is the highest in all cases.

Table 6. Energy data for European locations [25]

	Finland	Germany	Greece	Italy	Spain
EI electricity [kWh/m²]	278	268	273	230	177
Electricity price, Band IC (consumpion between 500 and 2000 MWh/y) – 2018 S1 [c€/kWh]					
· All taxes and levies included	8.44	19.67	11.60	16.42	12.82
· Excluding VAT and other recoverable taxes and levies	6.81	14.99	10.29	14.23	10.59
· Excluding taxes and levies	6.11	7.71	7.96	8.92	10.08
NG price Band I3 (consumption between 10’000 and 100’000 GJ/y) – 2018 S1 [c€/kWh]					
· All taxes and levies included	6.96	3.78	3.36	3.20	3.51
· Excluding VAT and other recoverable taxes and levies	5.61	3.17	2.91	2.86	2.90
· Excluding taxes and levies	3.82	2.77	2.59	2.63	2.85



a)



b)

Figure 16. Electricity (a) and NG (b) price with share of the different contributions.

In US the chosen locations are Baltimore (Maryland), Boulder (Colorado), Minneapolis (Minnesota) and Seattle (Washington). Data related to electricity and gas consumption were taken from an American database available online [4] from the U.S. energy department. The energy prices are referred to December 2018 and they are taken from the website of EIA (Energy Information Administration) [26] in which there are all prices of electricity and gas divided for sector (residential, commercial, industrial, transportation), state and month.

Table 1 Energy data for US locations [4].

	Baltimore - MD	Boulder - CO	Minneapolis - MN	Seattle - WA
Electricity annual consumption [kWh]	2’512’604	2’304’611	2’364’128	2’327’129
Gas annual consumption [kWh]	2’687’102	2’921’691	3’529’314	2’689’217
EI electricity [kWh/m2]	260	212	235	210
EI gas [kWh/m2]	244	263	320	247
Average price of electricity [c€/kWh]	9.65	8.59	8.83	7.77
Average price of gas [c€/kWh]	2.93	1.82	2.21	2.07

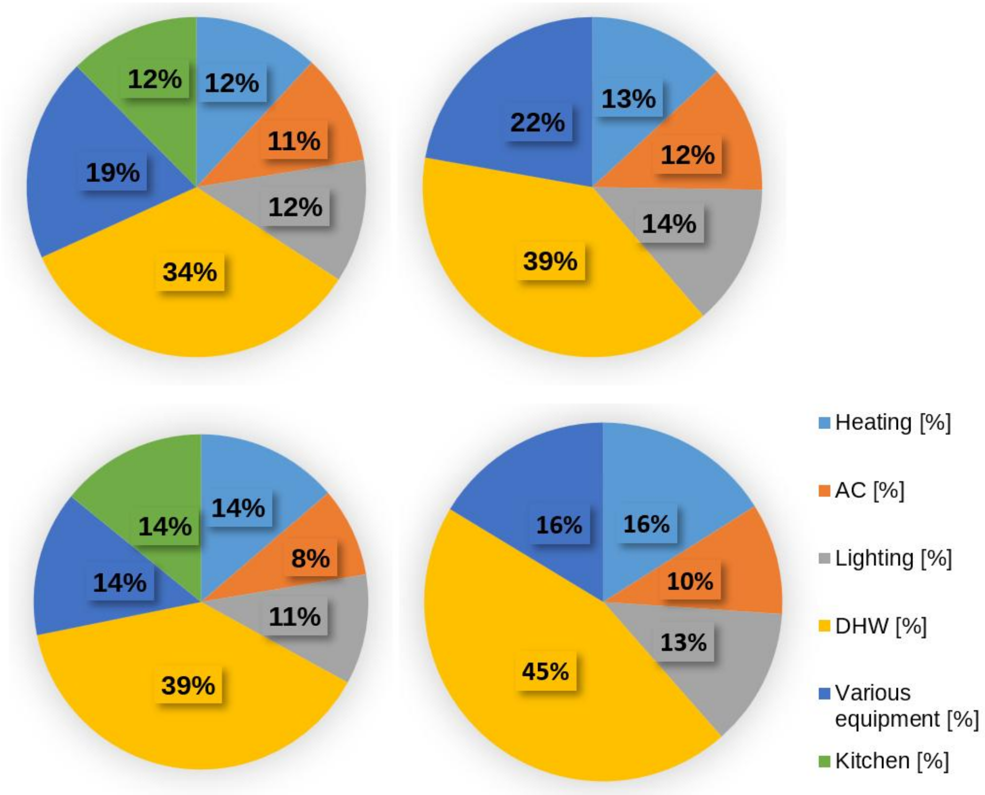


Figure 17. Subdivision of energy end use. Top left) With AC throughout the building with restaurant. Top right) With AC throughout the building without restaurant. Bottom left) With AC only in common area with restaurant. Bottom right) With AC only in common area without restaurant [27].

In all the four cities the electricity and gas consumptions are similar. The city in which hotel consumes more electricity is Baltimore while Minneapolis is the city with the highest consumption of gas, mostly for heating because it is in the north, near Canada.

<u>Singapore</u>

Singapore was chosen because it is the only Asian city for which in literature there is an in-depth study [24] on the hotel sector. The study was conducted on 29 hotels and for each hotel the total and specific consumption was obtained. The most important data are the energy intensity because they can be compared with the one of other countries. The value kWh/room is not so reliable because the dimension of a room is not a universal data, it depends on legislation of each country.

Table 2 Data of hotels in Singapore

Hotel	GFA [m2]	EUI el [kWh/m2]	EUI gas [kWh/m2]
1	42483	297.45	36.39
2	20799	449.68	6.92
3	32124	487.54	65.99
4	27829	364.06	27.45
5	101998	312.28	27.92
6	37809	431.58	104.56
7	35972	311.43	23.32
8	34293	402.18	47.21
9	43473	403.46	15.87
10	50470	426.34	45.44
11	94000	294.04	36.51
12	37877	302.72	56.98
13	19206	467.61	54.89
14	25916	391.80	44.13
15	23018	43.47	26.54
16	17194	375.73	25.11
17	21260	296.98	21.27
18	27291	453.12	33.97
19	14742	406.93	1.74
20	26866	312.76	0.60
21	28546	355.72	15.56
22	19410	441.80	45.82
23	50959	495.76	60.75
24	49424	314.67	24.47
25	28112	245.76	29.37
26	18133	263.74	2.72
27	20591	254.98	13.40
28	1648	229.82	70.28
29	24394	221.17	43.54

Table 3 Energy data for Singapore. [28]

Parameter	Value
Electricity annual consumption [kWh]	11’760’292
Gas annual consumption [kWh]	1’208’094
EUI electricity [kWh/m2]	427
EUI gas [kWh/m2]	43
Average price of electricity [c€/kWh]	15.84
Average price of gas [c€/kWh]	12.21

Comparison

From the data reported below it is clear how the Energy Intensity referred to electricity is quite equal for all countries except for Singapore in which the price of gas is very high and so electricity is the primary energy source for hotels. The difference of EI between countries could also be a consequence of level of comfort of hotels, number of rooms, geographical location and level of used technology.

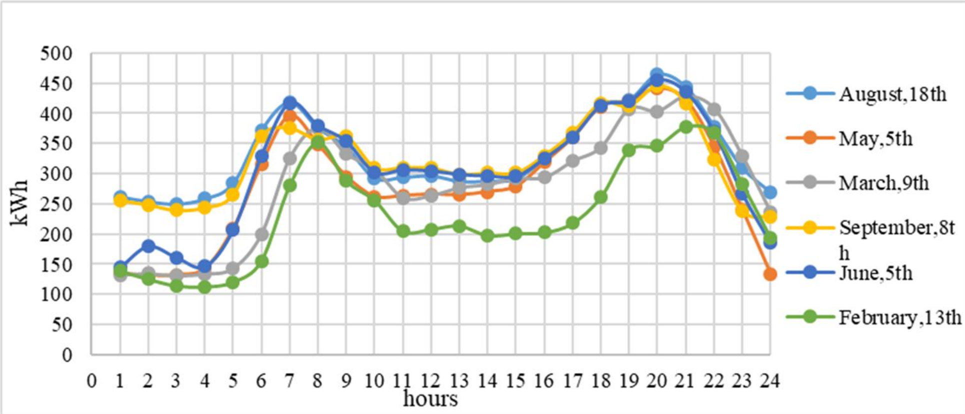
Table 4 Comparison between available data for chosen countries

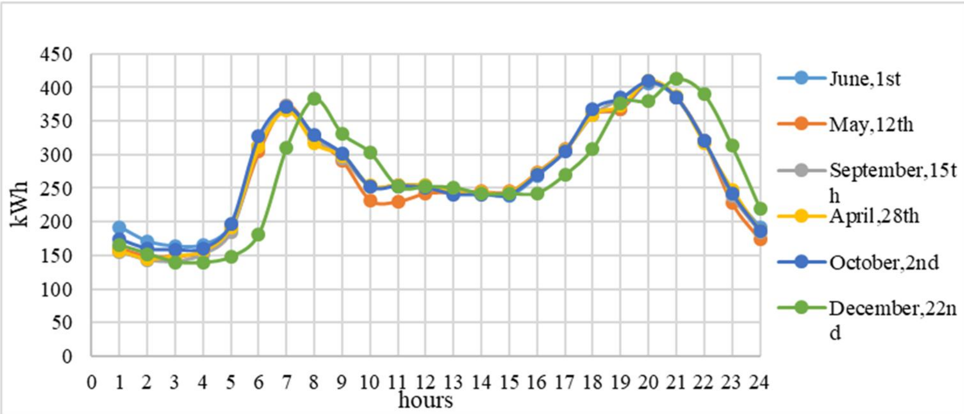
	Finland	Germany	Greece	Italy	Spain	Singapore	USA Baltimore	USA Boulder	USA Minneapoli s	USA Seattle
Electricity annual consumption [kWh]	n.a.	n.a.	n.a.	n.a.	n.a.	11’760’292	2’512’604	2’304’611	2’364’128	2’327’129
Gas annual consumption [kWh]	n.a.	n.a.	n.a.	n.a.	n.a.	1’208’094	2’687’102	2’921’691	3’529’314	2’689’217
EUI electricity [kWh/m^2]	278	268	273	230	177	427	260	212	235	210
EUI gas [kWh/m^2]	n.a.	n.a.	n.a.	n.a.	n.a.	43	244	263	320	247
Average price of electricity [c€/kWh]	8.44	19.67	11.60	16.42	12.82	15.84	9.65	8.59	8.83	7.77
Average price of gas [c€/kWh]	6.96	3.78	3.36	3.20	3.51	12.21	2.93	1.82	2.21	2.07

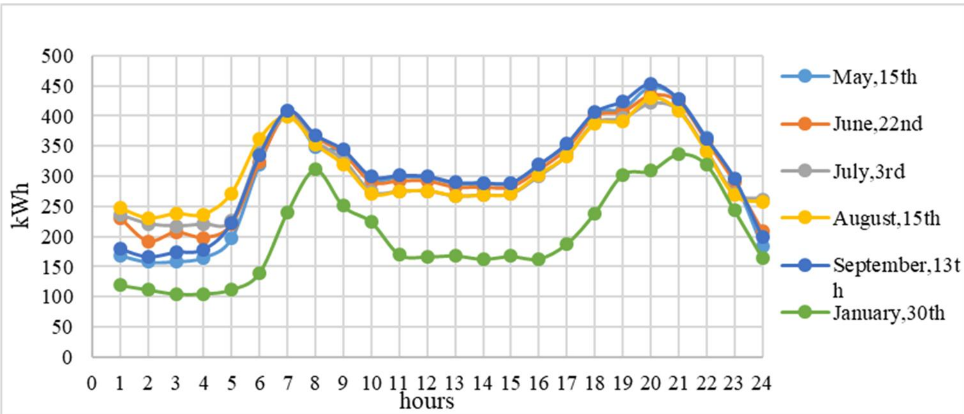
4.2 Load profiles

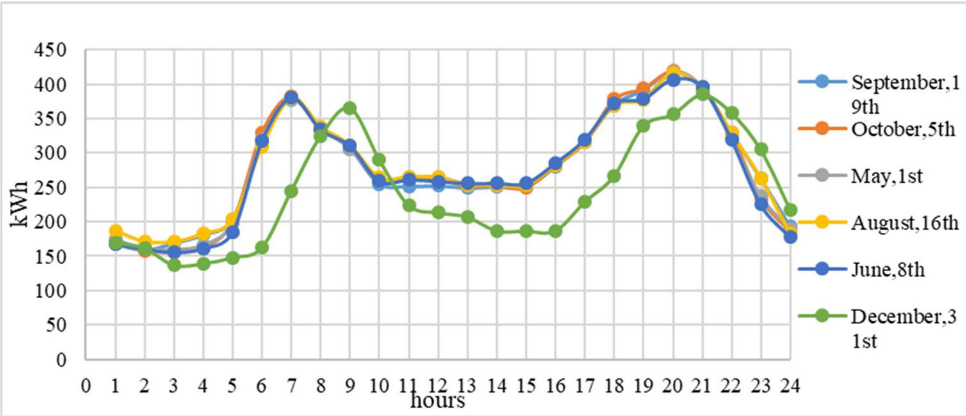
American data were used because US are the only states that have published hourly consumption for each type of buildings (offices, hospitals, hotels, supermarkets, schools, etc.). In this database [4] consumptions are divided in electricity and gas: electricity is given by the sum of kWh needed for fans, cooling, heating, interior lights and interior equipment while gas consumption is composed of heating, interior equipment and water heater. For both, electricity and gas, six days were chosen: five of them characterized by highest consume and one with lowest consumption (the green curve). As it is possible to see the first four graphs and the latest four one are characterized by the same trend even if days are very different from a climatic point of view.

In case of electricity in all cities there are two energies peak demand, one in the morning at 7-8 am and one in the evening at 8-9 pm. So a typical day is characterized by a base load of around 150 kWh and two peaks in correspondence of breakfast and dinner.


kWh
hours
August,18th
May,5th
March,9th
September,8th
June,5th
February,13th
A)


kWh
hours
June,1st
May,12th
September,15th
April,28th
October,2nd
December,22nd
B)

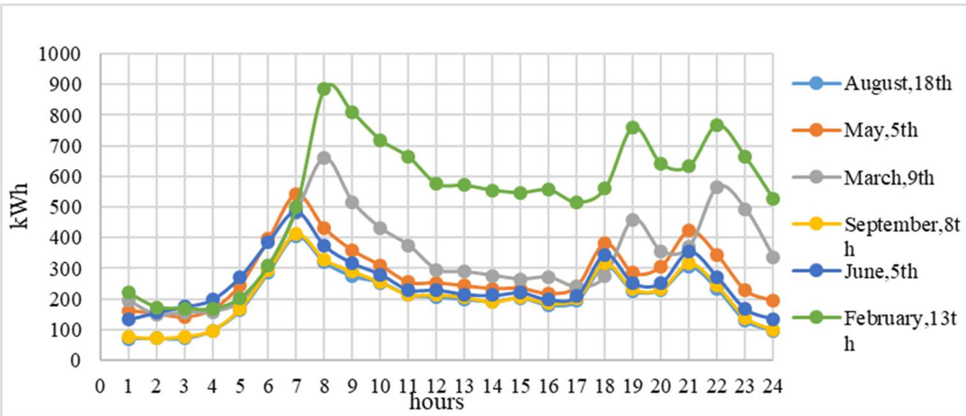

kWh
hours
May,15th
June,22nd
July,3rd
August,15th
September,13th
January,30th
C)



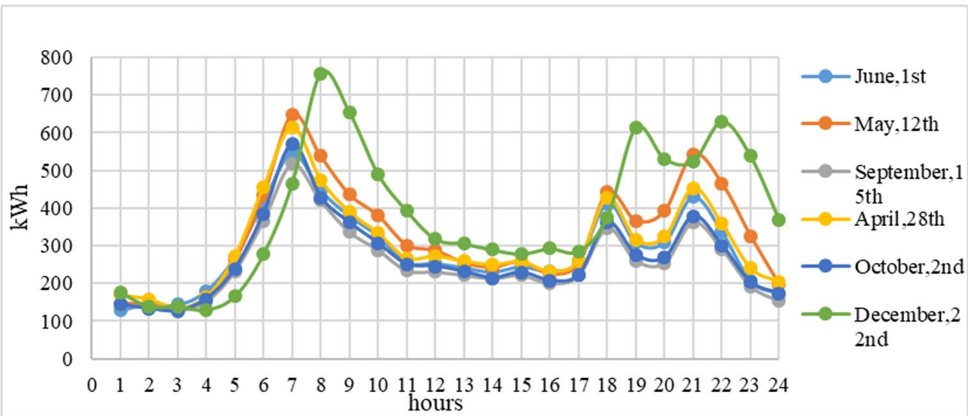
D)

Figure 18. Electricity daily load profiles. A) Baltimore, B) Boulder, C) Minneapolis, D) Seattle.

