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Title: Low-energy residential buildings in New Borg El Arab: simulation and survey based energy assessment

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Abstract: This paper discusses the design of a very low energy residential building, with regard to the climate of New Borg El Arab City (NBC). However, since the cost of a very energy efficient building can be high, two investment scenarios, low (LIS) and high (HIS) investments, have been considered. In the first case, the design includes exclusively low cost solutions, while in the second case technologies commonly associated with Net zero houses are included. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum requirements of the Egyptian energy code. The final energy consumption of LIS has been estimated around 15 kWh/m^2, which is half of the final energy consumption of the BaU building. Particularly interesting are the results of HIS: the final energy consumption varies from 5 kWh/m^2 to 1.48 kWh/m^2 and to 0.69 kWh/m^2 as the PV size increases. Very low energy and net zero energy buildings have been designed in line with the local context, using envelope solutions to lower their energy needs and renewable systems to achieve a near zero or a negative final energy balance.

***Cover Letter**

Dear Editor,
Allow me to tell you about my article submitted on January the 27th 2015 through the Elsevier Editorial System.

Title of the article: Low-energy residential buildings in New Borg El Arab: simulation and survey based energy assessment

Authors: **Francesco Redaa, Pekka Tuominena, Åsa Hedmana, Mona Gamal Eldin Ibrahimb**
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Conscious awareness on the Egyptian buildings energy consumption is already consolidates. Nearly 22% of the total energy consumption of Egypt comes from the residential sector. Moreover, residential electricity held the biggest share from the national energy consumption in 2012, around 44% of the total. Recently published studies have started to focus on energy saving in buildings. However, presently there are no comprehensive design guidelines for very energy efficient buildings in Egypt, be that low-energy buildings, passive buildings or near zero-energy buildings. On the other hand, various concepts for very energy efficient buildings are spreading worldwide.
The aim of the paper is to design and to assess the energy consumption of a very low energy residential building, with regard to the climate of New Borg El Arab City (NBC), which is situated on the North Coast, 40 km west from Alexandria. However, since the cost of a very energy efficient building can be high, two investment scenarios, low (LIS) and high (HIS) investments, have been considered. In the first case, the design includes exclusively low cost solutions, while in the second case technologies commonly associated with Net zero houses are included. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum requirements of the Egyptian energy code.
The research is part of the residential feasibility study of the New Borg El Arab EcoCity (Eco NBC) project. Moreover, it has been carried out in three phases: investigation of the principal behaviour patterns of people related to energy consumption, assessment of relevant technologies and, finally, energy analysis. The investigation phase was conducted as a survey. The goal of the survey was to understand the occupant behaviour concerning the use of windows, shading systems and domestic hot water in typical New Borg El Arab residential areas. Stakeholders, local authorities and energy market key players were involved in the technology assessment phase in order to list cost-effective systems and building envelope solutions for each scenario: BaU, LIS and HIS. Then, energy analyses of the three scenarios were done using dynamic simulation modelling.
The final energy consumption of LIS has been estimated around 15 kWh/m², which is half of the final energy consumption of the BaU. Particularly interesting are the results of HIS: the final energy consumption varies from 5 kWh/m² to 1.48 kWh/m² and to 0.69 kWh/m² as the PV size increases. In conclusion, very low energy and net zero energy buildings have been designed in line with the local context, using envelope solutions to lower their energy needs and renewable systems to achieve a near zero or a negative final energy balance. Ideally this study along with others should attract the interest of local and central administrations for planning and building new eco-friendly residential districts that include very energy efficient buildings.

Waiting your precious reply,
I wish you a nice day.

Yours sincerely,
Francesco Reda

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***Detailed Response to Reviewers**

Dear reviewers,

Allow me to reply to you accordingly to the list provided by the editor. Please consider that the text of the reviewers is in italics.

Reviewer #1: In my opinion, the paper is ready to be published. There are very few language mistakes, which, I think, could be ignored. One major issue is that the acknowledgement is followed by an entire article again, which is a repetition of the former sections. Please correct this.

The acknowledgement section has been modified accordingly to the reviewer specification and to the journal guidelines. Please find below the new text:

"**Acknowledgements**

Authors would like to express their thanks to the Finnish Ministry of Foreign Affairs, which supported this work, and to all the people involved in this research: NGO´s people, local authorities, stakeholders and energy market key players and finally professors and students of E-JUST, which contributed significantly to the accomplishment of this study."

Reviewer #2: The paper is tackling an important issue. It is well written and structured.

Thank you for taking the time to review the article,

Best regards.

Low-energy residential buildings in New Borg El Arab: simulation and survey based energy assessment

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Abstract

This paper discusses the design of a very low energy residential building, with regard to the climate of New Borg El Arab City (NBC). However, since the cost of a very energy efficient building can be high, two investment scenarios, low (LIS) and high (HIS) investments, have been considered. In the first case, the design includes exclusively low cost solutions, while in the second case technologies commonly associated with Net zero houses are included. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum requirements of the Egyptian energy code. The final energy consumption of LIS has been estimated around 15 kWh/m², which is half of the final energy consumption of the BaU building. Particularly interesting are the results of HIS: the final energy consumption varies from 5 kWh/m² to 1.48 kWh/m² and to 0.69 kWh/m² as the PV size increases. Very low energy and net zero energy buildings have been designed in line with the local context, using envelope solutions to lower their energy needs and renewable systems to achieve a near zero or a negative final energy balance.

Keywords

Energy efficient building

Photovoltaic

Solar thermal system

Dynamic energy simulation

Net zero energy building

1. Introduction

Egypt is facing increasing pressures on its energy system and environment. In the last five years, from 2009 to 2014, Egyptian population has increased by 2% annually, reaching 82 million of people ” [8]. Environmental concerns in Egypt are likely to keep solar technologies among the key solutions to reduce primary energy consumption and greenhouse gas emissions of the Egyptian buildings.

Recently published studies have started to focus on energy saving in buildings. Usually they refer to the Egyptian building energy code as a baseline to further investigate individual solutions. In particular, G. B. Hanna has found that decreasing the thermal transmittance of the external wall can strongly increase the thermal efficiency of a residential building [9]. This has been confirmed by M Fahmy, who has investigated the effect of an external wall with glass fibre reinforced concrete [10]. Both M. A. A. Abd El-Monteleb and M. M. Mahdy, M. Nikolopoulou showed that external shading systems can save energy in many Egyptian locations [11, [12]. M. M. Mahdy, M. Nikolopoulou have also analysed different window typologies, finding that a clear reflective glass has to be used, if the building has not shading systems [12].

However, presently there are no comprehensive design guidelines for very energy efficient buildings in Egypt, be that low-energy buildings, passive buildings or near zero-energy buildings. On the other hand, various concepts for very energy efficient buildings are spreading worldwide [13 - [20]. For Net zero energy buildings the aim is to produce as at least as much energy as is used. However, achieving the energy balance of a Net zero energy building depends on design characteristics, occupant behaviour and weather conditions [13]. Many designs and technologies, active and passive, can be found in Net zero energy buildings to meet part of their thermal and other energy requirements. In particular, PV and solar thermal systems play a central role in Net zero energy buildings, supplying the energy needs with clean and renewable-energy sources [21]. Indeed, in countries rich of sun irradiance, such as Egypt, solar technologies have been used to successfully design a number of very energy efficient buildings [17 - [20], showing, in some cases [17, [19], a payback time of about 10 years.

The aim of the paper is to design and to assess the energy consumption of a very low energy residential building, with regard to the climate of New Borg El Arab City (NBC), which is situated on the North Coast, 40 km west from Alexandria. However, since the cost of a very energy efficient building is typically high, depending on the used technologies, the authors investigated also the energy performance of a low-energy building concept, which is less ambitious than the Net zero model. These buildings relate to two investment scenarios: low (LIS) and high (HIS) investments. In the first case, the design includes exclusively low cost solutions, while in the second case technologies commonly associated with Net zero houses are included. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum requirements of the Egyptian energy code, as presented in the aforementioned studies. In particular, active and passive ventilation systems, different external envelope solutions, PV and solar thermal systems have been considered. Furthermore, different solar PV field sizes have been considered, but only for the high investment scenario.

After calculating and analysing the impact of the scenarios for one residential building, the result was multiplied to show the impact on the whole residential sector of New Borg El Arab. Data from the master plan of the extension of the city was used as a basis for these calculations. The impacts on energy usage and CO_2 emissions were analysed.

The research is part of the residential feasibility study of the New Borg El Arab EcoCity (Eco NBC) project. The scope of the feasibility study is analysing the most feasible solutions for different sectors (industry, residential, commercial and transportation) in NBC for turning the city into an EcoCity or low emission city. The Eco NBC project is an international collaboration between two Finnish and Egyptian scientific institutions: VTT Technical Research Centre of Finland and Egypt-Japan University of Science and Technology (E-JUST) Shady Attia, Mohamed Hamdy, William O'Brien, Salvatore Carlucci, Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design, Energy and Buildings, Volume 60, May 2013, Pages 110-124, ISSN 0378-7788;

[22].

2. Methodology

The research has been carried out in three phases: investigation of the principal behaviour patterns of people related to energy consumption, assessment of relevant technologies and, finally, energy analysis. The investigation phase was conducted as a survey. The goal of the survey was to understand the occupant behaviour concerning the use of windows, shading systems and domestic hot water in typical New Borg El Arab residential areas. Stakeholders, local authorities and energy market key players were involved in the technology assessment phase in order to list cost-effective systems and building envelope solutions for each scenario: BaU, LIS and HIS. Then, energy analyses of the three scenarios were done using dynamic simulation modelling, as recommended by various researchers [9, [10,[10 [17,[19]. Data from the master plan of the extension of New Borg El Arab has been used to multiply the one analysed case residential building to get the impacts of the whole residential sector of the city. The authors have considered the occupant behaviour information, findings of the survey, in the simulation analysis, as suggested by many researchers [23 - [26]. The simulation tool used was TRNSYS v. 17 [27] and TRNBuild [28], which is a TRNSYS tool, to assess respectively the energy production and consumption of the systems, including PV and solar thermal ones, and the thermal energy needs in the building. TRNSYS has been used for similar purposes in a number of previous studies [29 - [32].

2.1. Phase one: Investigation

The purpose of the authors was to understand the state of art of New Borg El Arab residential sector in terms of building features and utilization (occupant behaviour) with a survey. Indeed, it is extremely important, in order to achieve a successful replicable design of a very energy efficient building in New Borg El Arab, to select energy efficient systems and building envelope solutions that can be applied in the local context. This means that local building constructors can implement them and people do not reject them in their behaviour. The survey was carried out by local NGOs and 60 families were involved. The age composition of the sample was 43 infants, 70 school-age or students, 61 working age and 5 retired. **Error! Reference source not found.** shows the percentage share of the involved people by age, occupation and family financial status.

In accordance with the predominantly young age structure of Egypt, the dominant occupation in New Borg El Arab appears to be student, around 40%, followed by workers, 35%, then infants, 22%, and retired 3%. The results are in line with last census, done in 2006, as well as with [33]. Even though it is extremely hard to define a representative sample, the families involved can be considered to be representative. Indeed, a previous work, which considered Alexandria, the city closest to New Borg El Arab, showed a similar sample composition with same age distributions [3].

Figure 2 shows the most common building typologies in New Borg El Arab. It has been found that a four storey apartment building is the most common typology of residential building.

Figure 2 Survey results: Building typologies in New Borg El Arab.

Figure 3 shows how often people use the shower in summer and in winter and the average time spent in the shower. Although the number of showers in summer is higher, people take shower almost every day, the energy consumption of the DHW system is lower in summer than in winter. Expectedly, people mostly use cold water in summer and hot water in winter. This affects the consumption profiles of hot water.

Unfortunately real time consumption measurements for DHW are not available; therefore the authors have assumed that DHW summer load is 40% less than the DHW winter load according to the survey results. Thus, with regard to a single dwelling, the DHW profiles in e been selected respectively for the periods that extent from October to April and from May to September. This profile has been estimated using as a reference DHW profile of [34], which was modified according to the findings of the survey. Additionally, only decentralized heating systems were present in the survey.

have been selected respectively for the periods that extent from October to April and from May to September. This profile has been estimated using as a reference DHW profile of [34], which was modified according to the findings of the survey. Additionally, only decentralized heating systems were present in the survey.

Of particular interest are the findings about habits concerning the opening of windows and curtains in the living room and bedroom (Figure 5). It appears that the occupants interact often with both windows and curtains, leaving the windows open when they feel hot and the external air temperature is colder than the inside temperature. Moreover, occupants close the living room windows when they go to bed, whereas they leave the windows open while sleeping in the bedroom. On the other hand, they close the curtains in the bedroom while sleeping and only when the sunlight is strong they close them in the living room. Regarding the lighting system, only 46% use exclusively energy efficient lights; whereas 44% use also incandescent light bulbs and the 10% use only incandescent light bulbs.

Results of the survey show how people’s behaviour affect the DHW profiles and the building cooling load through opening the windows, witnessing their confidence with natural ventilation and shading systems. Moreover, it has been found that the main building typology is the four storey building. Conclusions of the survey have been discussed and verified in a workshop with experts from E-JUST and VTT. These findings have been used in the next phases, helping to find out systems and building envelope solutions suitable for each scenario and to calibrate the energy assessment simulations.

2.2. Phase two: Technology assessment

The aim of this phase was to create a list of technologies that suit New Borg El Arab in the local context for both high and low investment scenarios. A two-day meeting was organized by VTT and E-JUST with the local stakeholders, authorities and energy market key players in order to select, among other issues related to EcoNBC project, the most effective residential energy saving solutions. Particular attention was given to the capability of the construction workers, to the availability of technical passive and active solutions on the Egyptian market and to the recent local research findings, described within the introduction. Thus, the low investment scenario (LIS) is includes only simple and affordable solutions, while the high investment scenario (HIS) includes technologies commonly applied in Net zero energy buildings. In both scenarios, solar technologies were preferred, among others, because of the high level of solar irradiance in Egypt, as was stated in the introduction. The business as usual scenario (BaU), on the other hand, refers to the minimum requirements of the Egyptian energy code [4, [5]. The chosen technologies for each case are listed in Table 1. Moreover, for the three considered cases: BaU, LIS and HIS, an air to water heat pump was included for supplying cooling and heating energy.

2.3. Phase three: Energy analysis

2.3.1. Building

In this last phase all the information gathered within the two previous phases were employed for energetic analysis. As mentioned before, a dynamic simulation approach was selected to assess the building energy needs and the energy performance, in terms of supplied energy and final energy consumption, of the heating and cooling systems, including renewable energy systems, for each scenario in New Borg El Arab. The buildings of each case were modelled using TRNSYS3d [35], a particular plug-in of TRNSYS, which connects Google Sketch-up [36] to TRNSYS via TRNBuild [28]. The cases have a four storey building, based on the results of the survey. Each floor consists of one apartment. Two different building types were included, one for the BaU, presented in Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

a, and the other for both LIS and HIS, presented in Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

. These were done in accordance with the technologies selected for the scenarios in Table 1. There are not differences in the building envelope shapes between the LIS and HIS.

Different features were assigned to the building model used in each scenario. Once created the building in Sketch-up, thermal properties of the envelope, internal loads of people, appliances and lightings were assigned to the buildings in TRNBuild for each scenario. Then, each building model was imported through type 56 [27] into the TRNSYS system model of the related scenario. Since people in Egypt tend to use decentralized system, each apartment has its own system, made of the technologies listed in Table 1. Therefore, three different systems were created according to the related scenario. Results of the analysis refer to the highest floor, which, typically, has the highest thermal loads. The roof has been divided into four parts in order to give the same access to roof area for each apartment and, therefore, to allow the installation of similar solar systems. The indoor air temperature of all the apartments was kept at 26°C during the cooling months and at 20°C during the heating months. The energy assessment refers to both heating, from November to March, and cooling, from June to September, seasons. Type 15 has been used in TRNSYS to implement the weather data in the model [27]. EPW format weather file of Alexandria (Egypt), city close to New Borg El Arab and with the same climate, was used [50]. The time step used in the simulation analyses was 0.25 h.

