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MASTER DEGREE IN ENERGY AND NUCLEAR ENGINEERING

MASTER OF SCIENCE THESIS

ANALYSIS OF THE ENERGY CONSUMPTION IN THE HOTEL SECTOR AND FEASIBILITY STUDY FOR THE INSTALLATION OF SOFC-BASED COGENERATION SYSTEMS

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ABSTRACT

This master thesis is part of the ComSos European project that aims to demonstrate the market potential of mid-sized fuel cells.

In this work, only Solid Oxide Fuel Cells (SOFC) will be considered. A SOFC is an open electrochemical device able to produce electrical energy, and thermal energy as a byproduct, working at high temperatures and commonly using methane or hydrogen as fuels. The analysis of the energy consumption in the hotel industry will be performed in order to understand if the medium-high standard hotels represent a possible market for SOFCs development.

A typical upmarket hotel needs a very high amount of energy but at the same time, it possesses a remarkable potential to reduce its consumption. Due to the fact that sustainability is a worldwide current topic, international hotel companies are becoming increasingly interested in making their hotels more and more sustainable, and, as a consequence, understanding whether the SOFC systems can help this process is an important issue.

The analysis will be done considering the annual electrical and thermal consumption for the medium-high standard hotels in different areas of the world. They will be specifically identified for 3,4 and 5 stars hotels in different continents, and a comparison between seasonal and annual hotels and between 3 stars and 4-5 stars ones will be performed. Also, a survey on the Italian hotel industry was conducted to understand its energy consumption.

Considering the electrical consumption, in Europe hotels need between 99.7 and 168.9 $\frac{kWh}{m^2}$, in Asia between 134.1 and 388.8 $\frac{kWh}{m^2}$, in the US between 185 and 363 $\frac{kWh}{m^2}$.

About the thermal use, In Europe hotels use between 85.7 and 212.2 $\frac{kWh}{m^2}$, in Asia between 27.9 and 357.5 $\frac{kWh}{m^2}$, in the US between 127 and 463$\frac{kWh}{m^2}$.

Therefore, a Matlab®- based model in order to obtain the hourly consumptions from the annual ones will be explained. In order to reach this goal, the places where hotels are located will be divided according to their climate zones: the Koppen-Geiger Climate Classification will be utilized. A further simulation will be performed to understand the difference between the energy needs of seasonal and annual hotels.

Subsequently, these results will be used to perform a study for different hotels located in Italy, Portugal, Greece, and Taiwan to verify the feasibility of a SOFC based cogeneration system in these hotels. It has been found, that at the current prices, the cash flow analysis is always negative, but at the target price, the payback times in the best conditions result of 4.2 and 4.4 years for small and medium hotels in Italy, 9.3 and 8.7 years for medium and large hotels in Portugal, 7.6 and 7.1 years for small and medium hotels in Greece, and 7.4 years for large hotels in Taiwan.

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List of Indicators and Their Units

Indicators	Description	Units
CHCP	Combined heat, cooling, and power plants	-
DH	District heating	-
DHW	Domestic hot water	-
EUI	Energy use intensity	$\frac{kWh}{m^2}$
EUI_{el}	Electrical energy use intensity	$\frac{kWh}{m^2}$
EUI_{th}	Thermal energy use intensity	$\frac{kWh}{m^2}$
FC	Fuel Cell	-
HVAC	Heating Ventilation Air Conditioning	-
LPG	Liquefied Petroleum Gas	-
PBT	Payback time	years
PES	Primary energy saving	%
SOFC	Solid Oxide Fuel Cell	-

1 INTRODUCTION

This master thesis is part of the ComSos (Commercial Scale SOFC Systems) Project. The goal of this European project is to demonstrate the market potential of mid-sized fuel cells.[1]

A fuel cell is an open electrochemical device that transforms the chemical energy of the reactants received from the external environment into electrical energy plus thermal energy as a byproduct.

In order to understand the potential of this technology, several markets should be analyzed; in this work, the analysis of the energy consumption of the hotel industry will be performed.

Higher is the standard of the hotel, higher is its energy consumption, then higher is its saving potential; consequently, in this work, only the medium-high standard hotels' consumption in several areas of the world will be analyzed in order to verify the feasibility of the installation of a SOFC-based cogeneration system. The classification of the hotels is not uniform all over the world however, the medium-high quality hotels have similar facilities and services, and their energy consumption can be compared.

1.1 COMSOS PROJECT

Following the increasing sensibility to climate change issues, EU companies and research centers have developed the ComSos project. This is a 42-months project coordinated by VTT (Technical Research Centre of Finland Ltd) and developed with the cooperation of SOLIDpower, Politecnico di Torino, EnergyMatters, Htceramics, Sunfire, and Convion.

The core of this consortium is to bring zero-emissions cogeneration systems to new potential markets through Solide Oxide Fuel Cells (SOFC) installations. These systems can reach an electrical efficiency of 50% and an overall efficiency higher than 90% and so can be used in several markets with a significant primary energy saving and carbon dioxide reduction.

SOLIDpower, Sunfire, and Convion are the three SOFC system manufacturers; they produce similar fuel cells with different sizes: SOLIDpower and Sunfire produce modules of 12 kWe and 25 kWe respectively, Convion of 60 kWe; therefore, the SOFCs inserted in the project will have a size between 10 kWe and 60 kWe.

The SOFCs are well suited for activities with a constant electrical requirement, hence the end-users could be hospitals, supermarkets, hotels, office buildings, small data centers, and near-zero energy buildings.

1.2 FUEL CELL TECHNOLOGY

A fuel cell is an electrochemical device that transforms the chemical energy of the fuel, into electrical energy. This one-step transformation is more advantageous than multi-step transformation (e.g., from chemical energy to mechanical energy and then to electrical energy) of the combustion engines, from many points of view. Mainly, combustion is avoided, and this helps not to get worse the environmental problems like climate change or acidic rains. Other advantages are the higher thermodynamical efficiency and the fuel flexibility. Moreover, the static configuration without moving parts guarantees operation without noise and vibration, and flexibility in power generation[2].
A fuel cell is made of three layers: an anode, a cathode, and an electrolyte layer. The role of the electrolyte is very crucial considering that it determines the type of the FC and the operating temperatures.

There are several types of fuel cells on the market, though they can be grouped into two main categories:

- Low-temperature fuel cells (60-80°C):
  - PEMFC (Proton Exchange Membrane Fuel Cell);
  - DMFC (Direct Methanol Fuel Cell);
  - AFC (Alkaline Fuel Cell).
- High-temperature fuel cells (650-1000°C):
  - SOFC (Solid Oxide Fuel Cell);
  - MCFC (Molten Carbonate Fuel Cell).

In this work, only the SOFC will be discussed.

The chemical working mechanism is based on the REDOX reactions: the oxidation happens at the anode (releasing electrons), the reduction happens at the cathode (recombining electrons).
REDOX reactions also generate the charge separation that creates a voltage gradient between anode and cathode.
The combination of the electrons flow and charge separation produces electric power (Figure 1).
The fuel at the anode inlet can be pure hydrogen (H_2) or methane (CH_4); it reacts with O^{2-} in order to deliver electrons and to produce water (H_2O) or carbon dioxide (CO_2). The delivered electrons head for the cathode where pure oxygen O_2 reacts with the electrons; O^{2-} is generated and it can return towards the anode. A catalyst is usually used to reduce the energy pathway of the reaction by generating a modified activated complex at lower energy.
The produced voltage is thermodynamically fixed in view of the fact that it depends on

the reaction; to produce a suitable voltage, the cells are packed together in series creating a SOFCs stack.

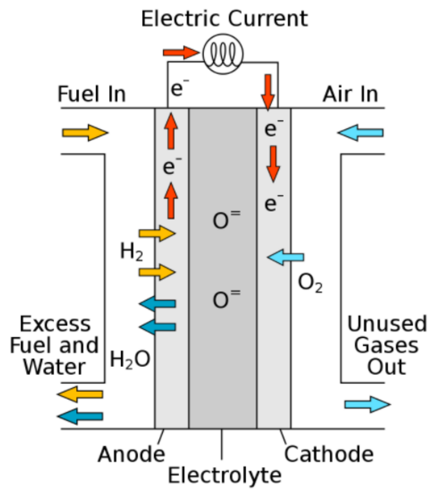

Figure 1. The basic scheme of a SOFC [3].

The SOFCs work between 800-1000°C and they are made of materials with remarked tolerance to high temperatures.
The electrolyte layer is made of ceramic materials that permit the mobility of the ions of Oxygen (O^{2-}); typically, solid yttria-stabilized zirconia (YSZ) is used. The anode is constructed of Cermet materials, usually, Nickel – YSZ composite, and the cathode is made of Strontium - doped Lanthanum manganite (LSM) materials.
These cells have the advantages to produce heat at high temperatures and they can be used in CHP (combined heat and power) plants, to work with high efficiencies, to be made of an inexpensive catalyst, and to produce very low emissions. They are not able to perform fast start-up and shut down, indeed, they should be used in plants with a constant baseload. The hotel loads comply with this feature, thus they will be analyzed.

1.3 Hotel Classification

In order to understand the potential market of the mid-sized fuel cells, the energy consumption of the hotel sector will be analyzed.
This work will be focused on the energy consumption of medium-high standard hotels.
The hospitality sector is divided into hotels and other structures; the hotels are usually grouped into five categories (star or diamonds) according to the services they offer. “One star” is assigned to hotels with a basic level of comfort; hotels that guarantee luxury levels in facilities and services are marked with “five stars”.
This classification is not equal all over the world, it is often based on national laws.

In Europe, the "Hotelstars Union" is a partnership, founded in 2009, of seventeen European Countries that aimed to create a standard hotel classification with common criteria and procedures. The member states are Austria, Belgium, Czech Republic, Denmark, Estonia, Germany, Greece, Hungary, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Slovenia, Sweden, and Switzerland. This classification is composed of one to five stars and for each class, have been established the correspondent services and the guaranteed quality [4]. In Table 1, the offered services as stated by the classification of stars are shown.

Table 1. Hotelstars criteria EU [4].

STARS	***	****	*****
SERVICES	10 hours staffed reception service, available via digital communication or telephone 24 hours.	16 hours staffed reception service, physically available via digital communication or telephone 24 hours.	24 hours staffed reception service, physically available via digital communication or telephone 24 hours.
	Lounge suite at the reception area, luggage service on demand.	Lobby with seats and beverage service, hotelbar or lounge area.	Valet parking service.
	Beverage offer in the room.	Breakfast buffet with service or equivalent breakfast menu card.	Concierge.
	Device for internal and external communication on demand.	Minibar or maxibar or 16 hours beverages via room service.	Shuttle or limousine service.
	Audio or multimedia entertainment.	Comfortable seating (upholstered armchair/couch) with side table/shelf.	Luggage service.
	Hair-dryer, cleansing tissue.	Bath robe and slippers on demand.	Personalized greeting for each guest with flowers or a present in the room.
	Dressing mirror, adequate place or rack to put the luggage/suitcase.	Cosmetic products (e.g. shower cap, nail file, cotton swabs), vanity mirror, large storage surface in the bathroom.	Minibar and food and beverage offer via room service during 24 hours.
	Laundry and ironing service.	International TV channels.	Internet device in the room on demand.
	Additional pillow and additional blanket on demand.		Safe in the room.
	Systematic complaint management system.		Ironing service (return within 1 h), shoe polish and sewing service.
	Bilingual, hotelown website.		Turndown service in the evening.
			Breakfast menu card via room service.

Italy is not a member of the "Hotelstars Union", it can be said in general, that for hotels in the medium-high range correspondent from three to five stars, the TVs are mandatory in all the rooms and a bar should be included; the presence of a restaurant is mandatory only for four and five stars hotels [5].

In the US, the classification is made through diamonds by the AAA (American Automobile Association)[6]; it is an association of motor clubs throughout North America that rates hotels and restaurants. In general, it can be said that [7]:

- Three diamond hotels are good for travelers with comprehensive needs.
- Four diamond hotels are upscale in all areas.
- Five diamond hotels present a high level of luxury and comfort.

A more detailed description is demonstrated in Table 2.

Table 2. Diamonds Classification USA [8].

DIAMOND	THREE DIAMOND	FOUR DIAMOND	FIVE DIAMOND
SERVICES	Uniformed staff.	Uniformed staff.	Staffed concierge area (minimum 16 hrs./day and 7 days/ week).
	One full-service restaurant.	Upscale, full-service restaurant i.e., comparable to a Three Diamond restaurant.	Multiple outlets including an upscale, full-service restaurant i.e., at least one is comparable to a Four Diamond restaurant.
	Grab-and-go option available.	Room service available for breakfast, lunch and dinner.	Room service available 24/7.
	Good variety of comfortable, coordinated pool furniture.	Good variety of comfortable, coordinated pool furniture, includes at least one additional feature e.g., hot tub, whirlpool spa, steam room, sauna, fountain, waterfall, zero-entry, infinity edge, children's splash pad, kiddie pool, water slide.	Good variety of upscale pool furniture, includes at least one additional feature e.g., hot tub, whirlpool spa, steam room, sauna, fountain, waterfall, zero-entry, infinity edge, children's splash pad, kiddie pool, water slide. Additional poolside amenities e.g., cabanas, Bali beds, umbrellas, lotions, food and beverage outlet. Attendants on duty .
	Full-length mirror, decorative frame/design enhancement.	Full-length mirror, upscale frame/design enhancement.	Full-length mirror, custom frame/design enhancement e.g., luxurious materials, artistic design, oversized, multiple viewing angles.
	TV 40-inch flat-panel.	TV 43-inch flat-panel.	TV >43-inch flat-panel.
	Conveniently located through-wall HVAC units.	Central system; digital thermostat control on wall.	Central system; quiet and inconspicuous form and function; digital thermostat control on wall.
	Decorative lighting fixtures in multiple locations.	Upscale design and materials in multiple locations; Illuminated shower; Excellent level of overall illumination at each location.	Upscale design and materials in multiple locations; Illuminated shower; Custom function(s) provides for ambience options e.g., dimmers, point lighting, multiple switches, and/or natural light sources; Leading-edge illumination effect.

In Asia, the situation is more heterogeneous:

- in China, the hotels are classified based on a “stars system” plus a platinum level for the highest quality[9]. The services for each class are described in the following Table 3.
- Japan is a developed country and only recently the Society of Tourism Informatic (STI)[10] proposed a self-assessment system.
- Singapore has not a “star rating system” due to several reasons; hotels and travel agents rate themselves according to their experiences of knowledge.[11]
- Hotels in Taiwan are classified on a Plum (Blossom) rating system and there are only 2 quality levels: four and five Plums.[11]
- Hong Kong hotels classification is based on five key indicators including “facilities”, “location”, “staff-to-room Ratio”, “average achieved room rates”, and “business mix”. Each hotel obtains a total score, and it is used as a total indicator according to a combination of quantitative and qualitative indicators. A public list of hotels divided by category is not available, however, each hotel is informed about its respective category so that the owners can compare its hotel against other hotels of the same category [12].

Table 3. Stars Classification China [9].

STARS	***	****	*****
SERVICES	Rooms should have air conditioning, free Wi-Fi, flat screen TV with satellite channels, free toiletries, hairdryer, ironing facility, minibar, electric kettle, and wake-up service.	Transportation services are provided, ranging from airport pickup to limousine service.	Their own fleets of Mercedes limousines of Toyota vans that make regular runs to the airport or city center.
	On- site facilities like bars and restaurants, fitness centers and some degree of room service. Business facilities often include fax service, meeting and banquets halls.	Fine dining with local and Western cuisine, high-class fitness centers, spas, sauna, massage, meeting rooms and business facilities. They also have concierge service, luggage storage, currency exchange, tour desk, ticket service, ironing, and dry-cleaning facilities.	Executive floors with concierges and free continental breakfasts; the best Western food and probably the best Chinese food in town, and the most luxurious breakfast buffets.
	Their location is usually convenient, near major attractions and business areas.		Many have magnificent ball rooms and lobbies and cater to foreign business people on expense accounts.
			Personal Jacuzzi tubs, large screen plasma TV, fresh flowers, high-end lavish bath products and a touch of elegance in everything you see.

1.4 ENERGY USE IN THE HOSPITALITY INDUSTRY

The concept of sustainability is a current topic in the hospitality sector. International hotel companies are becoming increasingly interested in making their hotels more and more sustainable. Energy is the most important source of CO_2 emissions, which lead negative impact on the environment, therefore, energy consumption should be monitored and reduced.

Several factors influence energy consumption in the hotel industry [13], some of them have a high impact, others medium or low impact (Table 4).

Table 4. Factors influencing energy consumption.

FACTORS	EFFECTS	IMPACTS
Location	Higher or lower use of air conditioning or heating.	High
Local policies	Impact the prices and CO2 emissions.	High
Category	Higher is the category, higher is the consumption.	High
Services/Facilities	Less facilities, less energy consumption.	High
Size of the building	The bigger the building, the higher energy needed.	Medium
Age of the building	New buildings are usually better insulated than older ones.	Medium
Occupancy	More people in the building, more energy needed.	Medium
Operational hours	May impact the energy prices in some areas.	Low

Hotels need electrical and thermal energy (from methane, propane, diesel, oil, etc.) in order to guarantee their services; the first one is usually used for cooling, lighting, or ventilation, the second one mainly for heating or cooking. The percentage of delivered energy by end-use is not fixed and it depends on several factors, still, generally, the HVAC systems are the largest end-users of energy, accounting for almost half of the total energy needed; domestic hot water is the second-largest user of the demand; the rest is used for lighting, cooking, office equipment, refrigeration and other.

The consumption of HVAC systems could be reduced in view of the fact that part of it is due to unnecessary losses: these systems often run even if the rooms are unoccupied and the thermostat settings are under full control of the guests, therefore, paying more attention, the saving potential of this part of the energy is very high.

It is completely accepted that the outdoor weather conditions (so the location), the category of the hotel, and the floor areas are the main factors influencing the energy consumption in a hotel; therefore, in this work, the analysis will be done for different areas of the world and similar hotel categories, and the energy consumption will be referred to the floor area of the buildings.

2 ENERGY CONSUMPTION IN THE HOTEL SECTOR

Hotels are energy-intensive buildings and their consumption should be reduced to make them more sustainable. In order to collect data, several scientific publications have been analyzed and the obtained results have been compared with each other.
The energy consumption varies between the categories of the hotels and the areas of the world; in this work, only the medium-high standard (from three to five stars/diamonds in Europe, China, and the US) and hotels for each area will be analyzed.
The collected data concern hotels in Europe, Asia, and United States.
The climate zone plays an essential role in energy consumption, and a description of it for each location is very useful in order to make comparisons between hotels located on different continents.
The average total energy consumption of hotels located in different places has been split into electric and thermal consumption. In order to make a comparison between the different areas of the world, the EUI index, the most widely used indicator, will be used.

2.1 KOPPEN - GEIGER CLIMATE CLASSIFICATION

Most of the analyzed hotels are located in places characterized by a temperate climate that extends from 30° to 60 ° of latitude: the temperature ranges are wide with specific seasonal changes and rainfall well distributed during the year. The temperate zone is often divided into smaller zones:

- Humid subtropical climate: hot and humid summers, cold to mild winters.
- Continental climate: characterized by large variations in temperature between summers and winters.
- Oceanic climate: mild summers and cool winters.
- Mediterranean climate: dry summers and mild and wet winters.

The first world climate classification was performed by the German Scientist Wladimir Köppen in 1900 and then updated by Rudolf Geiger at the end of the nineteenth century. This classification is still the most used. It was made considering five vegetation classes distributed according to the climate of the zones[14].
As a consequence, five classes of climates were adopted by Koppen:

- A: Equatorial climates.
- B: Arid climates.
- C: Warm temperate climates.
- D: Snow climates.
- E: Polar climates.

The data collected from the literature regards hotels located in the warm temperate zone; therefore more attention has been paid to this climate class.
The class "C" contains places characterized by a minimum temperature between −3 °C and +18 °C and it is divided into others two subgroups.
The first one contains three subclasses defined according to the lowest and highest monthly precipitations in winter and summer:

- "Cs" refers to a warm temperate climate with dry summer.
- "Cw" regard zones with warm temperate climate with dry winter.
- "Cf" is referred to places with a warm temperate climate, fully humid.

The second one contains information about the annual and monthly temperatures:

- "h": hot steppe-desert with an annual temperature higher than 18°C.
- "k": cold steppe-desert with an annual temperature lower than 18°C.
- "a": hot summer with a mean temperature of the warmest month higher or equal to +22 °C.
- "b": warm summer, different from "a" and with at least four mean monthly temperatures higher or equal to 10°C.
- "c": Cool summer and cold winter not in the subgroup "b" and with a mean temperature of the coldest month higher than −38 °C.
- "d": refers to extremely continental climate.

Most of the data collected from the scientific articles treat hotels located in the "Csa / Csb" and in the "Cfa" climate zones.
The "Csa / Csb" classes refer to locations characterized by the Mediterranean climate with hot or warm summer. Considering the fact that these two last climatic classes belong to the same "Cs" class, it has been assumed that there is no major impact in terms of energy consumption, therefore they have been considered as being interchangeable. The "Cfa" class refers to places with a warm temperate climate, fully humid, and characterized by hot summers.