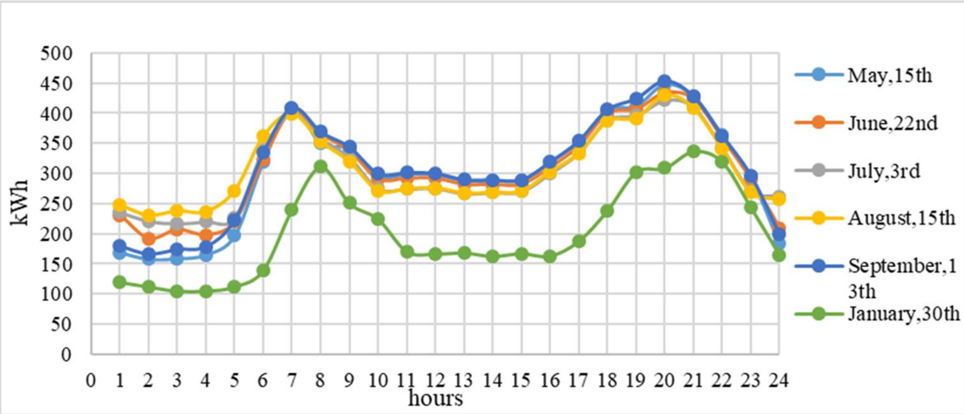
Graphs related to gas are also characterized by common trend: as for electricity, they have a base load of 150 kWh with a peak in the morning at 7 am and a flatter peak in the evening between 6 pm and 9 pm.



A)



B)

C) 

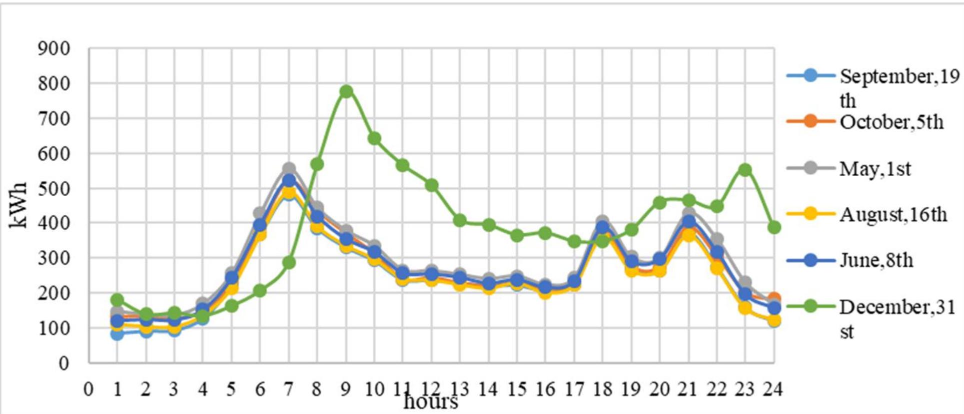
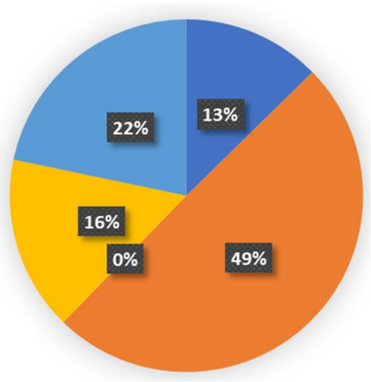
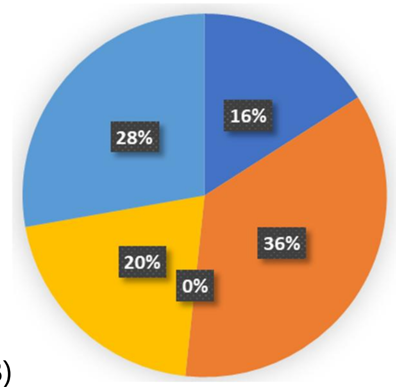
D) 

Figure 19. Gas daily load profiles. A) Baltimore, B) Boulder, C) Minneapolis, D) Seattle.

In most cases the majority of electricity is used for cooling in summer and for interior equipment in winter while gas is used for water heating in summer and for heating in winter, this also depends on the location and on the climate zone. The pie charts below represent the breakdown of consumption based on final use.



A)



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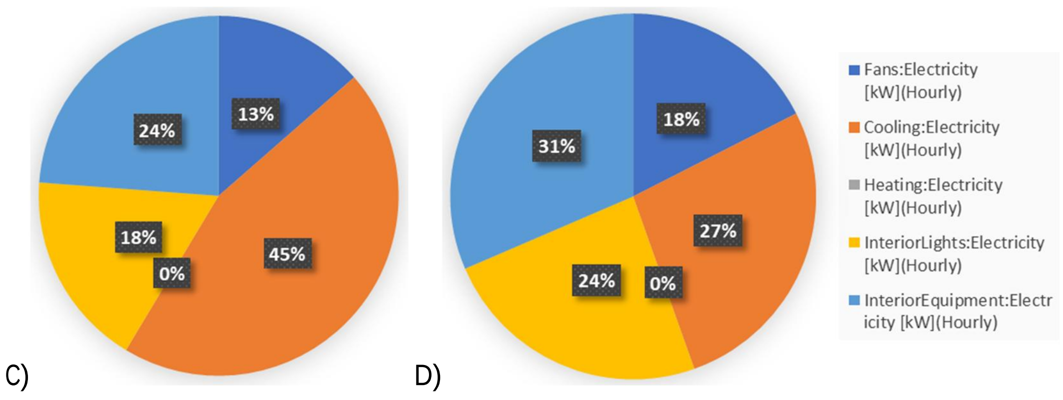

Figure 20. Share of electricity consumption. A) Electricity: August,18th – Baltimore; B) Electricity: December,22nd – Boulder; C) Electricity: May,15th – Minneapolis; D) Electricity: December,31st – Seattle.

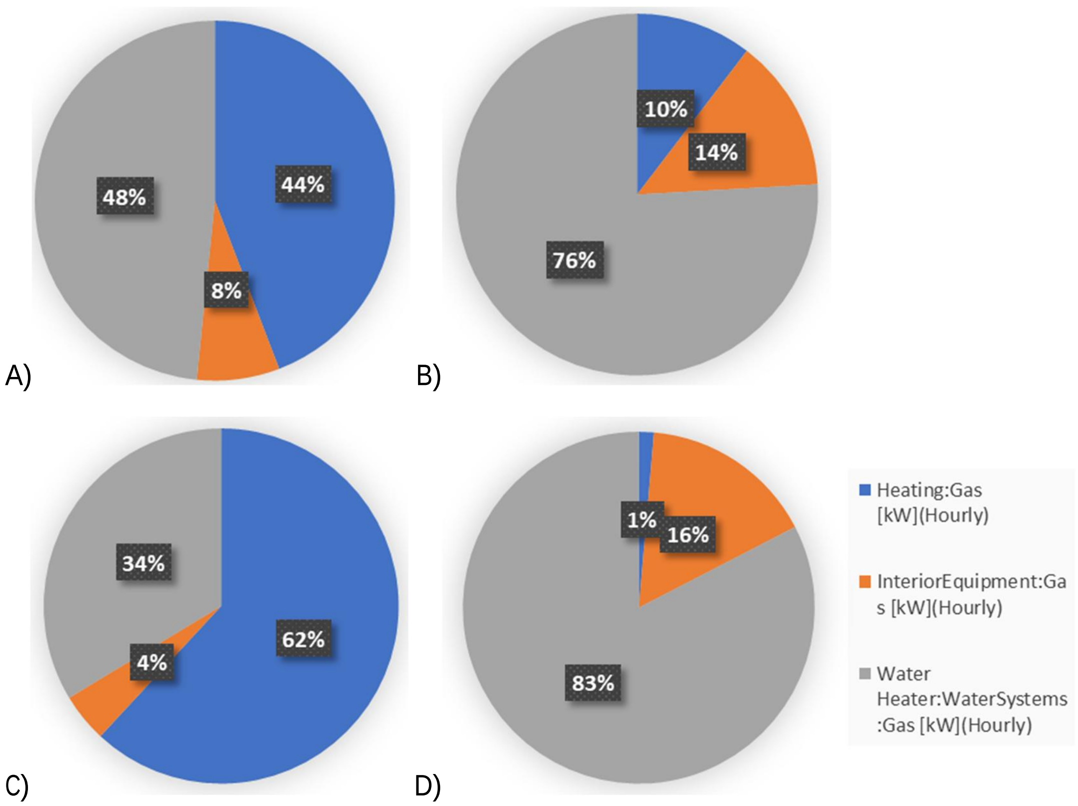

Figure 21. Sharen of gas consumption. A) Gas: February13th – Baltimore; B) Gas: June1st – Boulder; C) Gas: January30th – Minneapolis; D) Gas: September19th – Seattle

All graphs above show a very important issue: the demand of electricity and gas does not vary so much between day-time and night-time but there is a big difference between summer months and winter ones. As also reported in the histogram below, related to a hotel in Baltimore, the electricity consumed in winter season is lower than the one in summer because the majority of electricity is used for refrigeration. The opposite behaviour occurs for gas, that is requested for heating: in summer months the consumption of gas is almost half what has been requested in winter.

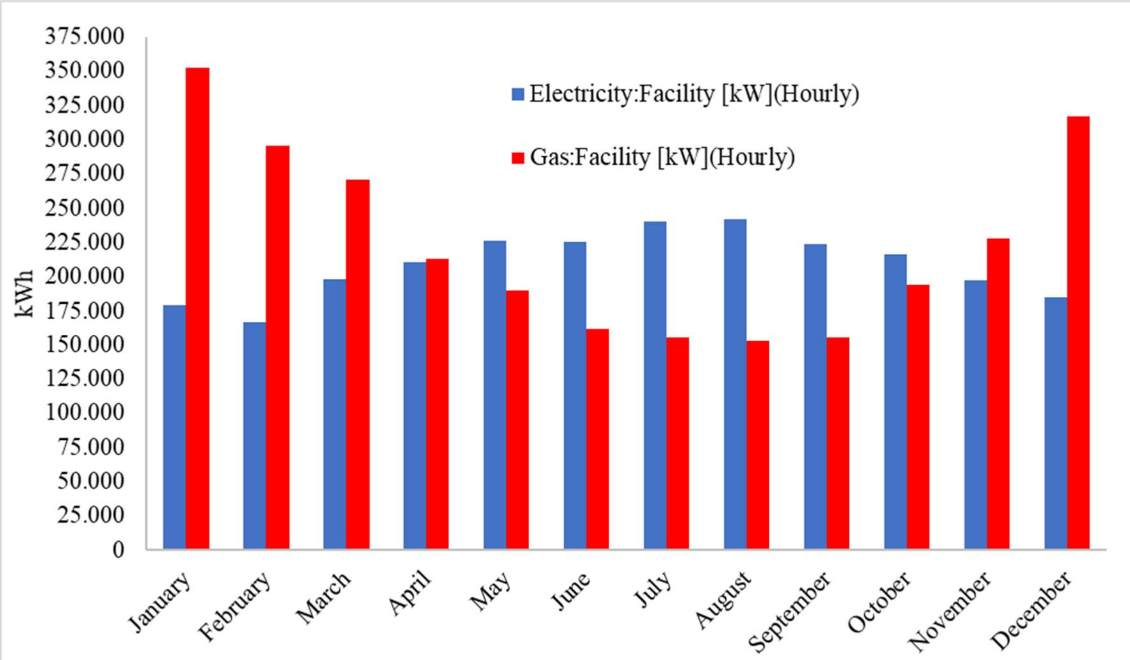

Figure 22 Variation of electric and NG consumption during the year.

5. Hospitals

Hospital sector needs a constant and stable load of energy, due to the necessity to keep the instruments continuously in operation and to maintain optimal environmental conditions, both for patients and staff. Hospitals are usually occupied 24 hours per day, all year round.

Electricity can be exploited to feed several equipments: cooling, heating, fans, water treatment system and medical devices. Depending on the technological level of these instruments and on the activities performed in the structure, we can have higher or lower values of electricity consumption. Thermal power provided by Natural Gas is splitted in various components: Heating, Interior Equipment and Water Heater. Gas consumption depends strongly on the climatic conditions, on the scope of the hospital facilities (kitchens, showers...), on building capacity, age and insulation.

This sector, in terms of energy consumption and size, is highly heterogeneous. US and Canada show the highest Electrical and Gas consumption per gross floor area. Probably because they have bigger buildings with respect to Europe, and with a good technology level.

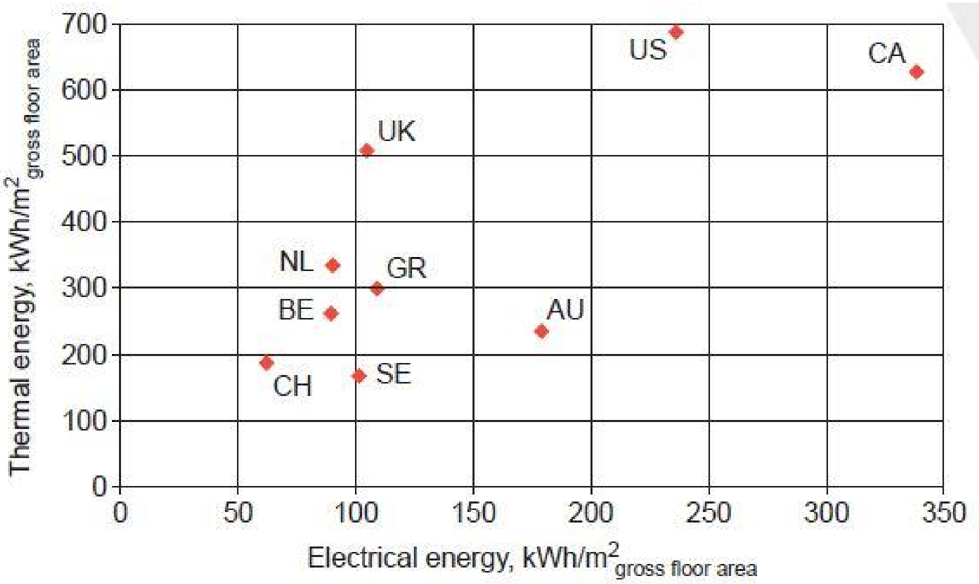

Figure 23. Average annual Electrical and Thermal energy consumption per gross floor area. [29]

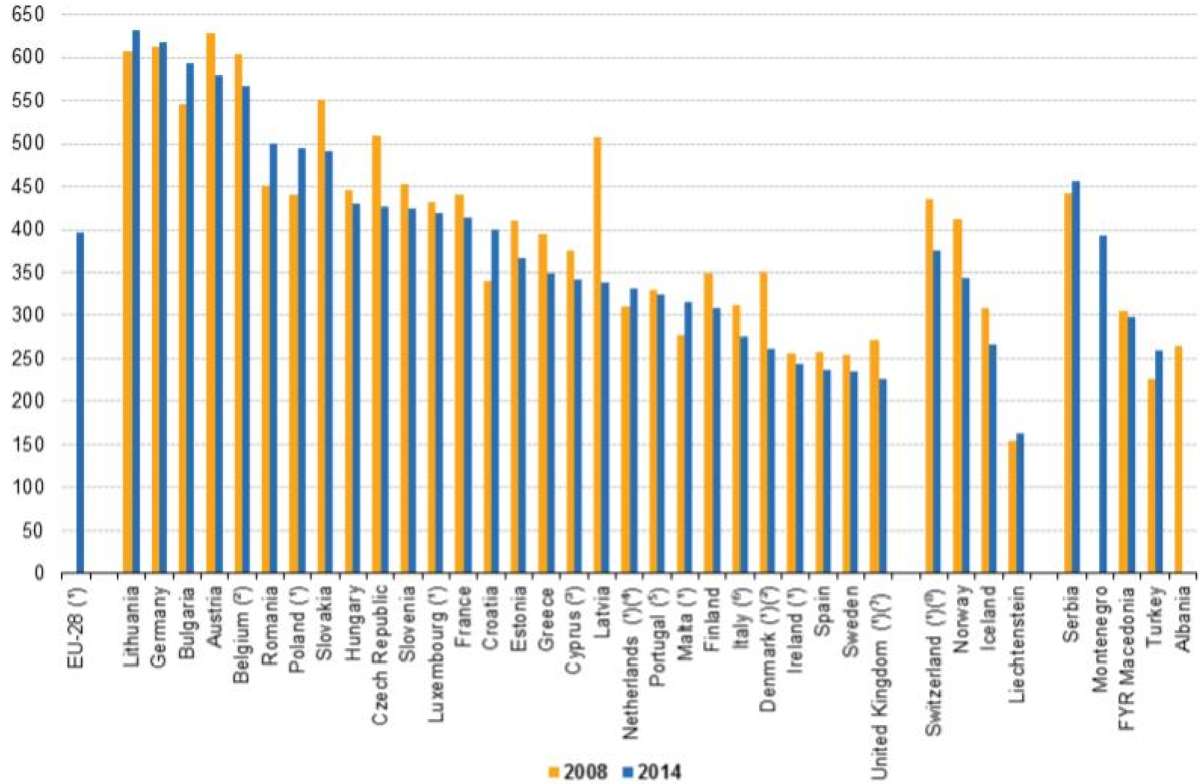

Figure 24. Curative care beds in hospitals, 2008 and 2014 (per 100 000 inhabitants) (thousands). [30]

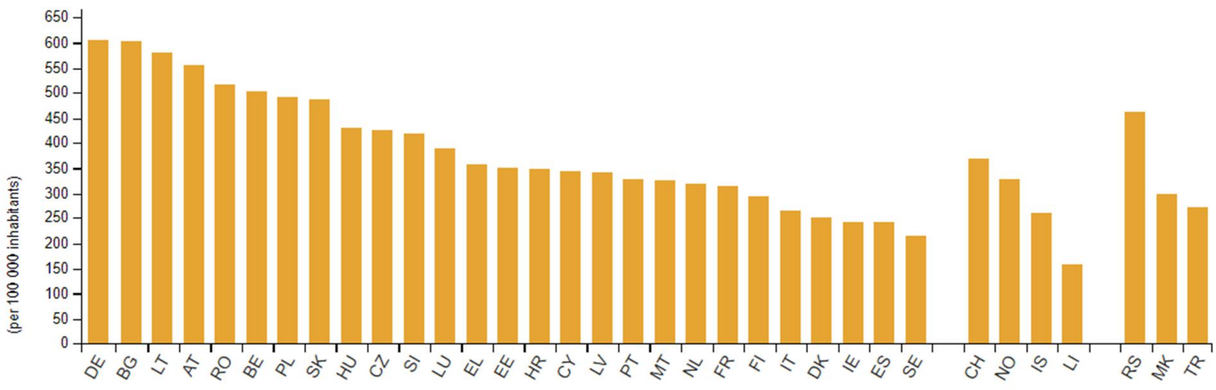

Figure 25. Curative care beds in hospitals, 2016. [30]

The Grevena Hospital (Greece) [31] covers an area of 13’800 m^2 and shows the lowest electrical energy consumption among the analysed cases, because it is the less technologically developed. It is a 110-bed hospital.