There were two sets of daily schedules: one related to the occupancy rate and the other to the lighting system. The occupancy schedules were set according to [3]. In particular, two schedules were used for summer and winter and a third one for the Ramadan period, which occurred from June the 29th to July the 28th in 2014. The year is divided into summer and winter periods: summer refers to the period from April to September and winter from October to March. Every room typology has its own schedule, except for the bathroom, which has the same schedule as the kitchen. The considered room typologies are: living room, bedroom and kitchen and their schedules are shown respectively in Figure 7 a, b and c. Moreover, occupant behaviour has been considered, based on the findings of the survey, in terms of natural ventilation and DHW (Figure 2 Survey results: Building typologies in New Borg El Arab.

Figure 3 Survey results: number of showers that people use to have in summer and in winter and the shower average time.

Figure 4) and included in the model. In particular, the occupancy schedules have been used to assign the internal loads and to control the natural ventilation in the BaU scenario (Table 1). The results of the survey showed that occupants open the windows if the external temperature is less than the internal one, therefore allowing free-cooling. This control strategy has been implemented in the BaU, checking if the room is occupied or not. On the other hand, in the others scenarios free cooling is allowed without checking if the room is occupied implying a control system. Moreover, in all the scenarios free-cooling is allowed until the indoor temperature is above 24°C. People, appliance and lightings contribute to the internal loads. From these, people and appliances are modelled based on the occupancy schedule, while lightings have their own schedules.

2.3.2. District level

In order to assess the scenarios impacts on the whole residential sector of the city, the results from the above mentioned residential building was multiplied with the amount of apartment units set up in the master plan. The master plan of New Borg El Arab City includes information about the total number of residents and number of housing units. The total amount of housing units is 178125 and the total number of inhabitants is 750 000. Since no other information about these types was available, an assumption was made that all residential buildings would be as the model unit chosen above, and the total amount was calculated from the total unit number.

The assessment of CO_2 emissions was done by multiplying the final energy demand by the average Egypt emission factor for electricity 466 g/kWh [51]. The more accurate would be to analyse the energy source distribution in each scenario and calculate the emissions based on the actual sources. However since the CO_2 emissions are not the main issue of this article it was not considered beneficial and the source division would have been based on assumptions only. The emission factor for natural gas which is the main source besides electricity is 529 g/kWh, which is very close to the average Egypt electricity CO_2 emission factor.

3. Case studies

Three models, consisting of the building and the associated system, were created in accordance with the specifications found out in the investigation and the technology assessment phases. In the model the whole building was created, but the results refer to the apartment of the highest floor for aforementioned reasons. In this section authors describe first the thermal features of the buildings for each analysed scenario and then their related systems, which include the technologies and envelope solutions described in the methodology section (Table 1).

3.1. Buildings

The layout of the considered apartment is shown in Figure 8; it is about 114 m². Table 2 shows fresh air and free cooling mechanical ventilation rates, number of fan coils and vents, lighting and the people and appliances internal loads related to different room typologies for each scenario. People loads refer to the number of persons and their activities, as suggested by the UNI EN ISO 7730 [37]. These have been listed in Table 2 for each room (Figure 8) and they have been applied to each scenario. Lighting and appliances internal loads of BaU refer to [3]. The appliances load is the same for all the scenarios. On the other hand, the lighting loads of the LIS and HIS, which refer to the technologies listed in Table 1, are 8 W/m² and 6 W/m² respectively for fluorescent and LED lamps [38]. These values have been applied for the smallest room and then scaled up for the others rooms, keeping the original lighting distribution density. It is interesting to note that there is not a big difference between the lighting load of the BaS and LIS. Indeed, as confirmed by the survey results, currently people in Egypt are using mostly energy saving lamps. The minimum required fresh air rates for the rooms have been set according to the standard UNI 10339 and EN 15251 [39, [40]. The number of fan coils has been estimated based on the maximum power of heating and cooling of each room and at the technical sheet of Omnia HL model (Aermec®), which has 870 W of heating capacity and 530W of cooling [41]. Free cooling was achieved through opening the windows in the BaU, and through vents (30cm x 30cm) in both LIS and HIS. The air change per hour depends on the temperature and pressure difference between inside and outside each room. In order to consider the relation between the air change per hour through the vents and the temperature and pressure difference between inside and outside each room, Type 932 has been used to estimate it in TRNSYS [27]. Mechanical ventilation with free cooling, made by means of the fan coils, was also implemented in the HIS (Table 2). The internal load values were timed by the associated daily schedule. Table 3 shows the thickness and the thermal transmittances of the external building envelop elements and also the solar energy transmittance of the window of BaU, LIS and HIS. The thermal features of the BaU building envelope refer to the Egyptian energy code for residential building [4, [5], as stated in the methodology section. Moreover, a reflective paint has been used as last layer of the external opaque elements (walls and roof) for the LIS and HIS, as listed in Table 1. Its solar reflectance and thermal emittance are both 0.9 [42]. Overhangs, placed above each window (Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

b), have been used in both LIS and HIS. They exceed the length of the window by 30% and they extend forward for 0.5 m.

3.2. Systems

The description of the systems associated to the BaU, LIS and HIS are presented in this section. Each system is coupled with the building of the respective scenario. Figure 9 shows a schematic view of the HIS system in TRNSYS. The dashed lines refer to the control systems connections. Secondary components, such as pumps, valves and controller are listed in Table 4. Figure 9 have been used to describe both BaU and LIS systems also, since it shows all the system components used.

Business as usual

The system used in this scenario is the simplest considered. It consists of a storage hot water tank and a heat pump (Figure 9). Since there are not solar technologies involved, the components C1, P2 (Table 4), solar collectors, PV, batteries and inverter (Figure 9) are not part of the BaU system. The considered air to water heat pump refers to the model ERLQ004-008CV3 of the series Daikin Altherma air to water heat pump. TRNSYS type 941 [27] has been used to model the HP; furthermore the catalogue data for both heating and cooling has been created according to the abovementioned product technical data sheet [43]. The main technical features of the heat pump are shown in Table 5. The heat pump supplies heating energy to the building via the storage tank, while cooling energy is supplied directly. The right part of Figure 9 shows the supply loop, components V4, V5 and P3. V5 is responsible to divert a part of the load flow rate to V4 in order to reach the inlet temperature required by the fan coils. The fan coils inlet temperatures are 45°C and 16°C respectively for heating and cooling supply. Moreover, C2 (Table 4) allows the heat pump to drive heating or cooling energy through V1 to the hot tank, until the temperature of the tank reaches 55°C, and to V3, in case cooling energy is required in the building. Only in summer both heating, for DHW, and cooling energies are required. Therefore, C2 gives priority to the cooling energy, forcing the heat pump to produce cooling energy first and then, when the building does not require cooling energy, C2 lets the heat pump charge the hot tank. Therefore, the hot storage tank supplies both

DHW and heating loads. TRNSYS type 60 has been used to model the storage tank [27]. All the requested parameters have been set in accordance with the data sheet of the manufacture [44]. Table 6 shows also the main design parameter of the tank.

Low investment scenario

LIS system adds to the BaU system the unglazed solar thermal collectors. This means that the components C1, P2 (Table 4) and solar thermal collectors (Figure 9) are included in the model. Table 6 shows unglazed solar thermal panel features and number. The tilt angle of the solar thermal collectors has been fixed to 40°, which is 10° more than the latitude, in order to maximize their efficiency in winter. Type 1 has been used in TRNSYS to model the solar thermal collectors [27]. Moreover, the power of the solar circulation pumps (P2, Figure 9, Table 4) is assumed to be 50W. C1 checks the temperature difference between the solar thermal field and the hot water tank and if the temperature difference exceeds 4°C when P2 is not running, it forces P2 to run, driving solar energy into the hot water tank. Instead, when P2 is running, C1 lets the solar circulation pump runs only if the aforementioned temperature difference exceeds 2°C.

High investment scenario

The authors have assessed the energy performance of the three PV system sizes used in the HIS to estimate the benefits of a PV driven cooling system. Coupling a heat pump to a PV system allows producing heating and cooling without consuming energy if the output power of the PV system is enough to supply the heat pump. Moreover, only one machine, the heat pump, is needed to supply both the heating and cooling systems. Recent research has shown the promising performance of this system configuration in the Mediterranean regions, stating that currently PV solar cooling solutions actually allow better results than the solar thermally driven ones [46]. Therefore three HIS cases: HISa,b and c have been considered; they differ only by the size of the PV system. In particular, HISc has more PV and batteries than HISb and HISa cases. Therefore, all HIS cases add to the LIS system a PV system, an inverter and batteries. In addition, instead of the unglazed solar thermal collectors, solar flat plate glazed collectors have been used. The same TRNSYS type has been used to model them. Table 6 shows flat plate collectors design features and their configuration for each HIS case.

Table 7 shows the main design parameters for PV, batteries and inverter systems and also their configuration for each HIS cases. The whole PV system (Figure 9) consists of PV modules, a set of batteries and a maximum power point tracking (MPPT) inverter. Types 194, 48 and 47 have been used to model, respectively, PV, inverter and batteries in TRNSYS [27]. All the parameters requested by the aforementioned types have been set according to the manufactures specifications [47-[49]. Therefore, the PV modules charge the battery through the MPPT and the batteries supply electricity to the loads through the inverter. The tilt angle of the PV modules of the HISa and b has been set 20° in order to optimize them for summer use. Instead with regard to the HISc case, since the available roof surface for each apartment is not enough to place all the PV modules, 8 modules have been placed on the south façade of the apartment.

4. Results

Here first the building energy needs of the different scenarios (BaU, LIS, HIS) are presented and, then, the energy performance, the supplied energy and the final energy consumption of the related systems. The energy needs were derived from the different building envelope solutions analysed, while the energy performance from the systems configurations. The envelope solutions and system technologies used in each scenario - the Business as usual scenario (BaU) and Low investment and

High investment scenarios (LIS, HIS) - are listed in Table 8. In LIS the aim was to create a very energy efficient building made with simple and affordable solutions. On the other hand in HIS the aim was coming near to a Net zero energy building. Three HIS cases have been assessed: HISa,b and c. They have different PV systems configurations (Table 8). These affect the system energy consumption results. Thus, HISa, b and c cases are discussed only in the systems results section. As the only differences between these three are in the energy system, the case is referred to simply as HIS within the buildings results section and as HISa, HISb and HISc within the systems energy performance section. With regards to the systems results, the energy efficiency ratio (EER) and the coefficient of performance (COP) of the heat pump have been estimated. Moreover, the seasonal performance factor (SPF) has also been calculated to assess the performance of the whole system. SPF is similar to COP or the EER, but it also takes into account to the consumption of the heat pump and also the energy consumption and production of the others system components, if any, such as the solar thermal circulation pump (P2), free cooling fans and the PV energy produced. It is stated as:

$$SPF = \frac{Q_u}{E_{tot}} = \frac{Q_H + |Q_C| + Q_{DHW}}{E_{FC} + E_{P2} + E_{HP} - E_{PV}} \quad (1)$$

It is worth to mention that if the PV energy matches the final energy demand of the system's considered components (heat pump, solar circulation pump, fans) the denominator of the SPF will be null, meaning that the system is consuming only PV energy.

4.1. Building energy needs

Figure 10 shows the monthly and annual building energy needs of the BaU, LIS and HIS. DHW load is the same for all the scenarios; therefore, it has been shown with a line within the Figure 10. As expected, BaU has the highest cooling and space heating monthly consumption, reaching a building annual cooling and heating (space heating and DHW) demands of respectively 60 kWh/m² and 39.64 kWh/ m²(26.64 kWh/m² space heating and 13 kWh/m² DHW).

Implementing the envelope solutions and the lighting system listed in Table 8, the annual cooling and heating demands of the LIS building drop to respectively 32.3 kWh/ m² and 29.4 kWh/ m² (16.4 kWh/m² space heating and 13 kWh/m² DHW); respectively 46% and 26% lower than the annual energy demands of the BaU. In particular, the cooling demand decreases more than the heating demand because, since it is the one significant, most of the building envelope solutions, such as reflective paint and shading systems (Table 8), are made for that purpose. Having already lowered the cooling load, the solutions used in the HIS aim to further reduce both cooling and heating energy needs.

The HIS building has more insulation layers in the external wall and in roof than the LIS building and both window and lighting typologies have been changed (Table 8). The last two solutions are useful to decrease the cooling load, even though they slightly increase the heating load, while increasing the thickness of the insulation layer is a well-known measure, especially to decrease the space heating load. Therefore, the building heating energy needs, driven by the DHW, of the HIS are higher than the cooling ones, while the contrary happens in both BaU and LIS. Indeed, the annual building heating and cooling demands of the HIS are respectively 24.71 kWh/ m² (11.71 kWh/m² space heating and 13 kWh/m² DHW) and 23.26 kWh/ m². They are respectively 16% and 28% less than the heating and cooling demands of the LIS building.

To design a very energy efficient building, firstly, the building energy needs have to be reduced. Good results for a very energy efficient building have been already achieved in the LIS with simple and relatively affordable solutions. However, a step further has been obtained in the HIS, which represents a good starting point for a Near zero energy building design.

4.2. Systems energy performance

The energy system has a central role in a very energy efficient building. Indeed, energy is needed to produce DHW and to cover both space cooling and heating demands. Moreover, electricity is needed for the home appliances. Their consumptions have been considered only in the final energy balance, calculated in the last stage.

In this section the system results of the HISa, HISb and HISc cases are presented. Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11, Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 and Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars

refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 show monthly results in terms of heating and cooling energy supplied, DHW, space heating and cooling loads, which refer to the left axis, and system performance indexes (COP, EER, SPF), which refer to the right axis, respectively of the BaU, the LIS and the HIS,a b and c cases. Only one figure has been used to summarize the results of the HIS cases, because only the SPF is different among the cases, since the PV system configuration does not affect the supplied energy. Therefore, the bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes. Obviously in the BaU, the COP is not null in summer, because the heat pump has to supply heating energy to satisfy the DHW loads (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11).

Natural ventilation, through opening the windows, covers a small share of the cooling loads (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11), around 4%. Instead in LIS (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12), it covers 26% of the related cooling loads. It is interesting to note that in LIS natural ventilation energy supplied is almost four times higher than in the BaU, although LIS building cooling loads are much lower compared to BaU. This is the effect of the free cooling approach done by means of vents, in this case, which allow the external air to come into the room whenever its temperature is below the internal one, even if the room is not occupied by persons.

Moreover, only five solar thermal unglazed panels satisfy the whole DHW demand from April to November (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12), reaching an annual solar fraction (SF) of 34 %, which is the ratio between the solar thermal energy supplied and the total heating energy demand (space heating and DHW demands). In particular, during the transitional months, the SPF reaches values up to 26, because the only the solar circulation pump consumes energy. Instead, the annual SPF, driven by the natural ventilation and the solar thermal supplied energies, is 3.95, while that one of the BaU is 3.27.

Of particular interest are the results of the HIS cases. Basically, they differ by the sizes of the PV systems; HISc system has more PV collectors and batteries than respectively HISb and HISa systems (Table 8). Therefore, the only difference is the amount of PV electricity produced and consumed and dumped energy; obviously, it only affects the SPF. Thus, despite the number of solar thermal collectors used in HIS cases being lower than in LIS, the SF reaches 90% because of the higher efficiency of the selected solar thermal collectors - flat plate glazed solar thermal collectors. Furthermore, the free cooling energy covers 18% of the cooling demand in all the HIS scenarios (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The

bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13). In particular, natural ventilation accounts for 15% and mechanical ventilation for the remaining 3% of the free cooling energy. Actually, free cooling energy accounts for a smaller part of the HIS building's cooling needs compared to the LIS because of the lower HIS building cooling energy needs.

Clearly, the SPF values of all HIS scenarios are higher than the LIS ones (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12). It is worth noting that for the HIS cases the SPF denominator (1) can be null due to the PV consumed energy, which covers the energy consumption of the considered system components. In particular with regard to HISa case (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The

bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13), SPF denominator is null in the period from April to May and from October to November. These periods extend going from HISa to HIS b and to HISc (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13). However, the annual SPFs are 9.26, 32.46 and 69.79 respectively for HISa, HISb and HISc systems. It is worth analysing the final energy demand and the PV energy produced, consumed and dumped energy of the HIS cases, shown in Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The

bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14. Dumped PV energy is the energy that the PV array does not collect due to full batteries. Clearly, the final energy consumption of the system components is the same in all the HIS cases, while the PV energies are different. Obviously, HISc system produces more PV energy than the others scenarios as it has the largest PV system.