2.2 Energy Use Intensity Index (EUI)

The energy use intensity index is an indicator of the energy use of the buildings as a function of their floor areas or other characteristics.
In this work, it has been useful in order to compare several hotels located in different areas of the world and with different sizes.
This index contains information about the electrical and thermal use of the buildings, in fact, it is defined as:

$$EUI = EUI_{el} + EUI_{th} \qquad \left[\frac{kWh}{m^2}\right] \qquad (1)$$

Where:

EUI_{el} is the electrical energy use intensity $\left[\frac{kWh}{m^2}\right]$;

EUI_{th} is the electrical energy use intensity$\left[\frac{kWh}{m^2}\right]$;

The lower the EUI, the lower the energy consumption, the higher is the energy efficiency of the buildings. It depends on several factors:

- Property types: some types of the building always use more energy than others, i.e. an elementary school consumes less energy than a high standard hotel or a hospital less than an athletic center.
- Climate: it plays an essential role in energy consumption, i.e. colder the climate, higher thermal energy consumption, hotter the climate, higher electrical energy consumption.
- Building structure: more recent the building construction, better the insulation, more efficient the energy systems, lower the EUI.
- Utilities: higher the degree of comfort, higher the EUI index, i.e. a house with a pool, a gym, a laundry, etc uses much more energy than a typical house with basic needs.
- Energetic choices: different trends are obtained if it has been considered to run all the heating and cooling systems through electricity, or with both electricity or methane (or even propane, LPG, etc.)

The factors considered in this analysis, regard the location (that gives information about the climate) and the floor areas.

2.3 EUROPE

Europe is characterized by a temperate climate. The analyzed hotels are located in the Mediterranean climate zones (Southern Europe) and oceanic climate zones (most of Western Europe). A better description of the climate is shown in Figure 2.

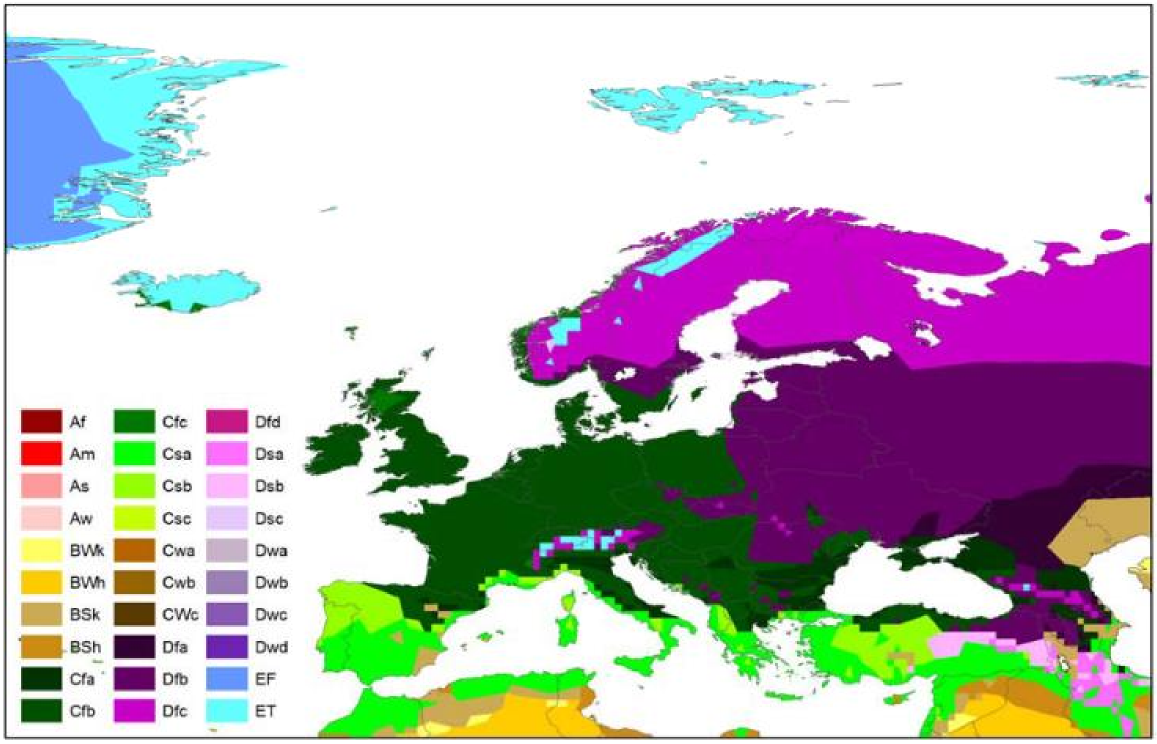

Figure 2. Köppen-Geiger climate type map of Europe [15].

Most of the data have been collected from CHOSE project[16]: this project aimed to investigate the technical and economic feasibility of combined heat, cooling, and power plants (CHCP) in the hotel sector.
The involved countries in the project were Italy, Greece, Cyprus, Portugal, and Sweden. The data regarding hotels located in the Balearic Islands, UK, and Croatia have been collected from other scientific publications. More details about the data will be explained in the following.

- **ITALY:** A survey[17] was performed in ten four-stars hotels, seven of them were in Northern Italy, two in Rome, and one in Agrigento. The electricity consumption by end-use is 84% for lighting and 16% for air conditioning (Figure 3); the thermal consumption is used mainly for heating and DHW (Figure 4). The percentage of delivered energy for air conditioning is much lower than the energy used for heating and it is probably since most hotels of the survey are located in Northern Italy.
  As predicted, the main part of the energy is used for HVAC systems and lighting.

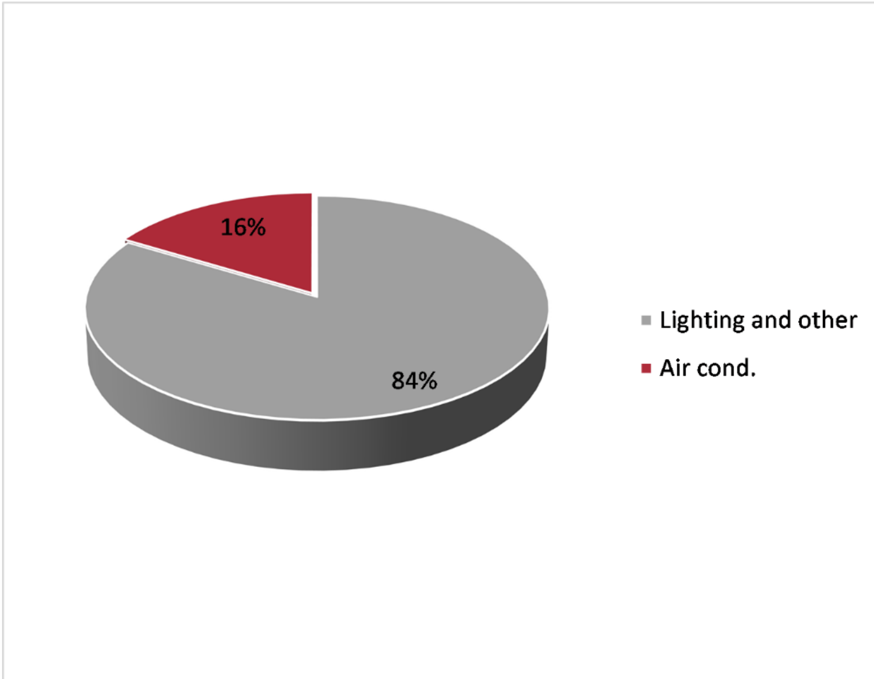

Figure 3. Electricity utilization by end-use Italy.

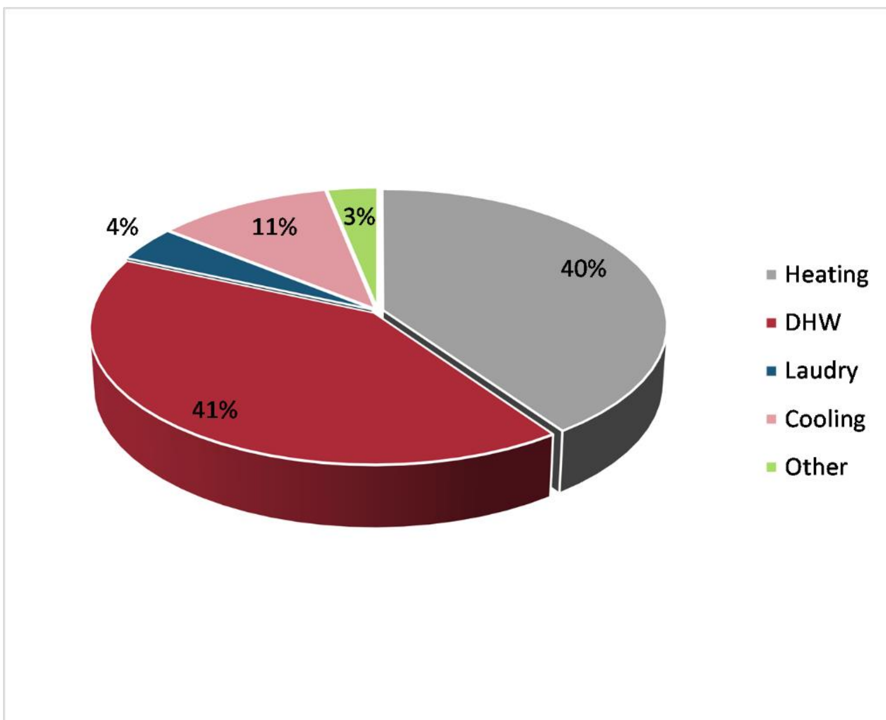

Figure 4. Thermal utilization by end-use Italy.

- **CYPRUS:** Five hotels were involved in the survey [18] of the CHOSE project: one of them was a five stars hotel, two had four stars and the others had three stars.

With the available data, a comparison between the consumption of the three stars and four-five stars ones will be done.

- **SWEDEN:** In this energy audit[19], nine business hotels were analyzed. There is no available data about the stars, therefore in this work, only the data of hotels with the same facilities and services have been considered.
- **PORTUGAL:** Eleven hotels were interviewed in Portugal[20]: two of them had 5*, four of them had 4* and three had 3*, for the others, there is no information about the stars classification. With the available data, a comparison between the consumption of the 3* and 4*-5* ones will be done.
- **BALEARIC ISLANDS (SPAIN):** In this survey[21], twenty hotels had 3* and eleven had 4*. Fourteen of them worked seasonally, seventeen of them worked the whole year. For this study, only four stars annual hotels have been included in the calculations, but with the available data, a comparison between seasonal and annual ones, and between three stars and four stars ones will be done.
- **UNITED KINGDOM:** The consumption of two 3* hotels was analyzed in this paper[22]. They were open all year and one hotel was smaller than the other.
- **GREECE:** In CHOSE project[23], eight business/luxury annual hotels and two touristic seasonal ones were studied. These buildings were placed in different zones (Thessaloniki, Rhodes, and Athens) in order to cover a wide range of climate characteristics.

  Another survey was performed in Attica[24] considering a sample of hotel buildings between three and five stars.
- **CROATIA:** In this energy audit[25], several hotels located in Dubrovnik, Istria, Rijeka, and Split were analyzed. In this work, only annual four- and five-stars hotels have been included in the calculations; even, in this case, the available data can be useful to compare annual and seasonal hotels.

The results for the EUI indexes are shown in **Errore. L'origine riferimento non è stata trovata.**: the range obtained for upscale hotels is between 199.8 and 364.4 $\frac{kWh}{m^2}$.

Table 5. Electrical and thermal consumption by hotel stars, Europe.

Electric and thermal consumption	Typology	EUI_{el}	EUI_{th}	EUI
Italy	4*	152.2	212.2	364.4
Cyprus	4* - 5*	145.6	179.2	324.8
Sweden	Business	148.3	189.6	338.0
Portugal	4* - 5*	116.0	108.9	224.9
Spain	4*	114.1	85.7	199.8
UK	3*	125	88	213.0
Greece	Business/Luxury	168.9	172.0	340.9
Croatia	4* - 5*	99.7	125.9	225.6

In general, the further north the hotel location, the higher the thermal consumption needed for heating (Sweden or Italy, i.e.), the further south the hotel location, the higher the electricity consumption needed for air conditioning (Greece or Cyprus); this can be true as a theory, thus in real cases, several factors can modify it.

It can be seen from Figure 5 that the highest EUI values have been obtained for Italy, Greece, and Sweden. These results are not only dependent on the location, but also the age of the buildings, the hotel occupancy, the type of buildings, insulation, the year in which the data were collected, etc., however, there are no specific data about these pieces of information.

Hotels on the Balearic island have the lowest consumption: it is probably due to the fact that, in this place characterized by the Mediterranean climate, the average monthly temperature varies from almost 15°C to 31 °C, therefore, the heating and cooling systems are less used and the energy used is lower.

The consumption of hotels located in the United Kingdom is comparable with the one of the Balearic island: here the climate is an oceanic type and the average monthly temperature varies from almost 3°C to 16°C, but the hotels involved in this survey have only three stars, therefore, they have fewer services and their consumption is lower than the others located in the same climate zone.

Hotel buildings located in Portugal and Croatia have a comparable EUI indicator; they have the same stars classification and either the locations are characterized by the Mediterranean climate.

Cyprus is characterized by a subtropical – Mediterranean climate; it has the warmest climate and the warmest winters in the Mediterranean part of the EU. It is supposed that during the summer, cooling consumes a consistent part of the energy since EUI_{el} is high; the most part of thermal energy is probably used for DHW. Despite the climate, the EUI index is considerable probably due to the degree of occupation of the hotel buildings: Cyprus in fact is the 40th popular destination in the world [26].

Hotel buildings placed in Greece and Sweden have a comparable EUI index. Greece has a climate predominantly Mediterranean; Sweden is characterized by a warm humid continental and oceanic climate with an average annual temperature of 7°C. Despite they belong to different climate zones, their consumption is similar. This is probably due to the high occupation of hotels located in Greece: it is one of the most visited countries in Europe and the world[27] as is shown in Figure 6.

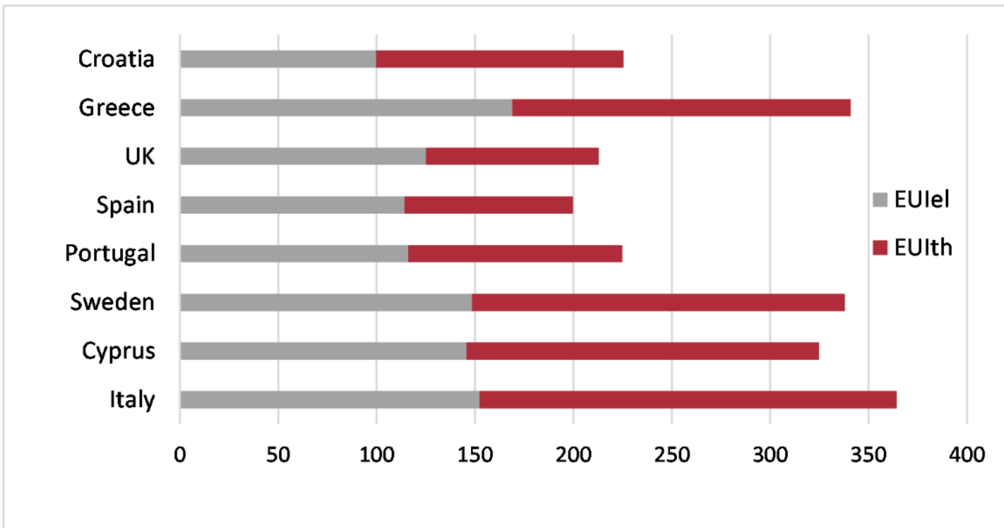

Figure 5. EUI (electrical and thermal) for the chosen EU countries.

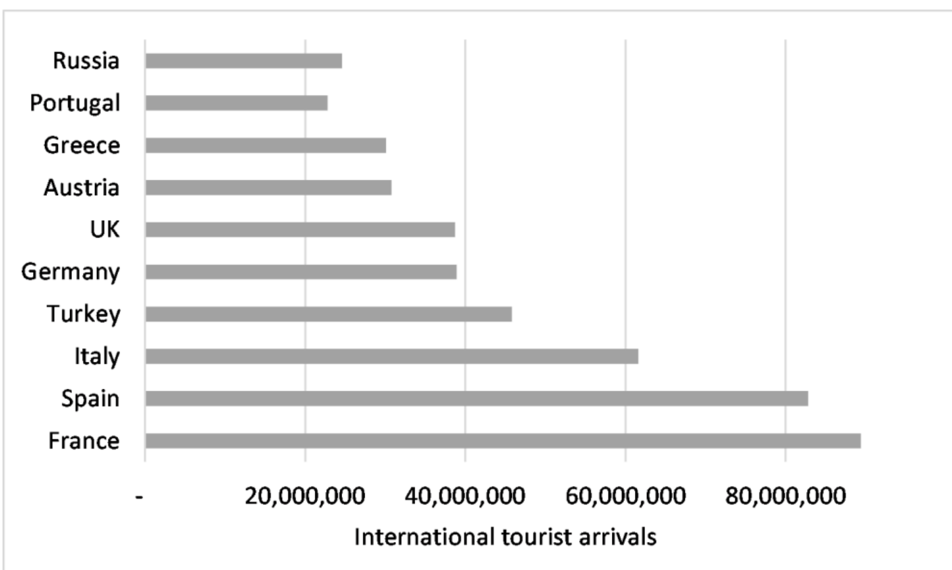

Figure 6. Most visited countries [27].

2.4 ASIA

Asia is characterized by a huge variety of climates. The data have been collected from hotels located in the subtropical climate zones (such as Taiwan, Hong Kong, and Shanghai), in the tropical ones (like Singapore) in the subtropical highland areas (China), in the continental ones (Iran), and finally, in the Mediterranean climate zones (Turkey). A better description of the climate zones of Asia is shown in Figure 7.

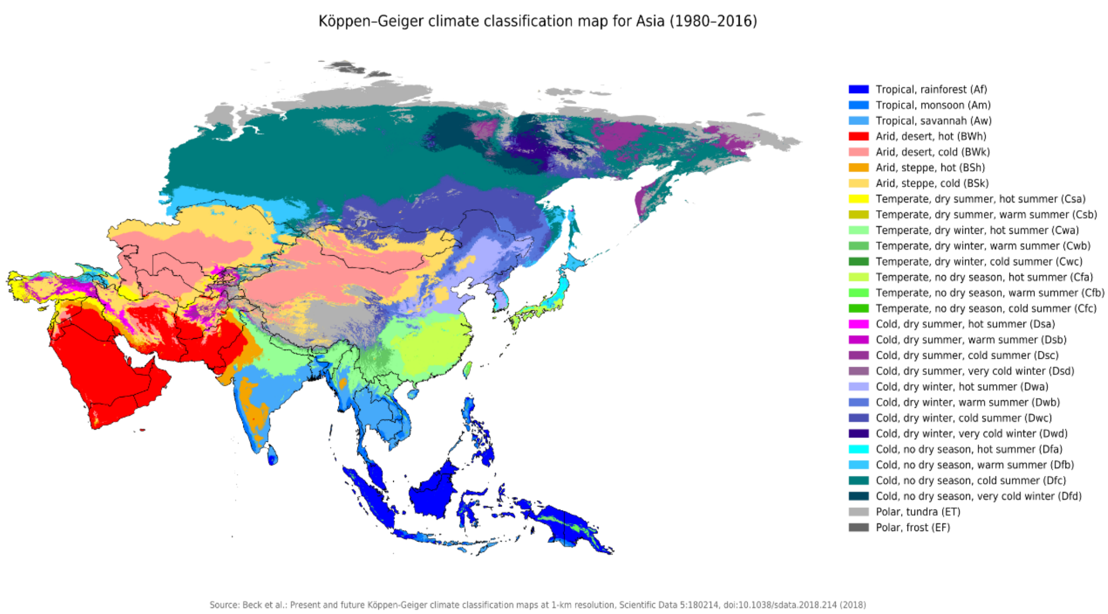

Figure 7. Köppen-Geiger climate type map of Asia [28].

As it has been written in the previous chapter, hotel classification in Asia is heterogeneous; therefore, in this study, the association of the classes has been done considering the hotel's facilities and services.

- **TAIWAN**: The study[29] analyzes the energy consumption of 45 Taiwanese international tourist hotels (as five stars hotels), 19 standard tourist hotels (as four stars hotels), 116 hotel enterprises (as three stars hotels), and 20 bed and breakfast facilities. Electricity consumption accounts on average for 83% and 86% of the total energy consumption for the international tourist and hotel enterprises, respectively; the EUI_{el} is obtained by multiplying the total EUI for the percentage of electricity utilization.
- **SINGAPORE:** The data of the energy audits[30] were collected from 29 hotels from

- 3 to 5 stars. Electricity and gas are used in all the samples, sometimes, also diesel. The study reveals a low correlation between energy utilization and occupation rate, which means that it is necessary to improve the energy management of hotels.
- **HONG KONG:** For this journal article [31], data from 30 hotels have been collected: 14 four stars hotels, and 16 five stars hotels. It reveals that there are no significant variations of energy consumption between the two analyzed classes.
- **SHANGHAI**: A survey[32] in 45 hotels was conducted in 2015. In this study, the relationship between the occupation rate and energy consumption is defined as difficult to identify. Electricity consumption accounts for 75% of total energy consumption.
- **LIJIANG:** The paper[33] surveyed 24 hotels in order to find the EUI index of hotels from one to four stars. Electricity utilization accounts for 81% of total energy consumption. Hotels in Lijiang have the lowest EUI index (Table 6. Electric and thermal consumption by hotel stars in Asia); this is because 80% of the sampled hotels chose solar energy technologies in producing hot water and this leads to a significant reduction in consumptions.
- **IRAN:** This study[34] was elaborated in 2020 and the results of EUI indicators are 3-4 times higher than the previous data collected in Iran in 2016. Six 5* and one 1* hotels are analyzed. According to this energy audit, energy use in the form of natural gas accounts for 65% to 87%. The reason might be in the lack of hotel administration's interest in saving energy, but also in the fact that some hotels in the sample are located in colder locations in Iran.
- **TURKEY:** An evaluation[35] of the energy efficiency of 32 five stars hotels was conducted in 2005. The results showed that 24 hotels were inefficient and therefore, the EUI indicators are high. Electricity is the primary form of energy utilized for air conditioning, heating, lighting, kitchen equipment, etc.