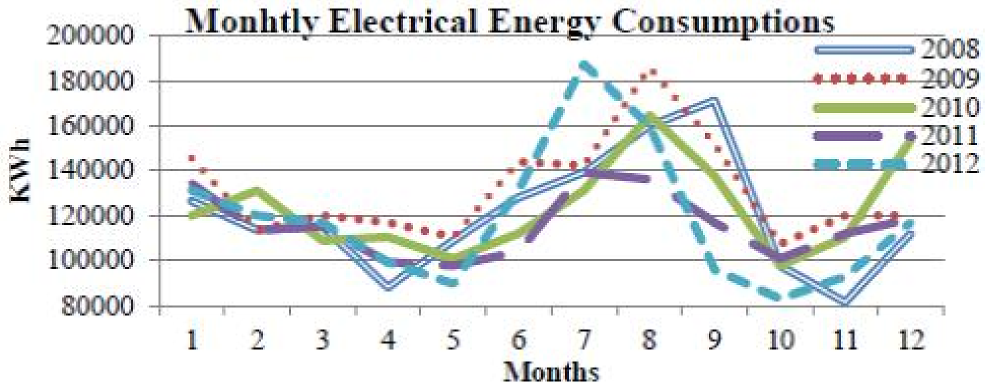

Figure 26.Electrical Energy Consumption for years 2008-2011. [31]

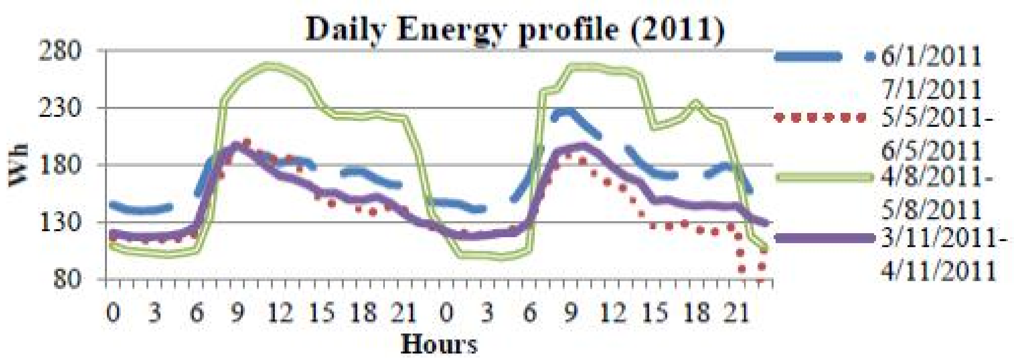

Figure 27. Daily energy profile for four distinctive periods of 48 hours. [31]

Electricity consumption mainly depends on the climatic characteristics of the location: it is higher in the summer months (from June to September), due to the use of the Air Conditioning system. Two lowest points occur in months in which there is the absence of Air Conditioning, good ambient light and no use of electric heaters. Average monthly consumption for all years is 121.8 MWh. So electric intensity is calculated: 105.87 kWh/m^2. In winter there is an increased consumption due to the use of electric heaters and high lighting needs. On an average basis during the years (2008-2012) 1.461 GWh were consumed every year.

Daily Energy profile shows a trend which is replicated every day of the year, obviously with higher or lower consumption depending on climatic conditions and activities performed in the hospital.

During summer there is a distinctive peak of energy between 7:00 a.m. and 22:00 p.m. For periods of time between 00.00 and 7.00 the profile is slightly lower than that of autumn and spring. Winter profile shows an increase on daily energy. This is due to lighting needs and the electric heating. Autumn and spring profile look very similar. This is expected if we assume that we have the same level of daylight and same level of needs for heating by electric appliances.

Table 7 shows the Electric and Gas consumption along the year, divided by month, for the Zucchi Clinic Institutes (Monza, Italy) [32]. Zucchi Clinic Institutes needs 2’374’026 kWh per year of Electricity. Considering the LHVGas=9.27 kWh/Sm^3, the total Gas consumption is calculated as 2’809’524 kWh per year. A comparative analysis is performed on three different Italians hospitals: two of them, Zucchi Clinic Institutes (ICZ) and San Gerardo Hospital, located in Monza, and the European Oncology Institution (IEO) located in Milan. The analysis has the aim to evaluate specific indicators for each structure, taking into account their dimension and size.

Table 7. Monthly Electric and Gas Consumption. [32]

Month	Electricity [kWh]	Gas [Sm^3]	Gas [kWh]
January	183’784	44’484	412’367
February	172’718	47’486	440’195
March	184’376	29’380	272’353
April	178’767	25’811	239’268
May	191’490	11’839	109’748
June	229’788	11’244	104’233
July	253’000	10’175	94’322
August	230’934	8’914	82’633
September	195’759	10’612	98’373
October	192’136	20’423	189’321
November	180’082	29’842	276’635
December	181’192	52’867	490’077
TOTAL	2’374’026	303’080	2’809’524

Table 8. Comparative analysis on Electric Consumption. [32]

Institute	Electricity [kWh]	Surface [m^2]	Volume [m^3]	Beds	kWh/m^2	kWh/m^3	MWh/bed
ICZ	2’374’026	11’362	46’471	180	209	51	13
IEO	12’751’463	28’240	82’720	264	452	151	48
S.G.	25’210’136	132’839	554’387	1105	190	45.5	23

Table 9- Comparative analysis on Gas Consumption. [32]

Institute	Gas [Sm^3]	Surface [m^2]	Volume [m^3]	Beds	Sm^3/m^2	kWh/m^2	Sm^3/m^3
ICZ	303’080	11’362	46’471	180	27	247.3	7
IEO	769’072	28’240	82’720	264	27	252.4	9
S.G.	3’664’150	132’839	554’387	1’105	27.7	256.8	6.6

It is also reported an average indicator of electric intensity of Piemonte, Lombardia and Liguria Hospitals: 141 kWh/m^2. Specific indexes calculated depend on several factors, and their use in making confrontations must be limited between similar structures (location, technologization, capacity), to avoid an incorrect evaluation. In this analysis it’s assumed a similar final use of the hospital environments in different structures, so the kWh/m^2 index is the one chosen (energy consumption per bed is not easily available in literature) for the confrontations.

- **MWh/Bed:** it allows comparison between structures located in the same climatic zone and with similar technologization. It provides per capita energy consumption based on the number of patients. This index is strongly influenced by the climate and the internal organization of the hospital;
- **KWh/m^2 and kWh/m^3:** if used for buildings with similar characteristics, they allow to compare structures that are very different in dimension. They may be inadequate if the intended use of the environments in question is not considered.

Table 10. Share of yearly electric consumption. [32]

Category	Electric consumption [kWh/year]
HVAC	1’003’419
Illumination	619’875
Lift	80’471
Electromedical	506’910
TOTAL	2’210’987

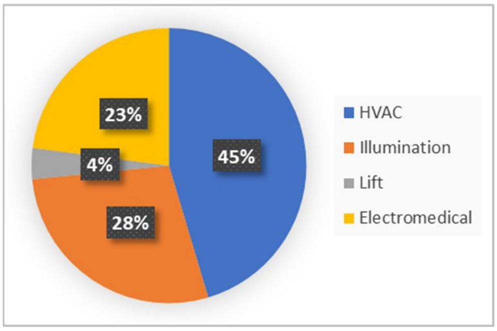

Figure 28.Electricity profile divided into various contributions.

HVAC represents, with lighting, the most significant consumption in electricity, due to the constant load requested to satisfy them during all the year.

The annual energy input to AOB (Brotzu Hospital Agency, Cagliari, IT) [33] is approximately 20’000 MWh, 43% composed of thermal energy (fuel), the remaining 57% of electricity. Hospital surface is of 62’250 m^2.

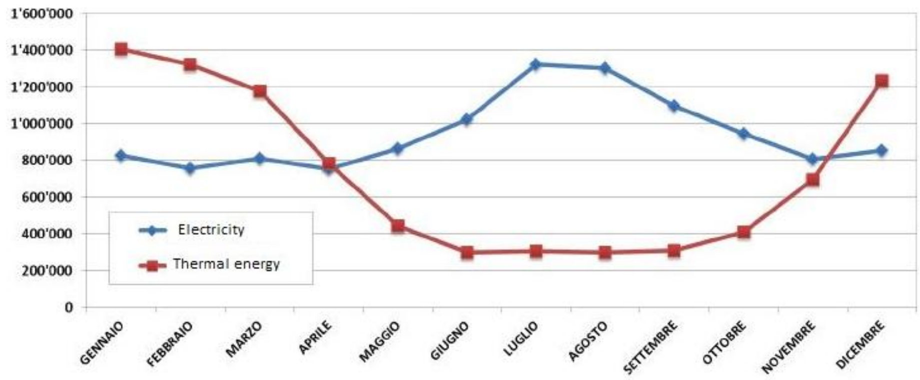

Figure 29. Monthly Energy consumption (kWh). [33]

Thermal energy consumption depends strongly on the use of heating: in the summer months the curve is flat, and it shows the lowest values.

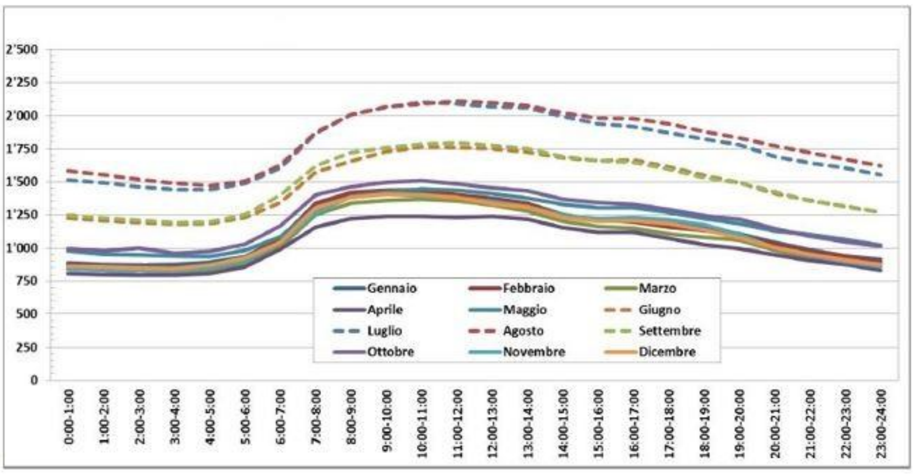

Figure 30.Monthly Average Electric consumption. [33]

Electricity consumption peaks are concentrated in the morning. In the summer (June - September) the peaks are particularly high (dotted lines). Indeed, during summer the refrigeration units are in operation. Anyhow, the profile has a very similar trend along the year: it means that the Electricity consumption depends only on the climatic conditions and on the activities performed in the Hospital, which are quite similar every day.

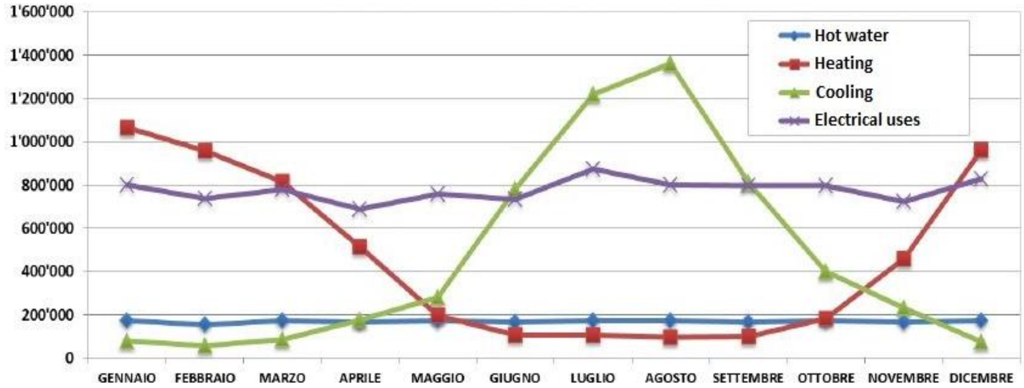

Figure 31. Monthly thermal energy consumption differentiated for final uses (kWh). [33]

Thermal energy consumption shows a constant value for Hot water and Electrical uses, which don't depend on the season. Instead, in summer its' evident the peak due to the cooling, and in the winter months there's a significant consumption due to the heating.

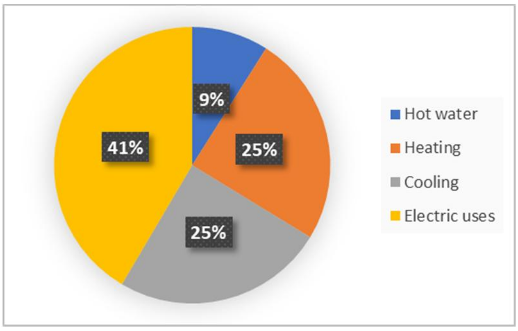

Figure 32.Gas consumption divided into various contributions.

Electric and Gas intensity are calculated in order to make a comparison between different hospitals:

- Electric intensity: 183 kWh/m^2
- Gas intensity: 140 kWh/m^2

US hospitals have, in average, a higher energy consumption in terms of electricity: 280 kWh/m^2 [33]. Indeed, American buildings in the non-residential sector are typically more extensive than those in Europe, and so they need a great amount of energy to satisfy their need. The usede dabatase is the same described for other sectors and available, from US Department of Energy, at [4].They are divided by sectors (hospitals, supermarkets, hotels, schools…) and by cities. These data are collected on an hourly basis, divided in electricity and gas consumption, splitted in the various terms (cooling, heating, fans, water treatment system…), so they are well organized and manageable.

1) Boulder- Colorado

To build the daily profile the day with the highest peak is chosen, to consider the highest demand for each selected month. The trend is rather flat in the central hours of the day, from 10:00 a.m. to 18:00 p.m. Daily profile is similar for each month: we have a peak in the afternoon and the lowest point during the night, when most equipments are not in operation.