As was mentioned before, the larger the PV system, the more energy is produced and, consequently, dumped and consumed and the higher is the number of months where PV energy is enough to cover the energy demand of the system components (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14). Actually, PV energy does not cover the whole energy demand only during five months (February, March, July, August and September) in the HISb, while in the HISc only during three months (February, July and August). It has to be noted that during those months there is the possibility of dumped PV energy, even though the amount of PV energy consumed is lower than the energy demand. Indeed, the hours when the batteries are full and the PV system still produces energy, energy dumps cannot be distinguished since Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars

refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 shows monthly results.

Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 Monthly system components final energy demand and PV produced, consumed, and dumped energy of HIS cases. Bars refer to the system components final energy consumptions and to dumped PV energies, while lines to the PV produced and consumed energy

Figure 15 shows the monthly and annual final energy consumption of the considered scenarios and, for HIS cases, consumed PV energy. The final energy consumption of LIS shows that a very energy efficient building can be achieved using simple and affordable envelope and system solutions (Table 8). Indeed, its consumption is almost half of the BaU building (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 Monthly system components final energy demand and PV produced, consumed, and dumped energy of HIS cases. Bars refer to the system components final energy consumptions and to dumped PV energies, while lines to the PV produced and consumed energy

Figure 15). Moreover, a big step toward a Net zero energy building has been obtained using PV and upgrading the solar thermal systems. Indeed, the final energy consumption of the HISa is about 65% (5.17 kWh/m²) lower than that one of LIS.

Finally, it is worth noting that both HISb and c buildings can be considered Net zero energy buildings, since the on-site renewable energy system (PV) supplies almost the whole energy needed by the heating and cooling system. In addition they achieve this using a PV system size within the range of the power capacity conventionally utilized in the residential sector of the Mediterranean countries [52]. As final stage of the energy analysis, the authors have also estimated the final energy balance of each scenario to complete the energy benefits assessment of implementing the very energy efficient building concept in Egypt.

Table 9 shows the annual figures of the final energy demand of the heating and cooling systems, the PV produced, consumed and dumped energy, the final energy consumption and the final energy balance of each scenario. Only the final energy balance includes the home appliances energy consumption and it has been roughly calculated as the algebraic sum of the final energy consumption, the home appliances electricity consumption and dumped PV energy. In fact, part of dumped PV energy is certainly used by the home appliances, such as fridge, TV, lights and so on. Although their energy consumption has not been analysed in this study, it has been roughly estimated. The average electricity consumption during April, May and October, evaluated by S. Attia for Alexandria (0.93 kWh/m² for month) [3], has been considered as the monthly consumed energy by the home appliances for all the scenarios.

Moreover, dumped PV energy has been assumed as being exported to the national grid. It interesting to note that the annual PV produced, consumed and dumped energies of HISb are respectively 1.8 – 1.65, which is two times higher than those of HISa. Moreover, comparing the HISb with the HISc, these numbers decrease to 1.26 – 1.18 – 1.45. Therefore, while the PV energy production grows, the consumed PV energy scarcely rises, although the final energy consumption of HISc is half of the HISb. Actually, the HISb final energy consumption is already low (Table 9), and in fact a small increment of the PV consumed energy is enough to lower quite a lot the final energy consumption.

The amount of dumped PV energy increases from HISa to HISc almost by half of the amount of produced PV energy that is dumped in HISc (Table 9). It is interesting to note that only the HISc has a negative final energy balance. This means that in the HISc the building produces a surplus of energy over the year; making it effectively a net energy-plus building. Instead, in the HISb, the building has a final energy balance that exceeds slightly zero. However, both HISb and HISc results state the potential success of the Net zero energy building concept in Egypt.

4.3. Districts' energy performance and emissions

Previous results were multiplied by the number of apartments in the whole city, 178 125 apartment units according to the master plan. It was assumed that all buildings had the same shape as the case building, being 4 stories high. It must be noted that this would probably in reality not be the case. It shall also be noted that if a building would be higher than 4 stories, the rooftop area will not anymore be enough for the amount of PV panels assumed in the earlier calculations. The Table 10 shows the energy performance of the district and the CO_2 emissions calculated on the energy balance. It is to be noted that even if these results indicate an overall surplus energy production in the scenario HISc, this applies for the residential sector only. Actually it would mean that the residential buildings would be able to sell surplus electricity to for example public buildings like schools or health centres or commercial buildings like offices. The overall CO_2 emissions in these results shall be interpreted as the residential buildings surplus energy would replace average electricity and therefore impact the other sectors' emissions. Since this analysis only takes the residential sector into account, these emissions are shown as negative for this sector.

5. Conclusions

Awareness about the energy consumption of the residential sector has been growing in the recent years in Egypt. Residential energy consumption represents a large share of the total Egyptian energy consumption and the largest of total Egyptian electricity consumption. Recently studies have started to focus on possible building energy saving solutions suitable for the Egyptian climate.

The aim of this paper is to design and to assess the energy consumption of a very low energy residential building, in the climate of New Borg El Arab City. Considering that the cost of a Net zero energy building is typically high, the authors investigated also the energy performance of a very energy efficient building concept, which intentionally stays a step behind the Net zero aim. The building types considered relate to two investment scenarios: low (LIS) and high (HIS) investments. The first one has been designed only with simple and affordable solutions, while the latter with commonly used technologies in Net zero buildings. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum level required by the Egyptian energy code.

The methodology of the research consists of three steps: investigation of the main behavioural patterns related to energy consumption, assessment of relevant technologies, and, finally, energy analysis. The energy savings solutions used in each scenario are listed in Table 8.

The fundamental aim of a very energy efficient building is to reduce the building energy needs. LIS shows good results for a very energy efficient building. Indeed the annual cooling and heating building needs, around 32 kWh/m^2 and 29 kWh/m^2 (16 kWh/m^2 space heating and 13 kWh/m^2 DHW), are respectively 46% and 26% less than the annual energy demands of the BaU case building. However, a step further towards a net zero energy building was taken in the HIS case. There, the annual building heating and cooling demands are respectively 24.71 kWh/m^2 (11.71 kWh/m^2 space heating and 13 kWh/m^2 DHW) and 23.26 kWh/m^2, respectively 16% and 28% less than the energy demands of the LIS case building.

The energy system has a central role in a very energy efficient building. Indeed, energy is needed to produce DHW and to cover both space cooling and heating demands. The HIS case was further divided into three: HISa, b and c; they have different PV systems configurations (Table 8). The final energy consumption of LIS, around 15 kWh/m², signifies that a very energy efficient building can be achieved using simple and affordable envelope and energy system solutions. Indeed, it is half of the final energy consumption of the BaU. Particularly interesting are the results of HISa: the final energy consumption, around 5 kWh/m², is about 65% less than that of LIS.

Finally, remarkable results were achieved in both HISb and c, using a PV system size that is within the range of the power capacities conventionally utilized in the residential sector of the Mediterranean countries [52]. In fact, both HISb and c buildings can be considered net zero energy buildings, since the on-site renewable system (PV) supplies almost the whole energy heating and cooling system demand. Their final energy consumptions are respectively 1.48 kWh/m² and 0.69 kWh/m². These figures do not include the home appliances' consumption. Instead, they have been considered within the final energy balance of each scenario, which considers also the dumped energy from the PV system as being exported to the national grid. Both HISb and HISc results support the potential success of a very low energy building concept in Egypt. Indeed, the HISb has a final energy balance that exceeds slightly zero, around 1 kWh/m², while the HISc has a negative final energy balance, around -5 kWh/m², meaning that the building produces a surplus of energy over the year.

It is evident that the impact on the whole city is very big if these scenarios would be applied in the whole city. Savings up to 605,7 GWh could be achieved and 282,2 1000 tons of CO_2 emissions could be avoided. This amounts to the total CO_2 emissions of 117853 Egyptians. This can be considered high impact since the city is planned to host 750000 inhabitants. These savings from only the residential sector would enable 15% of the population to live totally "carbon free", theoretically calculated. The figure becomes bigger when sustainability actions for other sectors as transport, service and industry sectors are taken into account.

In conclusion, very low energy and net zero energy buildings have been designed in line with the local context, using envelope solutions to lower their energy needs and renewable systems to achieve a near zero or a negative final energy balance. Ideally this study along with others should attract the interest of local and central administrations for planning and building new eco-friendly residential districts that include very energy efficient buildings.

6. Further work

The energy assessment of these very low energy buildings performed in this work should be considered as the first part of the feasibility study of a new residential district in New Borg El Arab. In particular, the findings of this research will be used as inputs in further research by the participating research team for assessing the cost-effectiveness of the case buildings studied. A quick calculation about financial impacts show that with an average energy cost for a resident of 0,23 pounds/kWh (around 3 c/kWh) gives a total saving of 139311000 pounds yearly (approx. 12000000 €). However it shall be noted that the energy prices in Egypt are expected to increase to the double within the next 5 years due to reductions of subsidies. A more thorough economic analysis taking the investment needs into account would naturally be needed in order to make more deep analysis about the economic impacts

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Reference

[1]. Consequently, the total energy consumption of the residential sector grew, reaching the 22% of the total energy consumption of Egypt in 2011,showing an annually average growth rate of 5%, from 2008 to 2011 [2]. Moreover, residential electricity held the biggest share from the national energy consumption in 2012, around 44% of the total with an annual average growth rate of 9% [2]. Indeed, a recent study tenaciously points out a high level of energy inefficiency in the residential building stock, mainly due to the lacking thermal performance of external envelopes and to the heavy subsidies on the domestic energy prices [3]. To counter the rise of residential buildings' energy consumption, the Egyptian code for improving the efficiency of energy use in buildings for residential buildings was enacted in 2008 [4, [5]. It gives recommendations about thermal properties values of the building envelope elements for energy efficient buildings in the different climatic areas of Egypt.

Moreover, the Egyptian government is making efforts to increase the renewable energy capacity, which was 3.4 GW in 2012 or about 11.6% of the total electricity power capacity [6]. Moreover, the national energy strategy target is to satisfy 20% of the electric energy demand from renewable energy resources by the year 2020; in particular, 12% from wind power and 8% from others renewable energy sources, such as PV and CSP systems [6]. With regard to PV installed capacity, it has increased from 15 MW in 2012 [6, [7] to 140 MW in 2013 [7]. Furthermore, the Ministry of Electricity and Energy, represented by the New & Renewable Energy Authority, proposed to convert the diesel power plants, which supply electricity to 20 cities and residential communities, with combined PV-diesel power plants [8]. In addition, it is going to electrify 265 remote villages with PV in cooperation with the United Arab of Emirates [8]. Regarding solar thermal panels, the main projects are in the tourism sector. The installed area, mostly in hotels, grew to 800 000 m² in 2012 [8]. Furthermore, 100 000 hotel rooms will be equipped with solar water heaters before the 2018, under the "Green Tourism Initiative" [8]. Environmental concerns in Egypt are likely to keep solar technologies among the key solutions to reduce primary energy consumption and greenhouse gas emissions of the Egyptian buildings.

Recently published studies have started to focus on energy saving in buildings. Usually they refer to the Egyptian building energy code as a baseline to further investigate individual solutions. In particular, G. B. Hanna has found that decreasing the thermal transmittance of the external wall can strongly increase the thermal efficiency of a residential building [9]. This has been confirmed by M Fahmy, who has investigated the effect of an external wall with glass fibre reinforced concrete [10]. Both M. A. A. Abd El-Monteleb and M. M. Mahdy, M. Nikolopoulou showed that external shading systems can save energy in many Egyptian locations [11, [12]. M. M. Mahdy, M. Nikolopoulou have also analysed different window typologies, finding that a clear reflective glass has to be used, if the building has not shading systems [12].

However, presently there are no comprehensive design guidelines for very energy efficient buildings in Egypt, be that low-energy buildings, passive buildings or near zero-energy buildings. On the other hand, various concepts for very energy efficient buildings are spreading worldwide [13 - [20]. For Net zero energy buildings the aim is to produce as at least as much energy as is used. However, achieving the energy balance of a Net zero energy building depends on design characteristics, occupant behaviour and weather conditions [13]. Many designs and technologies, active and passive, can be found in Net zero energy buildings to meet part of their thermal and other energy requirements. In particular, PV and solar thermal systems play a central role in Net zero energy buildings, supplying the energy needs with clean and renewable-energy sources [21]. Indeed, in countries rich of sun irradiance, such as Egypt, solar technologies have been used to successfully design a number of very energy efficient buildings [17 - [20], showing, in some cases [17, [19], a payback time of about 10 years.

The aim of the paper is to design and to assess the energy consumption of a very low energy residential building, with regard to the climate of New Borg El Arab City (NBC), which is situated on the North Coast, 40 km west from Alexandria. However, since the cost of a very energy efficient building is typically high, depending on the used technologies, the authors investigated also the energy performance of a low-energy building concept, which is less ambitious than the Net zero model. These buildings relate to two investment scenarios: low (LIS) and high (HIS) investments. In the first case, the design includes exclusively low cost solutions, while in the second case technologies commonly associated with Net zero houses are included. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum requirements of the Egyptian energy code, as presented in the aforementioned studies. In particular, active and passive ventilation systems, different external envelope solutions, PV and solar thermal systems have been considered. Furthermore, different solar PV field sizes have been considered, but only for the high investment scenario.

After calculating and analysing the impact of the scenarios for one residential building, the result was multiplied to show the impact on the whole residential sector of New Borg El Arab. Data from the master plan of the extension of the city was used as a basis for these calculations. The impacts on energy usage and CO_2 emissions were analysed.

The research is part of the residential feasibility study of the New Borg El Arab EcoCity (Eco NBC) project. The scope of the feasibility study is analysing the most feasible solutions for different sectors (industry, residential, commercial and transportation) in NBC for turning the city into an EcoCity or low emission city. The Eco NBC project is an international collaboration between two Finnish and Egyptian scientific institutions: VTT Technical Research Centre of Finland and Egypt-Japan University of Science and Technology (E-JUST) Shady Attia, Mohamed Hamdy, William O'Brien, Salvatore Carlucci, Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design, Energy and Buildings, Volume 60, May 2013, Pages 110-124, ISSN 0378-7788;

[22].

7. Methodology

The research has been carried out in three phases: investigation of the principal behaviour patterns of people related to energy consumption, assessment of relevant technologies and, finally, energy analysis. The investigation phase was conducted as a survey. The goal of the survey was to understand the occupant behaviour concerning the use of windows, shading systems and domestic hot water in typical New Borg El Arab residential areas. Stakeholders, local authorities and energy market key players were involved in the technology assessment phase in order to list cost-effective systems and building envelope solutions for each scenario: BaU, LIS and HIS. Then, energy analyses of the three scenarios were done using dynamic simulation modelling, as recommended by various researchers [9, [10,[10 [17,[19]. Data from the master plan of the extension of New Borg El Arab has been used to multiply the one analysed case residential building to get the impacts of the whole residential sector of the city. The authors have considered the occupant behaviour information, findings of the survey, in the simulation analysis, as suggested by many researchers [23 - [26]. The simulation tool used was TRNSYS v. 17 [27] and TRNBuild [28], which is a TRNSYS tool, to assess respectively the energy production and consumption of the systems, including PV and solar thermal ones, and the thermal energy needs in the building. TRNSYS has been used for similar purposes in a number of previous studies [29 - [32].

7.1. Phase one: Investigation

The purpose of the authors was to understand the state of art of New Borg El Arab residential sector in terms of building features and utilization (occupant behaviour) with a survey. Indeed, it is extremely important, in order to achieve a successful replicable design of a very energy efficient building in New Borg El Arab, to select energy efficient systems and building envelope solutions that can be applied in the local context. This means that local building constructors can implement them and people do not reject them in their behaviour. The survey was carried out by local NGOs and 60 families were involved. The age composition of the sample was 43 infants, 70 school-age or students, 61 working age and 5 retired. **Error! Reference source not found.** shows the percentage share of the involved people by age, occupation and family financial status.

In accordance with the predominantly young age structure of Egypt, the dominant occupation in New Borg El Arab appears to be student, around 40%, followed by workers, 35%, then infants, 22%, and retired 3%. The results are in line with last census, done in 2006, as well as with [33]. Even though it is extremely hard to define a representative sample, the families involved can be considered to be representative. Indeed, a previous work, which considered Alexandria, the city closest to New Borg El Arab, showed a similar sample composition with same age distributions [3].

Figure 2 shows the most common building typologies in New Borg El Arab. It has been found that a four storey apartment building is the most common typology of residential building.

Figure 2 Survey results: Building typologies in New Borg El Arab.