The data collected from these scientific papers have been used to perform the calculations in Table 6. In general, total EUI indicators for Asian hotels are higher than European ones, therefore hotel buildings in Asia are more energy-intensive. In particular, as shown in Figure 8, the electricity consumption is much bigger than thermal ones (except for Iran): it is probably due to the fact that Asian hotels use electricity either for heating and cooling.

Hotels in Lijiang are the most efficient because of the utilization of renewable technologies.

Shanghai and Taiwan belong to the same climate zone and the hotels in the sample have the same stars classification their consumption is comparable. Even Hong Kong is in the same climate zone, however, the hotel involved in the survey are only 4* and 5*, therefore their consumption is higher than the ones involved in the energy audits of

Shanghai and Taiwan (that include even 3*hotels).Hotels involved in the sample for Iran are located in mountainous zones, this can partly explain their considerable EUI_{th} index.

Table 6. Electric and thermal consumption by hotel stars in Asia.

Electric and thermal energy consumption	Typology	EUI_{el}	EUI_{th}	EUI
Taiwan	3*-4*-5*	197.8	35.7	233.5
Singapore	3*-4*-5*	361.4	65.6	427.0
Hong Kong	4*-5*	354.8	116.1	470.9
Shanghai	3*-4*-5*	182.6	60.9	243.5
Lijiang	3*-4*	119.1	27.9	147.0
Iran	5*	134.1	357.5	491.6
Turkey	5*	388.8	39.0	427.8

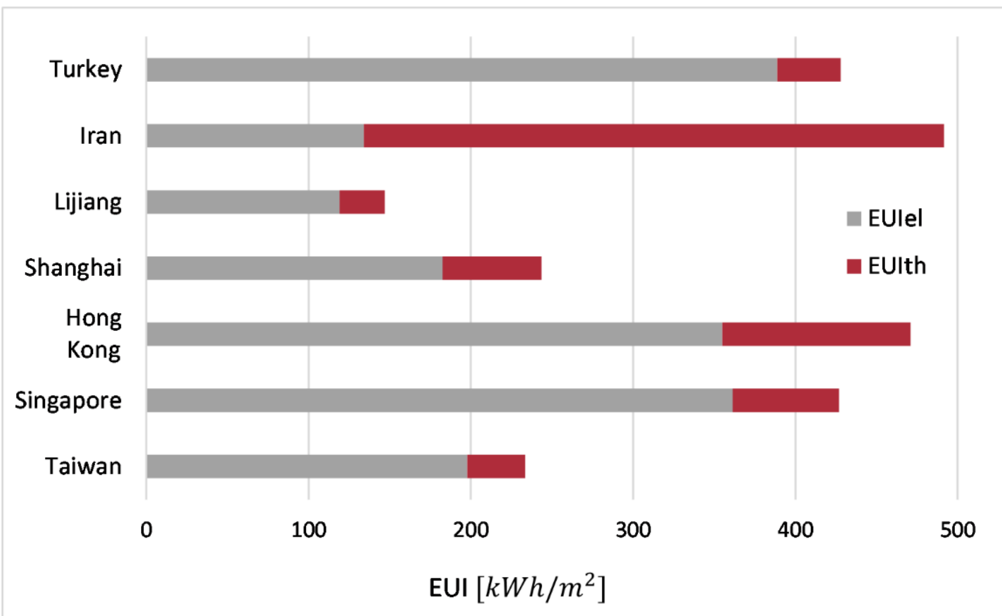

Figure 8. EUI (electrical and thermal) for the chosen Asian countries.

2.5 UNITED STATES

The overall climate of the United States is temperate, with some exceptions: Alaska has an Arctic tundra climate, Hawaii, and South Florida a tropical one. A better description is given in Figure 9.

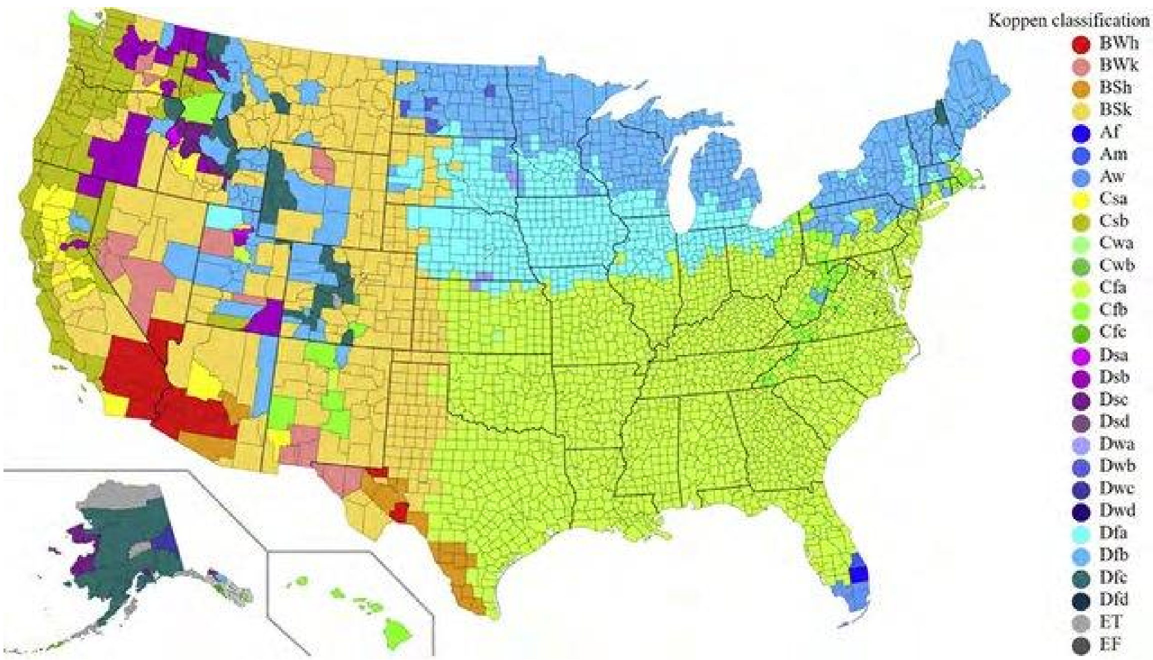

Figure 9. Climate regions of the U.S. according to the Köppen climate classification [36].

A humid continental climate is found in the northeast, from North Dakota to Maine; in the South-east, from Virginia to Oklahoma, the climate is humid subtropical; a Mediterranean climate prevails along most of the California coast; coastal areas of Oregon and Washington are instead oceanic climate zones. The available data have been collected from the Open data Catalog of the U.S. Department of Energy[37]. A software named EnergyPLus was used in order to simulate the energy consumption of 16 typologies of commercial buildings in 16 different locations across the US.

In 2020, on average, in the US, there were 313.1 rooms per hotel in the upper-upscale chain type [38] and 325 square feet ($\cong 30\ m^2$) per room [39], as a consequence, most of the hotels in the medium-high range, can be considered similar to a “large hotel” (following the definition of the U.S. Department of Energy[37]). Therefore, it has been considered as a reference building, a “large hotel” composed of six floors and with a total floor area of 11,345.3 m^2.

With the available data, the EUI indicators have been calculated for each of the 50 states following these steps:

1. From the Department of Energy Database, the hourly data of 365 days of a "large hotel" for each state are available and are expressed in kWh.

2. The yearly electrical and thermal consumption has been calculated as the sum of the hotel's needs for each day.

3. The previous consumptions have been divided for the total floor area of the reference hotel and therefore the EUI_{el} and EUI_{th} have been obtained in $[kWh/m^2]$.

On average, the hotels utilize most of the electricity for cooling, interior equipment, and lighting (Figure 10); most of the gas is used for DHW and heating (Figure 11).

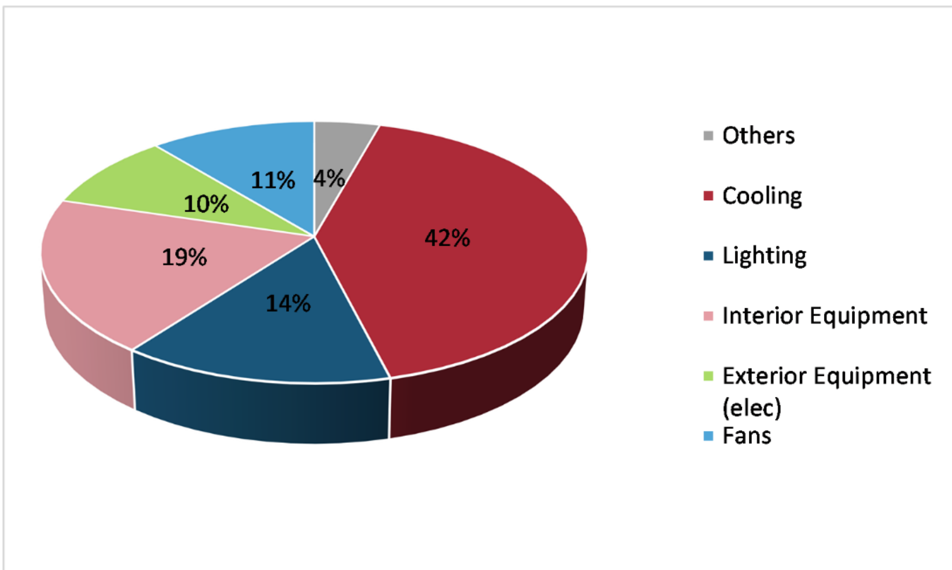

Figure 10. Electricity utilization by end-use, US.

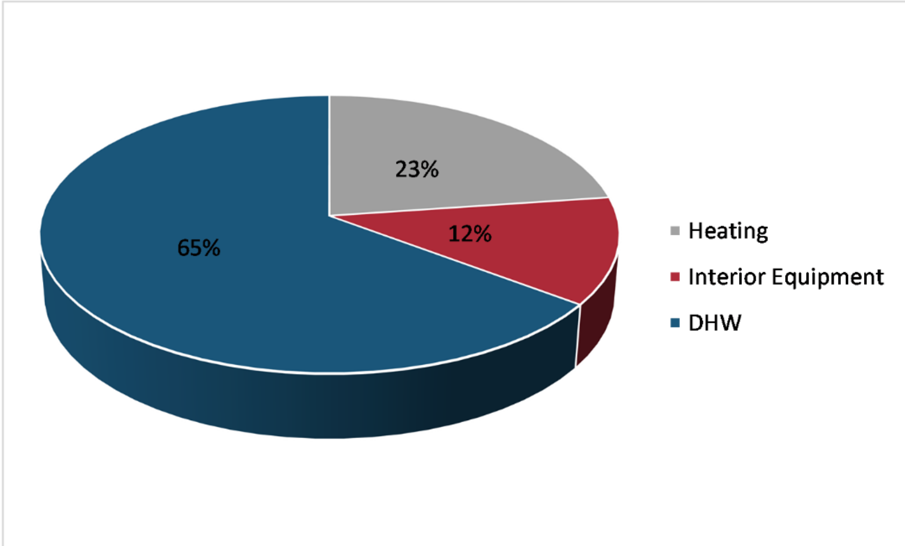

Figure 11. Thermal utilization by end-use, US.

In the following figures (Figure 12, Figure 13), the EUI_{el} and EUI_{th} are shown. The further north the hotels are located, the higher the thermal consumption needed for heating (e.g. Alaska), the further south the hotel location, the higher the electricity consumption needed for cooling (e.g. Florida or Hawaii).

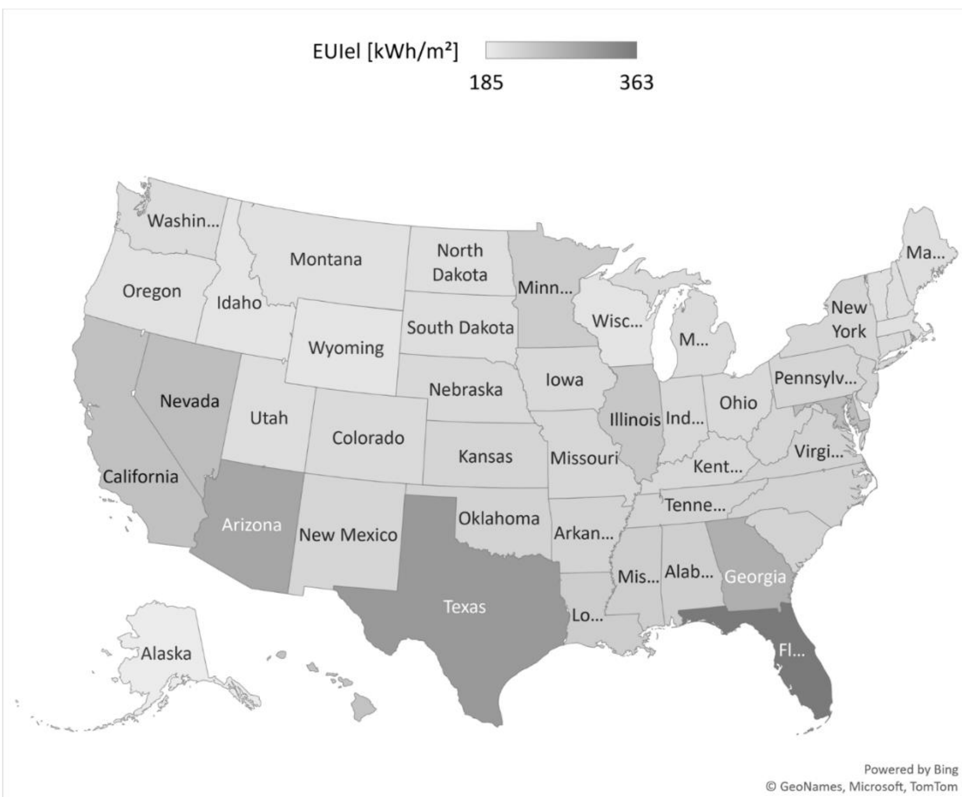

Figure 12. Electric EUI, US.

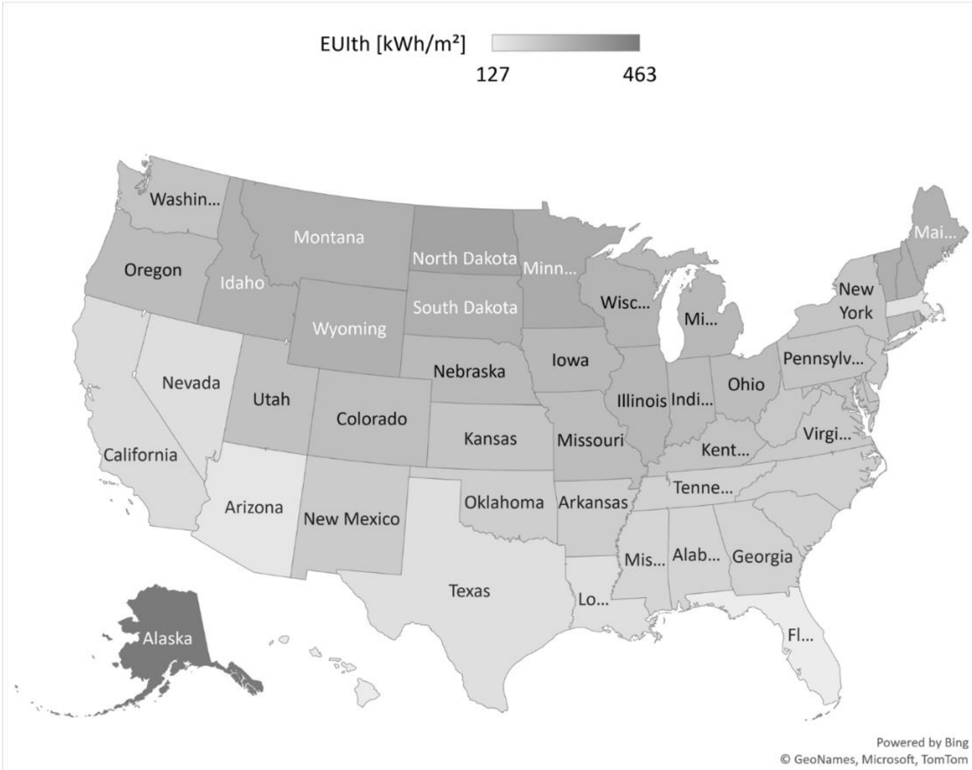

Figure 13. Thermal EUI, US.

2.6 COMPARISON BETWEEN HOTEL CLASSES AND TYPOLOGY

A deeper analysis has been done in order to understand which is the difference in consumption between three stars hotels and four-five ones.

Firstly, this study has been conducted in Europe.

Considering annual hotels, as a general trend, three stars hotels consume less electricity than upper-class hotels (Figure 14) except for Croatia where there are no significant differences, and for Portugal where the usual trend is reversed.

For the thermal case, the general behavior is that the 3* hotels use less energy than 4*-5* hotels except for Greece and Portugal (Figure 15).

The trend of the buildings located in Portugal is reversed in either electrical and thermal cases; this could be dependent on the occupancy rates of the 3* hotels (more people occupy the hotel, more energy is consumed) or also, on the better buildings insulation or the usage of renewable energy sources of the upper-class hotels; there is no information about these aspects on the scientific sources consulted.

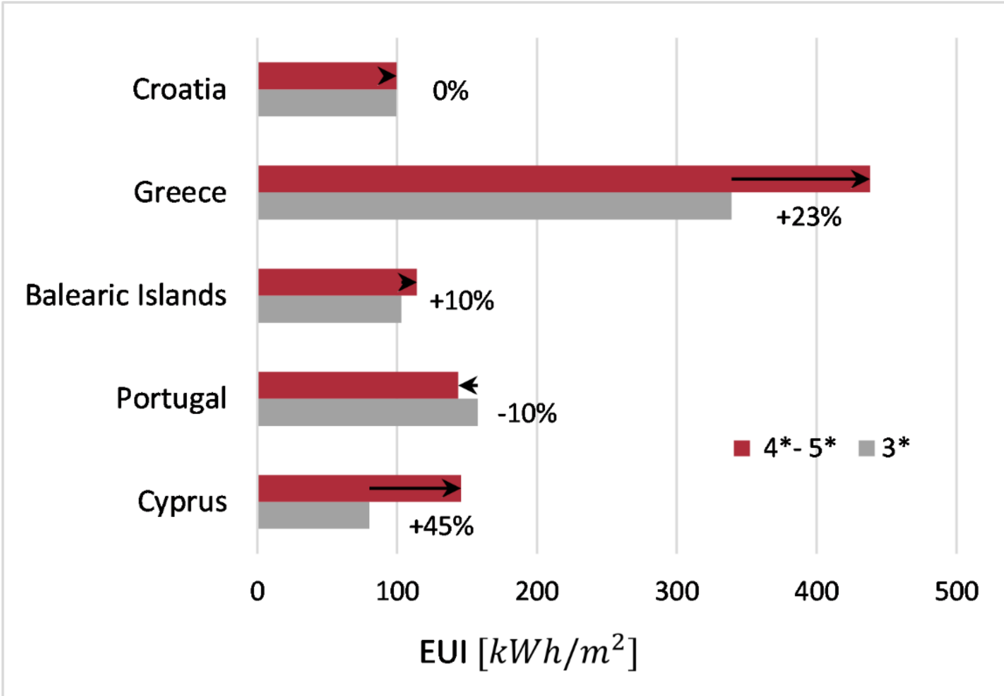

Figure 14. Electrical EUI, the difference between classes, EU.

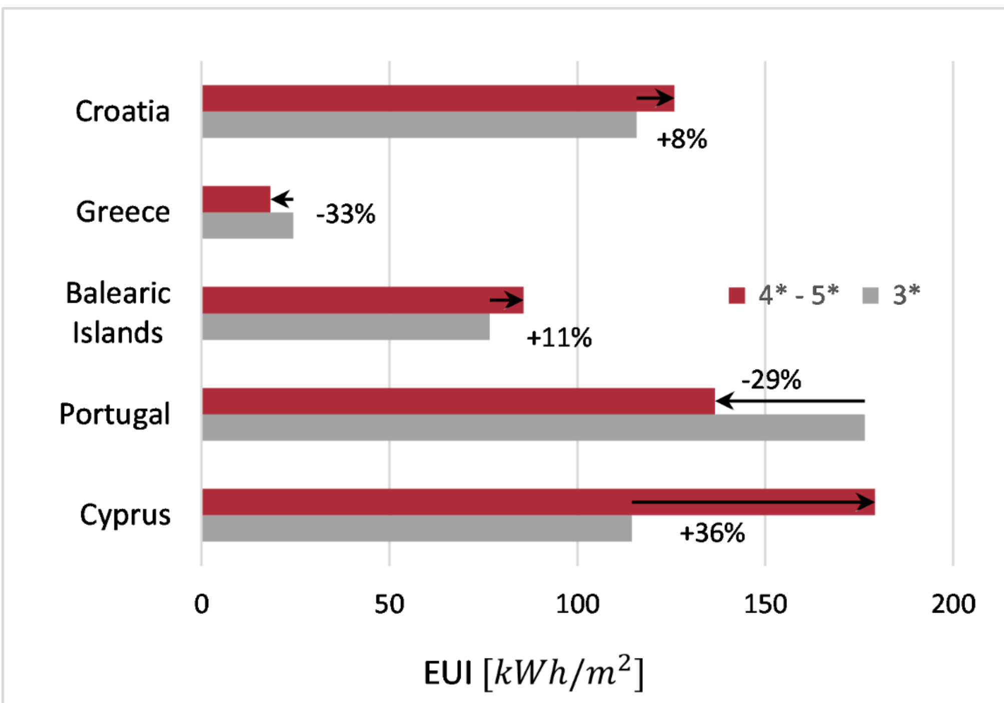

Figure 15. Thermal EUI, the difference between classes, EU.