	ELECTRICITY	GAS
Total Consumption [kWh/y]	8’439’819.44	3’576’522.2
Average Consumption [kWh]	963.46	391.1
Energy Intensity [kWh/m^2]	376.4	159.5

Table 11.Energy consumption and Intensity. [4]

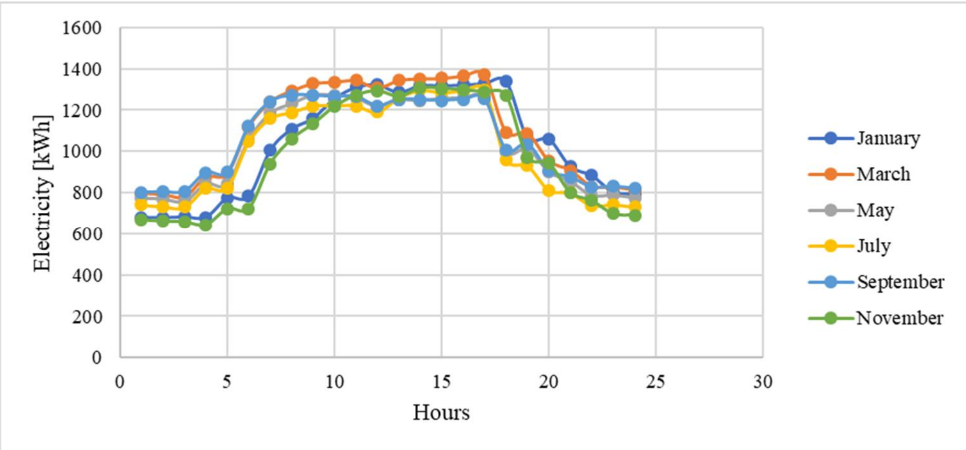

Figure 33.Boulder-Daily Electricity profile.

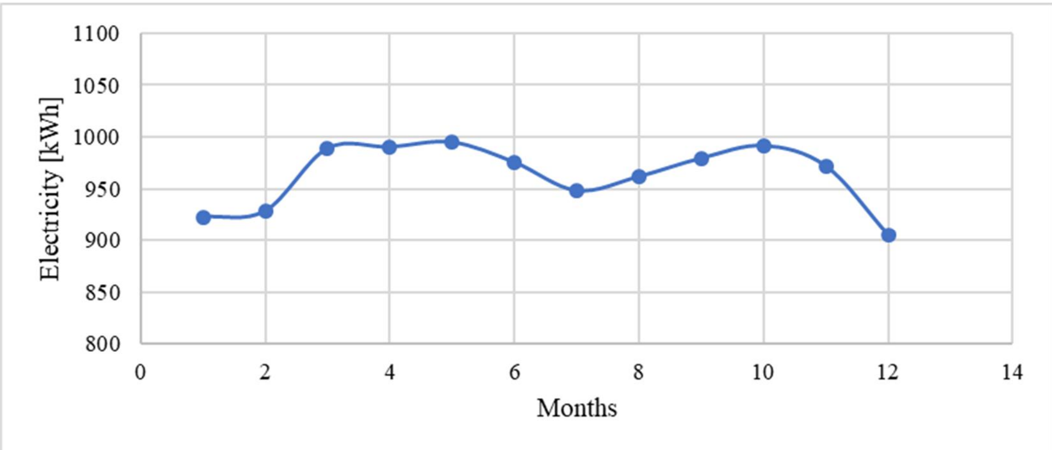

Figure 34.Monthly average consumption

May shows the highest average monthly electricity consumption with 995.02 kWh. December shows the lowest: 905.4 kWh.

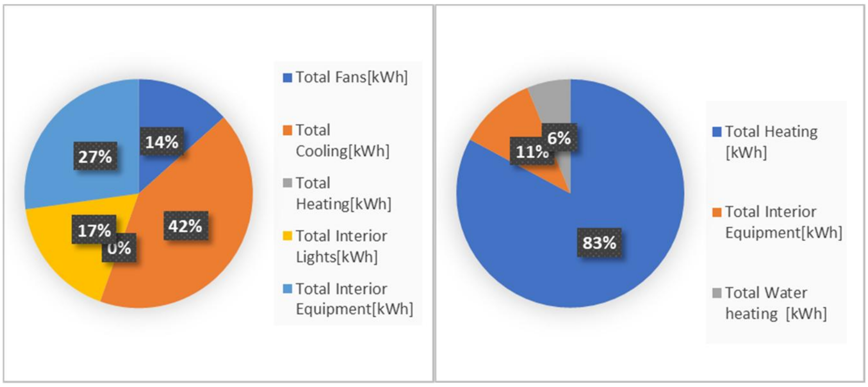

Figure 35. Electricity and Gas profile divided in various contributions. On the left: Electricity share; on the right: NG share.

Air conditioning and interior equipment represent the most significant part in Electricity and Gas consumption. In a Hospital, they are obviously a constant load to be satisfied, both in summer and winter.

2) <u>Baltimore- Maryland</u>

	ELECTRICITY	**GAS**
Total Consumption [kWh/y]	9’890’397.22	4’489’763.89
Average Consumption [kWh]	1135.06	480.98
Energy Intensity [kWh/m^2]	441.1	200.24

Table 12.Energy consumption and Intensity. [4]

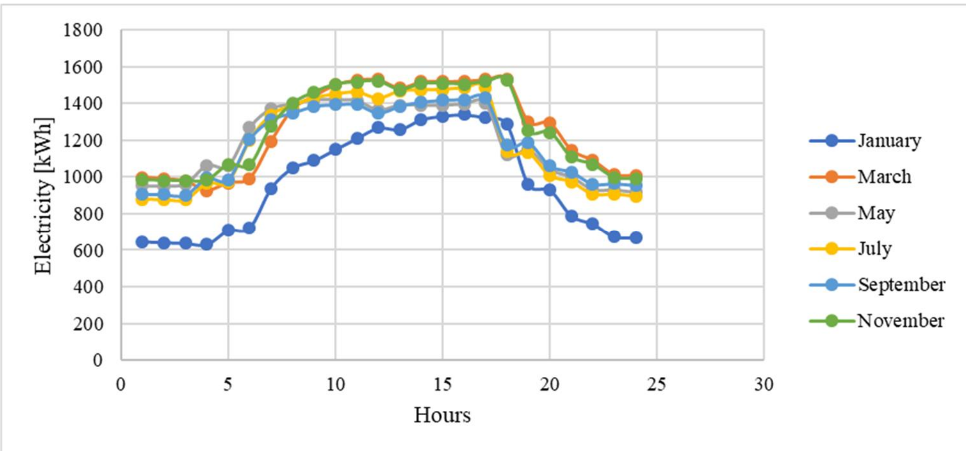

Figure 36.Baltimore-Daily Electricity profile.

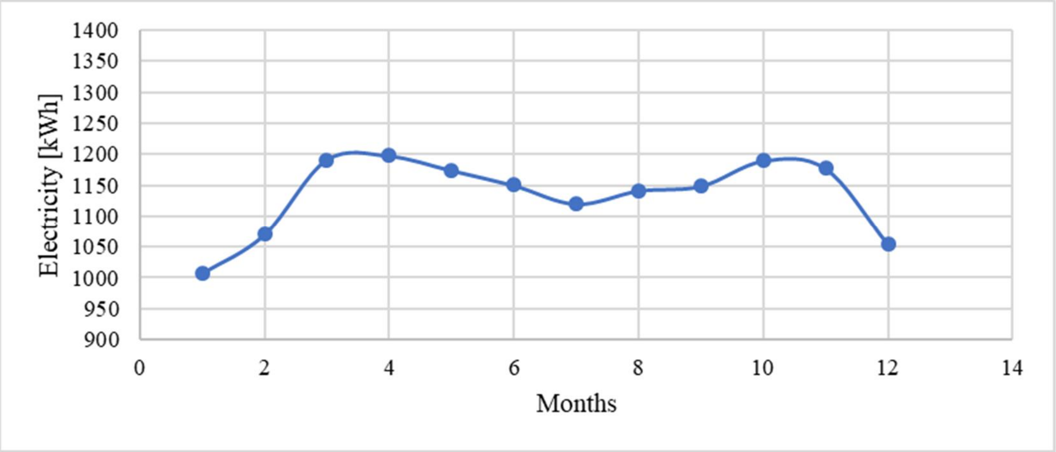

Figure 37.Monthly average consumption.

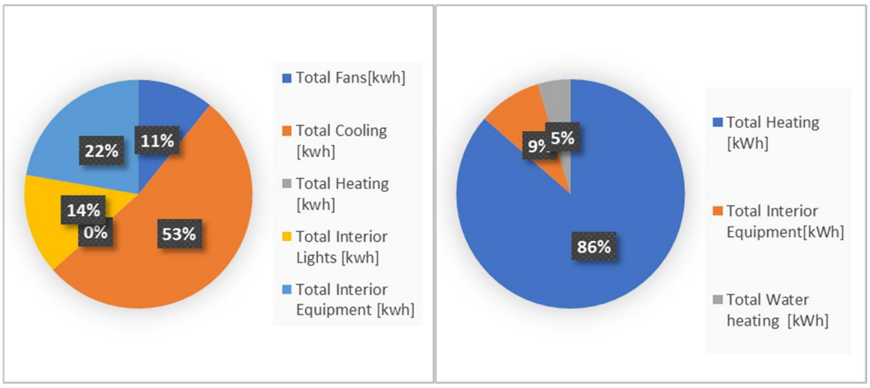

Figure 38. Electricity and Gas profile divided in various contributions. On the left: Electricity share; on the right: NG share.

3) <u>Minneapolis- Minnesota</u>

	ELECTRICITY	GAS
Total Consumption [kWh/y]	8’849’786.11	5’042’472.22
Average Consumption [kWh]	1001.87	573.13
Energy Intensity [kWh/m2]	394.7	224.9

Table 13. Energy consumption and Intensity. [4]

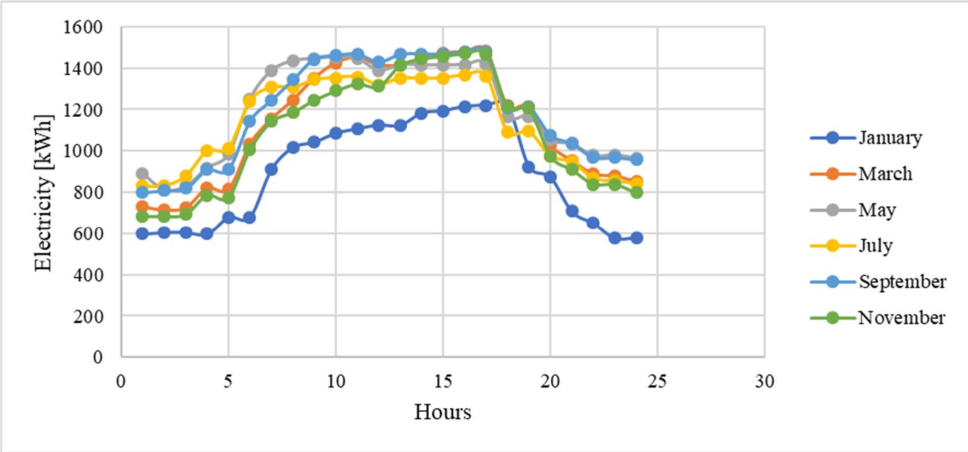

Figure 39. Minneapolis-Daily Electricity profile.

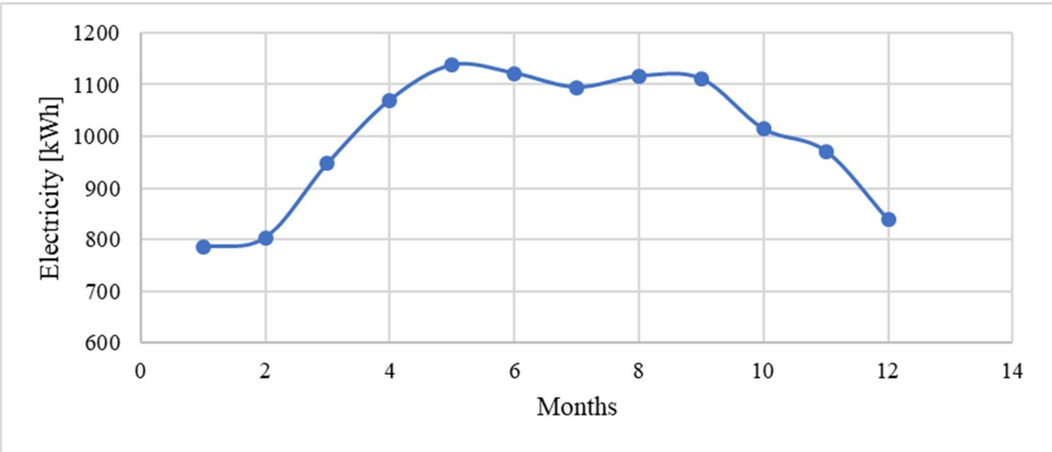

Figure 40. Monthly average consumption.

Higher variation on average electricity consumption during the year with respect to other cities. The peak is in May, and the lowest point in January.

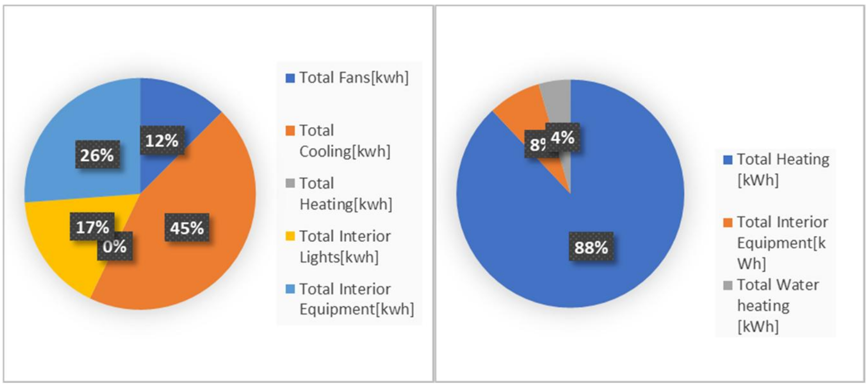

Figure 41. Electricity and Gas profile divided in various contributions. On the left: Electricity share; on the right: NG share.

4) Seattle- Washington

	ELECTRICITY	GAS
Total Consumption [kWh/y]	8’820’491.67	4’475’677.78
Average Consumption [kWh]	1008.56	493.4
Energy Intensity [kWh/m2]	393.4	199.6

Table 14. Energy consumption and Intensity. [4]

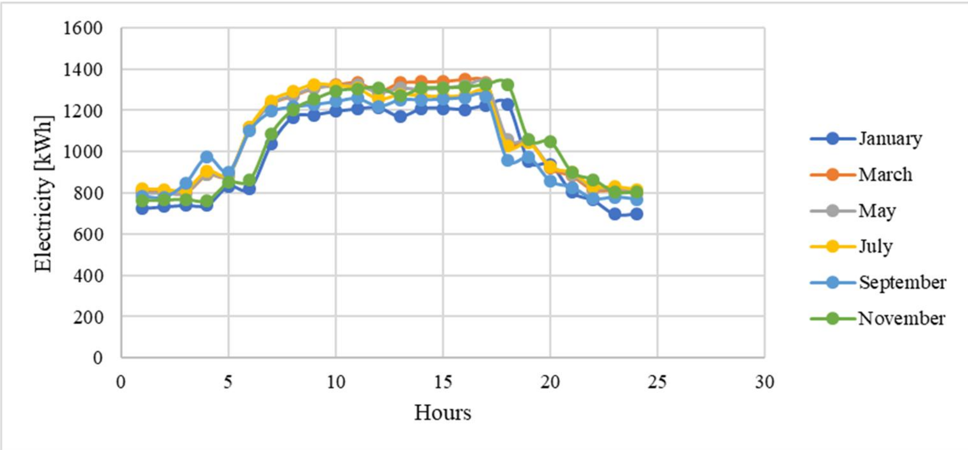

Figure 42. Seattle-Daily Electricity profile.

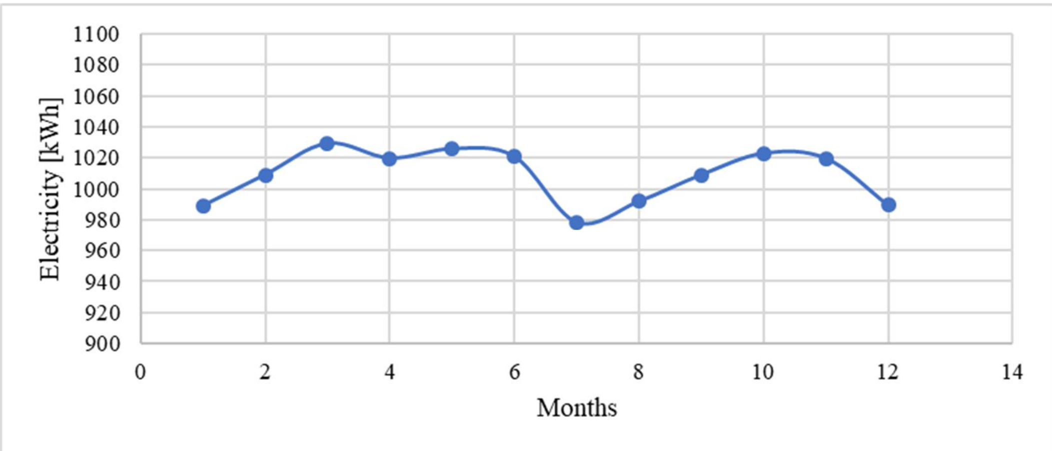

Figure 43. Monthly average consumption.