Figure 3 shows how often people use the shower in summer and in winter and the average time spent in the shower. Although the number of showers in summer is higher, people take shower almost every day, the energy consumption of the DHW system is lower in summer than in winter. Expectedly, people mostly use cold water in summer and hot water in winter. This affects the consumption profiles of hot water.

Unfortunately real time consumption measurements for DHW are not available; therefore the authors have assumed that DHW summer load is 40% less than the DHW winter load according to the survey results. Thus, with regard to a single dwelling, the DHW profiles in e been selected respectively for the periods that extent from October to April and from May to September. This profile has been estimated using as a reference DHW profile of [34], which was modified according to the findings of the survey. Additionally, only decentralized heating systems were present in the survey.

have been selected respectively for the periods that extent from October to April and from May to September. This profile has been estimated using as a reference DHW profile of [34], which was modified according to the findings of the survey. Additionally, only decentralized heating systems were present in the survey.

Of particular interest are the findings about habits concerning the opening of windows and curtains in the living room and bedroom (Figure 5). It appears that the occupants interact often with both windows and curtains, leaving the windows open when they feel hot and the external air temperature is colder than the inside temperature. Moreover, occupants close the living room windows when they go to bed, whereas they leave the windows open while sleeping in the bedroom. On the other hand, they close the curtains in the bedroom while sleeping and only when the sunlight is strong they close them in the living room. Regarding the lighting system, only 46% use exclusively energy efficient lights; whereas 44% use also incandescent light bulbs and the 10% use only incandescent light bulbs.

Results of the survey show how people’s behaviour affect the DHW profiles and the building cooling load through opening the windows, witnessing their confidence with natural ventilation and shading systems. Moreover, it has been found that the main building typology is the four storey building. Conclusions of the survey have been discussed and verified in a workshop with experts from E-JUST and VTT. These findings have been used in the next phases, helping to find out systems and building envelope solutions suitable for each scenario and to calibrate the energy assessment simulations.

7.2. Phase two: Technology assessment

The aim of this phase was to create a list of technologies that suit New Borg El Arab in the local context for both high and low investment scenarios. A two-day meeting was organized by VTT and E-JUST with the local stakeholders, authorities and energy market key players in order to select, among other issues related to EcoNBC project, the most effective residential energy saving solutions. Particular attention was given to the capability of the construction workers, to the availability of technical passive and active solutions on the Egyptian market and to the recent local research findings, described within the introduction. Thus, the low investment scenario (LIS) is includes only simple and affordable solutions, while the high investment scenario (HIS) includes technologies commonly applied in Net zero energy buildings. In both scenarios, solar technologies were preferred, among others, because of the high level of solar irradiance in Egypt, as was stated in the introduction. The business as usual scenario (BaU), on the other hand, refers to the minimum requirements of the Egyptian energy code [4, [5]. The chosen technologies for each case are listed in Table 1. Moreover, for the three considered cases: BaU, LIS and HIS, an air to water heat pump was included for supplying cooling and heating energy.

7.3. Phase three: Energy analysis

7.3.1. Building

In this last phase all the information gathered within the two previous phases were employed for energetic analysis. As mentioned before, a dynamic simulation approach was selected to assess the building energy needs and the energy performance, in terms of supplied energy and final energy consumption, of the heating and cooling systems, including renewable energy systems, for each scenario in New Borg El Arab. The buildings of each case were modelled using TRNSYS3d [35], a particular plug-in of TRNSYS, which connects Google Sketch-up [36] to TRNSYS via TRNBuild [28]. The cases have a four storey building, based on the results of the survey. Each floor consists of one apartment. Two different building types were included, one for the BaU, presented in Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

a, and the other for both LIS and HIS, presented in Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

. These were done in accordance with the technologies selected for the scenarios in Table 1. There are not differences in the building envelope shapes between the LIS and HIS.

Different features were assigned to the building model used in each scenario. Once created the building in Sketch-up, thermal properties of the envelope, internal loads of people, appliances and lightings were assigned to the buildings in TRNBuild for each scenario. Then, each building model was imported through type 56 [27] into the TRNSYS system model of the related scenario. Since people in Egypt tend to use decentralized system, each apartment has its own system, made of the technologies listed in Table 1. Therefore, three different systems were created according to the related scenario. Results of the analysis refer to the highest floor, which, typically, has the highest thermal loads. The roof has been divided into four parts in order to give the same access to roof area for each apartment and, therefore, to allow the installation of similar solar systems. The indoor air temperature of all the apartments was kept at 26°C during the cooling months and at 20°C during the heating months. The energy assessment refers to both heating, from November to March, and cooling, from June to September, seasons. Type 15 has been used in TRNSYS to implement the weather data in the model [27]. EPW format weather file of Alexandria (Egypt), city close to New Borg El Arab and with the same climate, was used [50]. The time step used in the simulation analyses was 0.25 h.

There were two sets of daily schedules: one related to the occupancy rate and the other to the lighting system. The occupancy schedules were set according to [3]. In particular, two schedules were used for summer and winter and a third one for the Ramadan period, which occurred from June the 29th to July the 28th in 2014. The year is divided into summer and winter periods: summer refers to the period from April to September and winter from October to March. Every room typology has its own schedule, except for the bathroom, which has the same schedule as the kitchen. The considered room typologies are: living room, bedroom and kitchen and their schedules are shown respectively in Figure 7 a, b and c. Moreover, occupant behaviour has been considered, based on the findings of the survey, in terms of natural ventilation and DHW (Figure 2 Survey results: Building typologies in New Borg El Arab.

Figure 3 Survey results: number of showers that people use to have in summer and in winter and the shower average time.

Figure 4) and included in the model. In particular, the occupancy schedules have been used to assign the internal loads and to control the natural ventilation in the BaU scenario (Table 1). The results of the survey showed that occupants open the windows if the external temperature is less than the internal one, therefore allowing free-cooling. This control strategy has been implemented in the BaU, checking if the room is occupied or not. On the other hand, in the others scenarios free cooling is allowed without checking if the room is occupied implying a control system. Moreover, in all the scenarios free-cooling is allowed until the indoor temperature is above 24°C. People, appliance and lightings contribute to the internal loads. From these, people and appliances are modelled based on the occupancy schedule, while lightings have their own schedules.

7.3.2. District level

In order to assess the scenarios impacts on the whole residential sector of the city, the results from the above mentioned residential building was multiplied with the amount of apartment units set up in the master plan. The master plan of New Borg El Arab City includes information about the total number of residents and number of housing units. The total amount of housing units is 178125 and the total number of inhabitants is 750 000. Since no other information about these types was available, an assumption was made that all residential buildings would be as the model unit chosen above, and the total amount was calculated from the total unit number.

The assessment of CO_2 emissions was done by multiplying the final energy demand by the average Egypt emission factor for electricity 466 g/kWh [51]. The more accurate would be to analyse the energy source distribution in each scenario and calculate the emissions based on the actual sources. However since the CO_2 emissions are not the main issue of this article it was not considered beneficial and the source division would have been based on assumptions only. The emission factor for natural gas which is the main source besides electricity is 529 g/kWh, which is very close to the average Egypt electricity CO_2 emission factor.

8. Case studies

Three models, consisting of the building and the associated system, were created in accordance with the specifications found out in the investigation and the technology assessment phases. In the model the whole building was created, but the results refer to the apartment of the highest floor for aforementioned reasons. In this section authors describe first the thermal features of the buildings for each analysed scenario and then their related systems, which include the technologies and envelope solutions described in the methodology section (Table 1).

8.1. Buildings

The layout of the considered apartment is shown in Figure 8; it is about 114 m². Table 2 shows fresh air and free cooling mechanical ventilation rates, number of fan coils and vents, lighting and the people and appliances internal loads related to different room typologies for each scenario. People loads refer to the number of persons and their activities, as suggested by the UNI EN ISO

7730 [37]. These have been listed in Table 2 for each room (Figure 8) and they have been applied to each scenario. Lighting and appliances internal loads of BaU refer to [3]. The appliances load is the same for all the scenarios. On the other hand, the lighting loads of the LIS and HIS, which refer to the technologies listed in Table 1, are 8 W/m² and 6 W/m² respectively for fluorescent and LED lamps [38]. These values have been applied for the smallest room and then scaled up for the others rooms, keeping the original lighting distribution density. It is interesting to note that there is not a big difference between the lighting load of the BaS and LIS. Indeed, as confirmed by the survey results, currently people in Egypt are using mostly energy saving lamps. The minimum required fresh air rates for the rooms have been set according to the standard UNI 10339 and EN 15251 [39, [40]. The number of fan coils has been estimated based on the maximum power of heating and cooling of each room and at the technical sheet of Omnia HL model (Aermec®), which has 870 W of heating capacity and 530W of cooling [41]. Free cooling was achieved through opening the windows in the BaU, and through vents (30cm x 30cm) in both LIS and HIS. The air change per hour depends on the temperature and pressure difference between inside and outside each room. In order to consider the relation between the air change per hour through the vents and the temperature and pressure difference between inside and outside each room, Type 932 has been used to estimate it in TRNSYS [27]. Mechanical ventilation with free cooling, made by means of the fan coils, was also implemented in the HIS (Table 2). The internal load values were timed by the associated daily schedule. Table 3 shows the thickness and the thermal transmittances of the external building envelop elements and also the solar energy transmittance of the window of BaU, LIS and HIS. The thermal features of the BaU building envelope refer to the Egyptian energy code for residential building [4, [5], as stated in the methodology section. Moreover, a reflective paint has been used as last layer of the external opaque elements (walls and roof) for the LIS and HIS, as listed in Table 1. Its solar reflectance and thermal emittance are both 0.9 [42]. Overhangs, placed above each window (Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

b), have been used in both LIS and HIS. They exceed the length of the window by 30% and they extend forward for 0.5 m.

8.2. Systems

The description of the systems associated to the BaU, LIS and HIS are presented in this section. Each system is coupled with the building of the respective scenario. Figure 9 shows a schematic view of the HIS system in TRNSYS. The dashed lines refer to the control systems connections. Secondary components, such as pumps, valves and controller are listed in Table 4. Figure 9 have been used to describe both BaU and LIS systems also, since it shows all the system components used.

Business as usual

The system used in this scenario is the simplest considered. It consists of a storage hot water tank and a heat pump (Figure 9). Since there are not solar technologies involved, the components C1, P2 (Table 4), solar collectors, PV, batteries and inverter (Figure 9) are not part of the BaU system. The considered air to water heat pump refers to the model ERLQ004-008CV3 of the series Daikin Altherma air to water heat pump. TRNSYS type 941 [27] has been used to model the HP; furthermore the catalogue data for both heating and cooling has been created according to the abovementioned product technical data sheet [43]. The main technical features of the heat pump are shown in Table 5. The heat pump supplies heating energy to the building via the storage tank, while cooling energy is supplied directly. The right part of Figure 9 shows the supply loop, components V4, V5 and P3. V5 is responsible to divert a part of the load flow rate to V4 in order to reach the inlet temperature required by the fan coils. The fan coils inlet temperatures are 45°C and 16°C respectively for heating and cooling supply. Moreover, C2 (Table 4) allows the heat pump to drive heating or cooling energy through V1 to the hot tank, until the temperature of the tank reaches 55°C, and to V3, in case cooling energy is required in the building. Only in summer both heating, for DHW, and cooling energies are required. Therefore, C2 gives priority to the cooling energy, forcing the heat pump to produce cooling energy first and then, when the building does not require cooling energy, C2 lets the heat pump charge the hot tank. Therefore, the hot storage tank supplies both

DHW and heating loads. TRNSYS type 60 has been used to model the storage tank [27]. All the requested parameters have been set in accordance with the data sheet of the manufacture [44]. Table 6 shows also the main design parameter of the tank.

Low investment scenario

LIS system adds to the BaU system the unglazed solar thermal collectors. This means that the components C1, P2 (Table 4) and solar thermal collectors (Figure 9) are included in the model. Table 6 shows unglazed solar thermal panel features and number. The tilt angle of the solar thermal collectors has been fixed to 40°, which is 10° more than the latitude, in order to maximize their efficiency in winter. Type 1 has been used in TRNSYS to model the solar thermal collectors [27]. Moreover, the power of the solar circulation pumps (P2, Figure 9, Table 4) is assumed to be 50W. C1 checks the temperature difference between the solar thermal field and the hot water tank and if the temperature difference exceeds 4°C when P2 is not running, it forces P2 to run, driving solar energy into the hot water tank. Instead, when P2 is running, C1 lets the solar circulation pump runs only if the aforementioned temperature difference exceeds 2°C.

High investment scenario

The authors have assessed the energy performance of the three PV system sizes used in the HIS to estimate the benefits of a PV driven cooling system. Coupling a heat pump to a PV system allows producing heating and cooling without consuming energy if the output power of the PV system is enough to supply the heat pump. Moreover, only one machine, the heat pump, is needed to supply both the heating and cooling systems. Recent research has shown the promising performance of this system configuration in the Mediterranean regions, stating that currently PV solar cooling solutions actually allow better results than the solar thermally driven ones [46]. Therefore three HIS cases: HISa,b and c have been considered; they differ only by the size of the PV system. In particular, HISc has more PV and batteries than HISb and HISa cases. Therefore, all HIS cases add to the LIS system a PV system, an inverter and batteries. In addition, instead of the unglazed solar thermal collectors, solar flat plate glazed collectors have been used. The same TRNSYS type has been used to model them. Table 6 shows flat plate collectors design features and their configuration for each HIS case.

Table 7 shows the main design parameters for PV, batteries and inverter systems and also their configuration for each HIS cases. The whole PV system (Figure 9) consists of PV modules, a set of batteries and a maximum power point tracking (MPPT) inverter. Types 194, 48 and 47 have been used to model, respectively, PV, inverter and batteries in TRNSYS [27]. All the parameters requested by the aforementioned types have been set according to the manufactures specifications [47-[49]. Therefore, the PV modules charge the battery through the MPPT and the batteries supply electricity to the loads through the inverter. The tilt angle of the PV modules of the HISa and b has been set 20° in order to optimize them for summer use. Instead with regard to the HISc case, since the available roof surface for each apartment is not enough to place all the PV modules, 8 modules have been placed on the south façade of the apartment.

9. Results

Here first the building energy needs of the different scenarios (BaU, LIS, HIS) are presented and, then, the energy performance, the supplied energy and the final energy consumption of the related systems. The energy needs were derived from the different building envelope solutions analysed, while the energy performance from the systems configurations. The envelope solutions and system technologies used in each scenario - the Business as usual scenario (BaU) and Low investment and

High investment scenarios (LIS, HIS) - are listed in Table 8. In LIS the aim was to create a very energy efficient building made with simple and affordable solutions. On the other hand in HIS the aim was coming near to a Net zero energy building. Three HIS cases have been assessed: HISa,b and c. They have different PV systems configurations (Table 8). These affect the system energy consumption results. Thus, HISa, b and c cases are discussed only in the systems results section. As the only differences between these three are in the energy system, the case is referred to simply as HIS within the buildings results section and as HISa, HISb and HISc within the systems energy performance section. With regards to the systems results, the energy efficiency ratio (EER) and the coefficient of performance (COP) of the heat pump have been estimated. Moreover, the seasonal performance factor (SPF) has also been calculated to assess the performance of the whole system. SPF is similar to COP or the EER, but it also takes into account to the consumption of the heat pump and also the energy consumption and production of the others system components, if any, such as the solar thermal circulation pump (P2), free cooling fans and the PV energy produced. It is stated as:

$$SPF = \frac{Q_u}{E_{tot}} = \frac{Q_H + |Q_C| + Q_{DHW}}{E_{FC} + E_{P2} + E_{HP} - E_{PV}} \quad (1)$$

It is worth to mention that if the PV energy matches the final energy demand of the system's considered components (heat pump, solar circulation pump, fans) the denominator of the SPF will be null, meaning that the system is consuming only PV energy.

9.1. Building energy needs

Figure 10 shows the monthly and annual building energy needs of the BaU, LIS and HIS. DHW load is the same for all the scenarios; therefore, it has been shown with a line within the Figure 10. As expected, BaU has the highest cooling and space heating monthly consumption, reaching a building annual cooling and heating (space heating and DHW) demands of respectively 60 kWh/m² and 39.64 kWh/ m²(26.64 kWh/m² space heating and 13 kWh/m² DHW).