This analysis has been done also for Asia where the situation is much less heterogeneous (Figure 16, Figure 17).

From either the electrical and thermal point of view, upper-class hotels consume from

16% to 37% more than three stars ones.
Hotels in Shanghai have a less remarked behavior than the other ones which are placed in different locations; this may be owing to the better performances of the upper classes hotels or the higher degree of occupancy of the three stars ones. Even in this case, there is no information about these types of features in the scientific articles consulted.

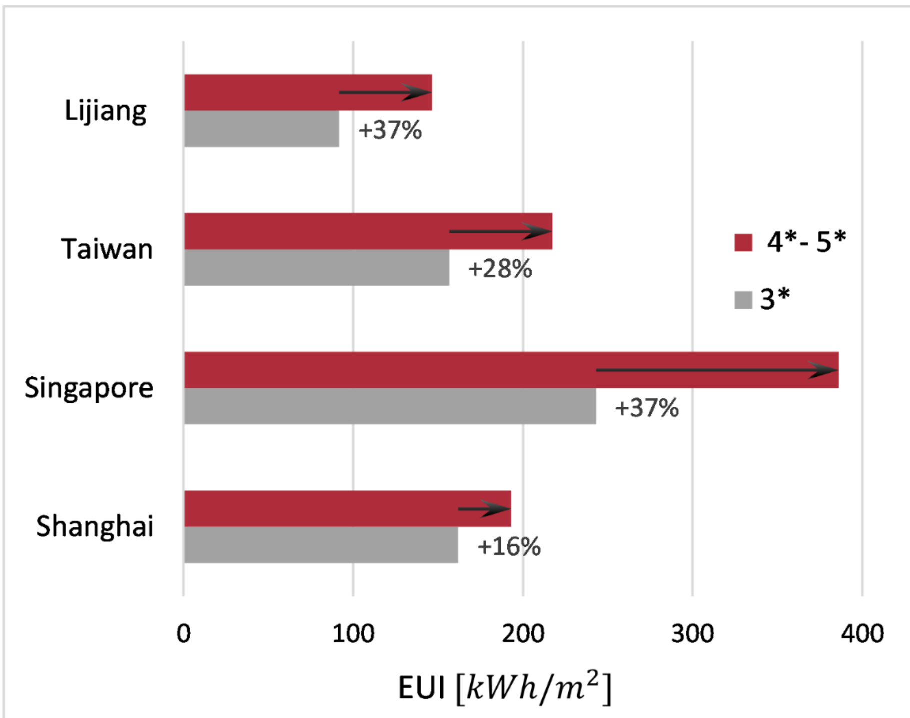

Figure 16. Electrical EUI, the difference between classes, Asia.

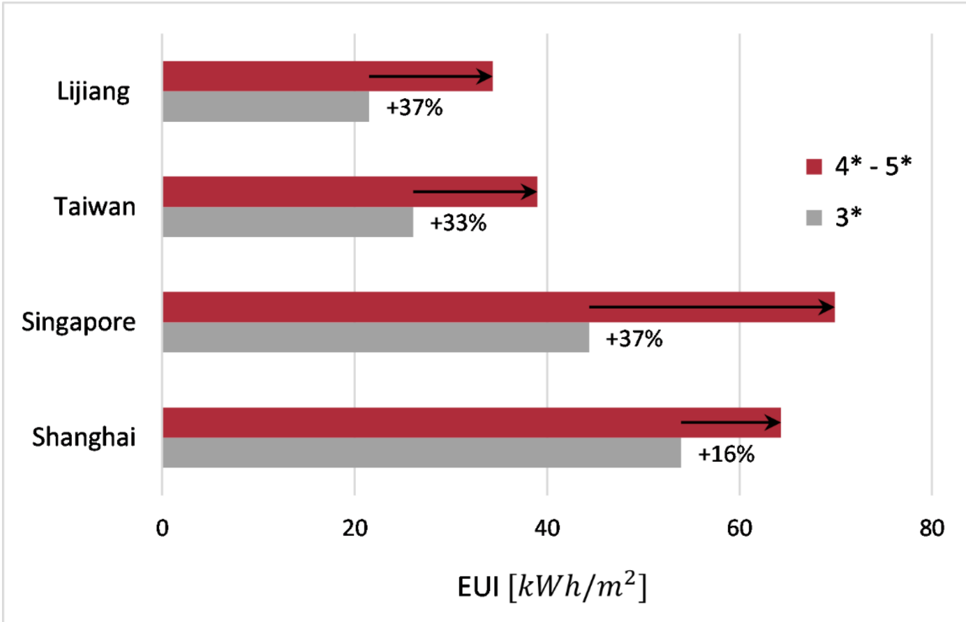

Figure 17. Thermal EUI, the difference between classes, Asia.

A different typology of analysis has been done between the differences in energy consumption of seasonal and annual hotels. Seasonal hotels work typically for no more than six months per year, annual hotels instead, the whole year.
The available data regards hotels located in the Balearic Islands and Croatia.
A typical annual hotel placed on the Balearic islands consumes more energy than a seasonal one: the indexes of EUI_{el} and EUI_{th} are 47% and 41% higher (Figure 18).
A less remarked trend has been obtained for hotels located in Croatia: the EUI_{el} and EUI_{th} indexes of annual hotels are only 19% and 14% higher than seasonal ones (Figure 19). This can be explained by the low occupancy rate between the period October – March [25], therefore fewer people occupy the hotel, lower is the energy consumption.

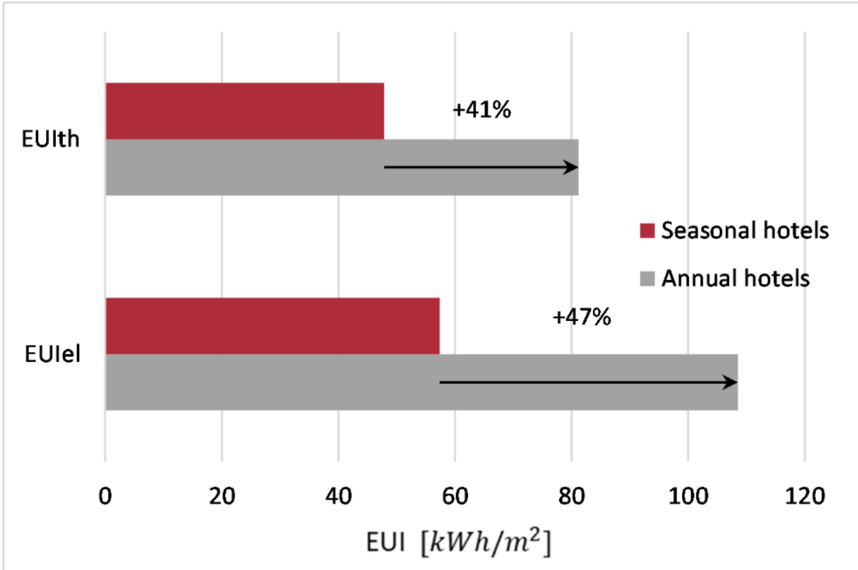

Figure 18. Comparison between seasonal and annual hotels - Balearic Islands.

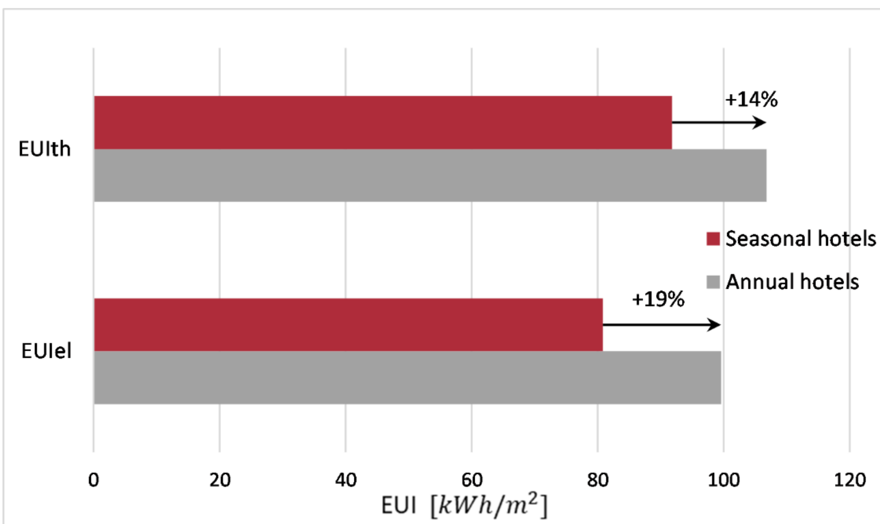

Figure 19. Comparison between seasonal and annual hotels – Croatia.

3 HOTELS HOURLY LOAD PROFILE

This chapter aims to obtain the hourly load profile of the hotels located in different areas of Europe and Asia.
The data from the scientific papers regards only the annual electrical and thermal consumption, therefore, to obtain the hourly load consumption, some steps must be performed.
Firstly, a climatic analysis has been done to classify the hotels according to their climatic zone. To achieve this goal the Koppen - Geiger Climate Classification has been used.
Secondly, from the Open Data Catalog of the U.S. Department of Energy[37], the hourly load profiles of some hotels located in established climate zones have been collected.
The climate of the United States is very heterogeneous, then the hourly load profiles have been used as a reference for the other hotels located in the same climate zones but on different continents. The software Matlab® has been used in order to scale the consumption of the analyzed hotels according to the EUI values.
To understand the situation of the Italian hotel industry, a survey was performed; 116 hotel owners were contacted through e-mail, but only five of them answered the questions.
Finally, a comparison between the consumption of annual and seasonal hotels has been performed.

3.1 ELECTRICAL AND THERMAL HOURLY CONSUMPTION

The analysis aims to obtain the hourly consumption of different hotels, starting from their annual electrical and thermal consumption.
The only information about the hourly consumption has been collected from the Open Data Catalog of the U.S. Department of Energy[37], therefore the hourly profile of some hotels in the United States will be used as a reference.
The idea is to understand the trend of the hourly consumption of the U.S hotels (located in "Csa/Csb" or "Cfa" zones) and apply this profile to the other hotels located in the same climate zone (but on different continents) using some "corrections" depending on the annual electrical or thermal consumption of the hotels under analysis.
Firstly, a climate classification according to the Koppen Climate map has been performed: most of the hotels are located in "Csa/Csb" or "Cfa" zones; the buildings under analysis are only four/five stars hotels and their electrical and thermal annual consumption is taken into account and it is shown in Table 7.
Therefore, the climate zones of the United States have been analyzed: Palm Springs (CA) and New York (NY) are characterized by "Csa/Csb" and "Cfa" climates respectively; then their annual and hourly consumption are used as reference (

Table 8).

Table 7. Koppen classification of the places where hotels are located with their EUI.

Places	Location	Koppen	EUI_{el}	EUI_{th}
1	Northern Italy	Cfa	152.2	212.2
2	Attica (Greece)	Csa/Csb	438.2	18.4
3	Cyprus	Csa	145.6	179.2
4	Turkey	Csa/Csb	388.8	39
5	Portugal	Csb	116	108.9
6	Spain	Csa/Csb	114.1	85.7
7	Greece	Csa/Csb	168.9	172
8	Croatia	Csa	99.7	125.9
9	Taiwan	Cfa	217.5	39
10	Shanghai	Cfa	193	64.3
11	Iran	Csa	134.1	357.5

Table 8. Koppen classification of the places where reference hotels are located with their EUI.

Ref.Places	Location	Koppen	EUI_{el}	EUI_{th}
1	Palm Springs (CA)	Csa/Csb	231.8	165.8
2	New York (NY)	Cfa	218.3	225.5

A further step has been performed to understand the trend of the electrical and thermal hourly consumption of the hotels located in the “Reference Places” for four days (in January, April, July and, October) scattered throughout the year. Since a hotel is open all the days during the entire week, there is no major difference between energy consumptions during the weekdays or weekends, then the significant variations are due to the seasonality as a consequence, it has been decided to consider as a reference the mid-month day of January, April, July, and October. These months are the middle months of the four-season Winter, Springs, Summer, and Autumn. The results are shown in the following figures (Figure 20, Figure 21, Figure 22, Figure 23).

As expected, the electrical consumption in Palm Springs on a typical day in July is higher than the other typical days because of the cooling systems; the thermal consumption in Palm Springs on a typical day in January is higher than the other typical days because of the heating systems; this last behavior is more remarkable for New York.

The curves represented in the figures have been obtained through a polynomial function that is useful to represent with fair approximation the available data collected from the Open Data Catalog of the U.S. Department of Energy[37]. In order to find the hourly energy needs of the other places, the functions “Polyfit” and “Polyval” have been used in Matlab®. They are defined as:

$$p = polyfit(x, y, n) \quad (2)$$

$$c = polyval(p, x) \quad (3)$$

The function “p” returns the coefficient for a polynomial function that is the best fit (in a least-squares sense) for the data in y. The function “c” returns the value of a polynomial p evaluated at x. The hours of the day have been defined as x, the hourly electrical (or thermal) consumption as y, and n is the polynomial degree.

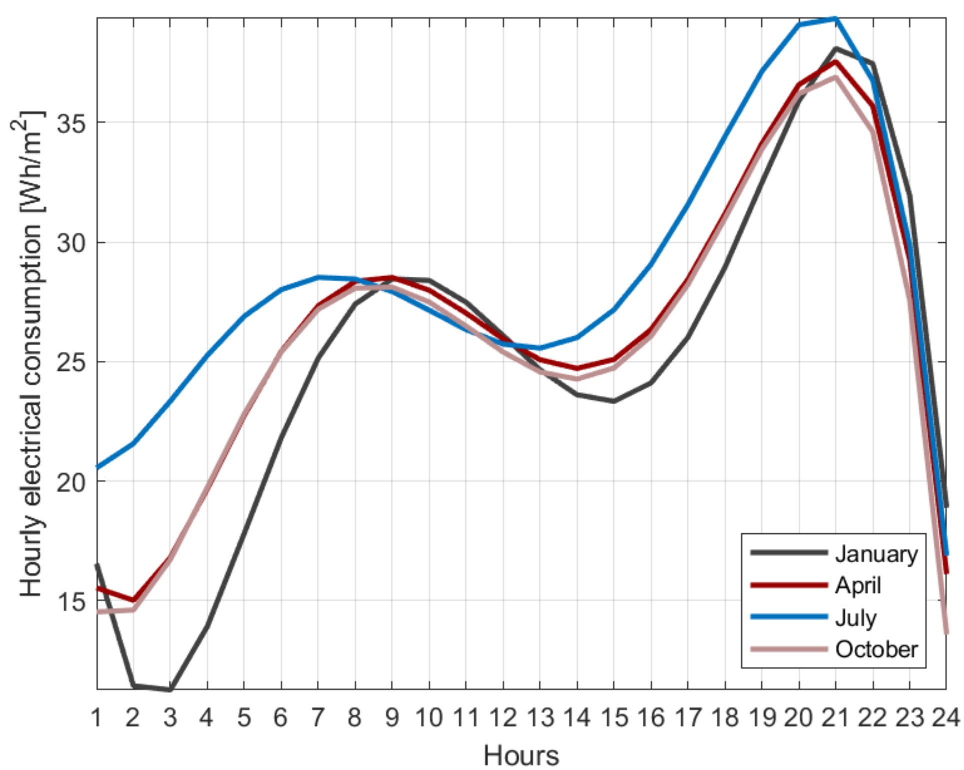

Figure 20. Palm Springs, hourly electrical consumption of four typical days in January, April, July, and October.

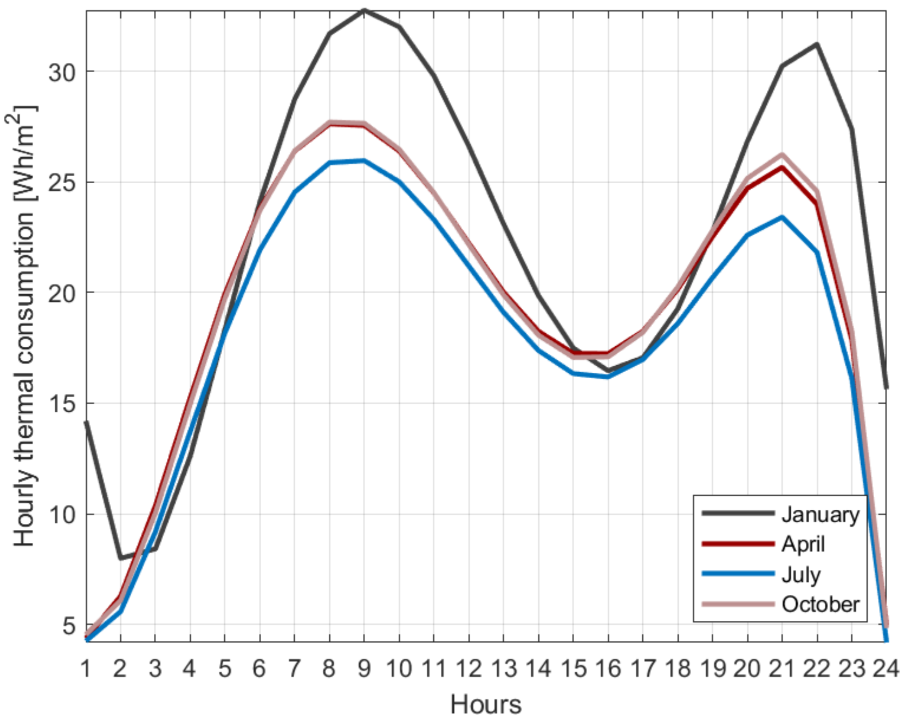

Figure 21. Palm Springs, hourly thermal consumption of four typical days in January, April, July, and October.

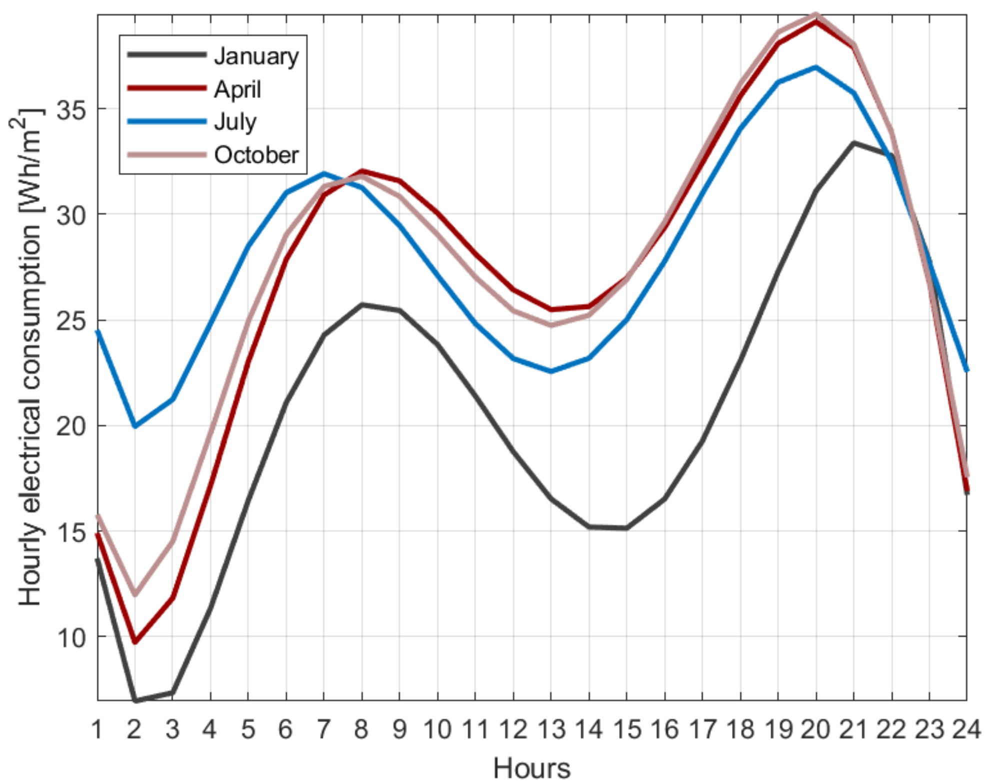

Figure 22. New York, hourly electrical consumption of four typical days in January, April, July, and October.