Highest consumption on March, lowest on July (Seattle has the lowest mean temperature on July with respect to other cities).

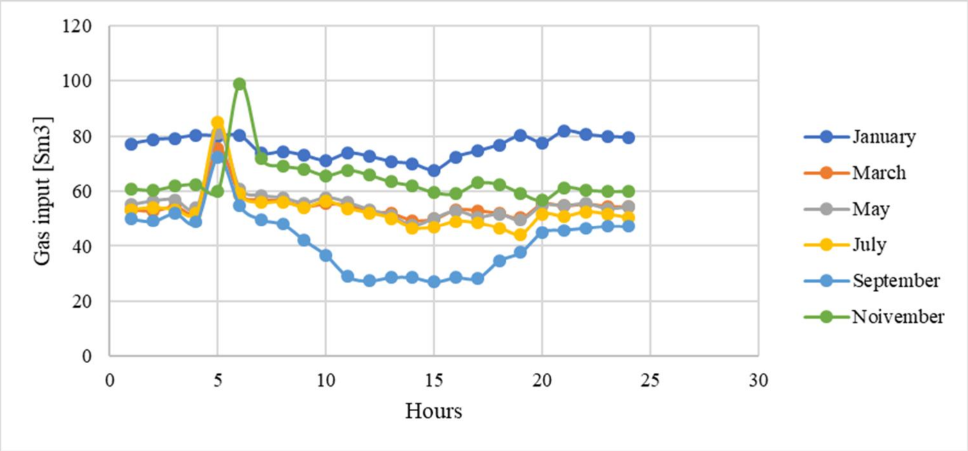

Figure 44. Seattle-Daily Gas input profile.

Gas profile shows a similar behaviour between different months, with a higher peak located on 5:00 am or 6:00 am (November). It's a huge variation with respect to the other values: probably it's the hour of the day in which heating and equipments are activated, so they need a bigger amount of energy to start their operation.

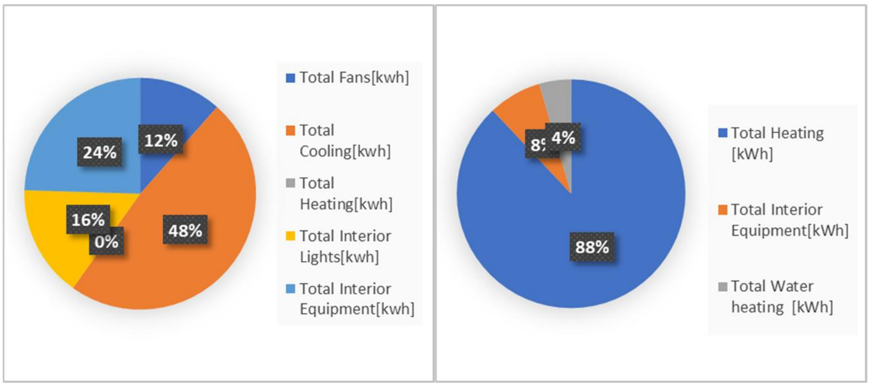

Figure 45. Electricity and Gas profile divided in various contributions. On the left: Electricity share; on the right: NG share.

Baltimore shows the highest consumption in terms of Electricity. Instead, Minneapolis shows the highest Gas consumption. Boulder has the lowest energy consumption, in both fields. Electric and Gas intensities show similar and comparable values.

From the above reported data, it can be seen that the Gas intensity is quite similar for all hospitals, instead the Electric intensity has a bigger variation. This variation could depend on the technology used in the structure: IEO has the highest index, probably because it s an innovative and modern hospital, so it utilizes equipments that need high energy load. Grevena hospital is a small centre, so it doesn't need a huge amount of electricity: it has the lowest electricity intensity index.

Table 15. Final comparison in terms of consumption and energy intensity.

	Boulder	**Baltimore**	**Minneapolis**	**Seattle**	**Grevena Hospital**	**ICZ**	**IEO**	**S.G.**	**AOB**
Surface [m^2]	22,422	22,422	22,422	22,422	13,800	11,362	28,240	132,839	62,250
Total Electricity Consumption [kWh/y]	8,439,819	9,890,397	8,849,786	8,820,491	1,461,000	2,374,026	12,751,463	25,210,136	11,376,361
Electric Intensity [kWh/m^2]	376.4	441.1	394.7	393.4	105.87	209	452	190	183
Total Gas Consumption [kWh/y]	3,576,522	4,489,763	5,042,472	4,475,677	n.d.	2,809,552	7,129,297	33,966,671	8,694,132
Gas Intensity [kWh/m^2]	159.5	200.24	224.9	199.6	n.d.	247.3	252.4	256.8	140

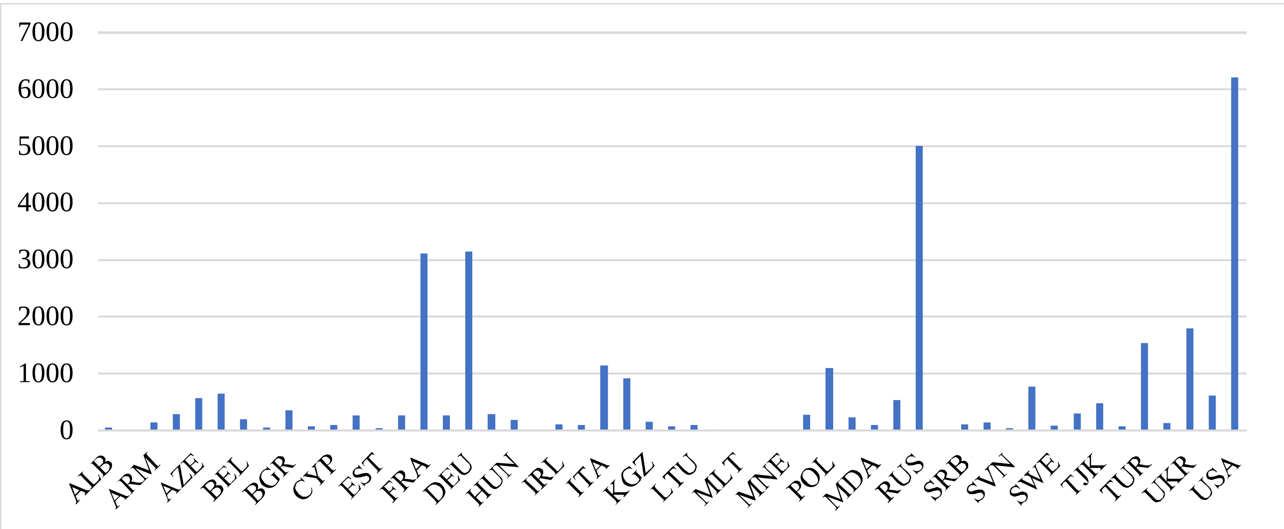

Figure 46.Hospitals distribution in EU and USA.

This analysis shows a similar trend in the daily load profiles for many types of hospitals. Both for big or small structures, the energy consumption has a time dependent behaviour that does not vary with the hospital, but it shows a common shape in most cases.

Considering health centres with analogue activities, is thus possible to have a unique model able to describe with a good accuracy a great range of different hospitals, and to calculate for each of them if the use of fuel cell system it is convenient or not.

6. Other markets

6.1 Shopping Centres-Malls

Another interesting sector, which will be analyzed in the framework of the COMSOS project, is the shopping centres and malls sector. These centres are usually opened 7 days per week and usually include a supermarket inside which provide also a night-time load. A SOFC system could be very interesting for this sector since it can also work as a backup system and thus guarantee continuity of power production. The figures below, taken from the Statista® website, show the dimension of the shopping centers in Europe. UK, France and Italy are the three countries with the highest number of centers (in total, more than 3000). The same list, in the next figures, is shown based not on the number of centers but on the area. In this case, UK is always at the first place followed by France and Russia. This shows the average size of these centers, which is for example small in Italy and very large in Russia.
The third graph shows indeed the different types of shopping centers, divided between traditional, retail parks and outlets. As can be seen, the largest share is related to the traditional shopping centers. The market segment will be studied in detail during the next months.

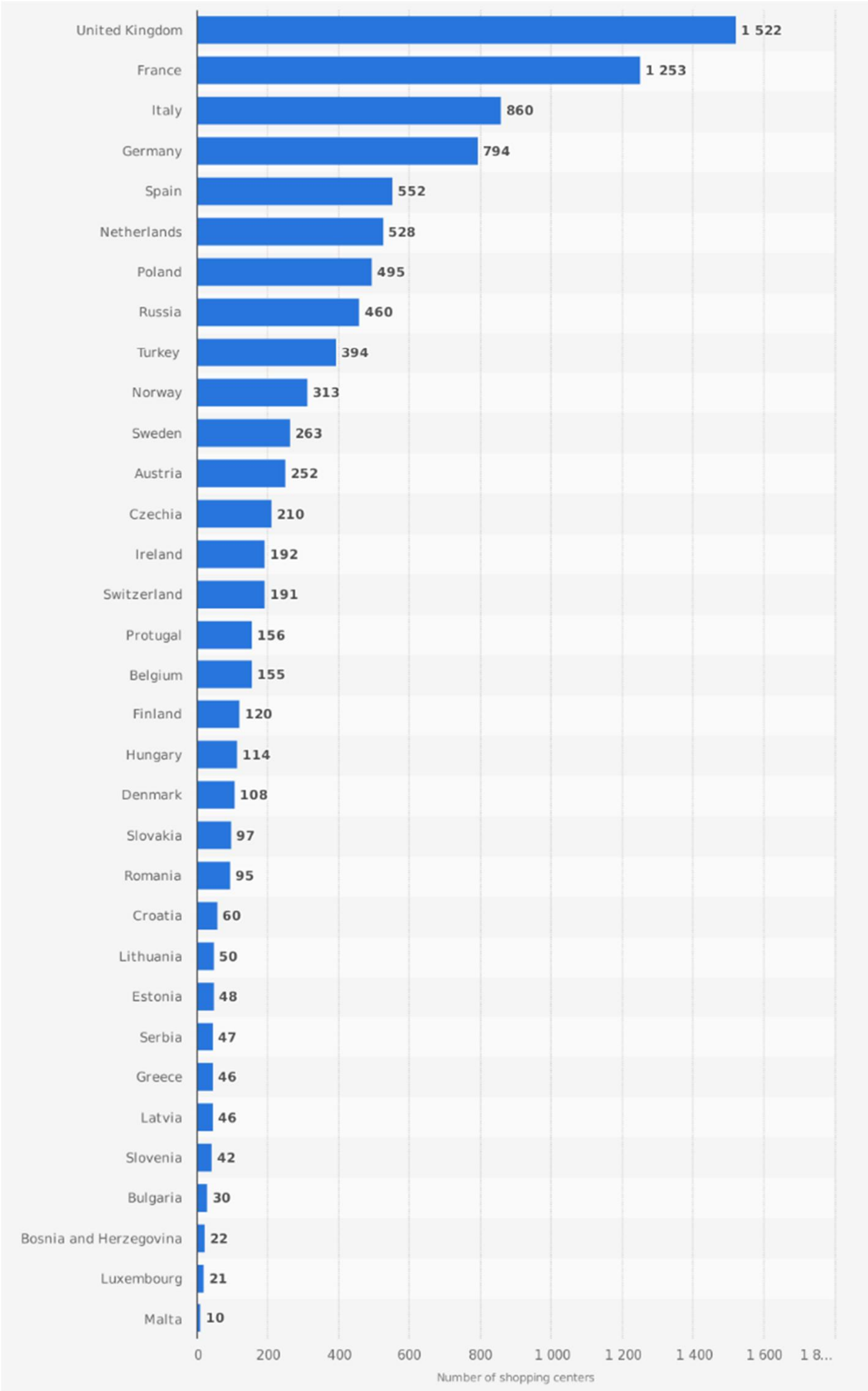

Figure 47. Number of shopping centers in EU (in 2017), by country.

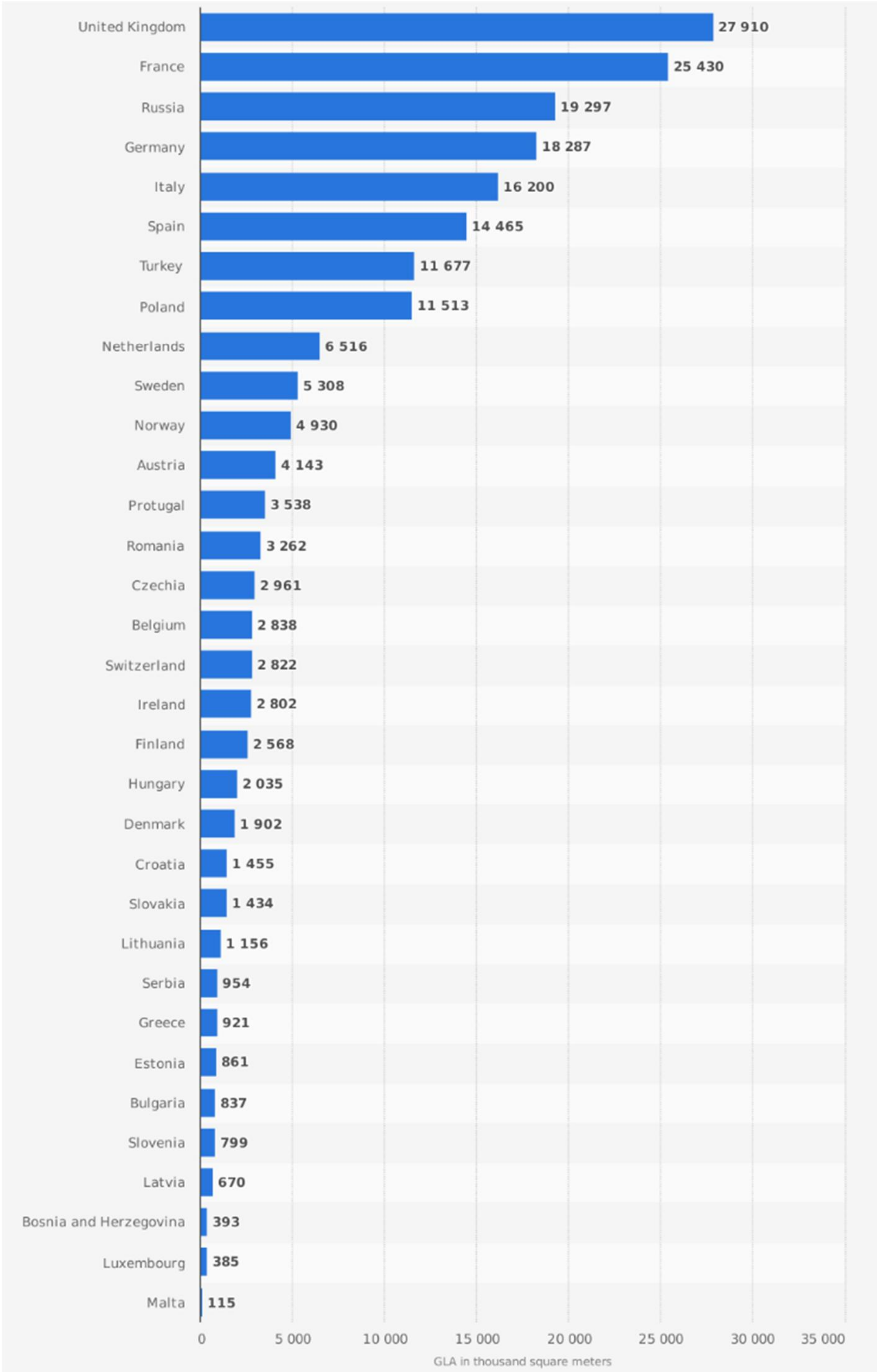

Figure 48. Total floor space of shopping centers in EU (as of July 2017), by country

6.2 Data centres

Another interesting sector with a high base load for fuel cell application is the data centers segment. The segment has not yet being studied in the framewokr of this activity but it will be analyzed in the next months. For giving an overview of the potential interest of this segment, some graphs are provided below:

- Volume of data stored (Figure 49) is increasing significantly every year since 2015 and projections for the future are still related to a strong increase.
- This increasing volume is connected with increasing money invested in this sector, as represented in **Error! Reference source not found.**.
- When looking at the worldwide share, the role of US in this field is strongly confirmed by the data (Figure 50). This market will be studied with a particular focus on key countries involved in investmenets in this specific sector.