Implementing the envelope solutions and the lighting system listed in Table 8, the annual cooling and heating demands of the LIS building drop to respectively 32.3 kWh/ m² and 29.4 kWh/ m² (16.4 kWh/m² space heating and 13 kWh/m² DHW); respectively 46% and 26% lower than the annual energy demands of the BaU. In particular, the cooling demand decreases more than the heating demand because, since it is the one significant, most of the building envelope solutions, such as reflective paint and shading systems (Table 8), are made for that purpose. Having already lowered the cooling load, the solutions used in the HIS aim to further reduce both cooling and heating energy needs.

The HIS building has more insulation layers in the external wall and in roof than the LIS building and both window and lighting typologies have been changed (Table 8). The last two solutions are useful to decrease the cooling load, even though they slightly increase the heating load, while increasing the thickness of the insulation layer is a well-known measure, especially to decrease the space heating load. Therefore, the building heating energy needs, driven by the DHW, of the HIS are higher than the cooling ones, while the contrary happens in both BaU and LIS. Indeed, the annual building heating and cooling demands of the HIS are respectively 24.71 kWh/ m² (11.71 kWh/m² space heating and 13 kWh/m² DHW) and 23.26 kWh/ m². They are respectively 16% and 28% less than the heating and cooling demands of the LIS building.

To design a very energy efficient building, firstly, the building energy needs have to be reduced. Good results for a very energy efficient building have been already achieved in the LIS with simple and relatively affordable solutions. However, a step further has been obtained in the HIS, which represents a good starting point for a Near zero energy building design.

9.2. Systems energy performance

The energy system has a central role in a very energy efficient building. Indeed, energy is needed to produce DHW and to cover both space cooling and heating demands. Moreover, electricity is needed for the home appliances. Their consumptions have been considered only in the final energy balance, calculated in the last stage.

In this section the system results of the HISa, HISb and HISc cases are presented. Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11, Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 and Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars

refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 show monthly results in terms of heating and cooling energy supplied, DHW, space heating and cooling loads, which refer to the left axis, and system performance indexes (COP, EER, SPF), which refer to the right axis, respectively of the BaU, the LIS and the HIS,a b and c cases. Only one figure has been used to summarize the results of the HIS cases, because only the SPF is different among the cases, since the PV system configuration does not affect the supplied energy. Therefore, the bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes. Obviously in the BaU, the COP is not null in summer, because the heat pump has to supply heating energy to satisfy the DHW loads (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11).

Natural ventilation, through opening the windows, covers a small share of the cooling loads (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11), around 4%. Instead in LIS (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12), it covers 26% of the related cooling loads. It is interesting to note that in LIS natural ventilation energy supplied is almost four times higher than in the BaU, although LIS building cooling loads are much lower compared to BaU. This is the effect of the free cooling approach done by means of vents, in this case, which allow the external air to come into the room whenever its temperature is below the internal one, even if the room is not occupied by persons.

Moreover, only five solar thermal unglazed panels satisfy the whole DHW demand from April to November (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12), reaching an annual solar fraction (SF) of 34 %, which is the ratio between the solar thermal energy supplied and the total heating energy demand (space heating and DHW demands). In particular, during the transitional months, the SPF reaches values up to 26, because the only the solar circulation pump consumes energy. Instead, the annual SPF, driven by the natural ventilation and the solar thermal supplied energies, is 3.95, while that one of the BaU is 3.27.

Of particular interest are the results of the HIS cases. Basically, they differ by the sizes of the PV systems; HISc system has more PV collectors and batteries than respectively HISb and HISa systems (Table 8). Therefore, the only difference is the amount of PV electricity produced and consumed and dumped energy; obviously, it only affects the SPF. Thus, despite the number of solar thermal collectors used in HIS cases being lower than in LIS, the SF reaches 90% because of the higher efficiency of the selected solar thermal collectors - flat plate glazed solar thermal collectors. Furthermore, the free cooling energy covers 18% of the cooling demand in all the HIS scenarios (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13). In particular, natural ventilation accounts for 15% and mechanical ventilation for the remaining 3% of the free cooling energy. Actually, free cooling energy accounts for a smaller part of the HIS building's cooling needs compared to the LIS because of the lower HIS building cooling energy needs.

Clearly, the SPF values of all HIS scenarios are higher than the LIS ones (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12). It is worth noting that for the HIS cases the SPF denominator (1) can be null due to the PV consumed energy, which covers the energy consumption of the considered system components. In particular with regard to HISa case (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13), SPF denominator is null in the period from April to May and from October to November. These periods extend going from HISa to HIS b and to HISc (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13). However, the annual SPFs are 9.26, 32.46 and 69.79 respectively for HISa, HISb and HISc systems. It is worth analysing the final energy demand and the PV energy produced, consumed and dumped energy of the HIS cases, shown in Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14. Dumped PV energy is the energy that the PV array does not collect due to full batteries. Clearly, the final energy consumption of the system components is the same in all the HIS cases, while the PV energies are different. Obviously, HISc system produces more PV energy than the others scenarios as it has the largest PV system.

As was mentioned before, the larger the PV system, the more energy is produced and, consequently, dumped and consumed and the higher is the number of months where PV energy is enough to cover the energy demand of the system components (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The

bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14). Actually, PV energy does not cover the whole energy demand only during five months (February, March, July, August and September) in the HISb, while in the HISc only during three months (February, July and August). It has to be noted that during those months there is the possibility of dumped PV energy, even though the amount of PV energy consumed is lower than the energy demand. Indeed, the hours when the batteries are full and the PV system still produces energy, energy dumps cannot be distinguished since Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

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Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 shows monthly results.

Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 Monthly system components final energy demand and PV produced, consumed, and dumped energy of HIS cases. Bars refer to the system components final energy consumptions and to dumped PV energies, while lines to the PV produced and consumed energy

Figure 15 shows the monthly and annual final energy consumption of the considered scenarios and, for HIS cases, consumed PV energy. The final energy consumption of LIS shows that a very energy efficient building can be achieved using simple and affordable envelope and system solutions (Table 8). Indeed, its consumption is almost half of the BaU building (Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 Monthly system components final energy demand and PV produced, consumed, and dumped energy of HIS cases. Bars refer to the system components final energy consumptions and to dumped PV energies, while lines to the PV produced and consumed energy

Figure 15). Moreover, a big step toward a Net zero energy building has been obtained using PV and upgrading the solar thermal systems. Indeed, the final energy consumption of the HISa is about 65% (5.17 kWh/m²) lower than that one of LIS.

Finally, it is worth noting that both HISb and c buildings can be considered Net zero energy buildings, since the on-site renewable energy system (PV) supplies almost the whole energy needed by the heating and cooling system. In addition they achieve this using a PV system size within the range of the power capacity conventionally utilized in the residential sector of the Mediterranean countries [52]. As final stage of the energy analysis, the authors have also estimated the final energy balance of each scenario to complete the energy benefits assessment of implementing the very energy efficient building concept in Egypt.

Table 9 shows the annual figures of the final energy demand of the heating and cooling systems, the PV produced, consumed and dumped energy, the final energy consumption and the final energy balance of each scenario. Only the final energy balance includes the home appliances energy consumption and it has been roughly calculated as the algebraic sum of the final energy consumption, the home appliances electricity consumption and dumped PV energy. In fact, part of dumped PV energy is certainly used by the home appliances, such as fridge, TV, lights and so on. Although their energy consumption has not been analysed in this study, it has been roughly estimated. The average electricity consumption during April, May and October, evaluated by S. Attia for Alexandria (0.93 kWh/m² for month) [3], has been considered as the monthly consumed energy by the home appliances for all the scenarios.

Moreover, dumped PV energy has been assumed as being exported to the national grid. It interesting to note that the annual PV produced, consumed and dumped energies of HISb are respectively 1.8 – 1.65, which is two times higher than those of HISa. Moreover, comparing the HISb with the HISc, these numbers decrease to 1.26 – 1.18 – 1.45. Therefore, while the PV energy production grows, the consumed PV energy scarcely rises, although the final energy consumption of HISc is half of the HISb. Actually, the HISb final energy consumption is already low (Table 9), and in fact a small increment of the PV consumed energy is enough to lower quite a lot the final energy consumption.

The amount of dumped PV energy increases from HISa to HISc almost by half of the amount of produced PV energy that is dumped in HISc (Table 9). It is interesting to note that only the HISc has a negative final energy balance. This means that in the HISc the building produces a surplus of energy over the year; making it effectively a net energy-plus building. Instead, in the HISb, the building has a final energy balance that exceeds slightly zero. However, both HISb and HISc results state the potential success of the Net zero energy building concept in Egypt.

9.3. Districts' energy performance and emissions

Previous results were multiplied by the number of apartments in the whole city, 178 125 apartment units according to the master plan. It was assumed that all buildings had the same shape as the case building, being 4 stories high. It must be noted that this would probably in reality not be the case. It shall also be noted that if a building would be higher than 4 stories, the rooftop area will not anymore be enough for the amount of PV panels assumed in the earlier calculations. The Table 10 shows the energy performance of the district and the CO_2 emissions calculated on the energy balance. It is to be noted that even if these results indicate an overall surplus energy production in the scenario HISc, this applies for the residential sector only. Actually it would mean that the residential buildings would be able to sell surplus electricity to for example public buildings like schools or health centres or commercial buildings like offices. The overall CO_2 emissions in these results shall be interpreted as the residential buildings surplus energy would replace average electricity and therefore impact the other sectors' emissions. Since this analysis only takes the residential sector into account, these emissions are shown as negative for this sector.

10.Conclusions

Awareness about the energy consumption of the residential sector has been growing in the recent years in Egypt. Residential energy consumption represents a large share of the total Egyptian energy consumption and the largest of total Egyptian electricity consumption. Recently studies have started to focus on possible building energy saving solutions suitable for the Egyptian climate.

The aim of this paper is to design and to assess the energy consumption of a very low energy residential building, in the climate of New Borg El Arab City. Considering that the cost of a Net zero energy building is typically high, the authors investigated also the energy performance of a very energy efficient building concept, which intentionally stays a step behind the Net zero aim. The building types considered relate to two investment scenarios: low (LIS) and high (HIS) investments. The first one has been designed only with simple and affordable solutions, while the latter with commonly used technologies in Net zero buildings. Both cases have been compared to a reference case, called business as usual (BaU), which refers to the minimum level required by the Egyptian energy code.

The methodology of the research consists of three steps: investigation of the main behavioural patterns related to energy consumption, assessment of relevant technologies, and, finally, energy analysis. The energy savings solutions used in each scenario are listed in Table 8.

The fundamental aim of a very energy efficient building is to reduce the building energy needs. LIS shows good results for a very energy efficient building. Indeed the annual cooling and heating building needs, around 32 kWh/m² and 29 kWh/m² (16 kWh/m² space heating and 13 kWh/m² DHW), are respectively 46% and 26% less than the annual energy demands of the BaU case building. However, a step further towards a net zero energy building was taken in the HIS case. There, the annual building heating and cooling demands are respectively 24.71 kWh/m² (11.71

kWh/m² space heating and 13 kWh/m² DHW) and 23.26 kWh/m², respectively 16% and 28% less than the energy demands of the LIS case building.

The energy system has a central role in a very energy efficient building. Indeed, energy is needed to produce DHW and to cover both space cooling and heating demands. The HIS case was further divided into three: HISa, b and c; they have different PV systems configurations (Table 8). The final energy consumption of LIS, around 15 kWh/m², signifies that a very energy efficient building can be achieved using simple and affordable envelope and energy system solutions. Indeed, it is half of the final energy consumption of the BaU. Particularly interesting are the results of HISa: the final energy consumption, around 5 kWh/m², is about 65% less than that of LIS.

Finally, remarkable results were achieved in both HISb and c, using a PV system size that is within the range of the power capacities conventionally utilized in the residential sector of the Mediterranean countries [52]. In fact, both HISb and c buildings can be considered net zero energy buildings, since the on-site renewable system (PV) supplies almost the whole energy heating and cooling system demand. Their final energy consumptions are respectively 1.48 kWh/m² and 0.69 kWh/m². These figures do not include the home appliances' consumption. Instead, they have been considered within the final energy balance of each scenario, which considers also the dumped energy from the PV system as being exported to the national grid. Both HISb and HISc results support the potential success of a very low energy building concept in Egypt. Indeed, the HISb has a final energy balance that exceeds slightly zero, around 1 kWh/m², while the HISc has a negative final energy balance, around -5 kWh/m², meaning that the building produces a surplus of energy over the year.

It is evident that the impact on the whole city is very big if these scenarios would be applied in the whole city. Savings up to 605,7 GWh could be achieved and 282,2 1000 tons of CO_2 emissions could be avoided. This amounts to the total CO_2 emissions of 117853 Egyptians. This can be considered high impact since the city is planned to host 750000 inhabitants. These savings from only the residential sector would enable 15% of the population to live totally “carbon free”, theoretically calculated. The figure becomes bigger when sustainability actions for other sectors as transport, service and industry sectors are taken into account.

In conclusion, very low energy and net zero energy buildings have been designed in line with the local context, using envelope solutions to lower their energy needs and renewable systems to achieve a near zero or a negative final energy balance. Ideally this study along with others should attract the interest of local and central administrations for planning and building new eco-friendly residential districts that include very energy efficient buildings.

11.Further work

The energy assessment of these very low energy buildings performed in this work should be considered as the first part of the feasibility study of a new residential district in New Borg El Arab. In particular, the findings of this research will be used as inputs in further research by the participating research team for assessing the cost-effectiveness of the case buildings studied. A quick calculation about financial impacts show that with an average energy cost for a resident of 0,23 pounds/kWh (around 3 c/kWh) gives a total saving of 139311000 pounds yearly (approx. 12000000 €). However it shall be noted that the energy prices in Egypt are expected to increase to the double within the next 5 years due to reductions of subsidies. A more thorough economic analysis taking the investment needs into account would naturally be needed in order to make more deep analysis about the economic impacts

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Table capitations

Table 1 List of technologies selected by local stakeholders, authorities, energy market key players, VTT and E-JUST expert.

Table 2 Fresh air and free cooling rates, number of fan coils, lighting, people and appliances internal loads for different rooms and scenarios (BaU, LIS, HIS)

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Table 4 HIS system secondary components list: valves, controllers, pumps

Table 5 Main technical features of the heat pump model Daikin Altherma air to water heat pump - ERLQ004-008CV3 [43]

Table 6 Main design parameters of solar unglazed and flat plate thermal collectors and a storage hot water tank

Table 7 Main design parameters of PV, batteries and inverter systems

Table 8 List of envelope solutions and system technologies used in each scenario: Business as usual scenario (BaU), Low investment and High investment scenarios (LIS, HIS)

Table 9 Annual final energy demand of the heating and cooling systems in one apartment, PV produced, consumed and dumped energies, final energy consumption, appliances energy consumption, and final energy balance of each scenario: business as usual scenario (BaU), low investment (LIS) and high investment a,b and c scenarios (HISa, HISb, HISc)

Table 10. Annual final energy demand of the heating and cooling systems for the residential sector in New Borg El Arab City, PV produced, consumed and exported energies and final energy balance,

which includes the appliances energy consumption of each scenario: business as usual scenario (BaU), low investment (LIS) and high investment a,b and c scenarios (HISa, HISb, HISc). Note: CO_2 emissions are calculated based on the final district energy balance and assuming the average Egyptian emission factor for electricity for all energy use.

Figure capitations

Figure 1 Survey sample information: percentage share of the involved people by age, occupation and family financial status.

Figure 2 Survey results: Building typologies in New Borg El Arab.

Figure 3 Survey results: number of showers that people use to have in summer and in winter and the shower average time.

Figure 4 DHW profiles of October – April and May – September for a single dwelling.

Figure 5 Survey results: opening of windows and the curtains in the living room and in the bedroom.