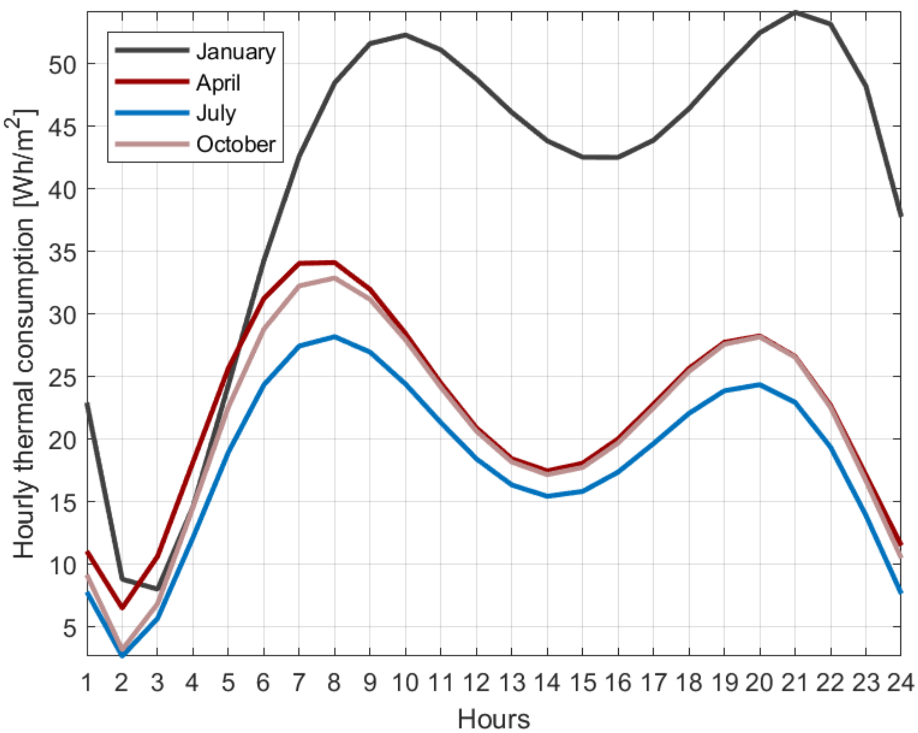

Figure 23. New York, hourly thermal consumption of four typical days in January, April, July, and October.

The hypothesis is based on the fact that the consumption of the hotels located in the same climate zone shows all the same hourly trend; therefore with this assumption, all the hotels located in the "Csa / Csb" climate zone, follow the curves of Palm Springs; all the hotels located in the "Cfa" climate zone, follow the curves of New York.
At this point, the hotels placed out of the U.S. has been "scaled" considering the annual EUI_{el} and EUI_{th} indexes.
For example, a hotel located in Turkey ("Csa" climate zone) behaves like the reference hotel placed in Palm Springs, but the curves are shifted up or down depending on whether the ratio between the (electrical or thermal) annual EUI index of Turkey and the annual EUI index of Palm Springs is lower or higher than one.
The model follows the equations above:

$$El.load_{Place}(x) = \frac{EUI_{EL_{Ref}}}{EUI_{EL_{Place}}} * El.load_{Ref}(x) \quad (4)$$

$$Daily = polyfit(x, hourly\_consumption\ , n) \quad (5)$$

$$El.load_{Ref}(x) = polyval(Daily, x) \quad (6)$$

Where:

- $\mathrm{El.}\,load_{Place}(\mathrm{x})$ is the hourly electrical consumption of the place, to be calculated;
- $El.\,load_{Ref}(\mathrm{x})$ refers to the hourly electrical load of the reference places (Palm Springs or New York);
- $\mathrm{EUI}_{\mathrm{EL}_{\mathrm{Ref}}}$ refers to the annual electrical energy use index of the reference places;
- $\mathrm{EUI}_{\mathrm{EL}_{Place}}$ is the annual electrical energy use index of the place where the hourly electrical consumption has to be found.

The same equations have been used for thermal loads.

In order to check if the chosen method is correct, the annual (electrical and thermal) EUI index is recalculated on the basis of the hourly hotel consumption. To achieve this purpose, another hypothesis has been assumed: the daily consumption of the four typical days is fixed as constant according to the seasonality; for example, the daily consumption of the typical day in January, is assumed as constant for the months of January, February, and March; the daily consumption of the typical day in April, is assumed as constant for April, May, and June; the daily consumption of the typical day in July is assumed as constant for July, August, and September; finally the daily consumption of the typical day in October is assumed non-variable for the months of October, November, and December.

As a consequence, the annual (electrical and thermal) EUI indexes have been calculated as the sum of the daily consumption. The results obtained by the model differ from one to four percent compared to the data collected from the literature (Table 9), therefore this method can be considered valuable.

This process will be used in the next chapter to establish the hourly load profile of the hotels in order to check if it is possible the installation of a SOFC-based cogeneration system.

Table 9. Electric and Thermal EUI results from the Matlab model.

Places	Location	$EUI_{el\text{-}model}$	$EUI_{th\text{-}model}$	EUI_{el}	EUI_{th}
1	Northern Italy	157.7	209.5	152.2	212.2
2	Attica (Greece)	437.0	19.2	438.2	18.4
3	Cyprus	145.2	187.1	145.6	179.2
4	Turkey	387.8	40.7	388.8	39
5	Portugal	115.7	113.7	116	108.9
6	Spain	113.8	89.5	114.1	85.7
7	Greece	168.5	179.6	168.9	172
8	Croatia	99.4	131.5	99.7	125.9
9	Taiwan	225.4	38.5	217.5	39
10	Shanghai	200	63.5	193	64.3
11	Iran	133.7	373.3	134.1	357.5

3.2 Survey on Italian Hospitality Sector

This part of the work aims to understand the situation of energy needs of the Italian hotel sector. Several hotel owners were contacted through e-mail but only five of them answered our questions. The location of the hotels is shown in Figure 24.

Figure 24. Location of the Italian hotels.

The first hotel under analysis is placed in Rome and it is one of the most fascinated hotels in the city center. It was built in 1889 and it is part of a hotel chain. Cooling and heating systems use only electrical energy; this explains the very low thermal load. Rome is considered a "Csa" climate zone.

The second and third buildings are located in Reggio Calabria ("Csa" climate zone). The second one was built at the end of the 60s and rebuilt at the beginning of 2000. It is placed in front of the seaside and it is also used for weddings or other ceremonies; it is a seasonal hotel, as a consequence, the electrical consumption during the cold months is very low.
The third one is one of the most beautiful hotels in the city center. It was built at the beginning of the 60s and restored in the 90s. These two hotels are not connected to the gas line, but, when it is needed, they fulfill their tanks of methane and propane respectively; they do not collect data on their consumption.
The 4th building located in Gubbio (PG) is a seventieth-century monastery that was recently restored. It is composed of 92 rooms, 4 restaurants, 8 meeting rooms each for 400 people, and SPA with a pool. Methane is used for heating systems. It is one of the most elegant hotels in the city and it is placed in a "Csa" climate zone.
The last hotel is located in a "Cfa" climate zone. This magnificent building was built at the beginning of the sixtieth century in one of the most beautiful hilly places in Piedmont, the "Langhe". It is a monastery surrounded by vineyards. GPL is used for running the heating systems.
A more general description is given in Table 10.

Table 10. Hotels information from the Italian survey.

Survey	Area [m^2]	Location	Stars	Typology	Position	Climate
HOTEL 1	7000	Rome	5*	Annual	Central Italy	Csa
HOTEL 2	8618	Reggio Calabria	5*	Seasonal	Southern Italy	Csa
HOTEL 3	2797	Reggio Calabria	4*	Annual	Southern Italy	Csa
HOTEL 4	8179	Gubbio (PG)	4*	Annual	Central Italy	Csa
HOTEL 5	5100	Cuneo	5*	Annual	Northern Italy	Cfa

As it can be seen from Table 11, the electrical energy consumption is higher during the summer months; this is because of the utilization of the cooling systems. The first hotel located in Rome has the highest annual electrical consumption due to the fact that the cooling and heating systems using electricity to run.
The lowest electrical energy consumption is reached from the hotel located in Gubbio; this could be because this ancient monastery has very thick walls, which causes a high thermal resistance during summer months and so the cooling systems use is reduced. On the other hand, this has the highest thermal energy demand (Table 12Table 11), probably because it takes a long time to achieve a comfortable temperature during the wintertime. The lowest thermal energy consumption is reached from the hotel located in Rome, as a consequence of the fact that it is used only for the heating of a "security tank" for DHW. However, if their consumption would be measured, the lowest thermal energy consumption would be probably reached from the hotels located in Reggio Calabria, due to the fact that one of them is located further South and the other is a seasonal one,

therefore it has been expected a lower thermal consumption.
The fifth hotel utilizes more or less the same amount of both electrical ad thermal energy; this can be due to the fact that the building has low energy efficiency, the degree of occupation is very high during all the year and the climate zone is different from the other ones. In the following tables (Table 11, Table 12), the data collected from the Italian Hotels are shown. In Figure 25 the monthly electrical energy consumption is shown: all the hotels consume more in the summer than the other seasons; this is due to the high usage of the air conditioning systems.

Table 11. Electrical monthly consumption, Italian Hotels.

EUI_{el}	HOTEL 1	HOTEL 2	HOTEL 3	HOTEL 4	HOTEL 5
January	27.5	1.9	19.9	4.8	17.2
February	26.6	1.4	19.4	4.3	15.2
March	26.7	1.4	19.0	5.0	17.1
April	29.9	5.1	17.8	7.9	17.0
May	32.4	12.2	20.8	12.9	18.6
June	34.7	19.0	21.8	14.7	23.0
July	40.8	25.1	25.2	15.0	26.6
August	37.2	27.3	27.1	16.6	27.9
September	34.9	23.7	24.4	14.7	23.9
October	33.1	10.8	22.0	8.3	17.8
November	30.0	1.9	17.9	5.1	16.7
December	33.1	3.4	18.4	12.8	17.1
Tot.Yearly [kWh/m2]	386.9	133.2	253.8	122.2	237.9

Table 12. Thermal monthly consumption, Italian Hotels.

EUI_{th}	HOTEL 1	HOTEL 2	HOTEL 3	HOTEL 4	HOTEL 5
January	2.3	N/A	N/A	47.9	31.7
February	4.6	N/A	N/A	44.0	37.0
March	3.6	N/A	N/A	48.4	31.1
April	1.2	N/A	N/A	29.7	14.4
May	0.7	N/A	N/A	16.7	6.4
June	0.1	N/A	N/A	17.0	6.1
July	0.1	N/A	N/A	8.7	3.2
August	0.1	N/A	N/A	12.1	5.5
September	0.9	N/A	N/A	15.5	9.6
October	1.5	N/A	N/A	21.3	15.4
November	0.7	N/A	N/A	35.5	16.1
December	1.9	N/A	N/A	40.2	24.8
Tot.Yearly [kWh/m2]	17.9	N/A	N/A	337.0	201.4

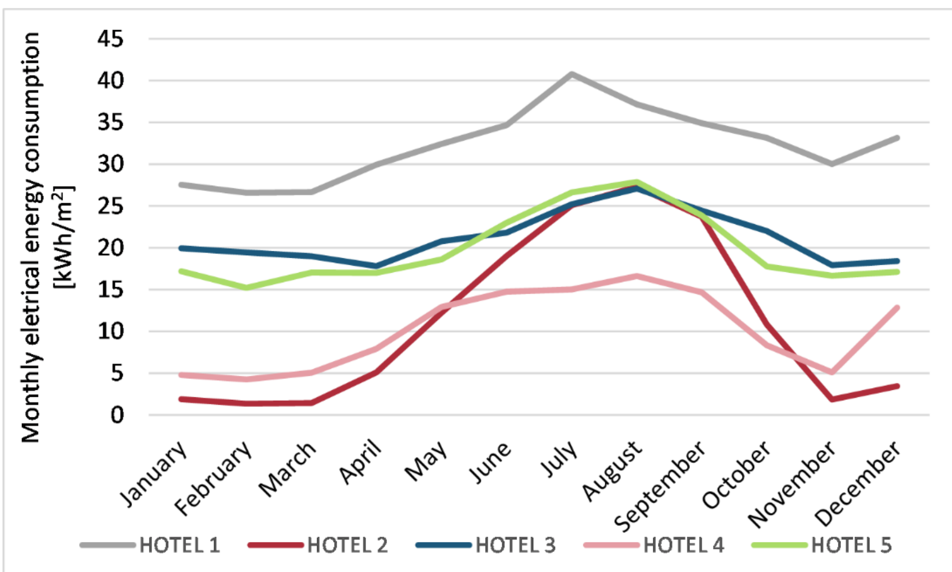

Figure 25. Monthly electrical consumption of Italian hotels.

In this analysis, the available data are the monthly electrical and thermal EUI. An analysis similar to the one of the previous paragraph has been done in order to understand the hourly consumption starting from the monthly EUI index.

All the hotels are located in a "Csa climate zone" except for the last one that is located in the "Cfa" zone. The following figures (Figure 26-Figure 27) show the results of the simulations aimed to obtain the hourly load profiles from the monthly ones considering the "Csa" climate zone. As expected, the hotel located in Gubbio has the best performance in terms of electric energy efficiency because it has thick walls which cause a high thermal resistance (during summer months the internal temperature does not increase rapidly), and a high heat capacity (during winter months they absorb a large amount of heat and therefore it is necessary to provide a high amount of thermal energy to heat the hotel up).

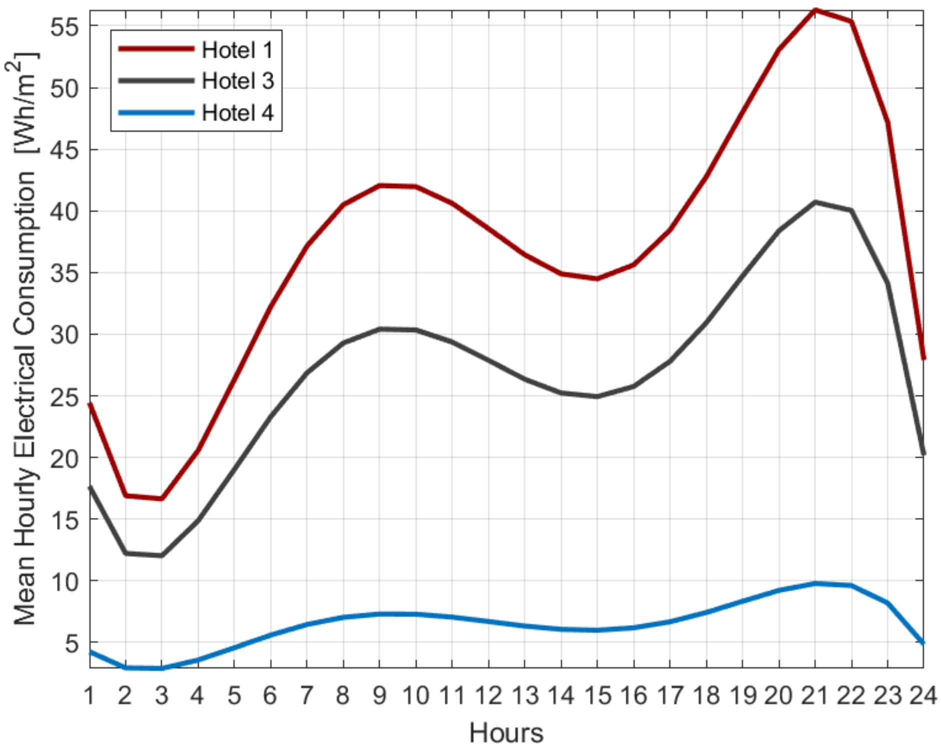

Figure 26. Simulation of the electrical consumption of a typical winter day.

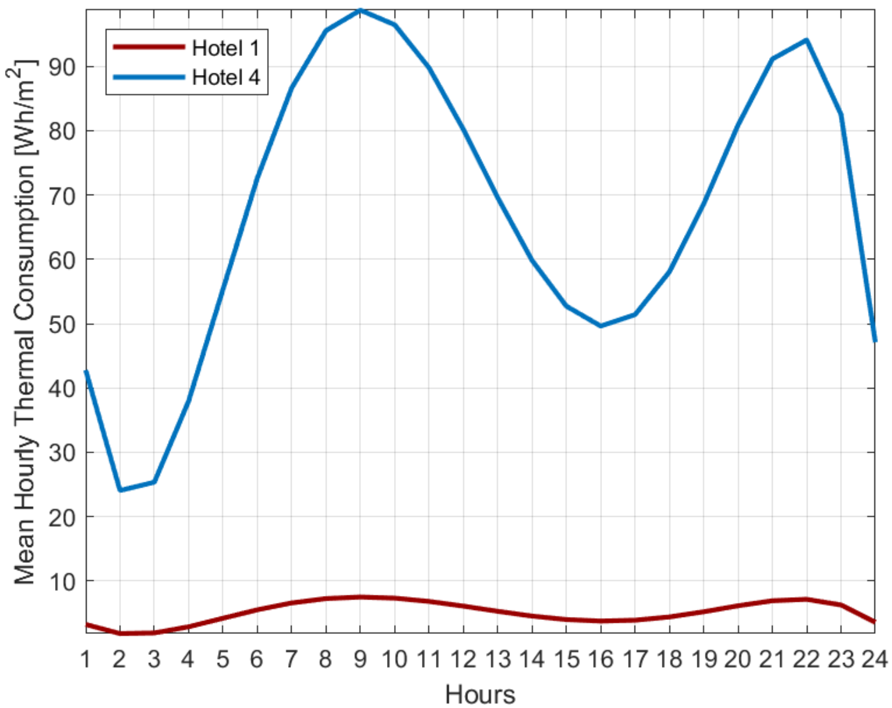

Figure 27. Simulation of the thermal consumption of a typical winter day (Csa).

Another simulation has been done for the hotel placed in Cuneo, taking into account the different climate zone. In Figure 28, considering the consumption of a typical day in January, the results picked up from the Matlab® simulation are shown. As expected, the thermal consumption is higher due to the low temperatures of Cuneo in the cold months than the other temperatures of the areas where are placed the analyzed hotels.

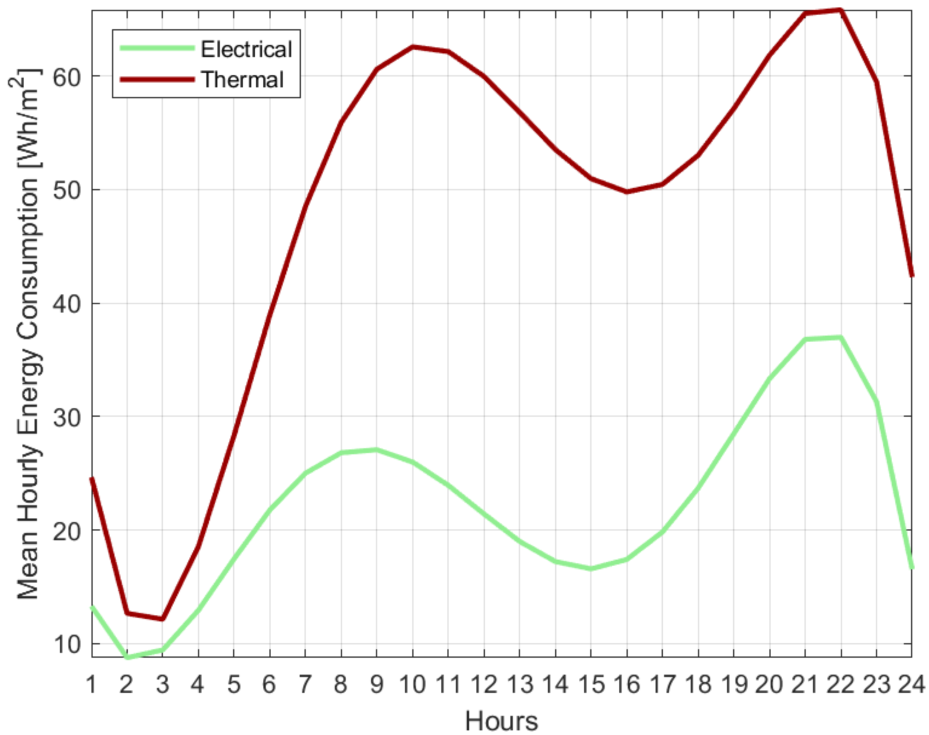

Figure 28. Simulation of electrical and thermal consumption of a typical winter day (Cfa, CN).

3.3 Comparison between Seasonal and Annual Hotels

In this paragraph, a comparison between annual and seasonal hotels has been performed. The only data about a seasonal and annual hotel placed in the same location regard the buildings in Reggio Calabria (Table 11Figure 29). These pieces of information are about the monthly consumption, while there are no data about the hourly profile. It is, therefore, necessary to build a model able to calculate the hourly profile of a seasonal hotel placed in Palm Springs and then apply this, to different locations belonging to the same climate zone.
The results have been obtained following these steps:

1. A proportion is imposed as:

$$seasonal_{PS}: annual_{PS} = seasonal_{RC}: annual_{RC}; \qquad (7)$$

Where $seasonal_{RC}$ is a vector that contains the monthly electrical consumption of a seasonal hotel and $annual_{RC}$ is a vector that contains the monthly electrical consumption of an annual hotel. These data are obtained from the hotel owners in Reggio Calabria. The vector $annual_{PS}$ contains the monthly electrical consumption of a hotel located in Palm Springs. These data are from the Open Data Catalog of the U.S. Department of Energy[37].

2. A vector A is defined in order to obtain which is the monthly relationship between a seasonal and an annual hotel. It contains twelve elements correspondent to twelve months, and it is defined as:

$$A = seasonal_{RC}/annual_{RC}; \quad (8)$$

3. The monthly electrical energy consumption of a seasonal hotel located in Palm Springs is obtained as:

$$seasonal_{PS} = A * annual_{PS}; \quad (9)$$

Figure 29 shows the results of the calculation. A seasonal hotel is open to visitors from about half of April to half of October in a Mediterranean place. During July and August, the projection of the seasonal one in Palm Springs is slightly higher than the annual one (Figure 29).