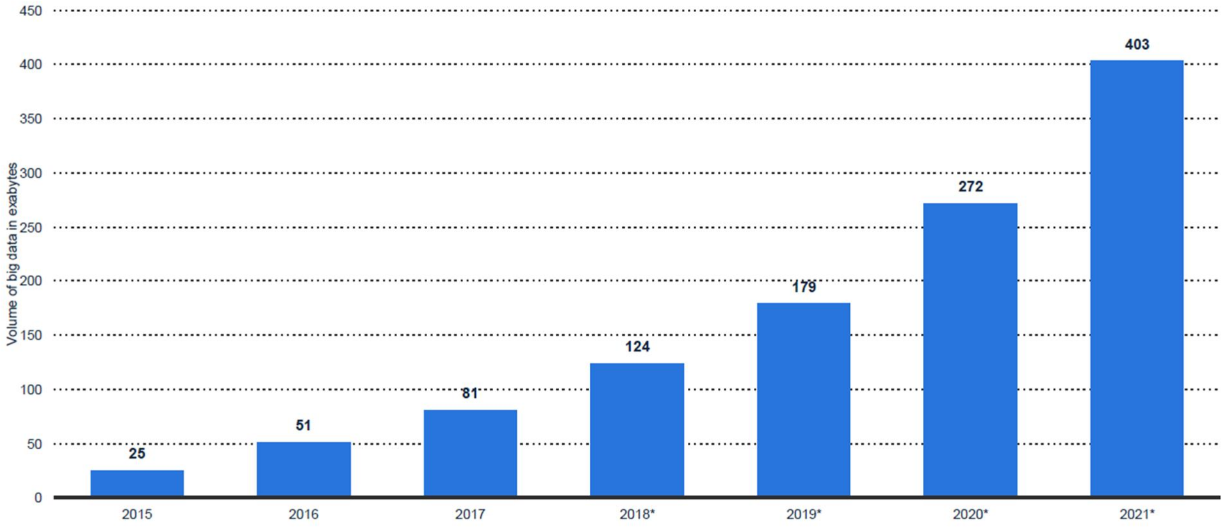

Figure 49. Volume of big data in data center storage worldwide from 2015 to 2021.

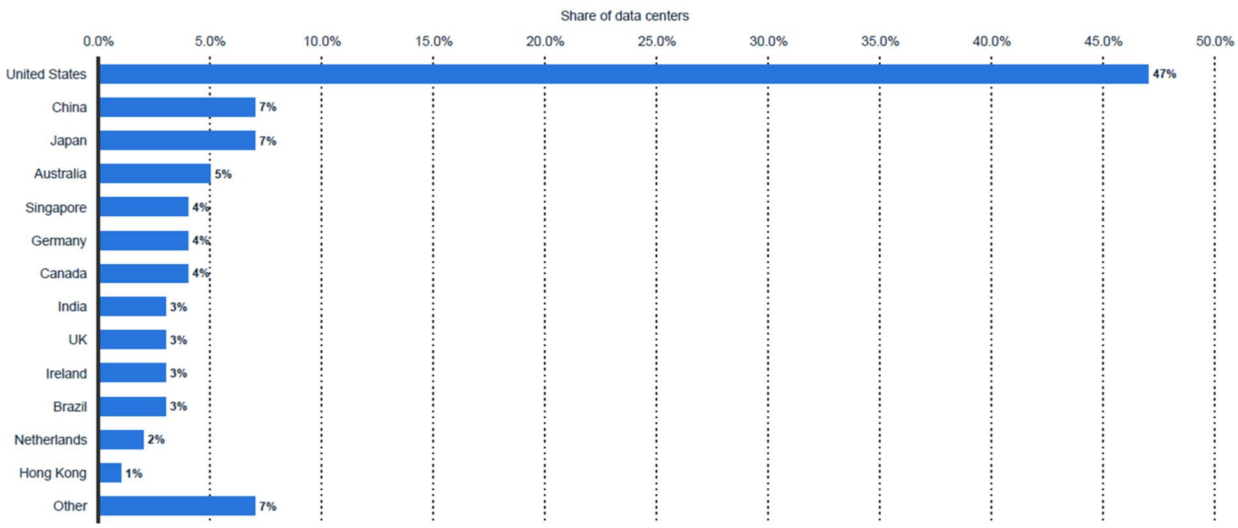

Figure 50. Share of hyperscale data centers by country, 2017. [20]

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8. Appendix: A supermarket case study

8.1 Locations

US cities

The chosen cities of the macro-geographic area of the US, among the ones available in the database from the DOE [4] are four: Boulder (Colorado), Baltimore (Maryland), Minneapolis (Minnesota) and Seattle (Washington). For the US cities, energy prices were taken from the U.S. energy information administration, EIA [26], which offers energy prices of all the American States for every months.

The locations studied for the European cases are four: Italy, Spain, UK and Sweden. The choice of countries was done based on available data from literature. The energy prices were taken from Eurostat [1], [2].

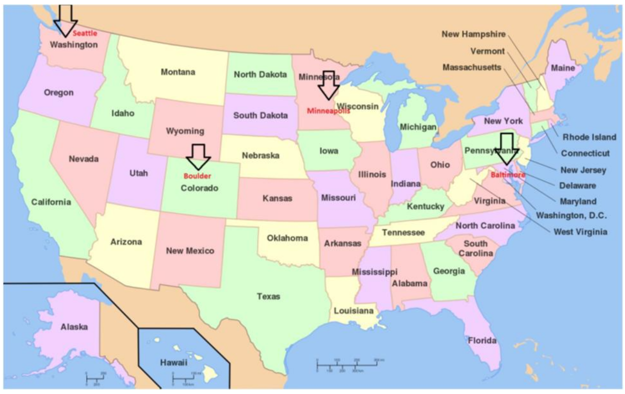

Figure 51. US locations.

Table 16. Energy prices for American Locations (October 2018).

Location	Electricity price [$cents/KWh$]	Gas price [$cents/KWh$]	Gas price [$cents/m^3$]
Boulder	9.24	2.10	20.71
Baltimore	9.22	2.48	24.42
Minneapolis	9.09	1.88	18.49
Seattle	7.69	2.44	24.03

Table 17. Energy prices for European Locations (October 2018) [1], [2].

Location	Electricity price [$cents/KWh$]	Gas price [$cents/KWh$]	Gas price [$cents/m^3$]
Italy	16.42	5.06	49.81
Spain	12.82	4.29	42.23
UK	16.03	3.09	30.42
Sweden	8.55	9.37	92.23

To build a model that can replicate – in a realistic way – the behavior of the supermarket, we have analyzed data on energy consumption of different shops. The model is based not only on the yearly energy consumption but also on the daily and hourly load profile, since this is strongly affecting the operation of the SOFC.

The hourly load profiles database used for this model is the one available from the US Department of Energy [4], which is including a high number of commercial buildings profiles, among which many supermarkets. The database collects on an hourly basis the electric consumption and the heat consumption of supermarket, and also their share among the different equipment and sections. The data collected are from 2004, and they refer to the same type of supermarket. The model for the US scenario, described in the next chapter, was applied to this dataset. A different approach was indeed applied to the EU cities, since hourly profiles were not available for these locations. For this scenario, the US profiles have been modified – based on the different yearly EI – to represent the EU cities.

8.2 Model description

The reference case layout is represented in Figure 52. Electricity is supplied by the grid and heat with a boiler fed with NG from the grid. Figure 53 indeed shows the layout when the SOFC system is installed. The fuel cell is providing electricity and heat to the supermarket; extra electricity is provided by the grid and extra heat by a NG-fed boiler.

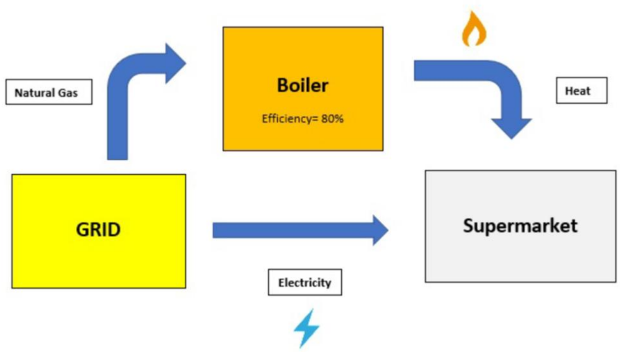

Figure 52. Base scheme.

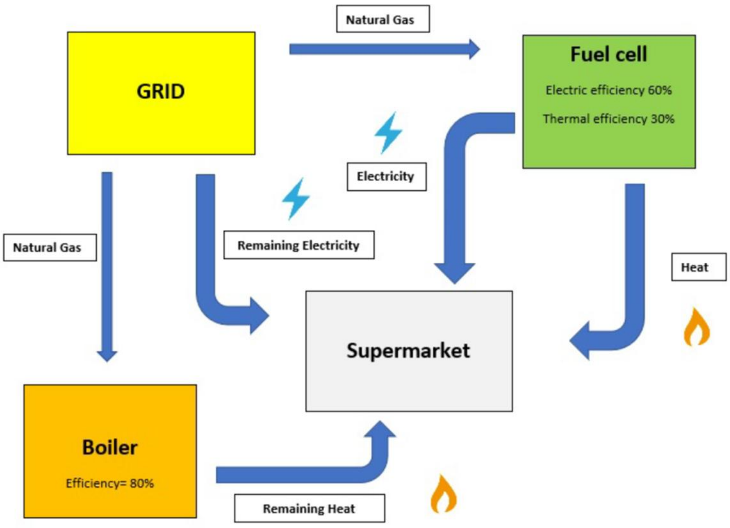

Figure 53. Scheme with the Fuel cell applied

The model – based in Excel® - requests as input the following information:

- SOFC model
- Energy capacity that wants to be installed (from Base-load to Full-Power)
- Location
- Price Scenario (Current or Target SOFC costs)

The model includes technical and economic features of the 3 SOFC systems studied in the COMSOS project, as detailed in D5.2. All these data are needed to evaluate the hourly performance of the fuel cell and to calculate the revenues and expenses for the lifetime of the project. The electrical efficiency curve is also included in the model to calculate how the electrical efficiency vary with the respect to the electric load.

From the load hourly profile, the minimum electrical load along the year is calculated, and used as minimum base load for the supermarket. This base load (P_{base}) is then multiplied for a coefficient (P_{coeff}) which represents the different sizing possibilities (from base load only coverage with constant operation to full power coverage with modulation), and then the final capacity is rounded to the closest multiple of the capacity of fuel cell chosen (P_{inst}).

$P_{inst} = P_{base} \cdot P_{coeff}$ (1)

Depending on the chosen location, a set of parameters depending on it are selected (price of energy and subsidies, is available). These parameters are shown in Table 18. Fort this study subsisides are considered as a percentage of the initial investment. The scaling coefficient is a coefficient used to scale the energy consumption for the country that are not in the US.

Table 18. Location specifications.

Technical information	Unit
Cost of electricity	$Euro/KWh$
Cost of Gas	$Euro/KWh$
Cost of Gas	$Euro/m^3$
Subsidy	[/]
Scaling Coefficient	[/]

The last information is related to the price scenario, which can be current or target. The current scenario represents the current situation of production of fuel cells, while target scenario is referred to a short/long term projection where larger production volumes would be reached by the companies. These data are also retrieved from D5.2.

Once the size of the SOFC cell is defined, depending on the power needed by the supermarket, on an hourly basis the balance between the needs and the CHP production can be evaluated. If the power needed by the supermarket is higher than the nominal power of the fuel cell, the SOFC will work at nominal power and the extra-request will be supplied by the grid. If the power needed by the supermarket is lower than the SOFC nominal power, then the fuel cell will modulate and produce only the required power. The electric efficiency of the fuel cell is calculated depending on the load with the power-efficiency curve given by the manufactures. The thermal efficiency is calculated with the same method if the thermal efficiency curve is available, while it is calculated with the hypothesis that the total efficiency is kept constant with the load, in case the curve is not available.

The thermal power hourly produced by the SOFC system is calculated from the electric power:

$$Q_{th} = P_{el} \cdot \frac{\eta_{th}}{\eta_{el}} \quad (2)$$

Since the regulation is made on the electricity request, there are hours in which the thermal production is higher than the supermarket load. This extra thermal power is wasted. The thermal load of the supermarkets used for the model includes only heating and the DHW requests.

To evaluate properly the electric efficiency, it is important not only to include the load modulation but also the degradation of the stack. To include this phenomenon in the study the degradation rate – supplied by the manufacturer in D5.2 – is included (the degradation rate – ε_{deg} – represents the percentage of efficiency lost per hour of work of the fuel cell). The degradation is supposed to be linear with time in the model and it is thus been evaluated as follow.

$$\eta'_{el} = \eta_{el} - \varepsilon_{deg} \cdot h_{work} \quad (3)$$

Based on the electric efficiency the NG flow can also be evaluated:

$$\dot{m}_{gas} = \frac{P_{el}}{LHV_{NG} \cdot \eta_{el}} \quad (4)$$

The CO_2 emissions are also calculated for the stack internal reaction:

$CH_4 + 2\,O_2 \rightarrow 2\,CO_2 + 2\,H_2O$ (5)

Starting from the molar flow rate of methane, the same molar amount of carbon dioxide is produced and it's on a mass basis as:

$\dot{m}_{CO2} = \dot{V}_{CH4} \cdot \rho_{CO2}$ (6)

During the operation of the SOFC, three streams are involved as input/output: the gas entering the system, the electricity and the heat produced. The first one is a cost since NG is bought from the grid, while the electricity and the heat produced are savings because less energy needs to be bought from the grid because of the internal production. To calculate savings and costs, it was assumed that costs of electricity ($price_{el}$) and NG ($price_{NG}$) were constant along the year. Savings (hourly and yearly) are calculated as:

$Saving_{el,h} = E_{el,h} \cdot price_{el}$ (7)

$Saving_{el,y} = \sum_{i=1}^{8760} E_{el,i} \cdot price_{el}$ (8)

$Saving_{th,h} = E_{th,h} \cdot price_{NG}$ (9)

$Saving_{th,y} = \sum_{i=1}^{8760} E_{th,i} \cdot price_{NG}$ (10)

While NG cost is calculated as:

$Cost_{NG,h} = \dot{m}_{NG,h} \cdot price_{NG}$ (11)

$Cost_{NG,y} = \sum_{i=1}^{8760} \dot{m}_{NG,h} \cdot price_{NG}$ (12)

Even if the sum is from 1 to 8760 (hours of the year), a maintenance time has been supposed to happen once per year (based on the manufacturers information).

The degradation rate does not affect only the electric efficiency and so the consumption of natural gas, but also the power output. To consider this, the electric load requested to the fuel cell was considered as an input. The electric efficiency (in that specific load point) is then calculated, considering also the degradation effect (as shown before). With the efficiency, the real power output from the SOFC can be evaluated. At the beginning of life, when the stack that it is not degraded yet, power output from the SOFC is equal to the load request (input). During the life, when the stack degrades, and the efficiency decreases, power output from SOFC starts to be lower than load request. A flow diagram showing the procedure is shown below.

Once the results of the first year were evaluated (as explained above), the most accurate way to proceed would be to repeat the same hourly calculation for the subsequent years until the end of the life. This approach, since the model must work for a multitude of cases, is too heavy in terms of computational time and not easy for a user-friendly Excel® file which was another goal of the model. For the following years all the results were calculated scaling the first-year values. By knowing how much the stack degrades in a year, the average electric and thermal efficiency for the following years can be calculated, and then all the other parameters. Interest rate and inflation are also updated on a yearly basis. Economic assumptions are shown in Table 19.

Table 19. Economic Parameters.

Economic information	Unit	Value
Inflation	[%]	2
Discount Rate	[%]	5
Interest Rate	[%]	3
Project Duration	[$years$]	15

To validate this approach, the second year was evaluated both with the hourly basis approach (used for year 1) and with the simplified approach described above. The relative difference between the two methods is around 1%, thus confirming the reliability of the simplified approach.

In terms of costs, the analysis includes both the investment expenditure, the maintenance and the operating cost (stack's replacement). The study assumes that that the initial investment is payed all upfront, in the first year, as happens for traditional heating systems. The investment costs (CAPEX) includes four main terms: stack manufacturing, BoP manufacturing, commissioning and installation, and the profit of the manufacturing company (the first 3 values were taken from real manufacturers data, provided in the framework of D5.2). The first two are defined as a cost of euro per kW electric installed, while the commission and installation cost are constant despite the capacity installed. The profit of the company was assumed as a percentage of the total initial investment (equal to 10%).

$CAPEX = (SOFC_{man} + BoP_{man} + Com\&Inst_{cost}) \cdot (1 + Profit)$ (13)

The operating costs (OPEX) includes the cost of the yearly maintenance the cost of stack replacement (when it has reached the end-of-life, expressed in hours of operation).

For a generic year *i*, the yearly cashflow is the sum of the savings (positive) and the OPEX (negative), and for first year the initial investment is also accounted. The cashflow then needs to be discounted in order to account for the time, with the above-mentioned discount rate.

The Net Present Value (NPV) of the investment is considered as the NPV at the end of the entire plant lifetime (assumed 15 years).

The second economic parameter analyzed is the Levelized Cost of Electricity (LCOE). It is evaluated as the sum of the total costs during divided by the total amount of electricity generated (in the entire lifetime), both discounted as done for the cashflow.