Figure 6 View of the modelled buildings; a) BaU and b) LIS and HIS with shading elements visible

Figure 7 Winter, Summer and Ramadan occupancy and lighting daily schedules of: a) living room, b) bedroom and c) kitchen

Figure 8 Layout of the considered dwelling. Internal rooms and their surfaces are shown within the map

Figure 9 TRNSYS schematic view of the HIS system

Figure 10 Monthly (left axis) and annual (dashed lines – left axis) building energy needs of the BaU, LIS and HIS. Bars refer to the monthly space heating and cooling energy needs and the continuous line to monthly DHW loads, left axis, while annual heating (space heating and DHW) and cooling energy needs refer to the numbers on the right axis

Figure 11 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the BaU. The

bars refer to heating and cooling energy supplied and the lines to DHW, space heating and cooling loads and system performance indexes

Figure 12 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the LIS. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 13 Monthly heating and cooling energy supplied (left axis), DHW, space heating and cooling loads (left axis) and system performance indexes (COP, EER, SPF – right axis) of the HISa. Bars refer to heating and cooling energy supplied and lines to DHW, space heating and cooling loads and system performance indexes

Figure 14 Monthly system components final energy demand and PV produced, consumed, and dumped energy of HIS cases. Bars refer to the system components final energy consumptions and to dumped PV energies, while lines to the PV produced and consumed energy

Figure 15 Monthly (left axis) and annual (right axis) final energy consumption of the considered scenarios, including for HIS cases, PV consumed energy. The bars refer to the monthly final energy consumption and the lines to the annual final energy consumption

Nomenclature

COP Coefficient of performance

DHW Domestic hot water

EER Energy efficiency ratio

E_{FC} Free cooling fan coils final energy consumption [kWh]

E_{HP} Heat pump final energy consumption [kWh]

E_{P2} Solar circulation pump final energy consumption [kWh]

E_{PV} PV electricity from the batteries [kWh]

E_{tot} Total energy consumption [kWh]

HIS High investment scenario

LIS Low investment scenario

SF Solar fraction

SPF Seasonal performance factor

Q_{DHW} DHW supplied energy [kWh]

$Q_{heating}$ Heating supplied energy [kWh]

Q_C Building cooling loads [kWh]

Q_H Building space heating loads [kWh]

Q_{sol} Solar hot tank supplied energy [kWh]

Q_u Useful supplied energy [kWh]

***Highlights (for review)**

- We assessed many building technology solutions and two investment scenarios
- We involved stakeholders, local authorities and energy market key players
- A residential survey and dynamic energy simulations have been carried out
- We designed very energy efficient residential buildings in New Borg El Arab (NBC)
- The CO_2 saved would enable the 15% of NBC population to live totally carbon free

Table 1

	Business as usual (BaU)	Low investment scenario (LIS)	High investment scenario (HIS)
System technologies	Incandescent 20 % and fluorescent lamp 80%	Fluorescent light bulbs	LEDs
	Free cooling system relying on opening windows when rooms are occupied (natural ventilation only)	Free cooling system using vents (natural ventilation only)	Mixed free cooling ventilation system (through vents + mechanical ventilation)
	-	Unglazed solar thermal collectors	Glazed solar thermal collectors
	-	-	PV
Envelope solutions	-	External reflective paint	External reflective paint
	Double wall of half red-brick with 5 cm air gap in between	Insulation (5cm on the ground floor and the Roof, 3 cm on the external walls)	Insulation (6cm on the ground floor and the Roof, 5 cm on the external walls)
	-	Shading system	Shading system
	Double glass window	Double glass window	Double glass low-e (low thermal emissivity) window

Table 1 List of technologies selected by local stakeholders, authorities, energy market key players, VTT and E-JUST expert

Table 2

				Free Cooling		**Internal Load**				
				Mechanical Ventilation, [ac/hr]	**Number of vents**	**Lighting**			**People [37]**	
	Fresh air[39,40] [ac/hr]	**Fan coils number, BaU**	**Fan coils number, LIS-HIS**	**HIS**	**LIS-HIS**	**BaU[3] [W/m²]**	**LIS[38] [W/m²]**	**HIS[38] [W/m²]**	**Max number of people [-]**	**Activity**
Living Room	0.7	3	2	27.10	3	17	15	11	4	Seated, very light writing
Kitchen	0.5	2	1	20.25	2	9	8	6	2	Seated, light work typing
WC	0.3	1	1	32.40	2	9	8	6	2	Seated at rest
BdRD1-BdRD2	0.2	2	1	20.25	1	13	12	9	2	Seated at rest
BdRS	0.2	1	1	32.40	1	13	12	9	1	Seated at rest
Corridor	0.3	2	1	**Fan power[41]**12 W	**TOT**=10	**Appliance load BaU, LIS and HIS [3]:** 5 W/m²				
	TOT	13	8	**Air flow rate per fan[41]** 120 [m^3/h]						

Table 2 Fresh air and free cooling rates, number of fan coils, lighting, people and appliances internal loads for different rooms and scenarios (BaU, LIS, HIS)

Table 3

	Thickness [m]	**BaU [4,5] [W/m²K]**	**LIS [W/m²K]**	**HIS [W/m²K]**
External Wall	0.31	1.5	0.8 (3cm insulation)	0.6 (5cm insulation)
External Roof	0.25	1.6	0.6 (5cm insulation)	0.5 (6cm insulation)
Ground Floor	0.25	1.6	0.6 (5cm insulation)	0.5 (6cm insulation)
Adjacent wall	0.14	2.4	-	-
Adjacent Ceiling/Floor	0.12	3.6	-	-
Window (Clear Glass-Air- Clear Glass)	-	2.95 (0.77 g-Value; 2.5-12.7-2.5 mm)	2.95 (0.77 g-Value; 2.5-12.7-2.5 mm)	1.76 (Low-e; 0.6 g-Value; 3-12.7-2.5 mm)

Table 3 Thickness and thermal transmittances of the external building envelope elements and the solar energy transmittance of the window of BaU, LIS and HIS

Table 4

Components	*Typology*	*Description*
C1	Differential Temperature Controller	Solar field - hot tank
C2	Temperature – Flow rate Controller	Heat pump – cooling load
V1	Two-way-Valve	Hot tank/Cooling load supply
V2	Valve	Hot tank/Cooling load return
V3	Two-way-Valve	Hot tank/Cooling loads supply
V4	Mixing valve	Heating/Cooling supply inlet
V5	Tempering valve	Heating/Cooling Load return
V6	Diverting Valve	Hot tank/Cooling loads return
P1	Circulation Pump	Heat pump to Hot tank/Cooling load
P2	Circulation Pump	Solar
P3	Circulation Pump	Load

Table 4 HIS system secondary components list: valves, controllers, pumps

Table 5

Heat pump technical data, model ERLQ004-008CV3, Daikin®[43]	
Max. water flow temperature for heating	55 °C
Air temperature operating limits (cooling mode)	-10 °C - 45 °C
Air temperature operating limit (heating mode)	-20 °C
Water temperature operating limits (cooling mode)	5 °C - 18 °C
Water temperature operating limits (heating mode)	25 °C - 60 °C
Cooling capacity / COP at A35/W7	6.82 – 2.9 kW ; -
Cooling capacity / COP at A45/W18	6.38 – 2.25 kW ; -
Heat output / COP at A7/W35	5.12 - 4.57 kW ; -
Heat output / COP at A2/W55	4.54 - 2.58 kW ; -
Blower power	53 W

Table 5 Main technical features of the heat pump model Daikin Altherma air to water heat pump - ERLQ004-008CV3 [43]

Table 6

Thermal panel model: Unglazed and Flat plate collector [45]				
Net surface (one panel)		2.3 m² (1.2X1.9 m)		
Nominal flow rate (one panel)		120 l/h		
LIS	*Solar thermal unglazed collector Efficiency [**Error! Reference source not found.**] η_{stc}*	η_0 = 0.9 (Intercept efficiency)	a_1= 20 W/m²K (Efficiency slope)	a_2= 0 W/m²K^2. (Efficiency curvature)
HIS	*Solar thermal flat plate collector Efficiency [**Error! Reference source not found.**] η_{stc}*	η_0 = 0.78 (Intercept efficiency)	a_1= 3.2 W/m²K (Efficiency slope)	a_2= 0.115 W/m²K^2. (Efficiency curvature)
Number of panels (connected in series)		**LIS**, Unglazed - 5; **HISa,b** and **c** Glazed: 3;		
Hot and cold storage tank model ECO COMBI 3 VC Cordivari [44]				
Capacity		500 l		
DHW Corrugated stainless heat exchanger 316L Capacity		26.6 l		
Solar fixed heat exchanger Capacity		11.5 l		
Solar fixed heat exchanger pressure drop		3000 Pa		
Insulation thickness		10 cm		
Insulation conductivity		0.135 W/mK		

Table 6 Main design parameters of solar unglazed and flat plate thermal collectors and a storage hot water tank

Table 7

Sharp PV module ND-R245A5 [47]			**GWL-power, battery model SP-LFP200AHA [48]**		
Module short-circuit current at reference conditions	8.68	A	*Cell Energy Capacity*	200	Ah
Module open-circuit voltage at reference conditions	37.6	V	*Cells in parallel*	3 - 2	-
Reference temperature	298.15	K	*Cells in series*	8-18	-
Reference insolation	1000	W/m²	*Charging efficiency*	0.9	-
Module voltage at max power point and reference conditions	30.9	V	*Max. current for cell charging*	400	A
Module current at max power point and reference conditions	8.1	A	*Max. current for cell discharge*	-400	A
Temperature coefficient of Isc at (ref, cond)	0.138	-	*Max. charge voltage for cell*	2.8	V
Temperature coefficient of Voc (ref, cond,)	-0.329	-	*Number of Batteries*	**HISa**: 18 connected in series; **HISb**: 36 (2 lines of 18 batt. each); **HISc**: 36 (3 lines of 18 batt. each);	
Module temperature at NOCT	320.65	K	**Inverter model ET6415N [49]**		
Ambient temperature at NOCT	293.15	K	*Regulator efficiency*	0.78	-
Insolation at NOCT	800	W/m²	*Inverter efficiency (DC to AC)*	0.96	-

Module area	1.65	m²	*High limit on fractional state of charge (FSOC)*	0.95	-
tau-alpha product for normal incidence	0.95	-	*Low limit on FSOC*	0.2	-
Tilt angle	**HISa** and **b**: 20°; **HISc**: 20° - 90°;	Degrees	*charge to discharge limit on FSOC*	0.3	-
Numer of modules	**HISa**: 5 strings of 2 modules each; **HISb**: 9 strings of 2 modules each; **HISc**: 13 strings of 2 modules each	**HISa**: 10 (Roof mounted); **HISb**: 18 (Roof mounted); **HISc**: 26 (18 mounted on the roof and 8 on the south façade);	*Power output limit*	**HISa, b and c**: 3200 (48V)	W
			Inverter efficiency (AC to DC)	0.8	-

Table 7 Main design parameters of PV, batteries and inverter systems

Table 8

<table>
<tr><th></th><th>Business as usual (BaU)</th><th>Low investment scenario (LIS)</th><th>High investment scenario HISa</th><th colspan="2">High investment scenario HISb</th></tr>
<tr><td rowspan="4">Envelope solutions</td><td>-</td><td>External reflective paint</td><td colspan="3">External reflective paint</td></tr>
<tr><td>Double wall of half red-brick with 5 cm air gap in between</td><td>Insulation (5cm on the ground floor and the Roof, 3 cm on the external walls)</td><td colspan="3">Insulation (6cm on the ground floor and the Roof, 5 cm on the external walls)</td></tr>
<tr><td>-</td><td>Shading system</td><td colspan="3">Shading system</td></tr>
<tr><td>Double window</td><td>Double window</td><td colspan="3">Double low-e window</td></tr>
<tr><td rowspan="4">System technologies</td><td>Incandescent and fluorescent lamp</td><td>Fluorescent light bulbs</td><td colspan="3">LEDs</td></tr>
<tr><td>Natural ventilation through opening the windows (natural ventilation)</td><td>Free Cooling System through vents (natural ventilation)</td><td colspan="3">Free Cooling: natural and mechanical ventilation (vents + fan coils)</td></tr>
<tr><td>-</td><td>Unglazed solar thermal collectors</td><td colspan="3">Glazed solar thermal collectors: 3 panels</td></tr>
<tr><td>-</td><td>-</td><td>PV (10modules+ 18 batteries)</td><td>PV (18modules+ 36 batteries)</td><td>PV (26modules+ 54 batteries)</td></tr>
</table>

Table 8 List of envelope solutions and system technologies used in each scenario: Business as usual scenario (BaU), Low investment and High investment scenarios (LIS, HIS)

Table 9

	BaU	LIS	HISa	HISb	HISc
Final energy demand [kWh]	3478.4	1771.1	1233.8	1233.8	1233.8
PV produced energy [kWh]	-	-	1883.5	3390.4	4283.8
PV consumed energy [kWh]	-	-	644.2	1064.8	1154.8
Dumped PV energy [kWh]	-	-	654.4	1326.1	1928.5
Final energy consumed [kWh / kWh/m²]	3478.4 / 30.51	1771.1 / 15.54	589.6 / 5.17	168.3 / 1.48	78.3 / 0.69
Appliances energy consumption [kWh]	1272.2				
Final energy balance [kWh / kWh/m²]	4750.6 / 41.6	3043.3 / 26.7	1207.4 / 10.59	114.4 / 1	-578 / -5.17

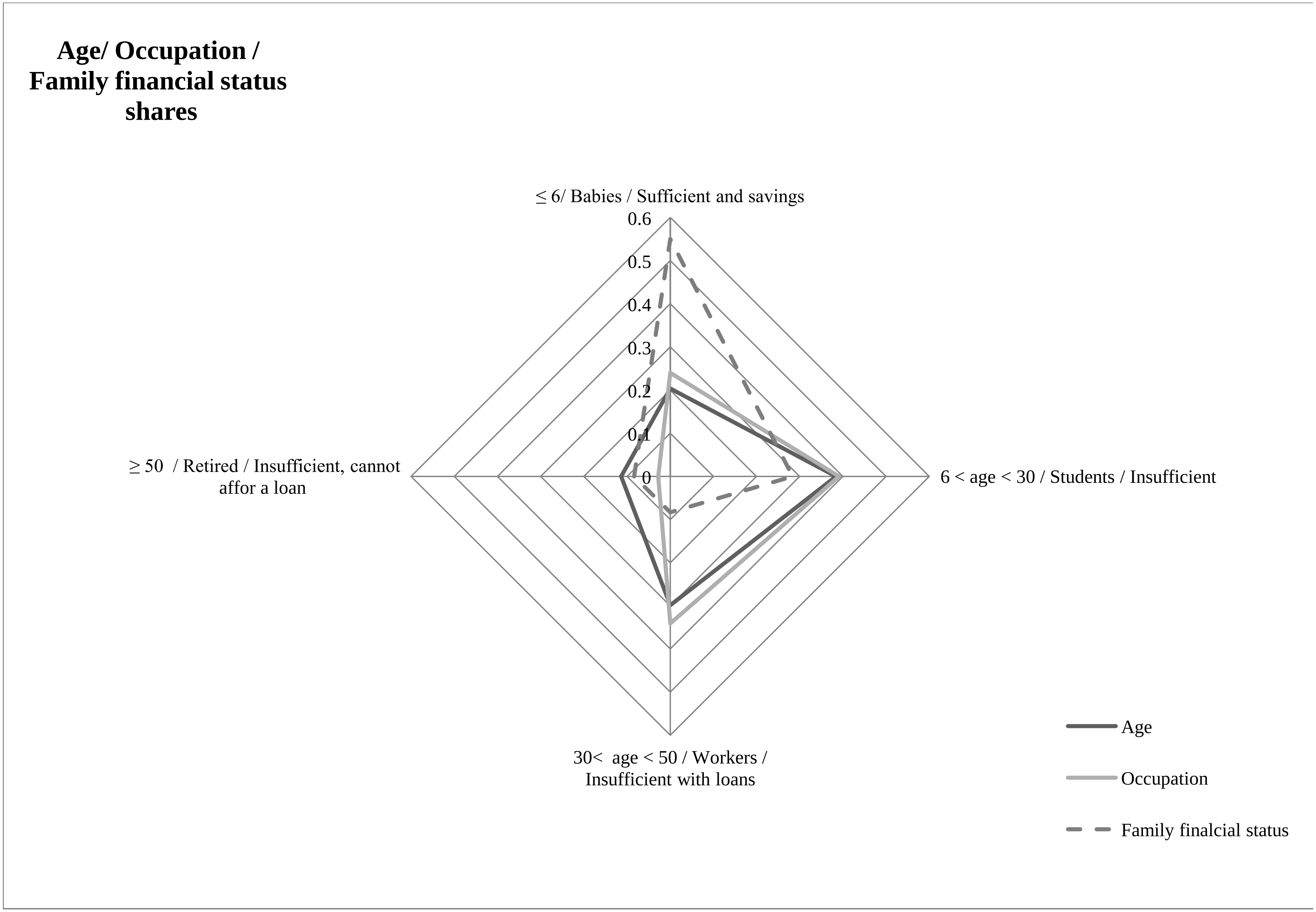
Table 9 Annual final energy demand of the heating and cooling systems in one apartment, PV produced, consumed and dumped energies, final energy consumption, appliances energy consumption, and final energy balance of each scenario: business as usual scenario (BaU), low investment (LIS) and high investment a,b and c scenarios (HISa, HISb, HISc)