4. The further step is using the US hourly load curves (36) as a reference for the calculation of the hourly profile of seasonal hotels located in the same climate zone.
   This analysis has been done for a hotel located in Rome.
   The following proportion has been set as:

$$hourly_{seasonal_{RM}} : seasonal_{RM} = hourly_{seasonal_{PS}} : seasonal_{PS}; \quad (10)$$

   Where $seasonal_{RM}$ is a vector that contains the electrical energy consumption of a seasonal hotel located in Rome and it is defined as:

$$seasonal_{RM} = A * annual_{RM}; \quad (11)$$

$annual_{RM}$ is a vector that contains the monthly electrical consumption of an annual hotel; these data are collected from the hotel owner in Rome.
As a hypothesis, it has been considered the $hourly_{annual_{PS}} = hourly_{seasonal_{PS}}$ and therefore these data have been collected for a mid - months day in April, May, June, July, August, September, October.
5. Finally, the hourly $hourly_{seasonal_{RM}}$ is defined as:

$$hourly_{seasonal_{RM}} = \frac{seasonal_{RM}}{seasonal_{PS}} * hourly_{seasonal_{PS}} \quad (12)$$

$hourly_{seasonal_{PS}}$ is a vector that contains the hourly electrical energy consumption of a seasonal hotel in Palm Springs for the months between April and October.

Figure 30 shows the different hourly curves of typical days from April to October. As expected, during a typical day in August, the electrical consumption is the highest, because of the external hottest temperatures.

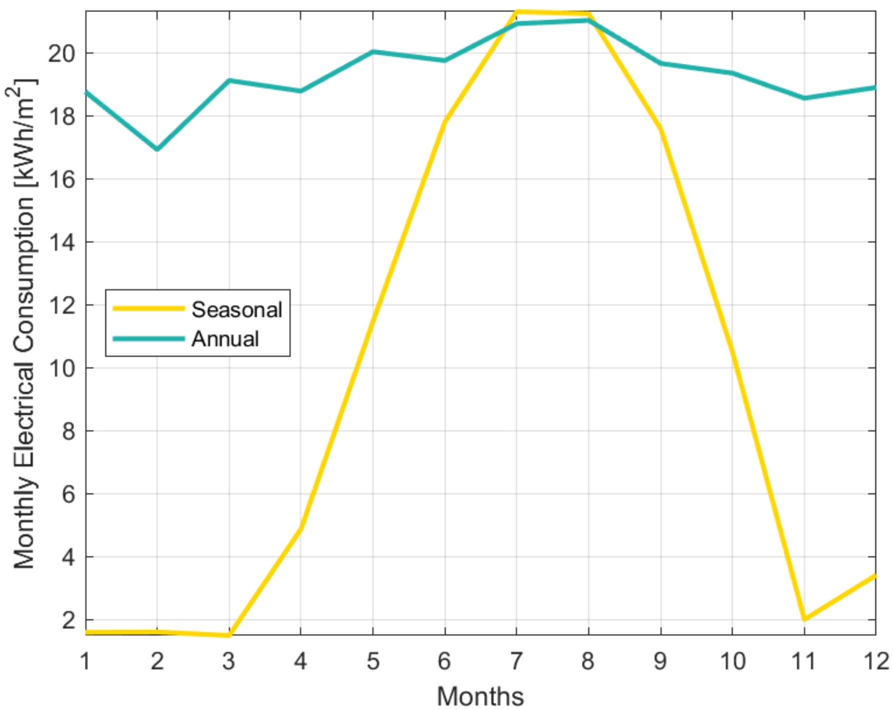

Figure 29. The monthly electrical consumption (Csa, Palm Springs)

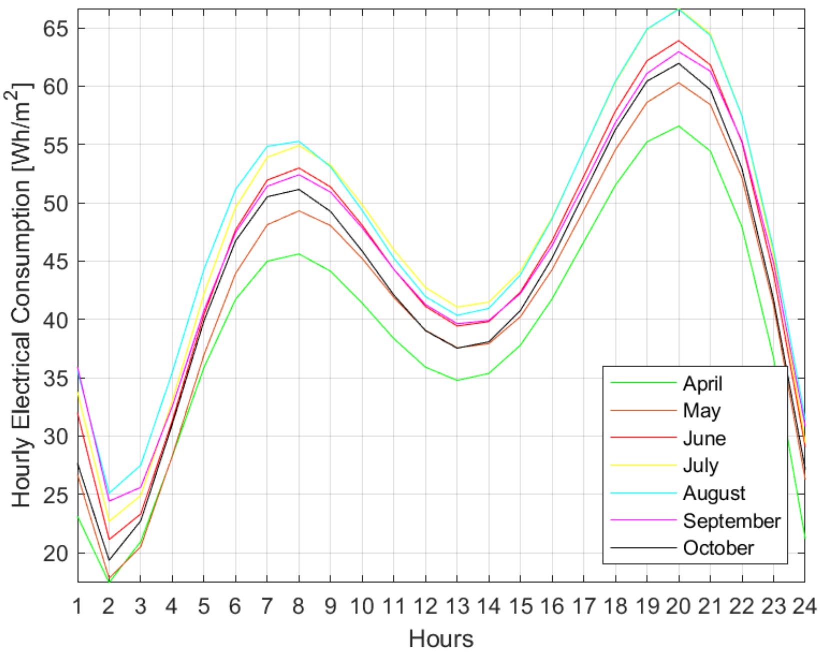

Figure 30. Hourly load profiles of typical days (Csa, Rome).

4 SOFC-Based Cogeneration System

This chapter aims to evaluate the application of a SOFC-based cogeneration system in upscale hotels.
The analysis will be performed with the hourly data obtained from the Matlab® model of the previous chapter and deciding to place hotels in Greece, Italy, Portugal, and Taiwan.
Firstly, for each place, research about the mean sizes of the hotels has to be done; therefore the proper baseload of a typical day must be selected.
It has been decided to chose two different sizes of the hotels between “small”, “medium” and “large”.
The optimal baseload has been selected considering the lowest payback time. Then, the analysis of the cost of electricity, gas, and also the presence of subsidies in these areas has been done.
Finally, an economic evaluation in order to understand the feasibility of the SOFC-based cogeneration systems in this market has been performed.

4.1 Hotels average sizes

The U.S. DOE (Department of energy) classified 16 commercial building types [37]. Among these, a “Small Hotel” has a floor area of $43'200\ ft^2$ that are almost equal to $4'000\ m^2$ and a “Large hotel “ has a floor area of $122'120\ ft^2$ ($\cong 11'345\ m^2$).
According to these definitions, it has been decided to define:

- Large hotel: minimum floor area of $10'000\ m^2$;
- Medium hotel: floor area between $4'001\ and\ 9'999\ m^2$;
- Small hotel: floor area below $4'000\ m^2$.

Following the data of the hotel areas collected from the literature [17–20, 23], in Europe, most of the buildings are on average “Medium” size hotels, as shown in Figure 31.

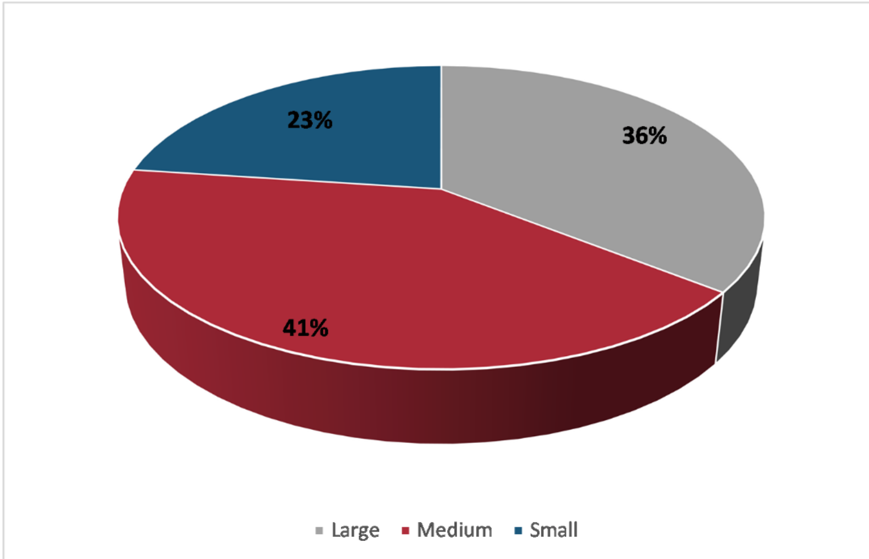

Figure 31. Average sizes hotels in Europe.

According to the data of the scientific papers, in Italy and Greece, most of the hotels are small and medium, while in Portugal medium and large. Therefore it has been decided to analyze only these categories, excluding large size hotels, which are not typical of the chosen EU countries. The average surface area for the most diffuse categories has been calculated and is shown in Table 13.
The average floor area for hotel buildings in Taiwan has been taken into account [29] and it is equal to $18{,}738\ m^2$, as a consequence, most are classified as "Large hotels".

Table 13. Hotels average floor areas in Italy, Greece, Portugal, and Taiwan

Area [m^2]	Small	Medium	Large
Italy	3'300	7'267	-
Portugal	-	6'293	18'264
Greece	2'190	5'964	-
Taiwan	-	-	18'738

4.2 System Description

The baseload choice for each type of hotel is not so simple; the idea is to choose the proper baseload in order to have the lowest payback time while maximizing the operating profile of the SOFC system (which should have a reduced number of thermal cycles per year). This analysis has been focused on the three possible baseloads, and the optimal system design has been chosen as the one able to minimize the PBT.

The baseload analysis is strictly connected to the determination of the size and the number of SOFC modules; in order to perform these analyses, two base SOFC module size

has been defined, SOFC 1 25 kW and SOFC 2 50 kW, and have been used for small/medium and large hotels respectively, in order to avoid to have a too high number of modules. They will be shown in Table 14.
The current stack technical lifetime has been set to 60,093 considering an average stack lifetime of 7 years (61,320 hours) and multiptlying it times the capacity factor of 0.98.
The electrical and thermal efficiencies have been defined as:

$$\eta_{el,AC} = \frac{W_{AC,net}}{\dot{m_{fuel}} * LHV} \tag{13}$$

$$\eta_{th} = \frac{Q_{HR}}{\dot{m_{fuel}} * LHV} \tag{14}$$

Where:

- $W_{AC,net}$: electrical net power (Alternating Power), equal to the SOFC system nominal size [kW];
- Q_{HR}: thermal power, SOFC system byproduct [kW];
- m_{fuel}: volumetric flow rate of the fuel (methane in this case) $\left[\frac{Smc}{h}\right]$;
- LHV: The lower heating value of the methane equal to 10 $\left[\frac{kWh}{Smc}\right]$.

Table 14. Technical Information of SOFCs used in the analysis.

Technical information	SOFC 1	SOFC 2	Units
SOFC system nominal size	25	50	kW
Electrical efficiency	55	55	%
Thermal efficiency	27	27	%
Average system availability	98	98	%
Current stack technical lifetime	60,093	60,093	h

The working mechanism of the SOFC system is shown in Figure 32. The fuel for the SOFC system is methane (natural gas from the grid, supposed as pure methane); the fuel cell stack produces an electrical output that is necessary to satisfy the electrical need of the hotel; the thermal energy output is used to heat up the water in the thermal storage and then used to satisfy the thermal need of the hotel. The peaks of the thermal energy needed are satisfied by the usage of a natural gas boiler. In the following calculations, the efficiency of the boiler is set at 98%. The excess heat produced by the stack can be sold to the DH network (the analysis is based on the assumption that a DH network is locally available nearby the hotel); the excess electricity is sold to the grid.

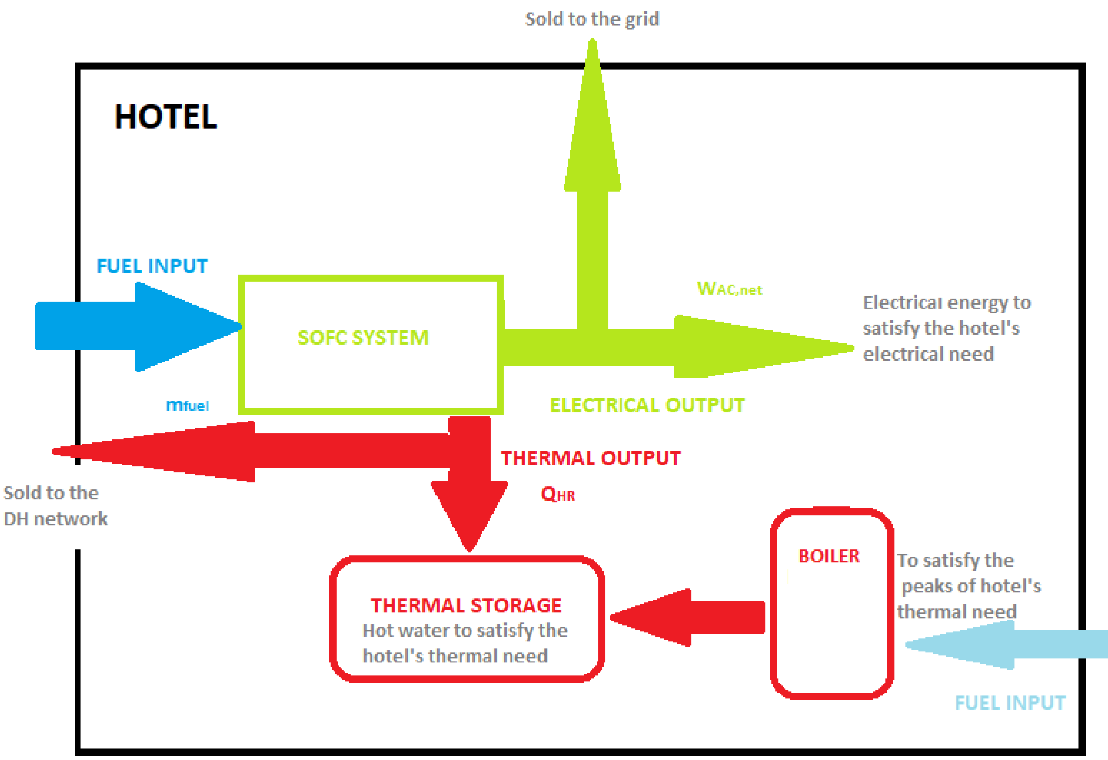

Figure 32. SOFC system.

4.3 Energy Prices and Subsidies

In order to perform the economic analysis, it is necessary to know the energy prices for each location. The data for electricity and gas natural prices have been taken from [40, 41] for the European countries, and from [42, 43] for Taiwan. The other data for Italy has been taken from the “Gestore Servizi Energetici” [44].

A deeper analysis has been performed for the subsidies in Italy: following the “*Decree-Law No 83/2014, art. 10*” [45], under certain conditions, the hotel owners can obtain a subsidy equal to the 65% of the initial CAPEX; these conditions are given for a maximum subsidy of 200,000€ and a Primary Energy Saving (PES) of at least 20%. The calculation for PES has been performed following the “*Ministerial Decree 4th August 2011*” [46] where it is defined as:

$$PES = 1 - \left(\frac{1}{\frac{CHP\ H}{Ref\ H}+\frac{CHP\ E}{Ref\ E}}\right) * 100 \qquad (15)$$

Where:

- $CHP\ H$: thermal efficiency of the cogeneration system;
- $Ref\ H$: reference efficiency for separated production of thermal energy ([46]);
- $CHP\ E$: electrical efficiency of the cogeneration system;
- $Ref\ E$: reference efficiency for separated production of electrical energy([46]).

Following the reference values of the analyzed SOFC systems, the PES is equal to 20%: as a consequence, the hotel owners can obtain the subsidy.
For Portugal, the data regarding the electricity selling price and the DH one, are taken from the "*Decree-Law No. 104/2019*" that sets the clawback contribution as $2.71\,\frac{€}{MWh}$ for coal electricity production and $4.18\,\frac{€}{MWh}$ for promoters of projects using other technologies [47] and from an analysis of district heating and cooling potential [48].
The electricity and DH selling prices for Greece have been taken from a website regarding the RES market in Greece [49] and the master thesis about the DH potential [50].
For Taiwan, the electricity selling price has been obtained from the website of "Taipower" [51] and the district heating selling price has been considered equal to the Chinese one because there is no information about Taiwanese prices [52].
A general overview of the energy prices is shown in Table 15.

Table 15. Energy prices for Italy, Portugal, Greece, and Taiwan

Costs	Italy	Portugal	Greece	Taiwan
Electricity price [€/kWh]	0.150	0.11	0.105	0.11
Electricity selling price [€/kWh]	0.06	0.04	0.08	0.06
Natural gas price [€/smc]	0.3	0.28	0.25	0.22
DH selling price [€/kWh]	0.025	0.040	0.030	0.018
Natural gas price [€/kWh]	0.030	0.028	0.025	0.022

4.4 Economic Evaluation

In order to perform an economic analysis, it is necessary to define first the CAPEX and OPEX.
CAPEX (Capital expenditure) is the initial investment cost that the hotel owner pays at the initial time; it includes the SOFC cost and the installation cost. At the current time, the CAPEX is set to $10{,}000\,\frac{€}{kW}$ but in the future, with the development of the technology, it may reach $4{,}000\,\frac{€}{kW}$ [53, 54].The OPEX are the operating costs that the hotel owner pays every year from the initial time to the end of life of the system, which in these analyses is set to 27 years. At the current time, OPEX costs are set to $1{,}500\,\frac{€}{y}$, but in the future, they

could be set to $750\frac{€}{y}$. These are average prices from manufacturers collected in the framework of the Comsos project.
A general overview is shown in Table 16.

Table 16. Economic information.

Economic information	SOFC Costs	Units
Total CAPEX - current	10,000	€/kW
Total CAPEX - target	4,000	€/kW
OPEX - current	1,500	€/y
OPEX - target	750	€/y

The capacity factor (CF) represents the percentage of SOFC system working hours per year and it is defined as (assuming 5 days of maintenance per year):

$$CF = \frac{working\ hours}{total\ hours\ per\ year} * 100 = \frac{working\ hours}{8760} * 100 = \frac{8585}{8760} * 100 = 98\% \qquad (16)$$

Following the technical information (Table 14) the stack replacement occurs every seven years.
The yearly incomes are calculated as:

$$Incomes = savings_{el} + savings_{th} + revenues_{el} + revenues_{th} - cost_{fuel_{SOFC}}\ [€] \qquad (17)$$

With:

$$savings_{el} = W_{AC,net} * Electricity_{cost} \qquad [€] \qquad (18)$$

$$savings_{th} = Q_{HR} * \frac{gas_{cost}}{\eta_{boiler}} \qquad [€] \qquad (19)$$

$$revenues_{el} = Electricity_{sold} * Electricity_{selling_{price}}\ [€] \qquad (20)$$

$$revenues_{th} = Thermal\ energy_{sold} * DH\_selling_{price}\ [€] \qquad (21)$$

$$cost_{fuel_{SOFC}} = m_{fuel} * gas_{cost} \qquad [€] \qquad (22)$$

The $Electricity_{cost}$, gas_{cost}, $DH\_selling_{price}$, $Electricity_{selling_{price}}$ of the different countries have been taken from Table 15.

Considering an analysis before taxes, the cash flow is defined as:

$$Cash\ flow = Incomes - costs\ \left[\frac{€}{y}\right] \qquad (23)$$

The discounting factor is the number by which a future cash flow has to be multiplied to obtain the present cash flow and it is set as:

$$Discounting\ factor = (1 + WACC)^{-(n-n_0)} \quad (24)$$

The discounting factor depends on WACC (Weighted Average Cost of Capital) that represents a firm's cost of capital in which every category is proportionally weighted.

As hypothesis $WACC = 3\%$; n is the lifetime of the plant set at 27 years, and n_0 the year where the $Discounting\ factor$ must be calculated.

$$Present\ cash\ flow = Cash\ flow * Discounting\ factor\ \left[\frac{€}{y}\right] \quad (25)$$

$$Cumulative\ cash\ flow = \sum_{n=0}^{i} Present\ cash\ flow_n \quad (26)$$

The year in which the cumulative cash flow starts to be positive is the year in which the hotel owner starts to earn money; this year is called Payback time. It is defined as [55]:

$$PBT = 1 + n_y - \frac{n}{p} \quad [y] \quad (27)$$

Where:

n_y= number of years at which the last negative value of cumulative cash flow occurs.

n = the value of the last negative cumulative cash flow.

p = the value of cash flow at which the first cumulative cash flow occurs.

The economic analysis will be performed for each country considering the sizes of the SOFC modules shown in Table 13.

4.4.1 Cash flow analysis

A cash flow analysis has been performed for each place considering three cases: CASE 1, CASE 2, CASE 3. The values of each case are shown in Table 17. These cases have been obtained considering the baseloads chosen from figures Figure 33,Figure 40Figure 41Figure 42 and multiply these for the correspondent areas in Table 13.

Table 17. Values of each case under analysis.

CASE	CASE 1	CASE 2	CASE 3
Italy	min. baseload	min.+40%	min.+70%
Greece	min. baseload	min.+30%	min.+50%
Portugal	min. baseload	min.+20%	min.+50%
Taiwan	min. baseload	min.+35%	min.+70%

These analyses have been performed considering the target costs for both CAPEX and OPEX that are shown in Table 16. Using the current costs, the investment has been considered unfeasible for each case under analysis, except for Italy, but this is only due to the presence of subsidies.