8.3 Case Study definition

In February 2018 the US congress has approved Section 48 and section 25D of the Investment Tax Credit for fuel cells for business and residential installations [34], [35]. The subsidy consists of a percentage of the total system and installation cost and it is calculated as the lower value between 3'000 $/kW of installed capacity or 30% of plant total cost.

Since the hourly data are available just for the US, these profiles have been modified to be used for the EU area. The energy intensity of the supermarket in the US was calculated, and its share between electricity and NG intensity. These values were then compared with one for the EU supermarket. The comparison was performed only for the supermarkets with a total energy consumption comparable with the US ones. To determine the supermarket's suitable for this comparison, study of Tassou at al. [10] was chosen. The criterium was to use supermarkets with an area higher than 1000 m^2 because they had the same energy intensity behavior of the US ones. Once the EU supermarket were chosen, the value of their energy intensity is divided by the energy intensity of the US supermarket, and then the hourly consumption is scaled with this factor. If both electricity and NG intensities are known, consumptions are scaled separately, otherwise they are scaled with the same scaling coefficient. Scaling coefficients are summarized in Table 20. In case of more than one supermarket data available per country, the energy intensity was calculated as average values between those.

Table 20. Scaling Coefficients [5], [8]–[12].

Country	Electricity Coefficient	Gas Coefficient	Reference
Italy	0.90	0.90	[21]
Spain	0.85	0.85	[19]
Uk	1.57	1.51	[23],[25],[20]
Sweden	0.65	1	[17]

Concerning the subsidies, in Italy there are no specific supporting schemes for fuel cell applications, but a subsidy called "*Certificati Bianchi*" is existing [36] for high efficient. The incentive is a tax reduction on the NG price but is applicable only for system with a size lower or equal to 50 kW, and thus not applicable in this analysis. For other EU countries it was not possible to find specific information on subsidies for CHP/SOFC but this activity will be continued during the COMSOS project.

If no subsidies are available in a specific location, the model is able to calculate the required investment subsidy to have the same economic performance of a the reference scenario after some years from the installation. By knowing the difference between the reference scenario and the SOFC cashflows, the relative advantage of the new system can be evaluated. The year in which this difference became zero and then positive the SOFC starts to be preferable with respect to the reference scenario. In this study, the time in which the SOFC becomes preferable to the reference scenario is called Relative Pay Back Time (RPBT).

8.4 Results

For the US case results are here shown for Boulder. The first section shows how the electric and heat load of the supermarket is affected by the system sizing. The value of the power coefficient (PC) used for this analysis were: 0.5 (60 kW), 1 (120 kW), 2 (180 kW), 3 (240 kW), 4 (360 kW).

The example is shown for the Convion system size, which is 60 kW, but also because 60 kW is a multiple of the other producers' sizes (respectively 20 and 12 kW for Sunfire and Solidpower). Power coefficients were chosen starting from the minimum electric load of the supermarket along the year, ~75 kW, the average, ~180 kW and the peaks, ~340 kW. In this report only the most significant graphs will be discussed; in particular, PC equal to 0.5, 2 and 4.

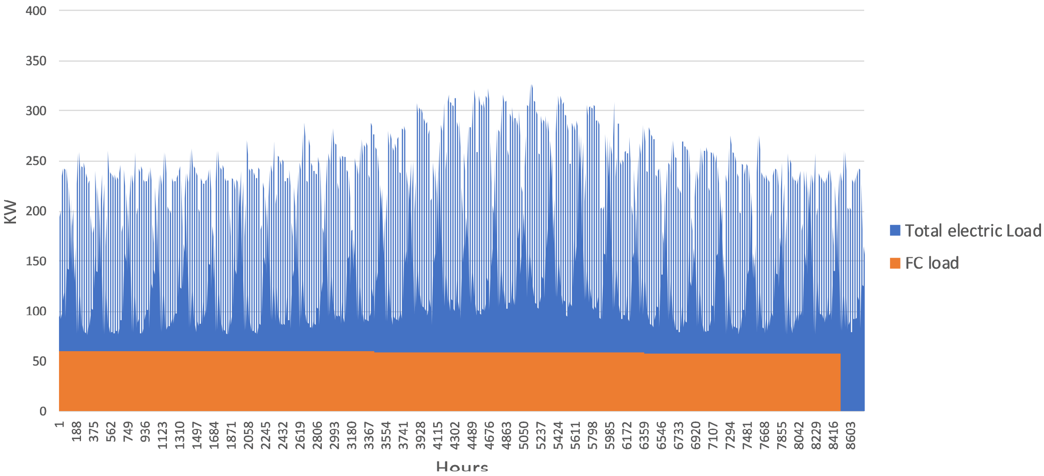

Figure 54. Yearly electric load, Boulder, PC 0.5.

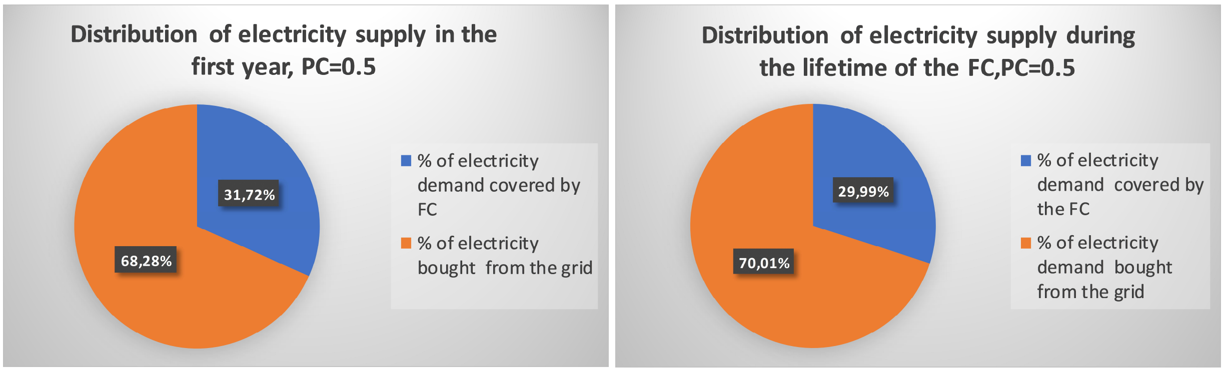

Figure 55. Share of electricity supply, PC 0.5.

In the first case (PC=0.5), the electric capacity installed is less than the minimum constant load of the supermarket and so the SOFC system works always in a steady state at constant power and efficiency. This is the optimal mode for the operation of the fuel cell. The missing electricity production for some days at the end of the year represents the maintenance time (Figure 54). In Figure 55 can be seen that the share of electricity covered in the first year is higher than the one covered in the lifetime of the system, since the stack degrades and efficiency and the electric power decreases.

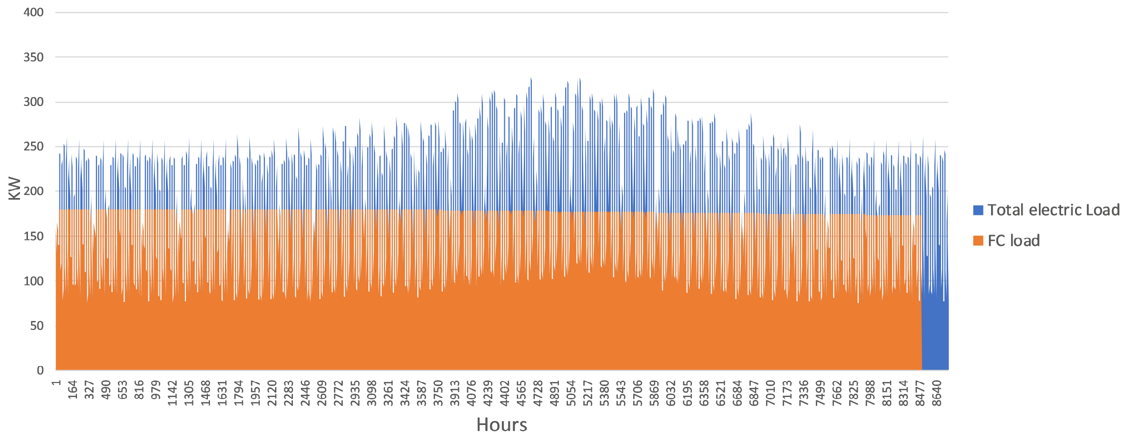

Figure 56. Yearly electric load, Boulder, PC 2.

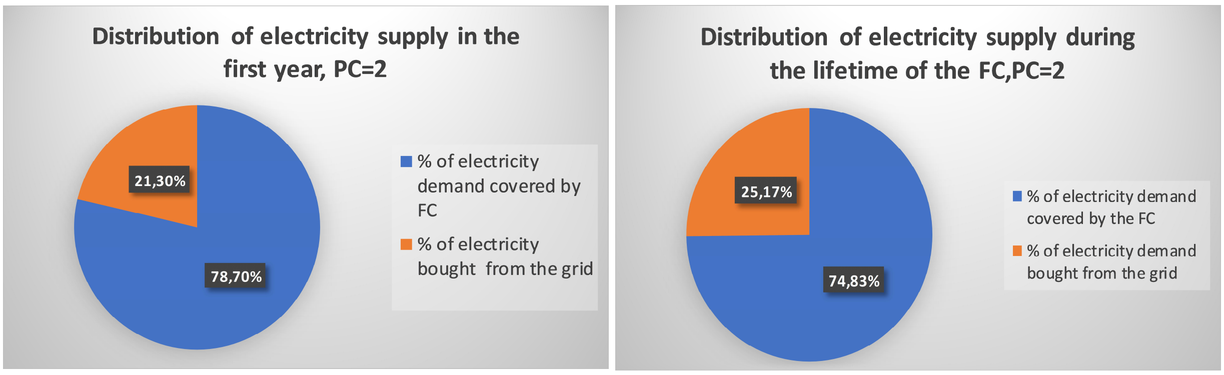

Figure 57. Share of electricity supply, PC 2.

As the electric capacity increases, the share of electric load covered by the fuel cell system increases too. In Figure 56 (PC=2) the capacity is 180 kW and the situation is completely different from the previous one. The CHP system does not cover only the base load, but also most of the required electric demand; the grid is used only for the peaks. The difference respect to PC=0.5 in the SOFC electric share is 44.84%, proving that the increase in share is not linear with the capacity installed. Here the fuel cell has to modulate in order to follow the load and this affects the electric efficiency and the thermal efficiency, so the natural gas consumption. The total amount of hours in which the system modulate is 3995, equal to 47% of the working time. The model – when there is more than one SOFC module installed – regulates all the modules in the same way, thus reducing the modulation range of each system and consequently the degradation rate.

Figure 58 shows the yearly electrical profile for the PC=4 case study, 360 kW SOFC size, where all the electric load is covered by the FC system. This is the full power application in which for most of the time, unless when there is the mandatory maintenance of the system, the supermarket does not need at all the grid, thus increasing the power supply reliability. The difference in the SOFC electric respect to PC=0.5 is 65.53%, with a total share during the lifetime of 95.52%; hours of modulation in a year are 8494.

For what concerning the heat load the situation is similar, but the heat load is much more variable seasonally than the electric one, and so it often happens that, for a long period, a large part of the heat produced is wasted. Increasing the SOFC size, the share of heat covered by the fuel cell increases too (as happened in the electrical load), but also the share of heat wasted increases.

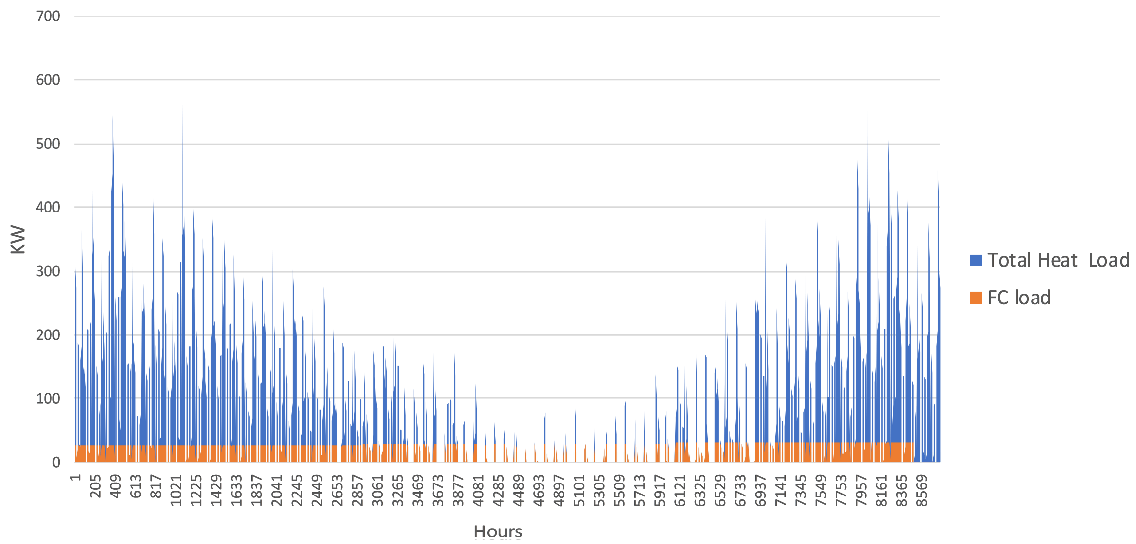

Figure 58. Yearly electric load, Boulder, PC 0.5.

As can be seen in Figure 59, during summer the FC system can cover most of the heat load, while the same does not apply for the rest of the year. The SOFC share of heat is 16-19% of the total heat need. This applies for the total consumption of the year, but the distribution can vary hugely during the seasons. Even with the lowest PC (0.5), almost half of the heat produced is wasted, since during the night the heat demand is nearly zero in the supermarket. In the reality, it would be useful and economic advantageous to consider a simple heat storage to use the heat currently wasted. It can be also observed that the heat covered by the FC in the first year is lower than the heat covered in the lifetime, contrary to what happened in the electric load supply. The stack indeed degrades and produces less electricity and more heat.

Furthermore, even with PC=4 (360 kW), more than half of the heat is still supplied by the boiler, reinforcing the fact that a heat tank is advisable. The increase of heat coverage from PC=0.5 to 2 is 25.77% while between 0.5 and 4 is 31.16% (increasing the size of a factor of 6 increases the share of just 31.16%).

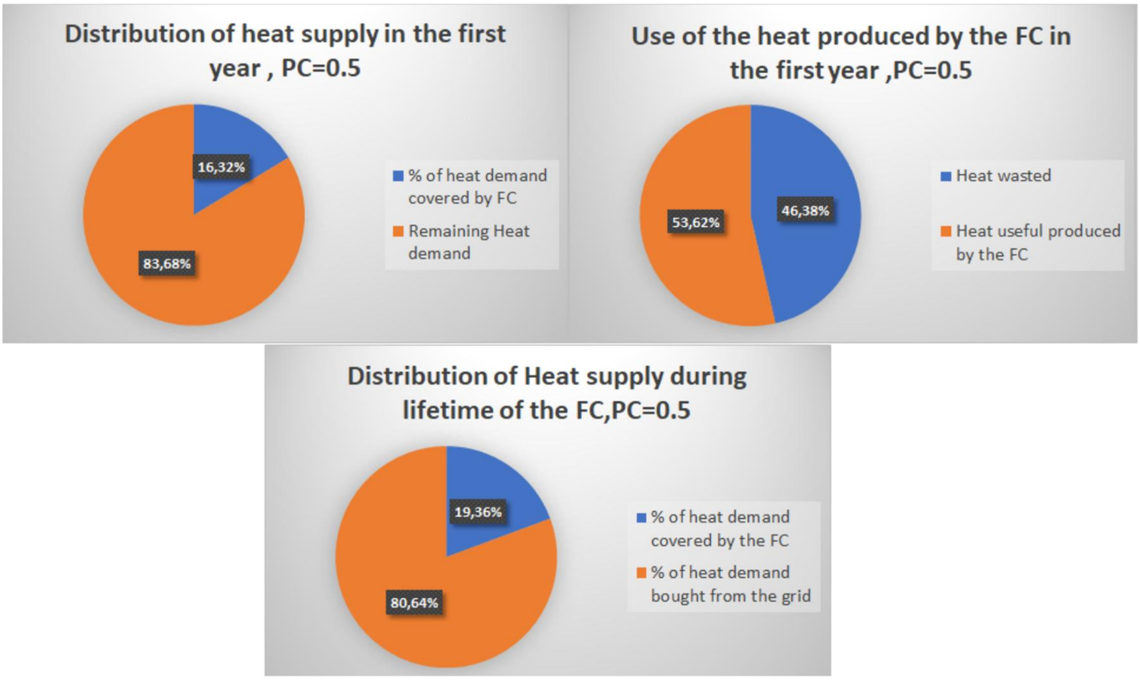

Figure 59. Share of heat supply, PC 0.5.