Table 10

	BaU	LIS	HISa	HISb	HISc
Final district energy demand [GWh]	619,6	315,5	219,8	219,8	219,8
Districts' produced PV energy [GWh]	-	-	335,5	603,9	763,1
Districts' consumed PV energy [GWh]	-	-	114,7	189,7	205,7
Districts' exported PV energy [GWh]	-	-	116,6	236,2	343,5
Final districts energy balance [GWh]	846,2	542,1	215,1	20,4	-103,0
CO_2 emission [1000t]	394,3	252,6	100,2	9,5	-48,0

Table 10. Annual final energy demand of the heating and cooling systems for the residential sector in New Borg El Arab City, PV produced, consumed and exported energies and final energy balance, which includes the appliances energy consumption of each scenario: business as usual scenario (BaU), low investment (LIS) and high investment a,b and c scenarios (HISa, HISb, HISc). Note: CO_2 emissions are calculated based on the final district energy balance and assuming the average Egyptian emission factor for electricity for all energy use

Figure 1



Age/ Occupation / Family financial status shares
≤ 6/ Babies / Sufficient and savings
0.6
0.5
0.4
0.3
0.2
0.1
0
6 < age < 30 / Students / Insufficient
30< age < 50 / Workers / Insufficient with loans
≥ 50 / Retired / Insufficient, cannot affor a loan
Age
Occupation
Family finalcial status

Figure 2

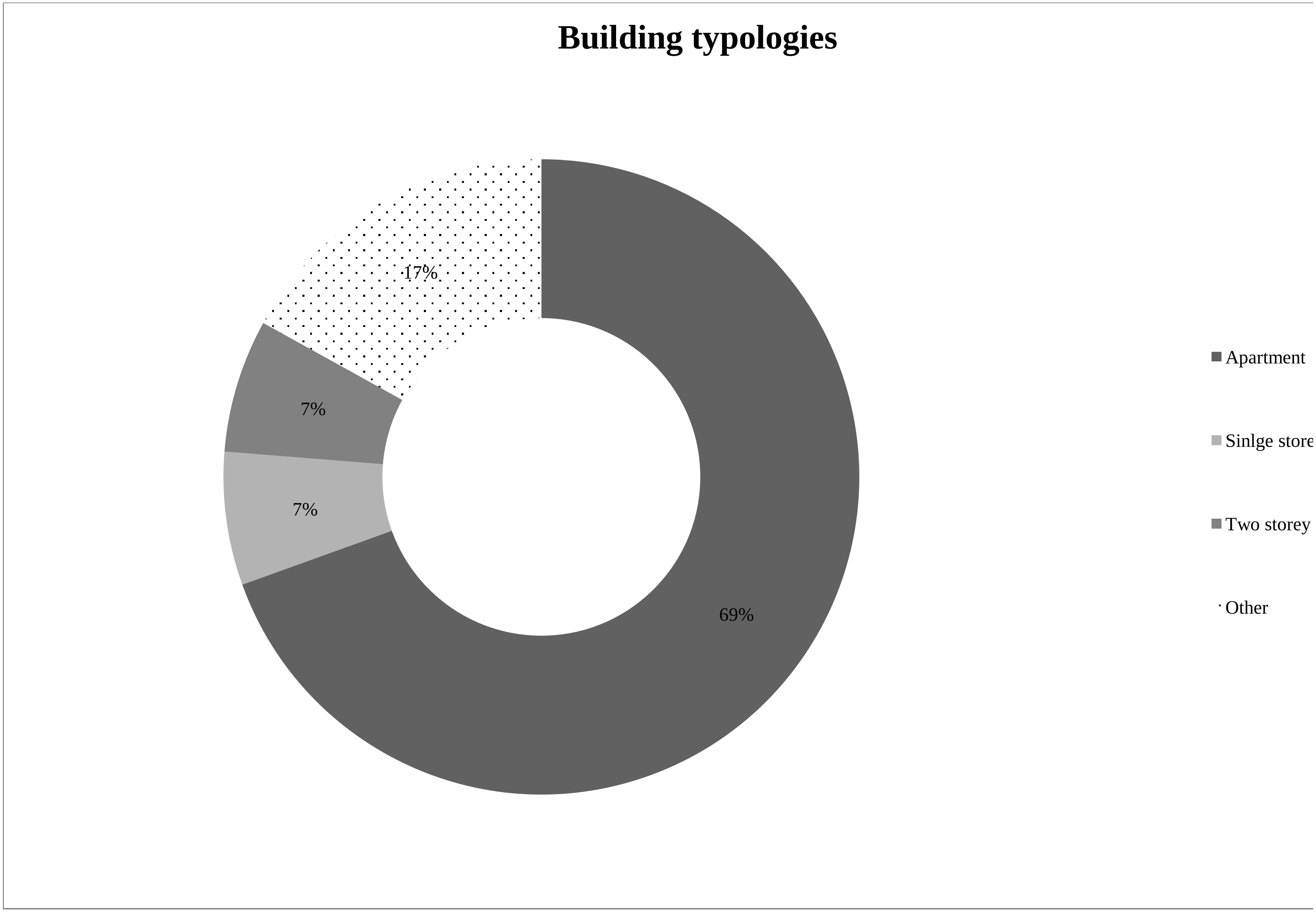
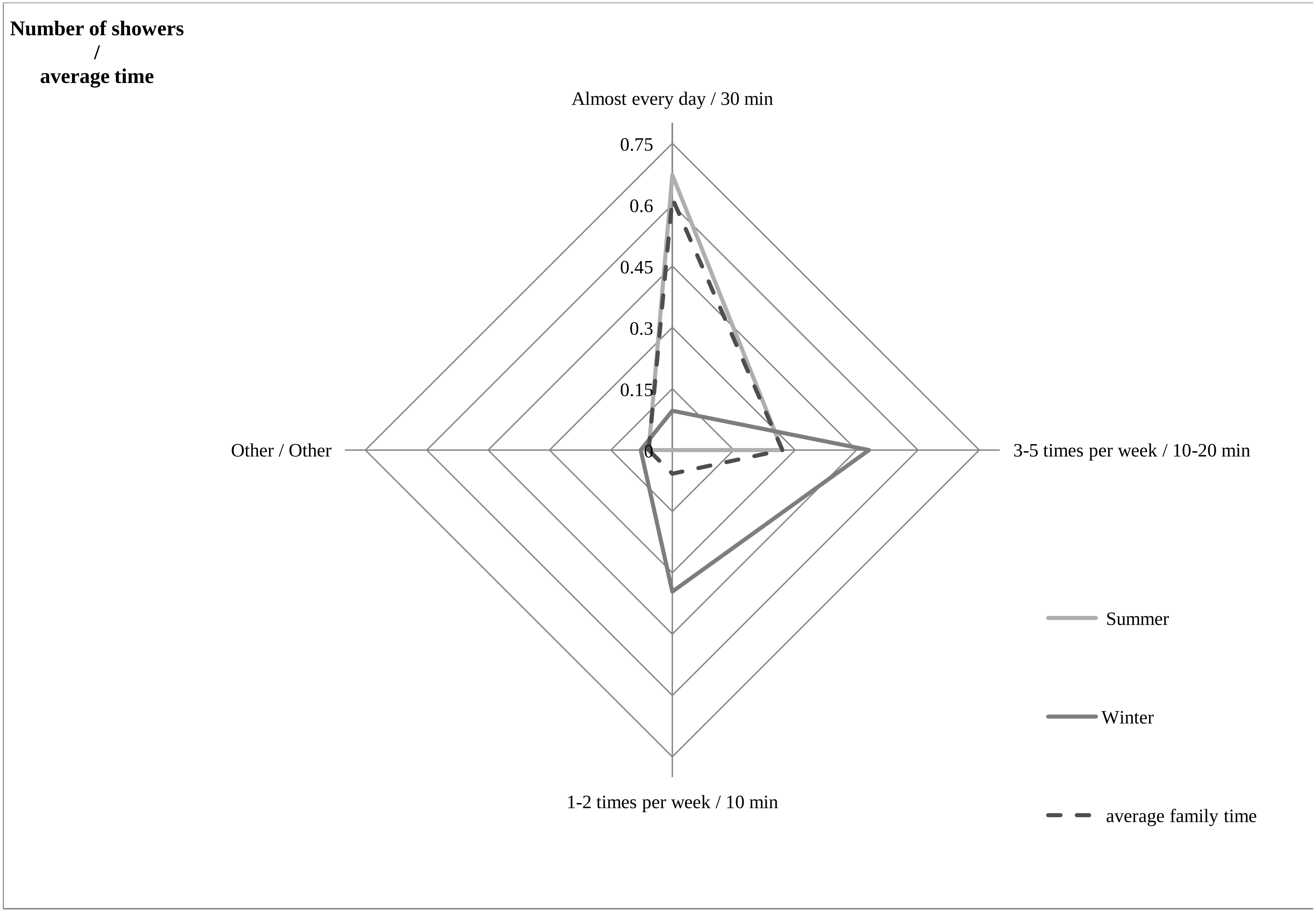

Building typologies
17%
7%
7%
69%
Apartment
Sinlge store
Two storey
Other

Figure 3



Number of showers
/
average time
Almost every day / 30 min
0.75
0.6
0.45
0.3
0.15
0
3-5 times per week / 10-20 min
1-2 times per week / 10 min
Other / Other
Summer
Winter
average family time

Figure 4

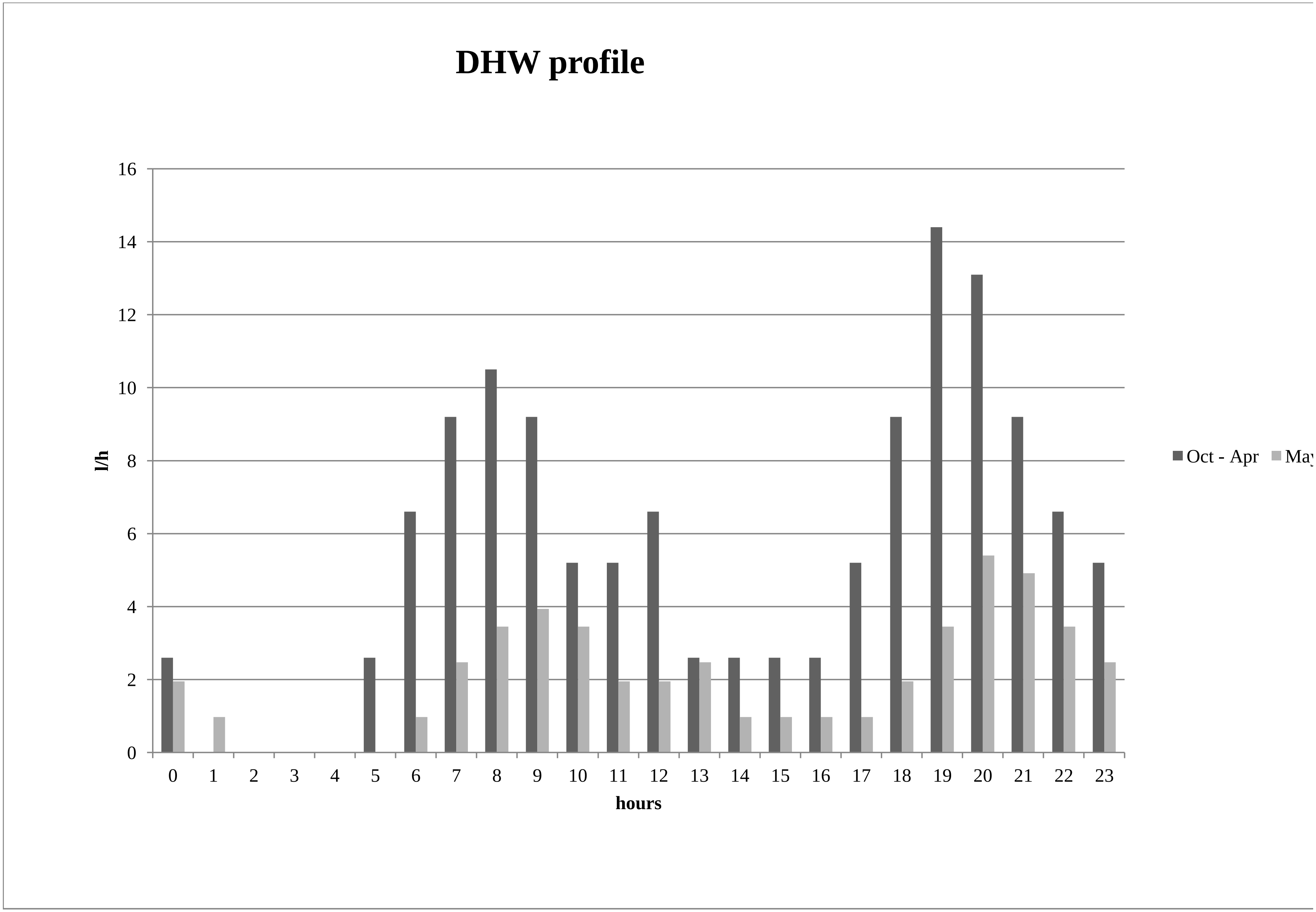
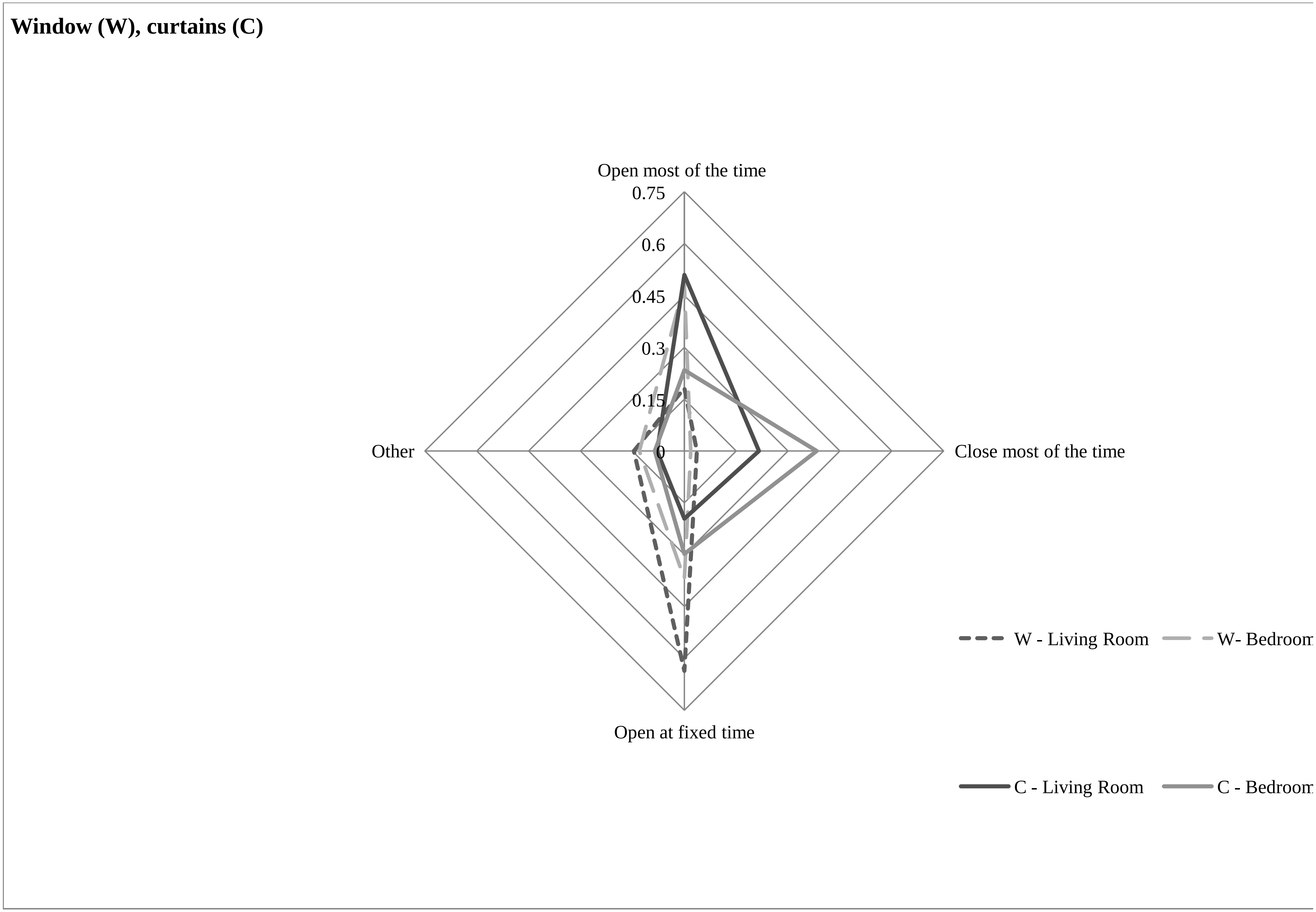