Considering the daily electrical load of an Italian hotel, three cases have been considered to be analyzed (Figure 33). The three cases 1, 2, and 3 correspond to the minimum baseload (minimum point of the electrical load curve), 1.4 times the minimum, 1.7 times the minimum respectively.

According to the baseload considered, the numbers and powers of SOFC modules have been decided, and therefore the electrical and thermal powers sold.

In Table 18, the results considering the three baseloads are shown; the baseload (in kW) has been obtained considered the three cases of Figure 33, and multiply these by the correspondent area on Table 13.

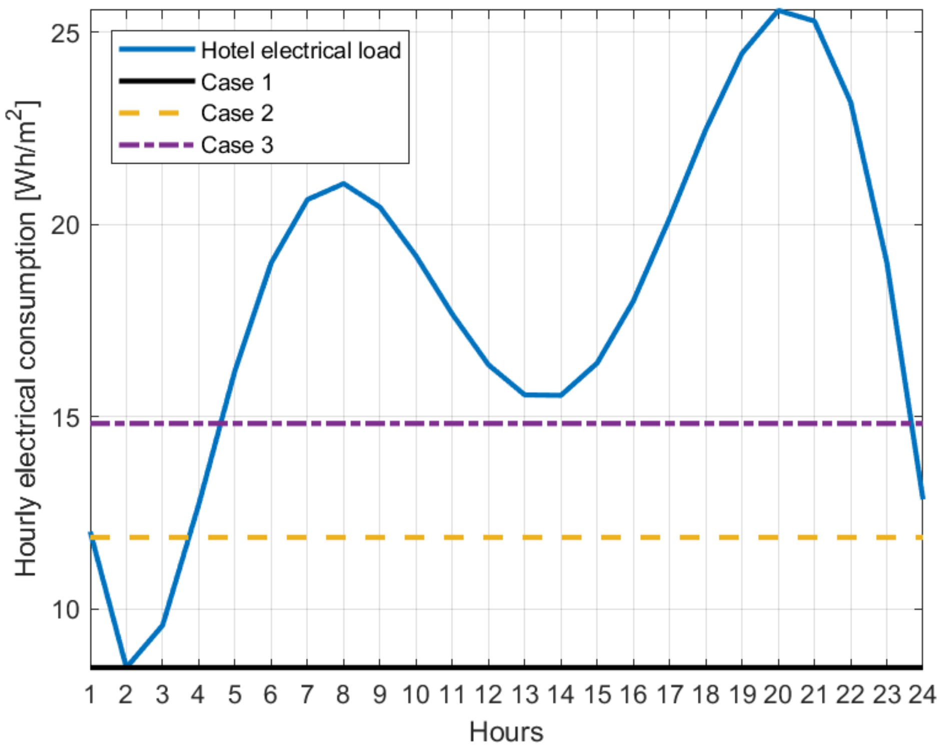

Figure 33. Italian hotel baseload.

Table 18. Specifications of the system, small Italian hotel.

SMALL HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	27.95	39.60	49.50
SOFC base size [kW]	25.00	25.00	25.00
Quantity SOFC	1.12	1.58	1.98
Number of modules SOFC	1.00	2.00	2.00
Wac,net SOFC [kW]	**25.00**	**50.00**	**50.00**
QHR SOFC [kW]	12.27	24.55	24.55
Wac, net SOFC daily [kWh]	600.00	1200.00	1200.00
QHR SOFC daily [kWh]	294.55	589.09	589.09
Daily el. Load hotel [kWh]	1422.30	1422.30	1422.30
Daily th. Load hotel [kWh]	1907.40	1907.40	1907.40
Daily Electricity sold [kWh]	0.00	66.15	66.15
Thermal energy sold [kWh]	0.00	0.00	0.00
Gas SOFC[m3/h]	4.55	9.09	9.09
Daily gas SOFC [m3/day]	109.09	218.18	218.18
Share of el. coverage [%]	42%	84%	84%
Share of th. coverage [%]	15%	31%	31%

Table 18 specifies the three different baseloads, the power size of the SOFC chosen, the number of modules required to satisfy the baseloads, the thermal power produced by the SOFC, the amount of gas required to run the SOFC, the daily electrical and thermal load of the hotel, and the amount of electrical and thermal energy sold, and finally the share of electrical and thermal coverage by the SOFC system.
According to these results, an economic analysis has been performed as shown in Table 19.
In this analysis has been considered:

- The daily electricity and thermal savings are the savings produced by the SOFC – based cogeneration system (the hotel owner no longer has to purchase this amount of energy from the grid). These savings are taken into account for the yearly incomes.
- The daily electrical and thermal revenues are the ones generated by the SOFC – based cogeneration system (the hotel owner can sell this amount of energy to the grid in case of electricity and to the DH in case of thermal energy). These revenues are taken into account for the yearly incomes.
- The daily electrical and thermal costs are the ones that the hotel owner has to pay in order to satisfy all the electrical and thermal needs of the hotel, but they are not taken into account for the yearly incomes.
- The daily gas-SOFC cost is the cost that the hotel owner has to pay in toder to run the SOFC – based cogeneration system. It is taken into account in the yearly incomes.

In this analysis has been taken into account only the revenues, savings and costs about the SOFC-based cogeneration system and therefore only these have been inserted into the yearly incomes.

Table 19. Economic analysis, small Italian hotel

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 90.00	€ 180.00	€ 180.00
Daily Savings thermal	€ 9.02	€ 18.03	€ 18.03
Daily Revenues electricity	€ -	€ 3.97	€ 3.97
Daily Revenues thermal	€ -	€ -	€ -
Daily el. Costs	-€ 123.35	-€ 33.35	-€ 33.35
Daily th. Costs	-€ 48.39	-€ 39.55	-€ 39.55
Daily gas-SOFC cost	-€ 32.73	-€ 65.45	-€ 65.45
Daily incomes	€ 66.29	€ 136.55	€ 136.55
Yearly incomes	€ 23,711.73	€ 48,843.10	€ 48,843.10

The results for the medium hotels in Italy and Portugal, Greece, and Taiwan are shown in the 6 Appendix.
The PBTs for each cash flow analysis have been calculated and they are shown in Table 20. Considering the PBT as a reference, the best solution (highlighted with red cells in the table) is to cover the minimum amount of electricity required by the hotel (CASE 1, minimum baseload) through the SOFC systems for almost all the hotels except for the small hotels in Greece and the large hotel in Taiwan. This is probably due to the fact that the hotels under analysis in these last two places have low thermal needs and therefore more revenues have been obtained for the thermal energy sale to the local DH. For almost all the cases, even if the PBT is higher for higher baseload coverage (CASE 2 and CASE 3), the revenues at the end of the lifetime of the systems are higher as shown in Table 21.

Table 20. Payback times for all the analyzed cases (variation of the baseload) and countries. Red cells are the optimal solution (the one with the lowest PBT).

PBT	CASE 1	CASE 2	CASE 3
Italy, small	4.3	4.5	4.5
Italy, medium	4.4	4.6	4.6
Portugal, medium	9.3	9.6	9.9
Portugal, large	8.7	8.8	8.9
Greece, small	8.9	7.6	7.6
Greece, medium	7.1	7.3	7.6
Taiwan, large	7.7	7.4	7.5

Table 21. Net Present Value (NPV) at the end of the lifetime.

Earnings	CASE 1	CASE 2	CASE 3
Italy, small	€ 197,386	€ 427,049	€ 427,049
Italy, medium	€ 414,850	€ 877,680	€ 877,680
Portugal, medium	€ 78,078	€ 167,895	€ 277,151
Portugal, large	€ 447,382	€ 682,252	€ 951,562
Greece, small	€ 236,253	€ 559,341	€ 559,341
Greece, medium	€ 736,172	€ 1,040,926	€ 1,387,642
Taiwan, large	€ 2,294,804	€ 2,627,971	€ 3,530,815

For all the cases with the lowest PBTs, the results of the cash flow analysis are shown in Figure 34a-b. The curve of Taiwan is steeper than the other because the hotel has the largest floor areas and so the largest consumption among all the hotels under analysis; therefore it a high number of modules is required to satisfy the electrical needs and then, a high initial investment but at the same time, high revenues at the end of the lifetime of the system.

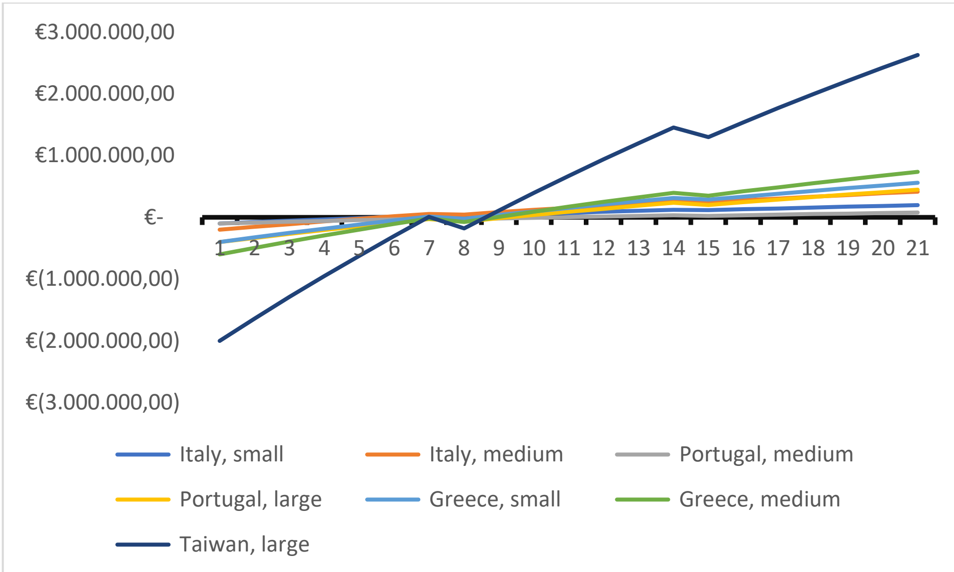

Figure 34a. Cash flow analysis for all the selected countries in the optimal solution (lowest PBT).

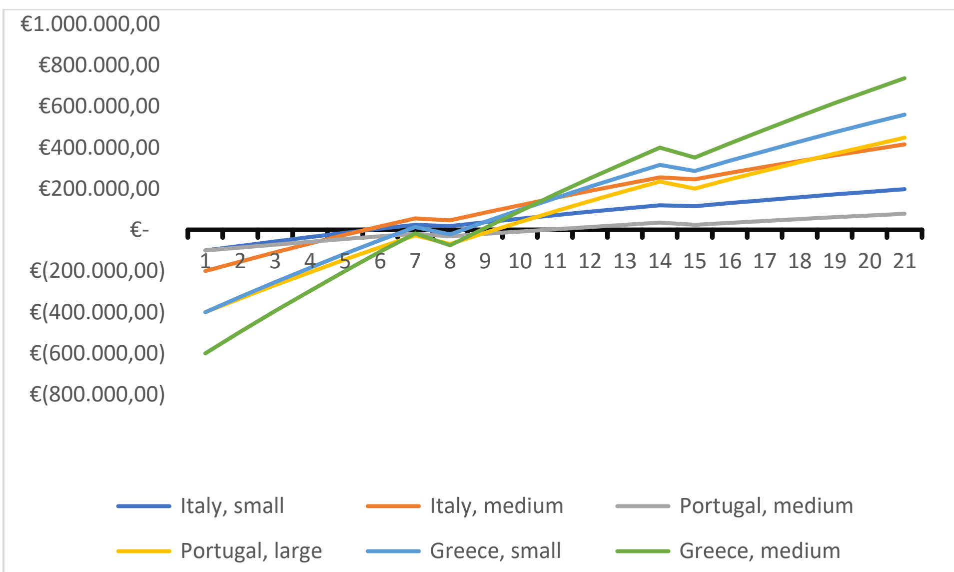

Figure 35b. Cash flow analysis for all the selected countries in the optimal solution (lowest PBT) without Taiwan.

4.5 Sensitivity Analysis

A sensitivity analysis has been performed in order to understand how much the CAPEX, OPEX, thermal recovery, energy costs, and presence of subsidies influence the cash flows analysis. The studies have been done only for the Italian hotels considering always the target costs of Table 16, except where expressly indicated.

In Figure 36, the cash flows at current prices of the small Italian hotel for "Case 1", always remain negative; considering at each step a CAPEX and OPEX reduction of 1.5 k€ and 0.250 k€ respectively, the PBTs reduce considerably; this means that these two values affect the cash flows remarkably.

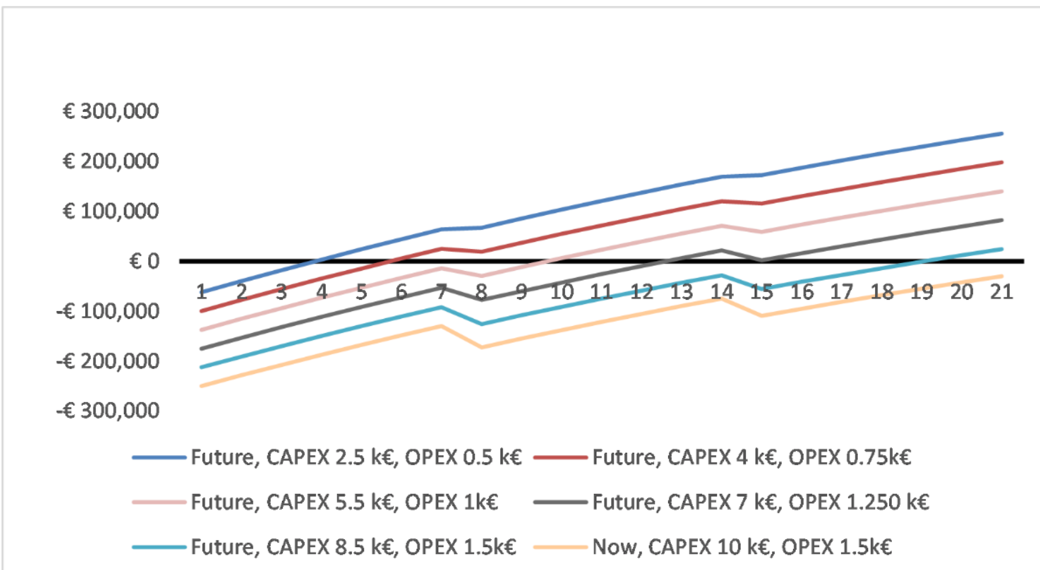

Figure 36. Sensitivity to CAPEX and OPEX between the current and future scenarios.

Figure 37 shows the influence on the PBTs of the thermal savings. In this case, the analysis has been performed with the target costs. Considering the small and medium Italian hotels for "Case 1", if the thermal energy is not recovered, the PBTs are higher, and the earnings at the end of the lifetime of the systems, are lower. The use of thermal energy throughout the year is not easy to perform in traditional buildings, but this analysis shows that it is important to maximize the heat exploitation within the building (for example employing an adsorption chiller during summer) to reach the economic feasibility of the investment. Furthermore, heat recovered from the SOFC could also be transferred at high temperatures for specific uses.

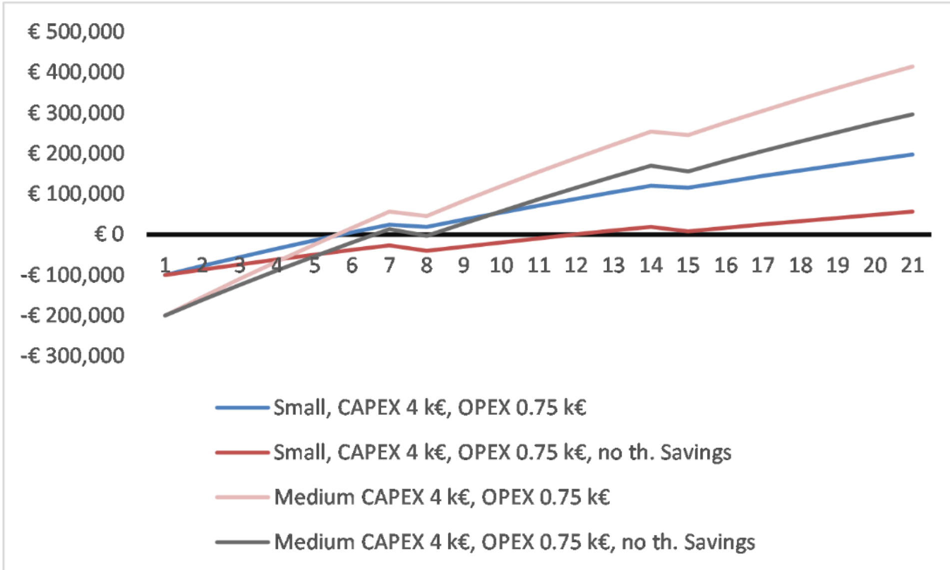

Figure 37. Sensitivity to thermal savings considering the target costs.

For all these analyses, it has been assumed that the energy costs will be fixed for all the lifetime of the systems, and set as is shown in Table 15; at current prices, the cash flows remain always negative.

Analyzing the data on the energy prices of the last 10 years [56], it can be reasonably assumed that the cost of electricity has been increased, and the cost of methane has been reduced. Analyzing these data, and considering the average of the rises and decreases of the prices of these last 10 years, it can be reasonably set a rise of the electricity cost of 3% per year and a reduction of gas cost of 1% per year. The analysis is shown in Figure 38 and it has been performed at current costs: the cash flows become positive between the 15th and 16th year, even considering the high current prices due to the high increase of the electricity cost.

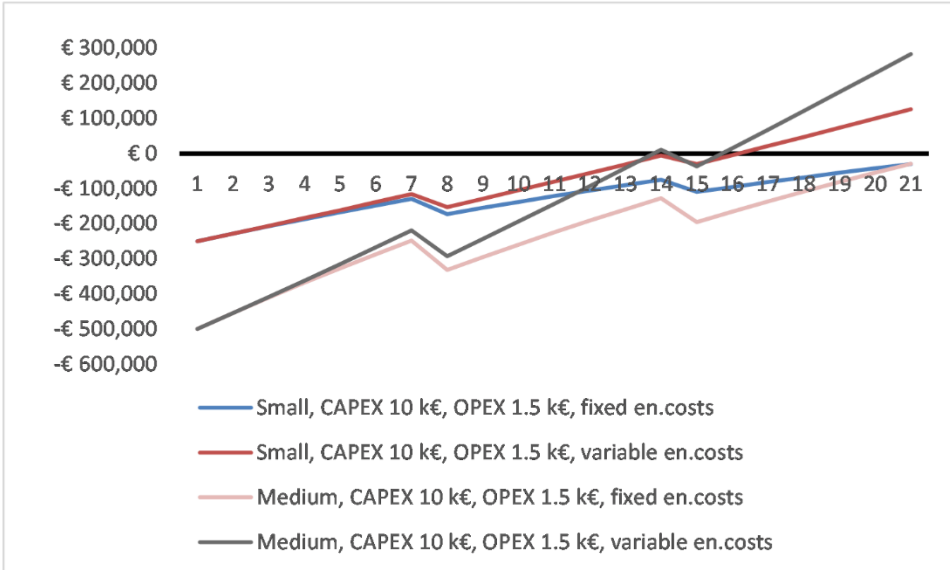

Figure 38. Sensitivity to energy costs considering current costs.

Finally, a sensitivity analysis considering the presence of subsidies has been performed. Analyzing only the "Case 1" for small and medium hotels in Italy, the cumulative cash flow becomes positive in case of subsidies even at current prices; in case of no subsidies instead, the cumulative cash flows remain negative for all the years, for both small and medium hotels (Figure 39). Therefore, it has been resumed that incentivizing the technology brings better performances in terms of reduction of PBTs.

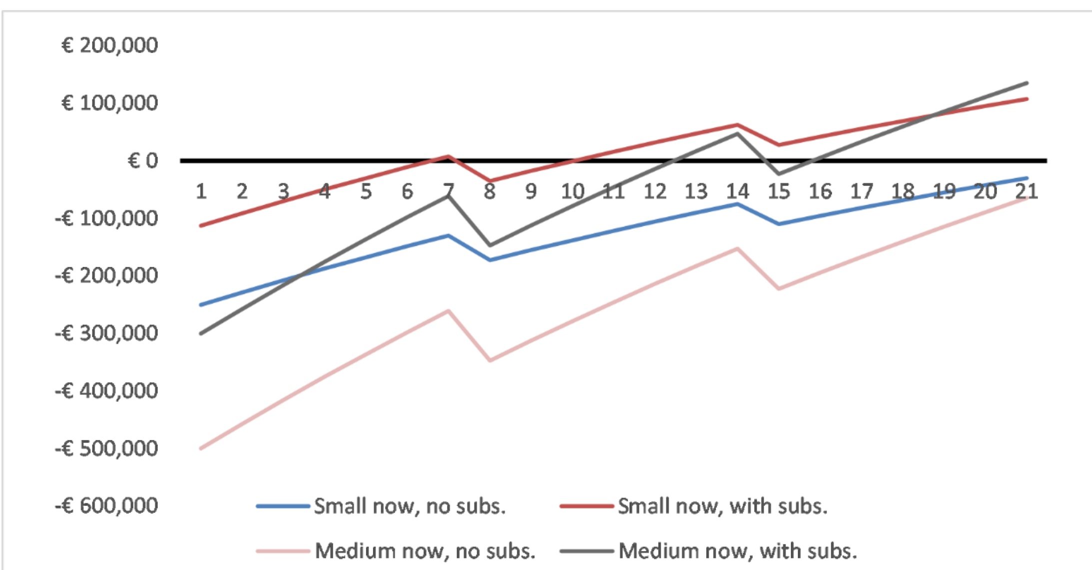

Figure 39. Cumulative cash flow, Italy, with and without the subsidy (65% reduction on the CAPEX).