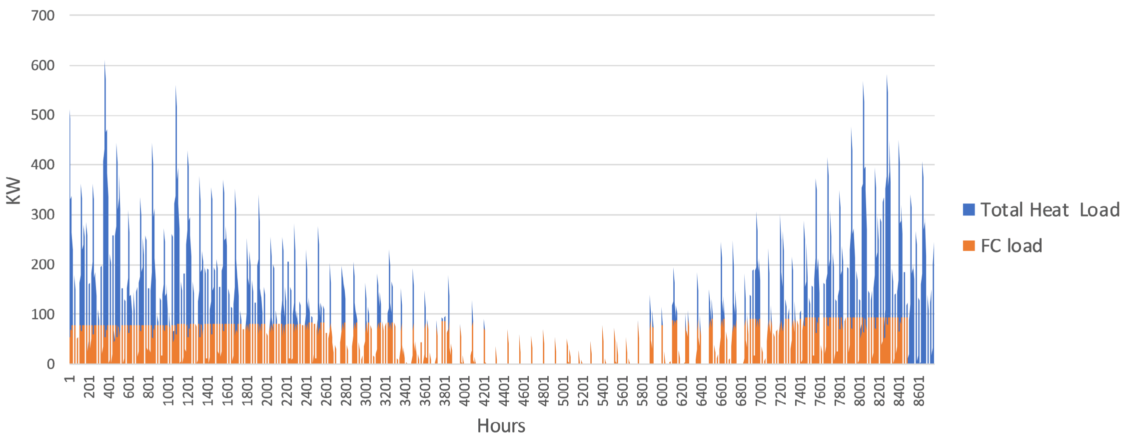

Figure 60. Yearly electric load, Boulder, PC 2.

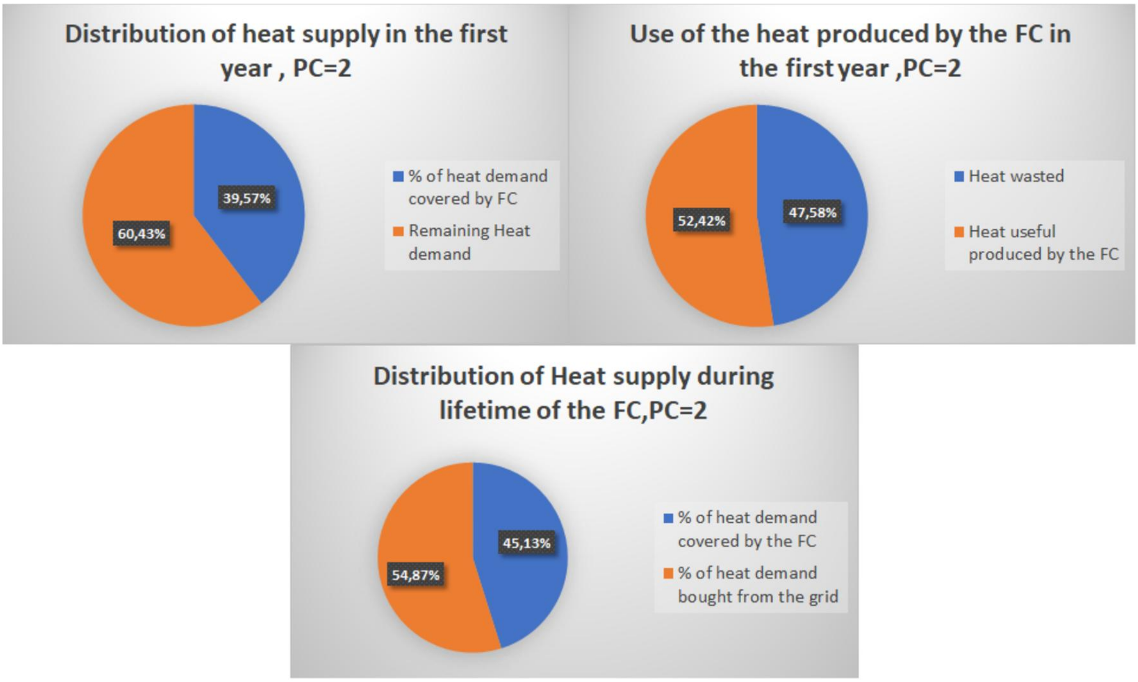

Figure 61. Share of heat supply, PC 2.

All the calculation in the following section are evaluated with **current costs**. NPV is defined as the NPV of the SOFC system itself in absolute terms), while Savings is defined as the monetary difference of the cashflows between the reference scenario (boiler + electricity from the grid) and the SOFC system. After showing the effect of different values of PC on NPV and Savings, the PC will be fixed as the one that maximizes the savings during the lifetime.

The single producer cashflow are not shown here since economic data are confidential and the trend would directly lead to the investment and operating costs. Being in the US case study, subsidies are always considered in the form explained above.

Evaluation of NPV and savings, Boulder (US)

The table below collects the ranges of RPBT (for the different manufactures) varying the PC for the installation. RPBT are not so high and this is due to the relatively low different between electricity and NG cost, even with dedicated incentives, which reduces the yearly incomes.

Table 21. RBPT with and without subsidies with different PC.

PC	RPBT with subsidies (yr)	RPBT w/o subsidies (yr)
0.5	6-9	8-11
1	7-10	11-13
2	8-13	14- never

3	13-14	never
4	never	never

Anyway, it is clearly visible that the best scenario is the base load coverage, which is also the best operating mode from the manufacturer point of view. The table below indeed shows the PC that maxims respectively the NPV and the Savings.

Table 22. PC to maximize NPV and Savings.

	Size (kW)
Best size for Savings with subsidies	96-120
Best size for Savings w/o subsidies	48-120
Best size for NPV with subsidies	12-60
Best size for NPV w/o subsidies	12-60

In the US, for a supermarket with an area of 4180 m^2 (Boulder case study), the best capacity to be installed is between 48 and 120 kW (depending on the chosen supplier and so on the minimum available size). The best size reflects the choice of covering just the base load or slightly above it, to have an optimal SOFC operation.

<u>LCOE at current and target costs, US (Boulder)</u>

This section analyses how the results are affected by applying the target costs that the manufacturing companies predict to have once larger production volumes will be reached.

Since it is not known if, in the target scenario, there will be subsidies the comparison has been done without considering any subsidies in both cases (this is also realistic since subsidies are used to start the commercialization of the product but are usually removed when target costs are reached). In this case the cashflow is even with a positive trend thus generating incomes for the supermarket, not only savings compared with the reference scenario but real incomes due to the yearly electricity and NG avoided. Cashflow trends for the single manufacturers are again not inserted for confidentiality issue.

LCOE for the system sizes – shown before – that maximizes the saving, for the current and target scenario, is shown in the table below.

Table 23. LCOE in current and target scenarios.

	LCOE (c€/kWh)
LCOE, current, with subsidies	16.6-18.7
LCOE, current, w/o subsidies	20.0-22.4
LCOE, target, w/o subsidies	4.6-5

As expected, a large difference can be seen between the current and the target scenarios. Not only the savings compared to the reference scenario are much higher, but also the NPV of the SOFC system is positive after 2 years only (PBT equal to 2). The LCOE is also affected by the reduced CAPEX values. The cost of electricity in Boulder is 9.24 c€/kWh, so even with the subsidies the current LCOE is much higher than buying electricity from the grid.

Evaluation of NPV and savings, Italy

As expected (based on the energy prices) the best capacity to maximize the NPV in Italy is the smallest one (Table 24). For the total savings the best thing is indeed to choose a size close to the average load request (180 kW). The different behavior can be justified by the high price of electricity in Italy. In fact, even if at larger sizes the system has to modulate for some hours of the day (thus working in non-optimal points), the benefits in terms of savings are higher than applying the smallest capacity.

Table 24. PC to maximize NPV and Savings.

	Size (kW)
Best size for Savings	180-192
Best size for NPV	12-60

For the US the best capacity was 120 kW, while in Italy it is more convenient to install a capacity of 180 kW. The rest of the analysis for this country have been done with the PC that maximizes the savings.

This section evaluates the subsidies necessary to have a RPBT equal to 5 years. By applying the subsidies, the cumulative cashflow trend is shifted up, since CAPEX is reduced.

Table 25. Subsidy needed to have RPBT = 5.

	Subsidy (% of initial investment)
Subsidy	6.6-14.6

LCOE at current and target costs, Italy

As shown for the US case study, the difference in the NPV between the current and the target scenario is huge, and the NPV of the SOFC system becomes positive after 3 years. LCOE (current and target) without subsidies and with subsidies discussed above in also shown here.

Table 26. LCOE in current and target scenarios.

	LCOE (c€/kWh)
LCOE, current, with subsidies	23.4-27.0
LCOE, current, w/o subsidies	24.2-22.5
LCOE, target, w/o subsidies	5.5-6.0

The current cost of electricity in Italy, for this application, is 16.42 c€/kWh including taxes, so today the LCOE of the SOFC system is still higher than cost of electricity. The technology is in any case in the current situation viable and even profitable for some capacity, thus Italy is one of the best locations for the application for the technology.

<u>Evaluation of NPV and savings, Spain</u>

The effect of PC on the economic performance in Spain is shown in Table 27. Since the NG cost is comparable with the Italian one, but the electricity one is lower, the economic performance in Spain is not as good as it is in Italy. For this case the best size to maximize the NPV is the minimum one. The same technical considerations made for the Italian case apply also for the Spanish one.

Table 27. PC to maximize NPV and Savings.

	Size (kW)
Best size for Savings	120-180
Best size for NPV	12-60

The best capacity that should be installed in Spain is 120-180 kW as it was in Italy. The subsidy needed to have a RPBT=5 is shown in the table below.
and how the NPV and the Total savings change with that subsidy. For the two model the subsidy is reported in the table below. It is now reminded that with subsidies in this case it is intended as a percentage of the initial investment.

Table 28. Subsidy needed to have RPBT = 5.

	Subsidy (% of initial investment)
Subsidy	19.7-37.3

<u>LCOE at current and target costs, Spain</u>

The target scenario affects the economic performance in a significant way also in Spain. As happened for Italy the NPV becomes positive after just three years and increases until the end of lifetime. For the current scenario with the best capacity installed the RPBT is in the range 6-7 years.

Table 29. LCOE in current and target scenarios.

	LCOE (c€/kWh)
LCOE, current, with subsidies	18.8-20.6
LCOE, current, w/o subsidies	23.8-24.1
LCOE, target, w/o subsidies	4.9-6.0

The current cost of electricity in Spain is 12.82 c€/kWh including taxes, and thus the current LCOE of the SOFC system is almost twice the cost of electricity in Spain.

<u>Evaluation of NPV and savings, UK</u>

The scaling coefficient for this country is the highest among the European countries, and this is reflected in the base electric load. Since the energy load is shifted up with the scaling coefficient, in this case the electric load is shifted above the 120 kW, so the fuel cells can work at nominal efficiency even with that size. Secondly in UK there is the highest difference of price between the price of electricity and gas among the countries studied in this study. All the previous specifications make the UK a perfect field for the initial spread of the technology, since for some capacity the investment is not only convenient but also profitable. The capacities that maximize the savings and the NPV for the two model are collected in the table below

Table 30. PC to maximize NPV and Savings.

	Size (kW)
Best size for Savings	300-360
Best size for NPV	12-120

The best size for maximizing the savings is 300-360 kW, for which the system covers an important part of the electricity load.

Table 31. Subsidy needed to have RPBT = 5.

	Subsidy (% of initial investment)
Subsidy	17.3-24.2

Since the location is so advantageous for the application of SOFC one might think why the subsidies needed to have RPBT are even up to 24%. The reason is that the subsidy reported are the one needed for the best capacity for saving, which is 360 kW. This size requires an important initial investment, so it takes more time to reach the convenience with the reference scenario. There are in fact lower system sizes for which no subsidies are needed to reach a RPBT=5. The same consideration applies for the Italian case and the Spanish case.

LCOE at current and target costs, Spain

The situation here is not different from the other countries. For the target scenario the NPV of the investment becomes positive even before, at the second year of life.

Table 32. LCOE in current and target scenarios.

	LCOE (c€/kWh)
LCOE, current, with subsidies	21.2-21.5
LCOE, current, w/o subsidies	24.5-26.0
LCOE, target, w/o subsidies	5.3-6.2

The current cost of electricity in UK is 16.03 c€/kWh including taxes, so today the LCOE of the SOFC system is higher than cost of electricity. Despite this the UK, thanks also the low NG cost in the countries analyzed in Europe, is the best location for the application of the technology at the current state.

Evaluation of NPV and savings, Sweden

In Sweden the cost of electricity is low in comparison with the other countries, and the cost of NG is most of the time twice the cost of NG in other countries. This is the worst scenario for the application of SOFC, and this situation is reflected into the NPV which is never positive and follow the same expected behavior of the previous countries, except the UK. The PCs that maximize the savings and the NPV for the two model are collected in the table below.

Table 33. PC to maximize NPV and Savings.

	Size (kW)
Best size for Savings	60
Best size for NPV	12-60

Table 34. Subsidy needed to have RPBT = 5.

	Subsidy (% of initial investment)
Subsidy	24.0-24.5

It should be noticed that even with the lowest capacity the subsidy that would have been needed is ~ 25%.

LCOE at current and target costs, Sweden

The current cost of electricity in Sweden is 8.55 c€/kWh including taxes, and the cost of NG is 9.37 c€/kWh. LCOE is two times higher than the cost of electricity bought from the grid.

Table 35. LCOE in current and target scenarios.

	LCOE (c€/kWh)
LCOE, current, with subsidies	16.5-18.6
LCOE, current, w/o subsidies	19.1-22.6
LCOE, target, w/o subsidies	4.8-5

Comparative Results

In this section some comparative results will be shown to verify how the boundary conditions affects the model. To find out a connection between the model variables and the countries, a new variable was introduced. This parameter is the difference between the cost of electricity and the cost of NG in a specific country and is called Delta energy (Deltaen), represented as:

$Deltaen = price_{el} - price_{NG}$ (14)

The comparison was done using as input the same capacity for all the countries, which was 60 kW. The fuel cell model used was the Convion one, but the same considerations apply also for the other models.

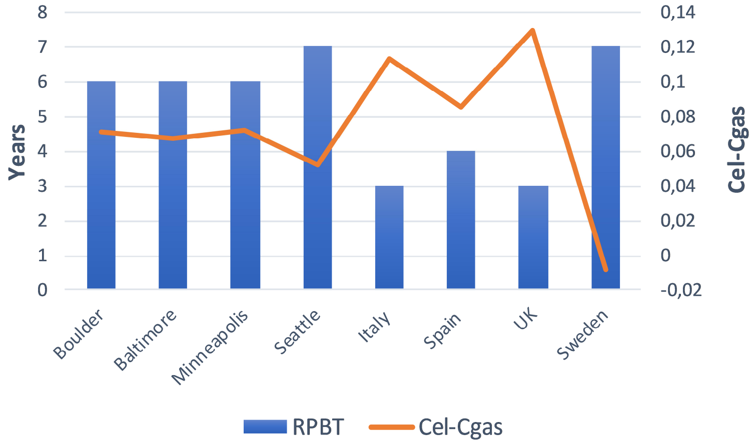

Figure 62. RPBT comparative analysis.

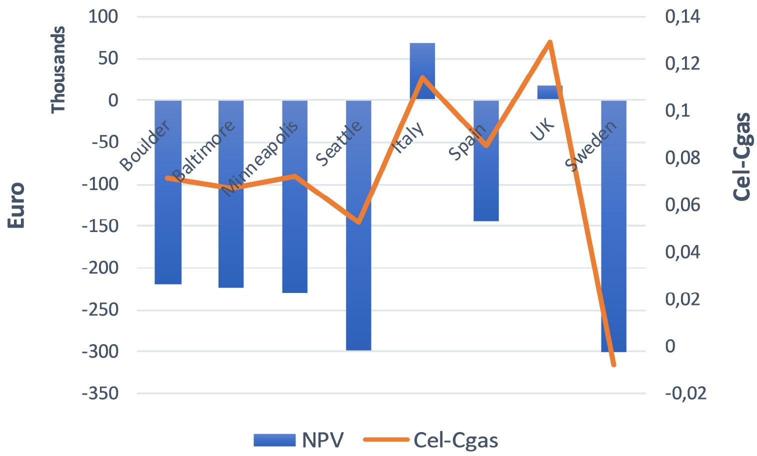

Figure 63. NPV comparative analysis.

Figure 64. Savings comparative analysis.

As expected, it is possible to find a connection between the Delta energy and the performance of the fuel cell system. In the countries where the Delta energy is higher, so there is a high cost of electricity and a relatively low cost of NG, the RPBT is lower than 5 years even without subsidies, while in country like Sweden or in the city of Seattle the RPBT reaches 7 years. The same behavior applies to the NPV. For the countries with low Delta energy the NPV of the fuel cell system is always negative, while for Italy and UK the NPV is not only higher, but it is also positive, proving the huge impact of price regulations on the exploitation of the technology.

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