5 CONCLUSIONS

This work has been focused on the feasibility study of a SOFC system installation in the hotel sector.

After long literature research of the consumptions of hotels in different continents, a model was built and an economic evaluation was performed in order to understand the convenience of the SOFCs even in the future.

Regarding the consumption, it was obtained in general the following EUI indexes shown in Table 22. As it can be seen, the situation is a lot heterogeneous; this is due to several factors: the data from the scientific papers were collected in different years and locations, the buildings under analysis were built in different years and they had different structures and occupancy. Anyway, it can be said that hotels are very energy-intensive buildings and that their consumption should be reduced as much as possible.

Table 22. EUI summary

Results	$EUI_{el,min}$	$EUI_{el,max}$	$EUI_{th,min}$	$EUI_{th,max}$
Europe	100	169	88	212
Asia	119	389	36	358
US	185	363	127	463

The hourly electrical consumptions obtained from the Matlab® model (i.e. Figure 40. Portuguese hotel baseloadFigure 40) shows that the electrical needs cannot be considered as constant during the day, but there is two peaks, correspondent to the hours of lunch and dinner; it can be said that maybe the restaurants impact a lot on the electrical energy consumption and that tourists prefer to come back to the hotel's restaurant to have lunch or dinner. The highest peak is reached in the evening, and this can be because the tourists come back to the hotels after visiting the cities and therefore they utilize all the hotel's services, i.e. cooling or heating systems (that during the day can be switched off), restaurants, hairdryers, gyms, etc., therefore this generates a rise on the daily consumptions.

Finally, an economic evaluation was performed considering the installation of a SOFC based cogeneration system in hotels located in Italy, Portugal, Greece, and Taiwan.

At current prices, the investment is not convenient in any place due to the high costs of the system. This result changes if it is considered the presence of subsidies, in fact, in Italy, considering the "Decree-Law No 83/2014, art. 10" [45], the return of the investment would be verified between ten and twelve years. At target prices, in the future, when the technology will be more diffused, for each case under analysis, the cash flows would

become positive and then the investment would be considered as convenient.
This technology reaches very high efficiencies and produces very low emissions, therefore it could be really useful in order to make hotels more energy independent and also to reduce the CO_2 emissions caused by the production of energy with the actual traditional methodologies (i.e. combustion engines).

6 APPENDIX

ITALY

Table 23. Specifications of the system, medium Italian hotel.

MEDIUM HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	61.55	87.20	109.01
SOFC [kW]	50.00	50.00	50.00
Quantity SOFC	1.23	1.74	2.18
Number of modules SOFC	1.00	2.00	2.00
Wac,net SOFC [kW]	50.00	100.00	100.00
QHR SOFC [kW]	30.19	60.38	60.38
Wac, net SOFC daily [kWh]	1200.00	2400.00	2400.00
QHR SOFC daily [kWh]	724.53	1449.06	1449.06
Daily el. Load hotel [kWh]	3132.08	3132.08	3132.08
Daily th. Load hotel [kWh]	4200.33	4200.33	4200.33
Daily Electricity sold [kWh]	0.00	115.35	115.35
Thermal energy sold [kWh]	0.00	0.00	0.00
Gas SOFC[m3/h]	9.43	18.87	18.87
Daily gas SOFC [m3/day]	226.42	452.83	452.83
Share of el. coverage [%]	38%	77%	77%
Share of th. coverage [%]	17%	34%	34%

Table 24. Economic analysis, medium Italian hotel.

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 180.00	€ 360.00	€ 360.00
Daily Savings thermal	€ 22.18	€ 44.36	€ 44.36
Daily Revenues electricity	€ -	€ 6.92	€ 6.92
Daily Revenues thermal	€ -	€ -	€ -
Daily el. Costs	-€ 289.81	-€ 109.81	-€ 109.81
Daily th. Costs	-€ 104.27	-€ 82.54	-€ 82.54
Daily gas-SOFC cost	-€ 67.92	-€ 135.85	-€ 135.85
Daily incomes	€ 134.25	€ 275.43	€ 275.43
Yearly incomes	€ 48,022.98	€ 98,521.51	€ 98,521.51

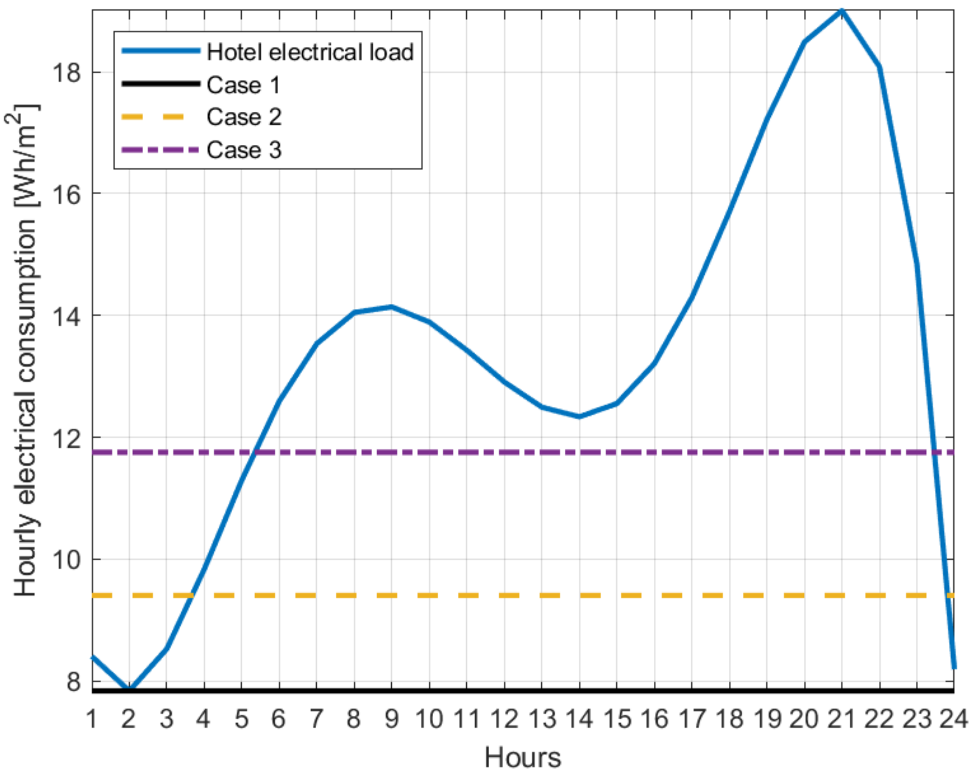

Figure 40. Portuguese hotel baseload.

PORTUGAL

Table 25. Specifications of the system, medium Portuguese hotel.

MEDIUM HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	49.27419	59.1542	73.94275
SOFC [kW]	25.00	25.00	25.00
Quantity SOFC	1.97	2.37	2.96
Number of modules SOFC	1.00	2.00	3.00
Wac,net SOFC [kW]	25.00	50.00	75.00
QHR SOFC [kW]	12.27	24.55	36.82
Wac, net SOFC daily [kWh]	600.00	1200.00	1800.00
QHR SOFC daily [kWh]	294.55	589.09	883.64
Daily el. Load hotel [kWh]	1994.88	1994.88	1994.88
Daily th. Load hotel [kWh]	1963.42	1963.42	1963.42
Daily Electricity sold [kWh]	0.00	2.61	92.61
Thermal energy sold [kWh]	0.00	0.00	0.00
Gas SOFC[m3/h]	4.55	9.09	13.64
Daily gas SOFC [m3/day]	109.09	218.18	327.27
Share of el. coverage [%]	30%	60%	90%
Share of th. coverage [%]	15%	30%	45%

Table 26. Economic analysis, medium Portuguese hotel.

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 66.00	€ 132.00	€ 198.00
Daily Savings thermal	€ 8.42	€ 16.83	€ 25.25
Daily Revenues electricity	€ -	€ 0.11	€ 3.87
Daily Revenues thermal	€ -	€ -	€ -
Daily el. Costs	-€ 153.44	-€ 87.44	-€ 21.44
Daily th. Costs	-€ 46.73	-€ 38.48	-€ 30.23
Daily gas-SOFC cost	-€ 30.55	-€ 61.09	-€ 91.64
Daily incomes	€ 43.87	€ 87.85	€ 135.48
Yearly incomes	€ 15,692.35	€ 31,423.76	€ 48,461.77

Table 27. Specifications of the system, large Portuguese hotel.

LARGE HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	143.01	171.68	214.60
SOFC [kW]	50.00	50.00	50.00
Quantity SOFC	2.86	3.43	4.29
Number of modules SOFC	2.00	3.00	4.00
Wac,net SOFC [kW]	100.00	150.00	200.00
QHR SOFC [kW]	49.09	73.64	98.18
Wac, net SOFC daily [kWh]	2400.00	3600.00	4800.00
QHR SOFC daily [kWh]	1178.18	1767.27	2356.36
Daily el. Load hotel [kWh]	5789.69	5789.69	5789.69
Daily th. Load hotel [kWh]	5698.37	5698.37	5698.37
Daily Electricity sold [kWh]	0.00	25.17	205.17
Thermal energy sold [kWh]	0.00	0.00	0.00
Gas SOFC[m3/h]	15.34	23.01	30.68
Daily gas SOFC [m3/day]	368.18	552.27	736.36
Share of el. coverage [%]	41%	62%	83%
Share of th. coverage [%]	21%	31%	41%

Table 28. Economic analysis, large Portuguese hotel.

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 264.00	€ 396.00	€ 528.00
Daily Savings thermal	€ 33.66	€ 50.49	€ 67.32
Daily Revenues electricity	€ -	€ 1.05	€ 8.58
Daily Revenues thermal	€ -	€ -	€ -
Daily el. Costs	-€ 372.87	-€ 240.87	-€ 108.87
Daily th. Costs	-€ 126.57	-€ 110.07	-€ 93.58
Daily gas-SOFC cost	-€ 103.09	-€ 154.64	-€ 206.18
Daily incomes	€ 194.57	€ 292.91	€ 397.72
Yearly incomes	€ 69,598.20	€ 104,773.70	€ 142,264.14

Greece

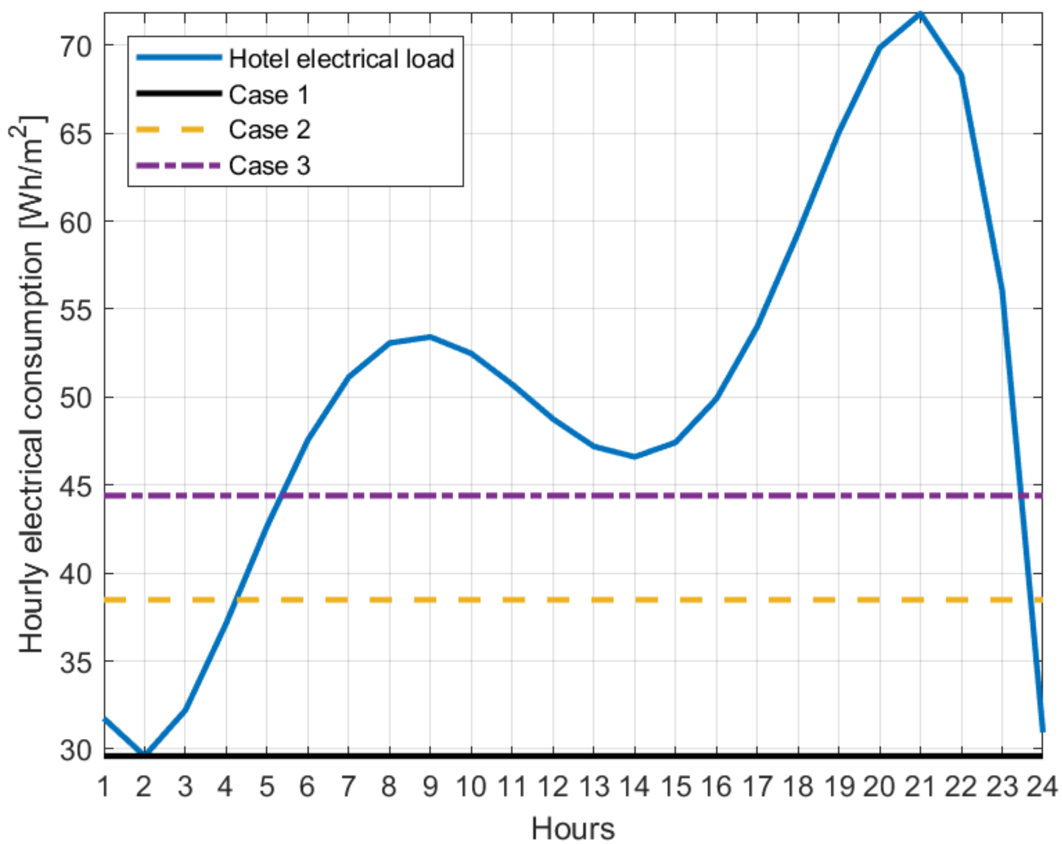

Figure 41. Greek hotel baseload.

Table 29. Specifications of the system, small Greek hotel.

SMALL HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	64.605	84.315	97.236
SOFC [kW]	50.00	50.00	50.00
Quantity SOFC	1.29	1.69	1.94
Number of modules SOFC	1.00	2.00	2.00
Wac,net SOFC [kW]	50.00	100.00	100.00
QHR SOFC [kW]	24.55	49.09	49.09
Wac, net SOFC daily [kWh]	1200.00	2400.00	2400.00
QHR SOFC daily [kWh]	589.09	1178.18	1178.18
Daily el. Load hotel [kWh]	2621.43	2621.43	2621.43
Daily th. Load hotel [kWh]	115.35	115.35	115.35
Daily Electricity sold [kWh]	0.00	134.50	134.50
Thermal energy sold [kWh]	473.74	1062.83	1062.83
Gas SOFC[m3/h]	9.09	18.18	18.18
Daily gas SOFC [m3/day]	218.18	436.36	436.36
Share of el. coverage [%]	46%	92%	92%
Share of th. coverage [%]	511%	1021%	1021%

Table 30. Economic analysis, small Greek hotel.

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 126.00	€ 252.00	€ 252.00
Daily Savings thermal	€ 15.03	€ 30.06	€ 30.06
Daily Revenues electricity	€ -	€ 10.76	€ 10.76
Daily Revenues thermal	€ 14.21	€ 31.89	€ 31.89
Daily el. Costs	-€ 149.25	-€ 23.25	-€ 23.25
Daily th. Costs	€ 11.84	€ 26.57	€ 26.57
Daily gas-SOFC cost	-€ 54.55	-€ 109.09	-€ 109.09
Daily incomes	€ 100.69	€ 215.61	€ 215.61
Yearly incomes	€ 36,018.49	€ 77,123.65	€ 77,123.65

Table 31. Specifications of the system, medium Greek hotel.

MEDIUM HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	175.94	229.61	264.80
SOFC [kW]	50.00	50.00	50.00
Quantity SOFC	3.52	4.59	5.30
Number of modules SOFC	3.00	4.00	5.00
Wac,net SOFC [kW]	150.00	200.00	250.00
QHR SOFC [kW]	73.64	98.18	122.73
Wac, net SOFC daily [kWh]	3600.00	4800.00	6000.00
QHR SOFC daily [kWh]	1767.27	2356.36	2945.45
Daily el. Load hotel [kWh]	7138.91	7138.91	7138.91
Daily th. Load hotel [kWh]	314.12	314.12	314.12
Daily Electricity sold [kWh]	0.00	91.44	281.44
Thermal energy sold [kWh]	1453.15	2042.24	2631.33
Gas SOFC[m3/h]	27.27	36.36	45.45
Daily gas SOFC [m3/day]	654.55	872.73	1090.91
Share of el. coverage [%]	50%	67%	84%
Share of th. coverage [%]	563%	750%	938%

Table 32. Economic analysis, medium Greek hotel.

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 378.00	€ 504.00	€ 630.00
Daily Savings thermal	€ 45.08	€ 60.11	€ 75.14
Daily Revenues electricity	€ -	€ 7.31	€ 22.51
Daily Revenues thermal	€ 43.59	€ 61.27	€ 78.94
Daily el. Costs	-€ 371.59	-€ 245.59	-€ 119.59
Daily th. Costs	€ 36.33	€ 51.06	€ 65.78
Daily gas-SOFC cost	-€ 163.64	-€ 218.18	-€ 272.73
Daily incomes	€ 303.04	€ 414.51	€ 533.87
Yearly incomes	€ 108,397.98	€ 148,270.78	€ 190,964.10

TAIWAN

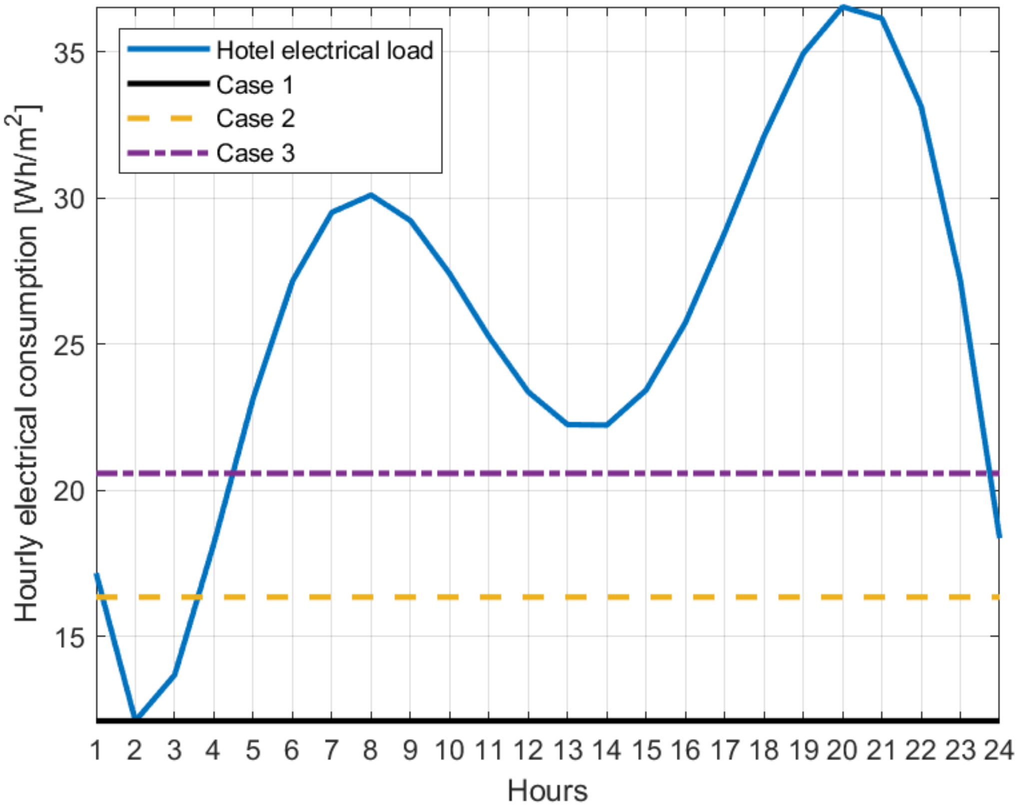

Figure 42. Taiwanese hotel baseload.

Table 33. Specifications of the system, large Taiwanese hotel.

LARGE HOTEL	CASE 1	CASE 2	CASE 3
Baseload [kW]	226.73	305.43	386.00
SOFC [kW]	50.00	50.00	50.00
Quantity SOFC	4.53	6.11	7.72
Number of modules SOFC	8.00	10.00	13.00
Wac,net SOFC [kW]	400.00	475.00	617.50
QHR SOFC [kW]	241.51	286.79	372.83
Wac, net SOFC daily [kWh]	9600.00	11400.00	14820.00
QHR SOFC daily [kWh]	5796.23	6883.02	8947.92
Daily el. Load hotel [kWh]	11561.35	11561.35	11561.35
Daily th. Load hotel [kWh]	1967.49	1967.49	1967.49
Daily Electricity sold [kWh]	173.27	236.10	477.82
Thermal energy sold [kWh]	3828.74	4915.53	6980.43
Gas SOFC[m3/h]	75.47	89.62	116.51
Daily gas SOFC [m3/day]	1811.32	2150.94	2796.23
Share of el. coverage [%]	83%	99%	128%

Share of th. coverage [%]	295%	350%	455%

Table 34. Economic analysis, large Taiwanese hotel.

Economic analysis	CASE 1	CASE 2	CASE 3
Daily Savings electricity	€ 1,056.00	€ 1,254.00	€ 1,630.20
Daily Savings thermal	€ 130.12	€ 154.52	€ 200.87
Daily Revenues electricity	€ 10.40	€ 14.17	€ 28.67
Daily Revenues thermal	€ 68.92	€ 88.48	€ 125.65
Daily el. Costs	-€ 215.75	-€ 17.75	€ 358.45
Daily th. Costs	€ 84.23	€ 108.14	€ 153.57
Daily gas-SOFC cost	-€ 398.49	-€ 473.21	-€ 615.17
Daily incomes	€ 866.94	€ 1,037.95	€ 1,370.22
Yearly incomes	€ 310,105.25	€ 371,276.38	€ 490,127.31

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