DHW profile
16
14
12
10
8
6
4
2
0
l/h
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
hours
Oct - Apr
May

Figure 5



Window (W), curtains (C)
Open most of the time
0.75
0.6
0.45
0.3
0.15
0
Other
Close most of the time
Open at fixed time
W - Living Room
W- Bedroom
C - Living Room
C - Bedroom

Figure 6a
Click here to download high resolution image

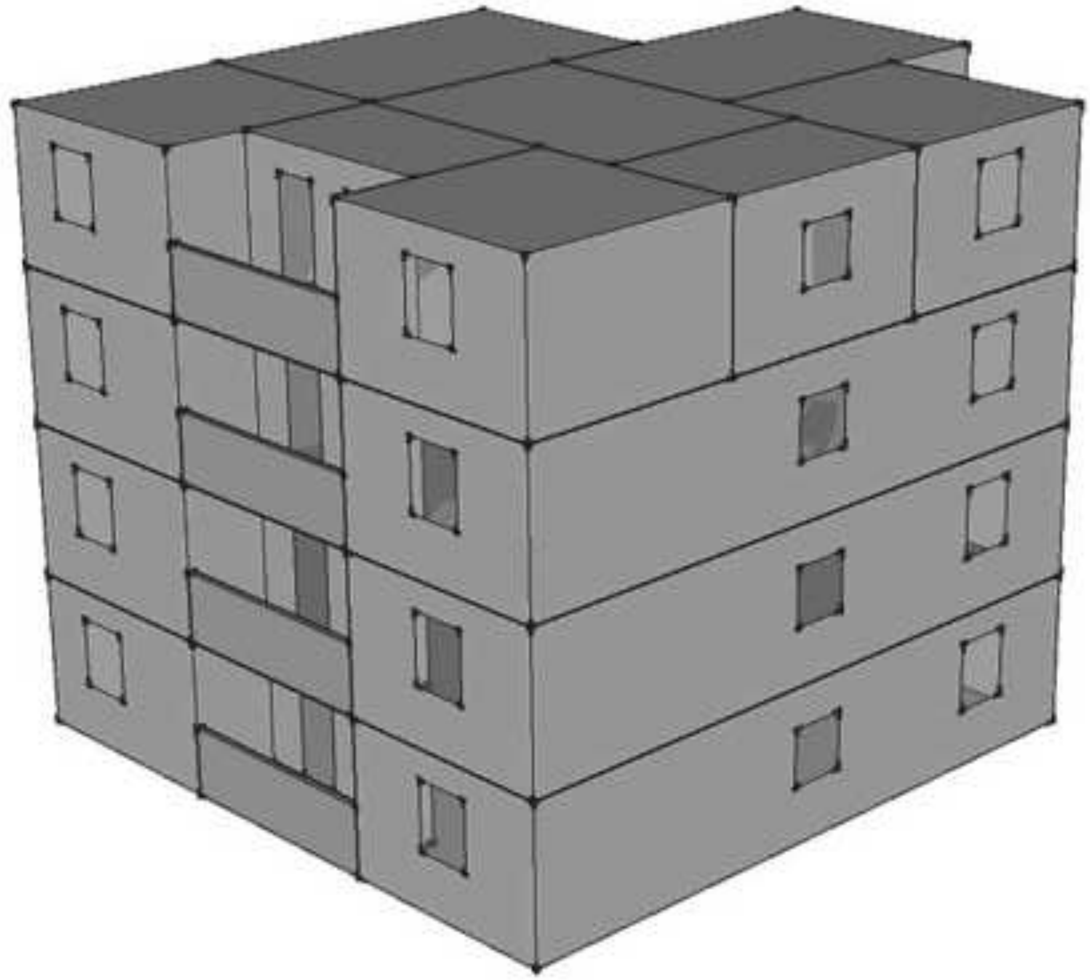


Figure 6b

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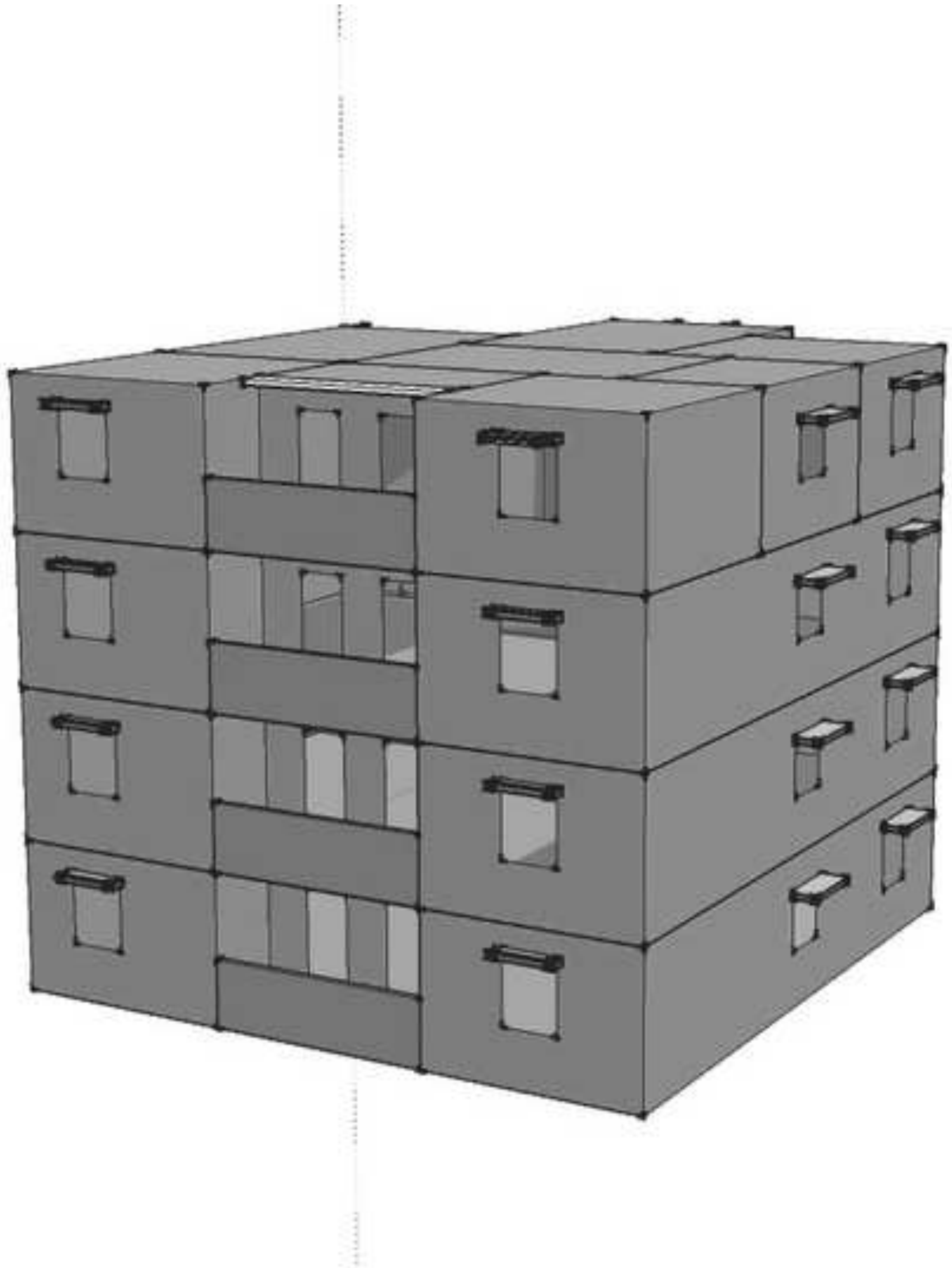


Figure 7a

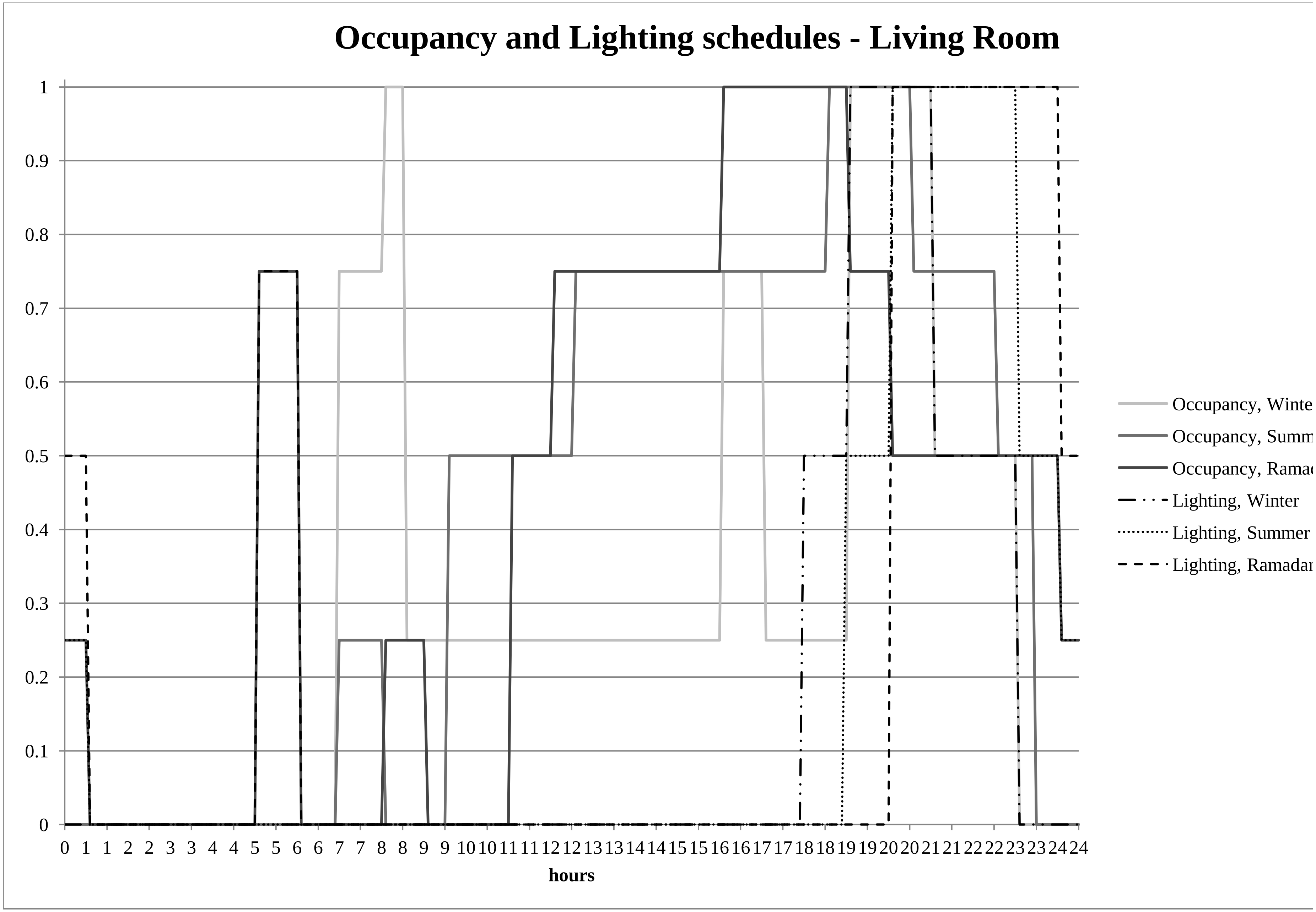

Occupancy and Lighting schedules - Living Room
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 1 2 2 3 3 4 4 5 5 6 6 7 7 8 8 9 9 10 10 11 11 12 12 13 13 14 14 15 15 16 16 17 17 18 18 19 19 20 20 21 21 22 22 23 23 24 24
hours
Occupancy, Winte
Occupancy, Summ
Occupancy, Rama
Lighting, Winter
Lighting, Summer
Lighting, Ramadar

Figure 7b

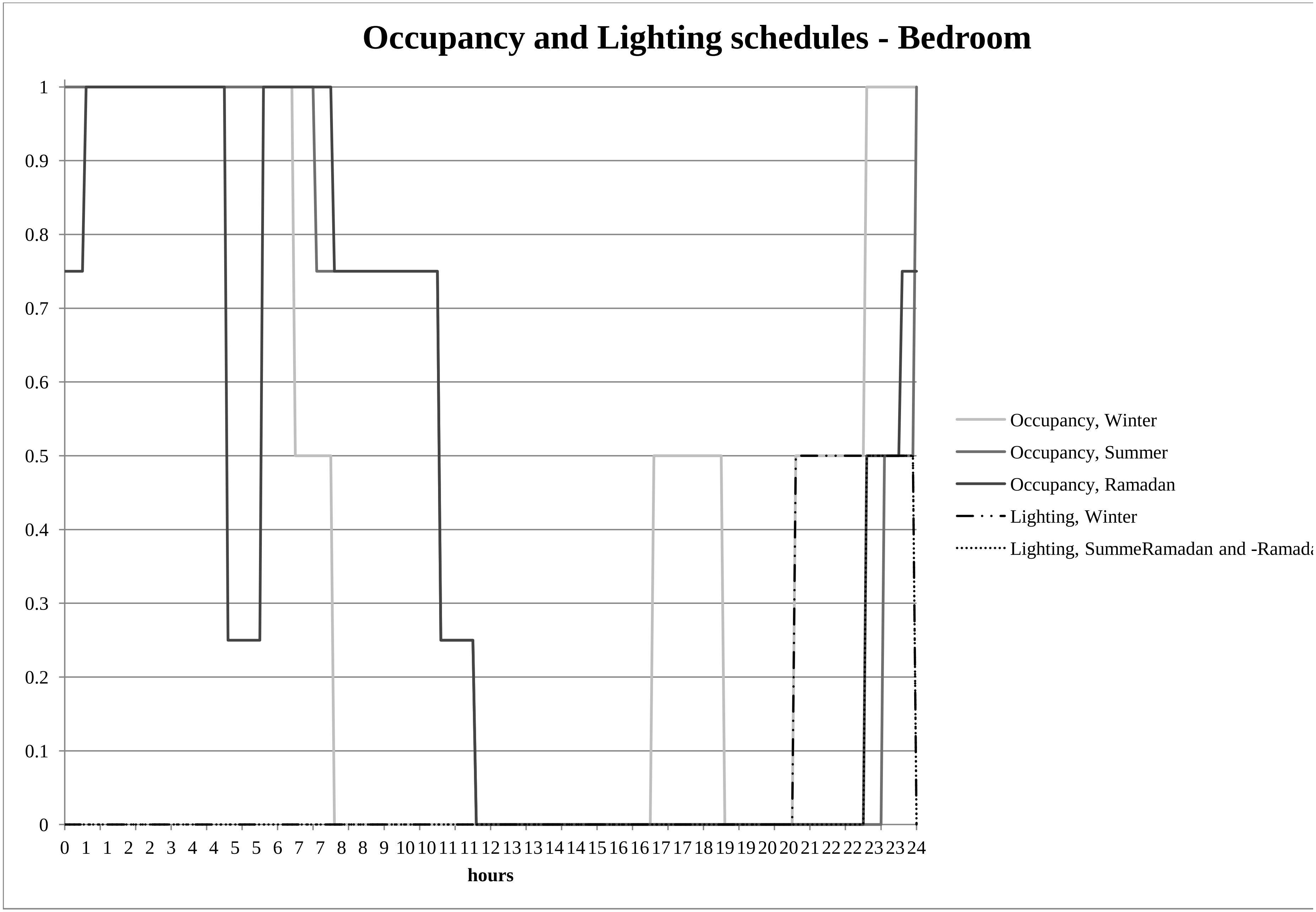
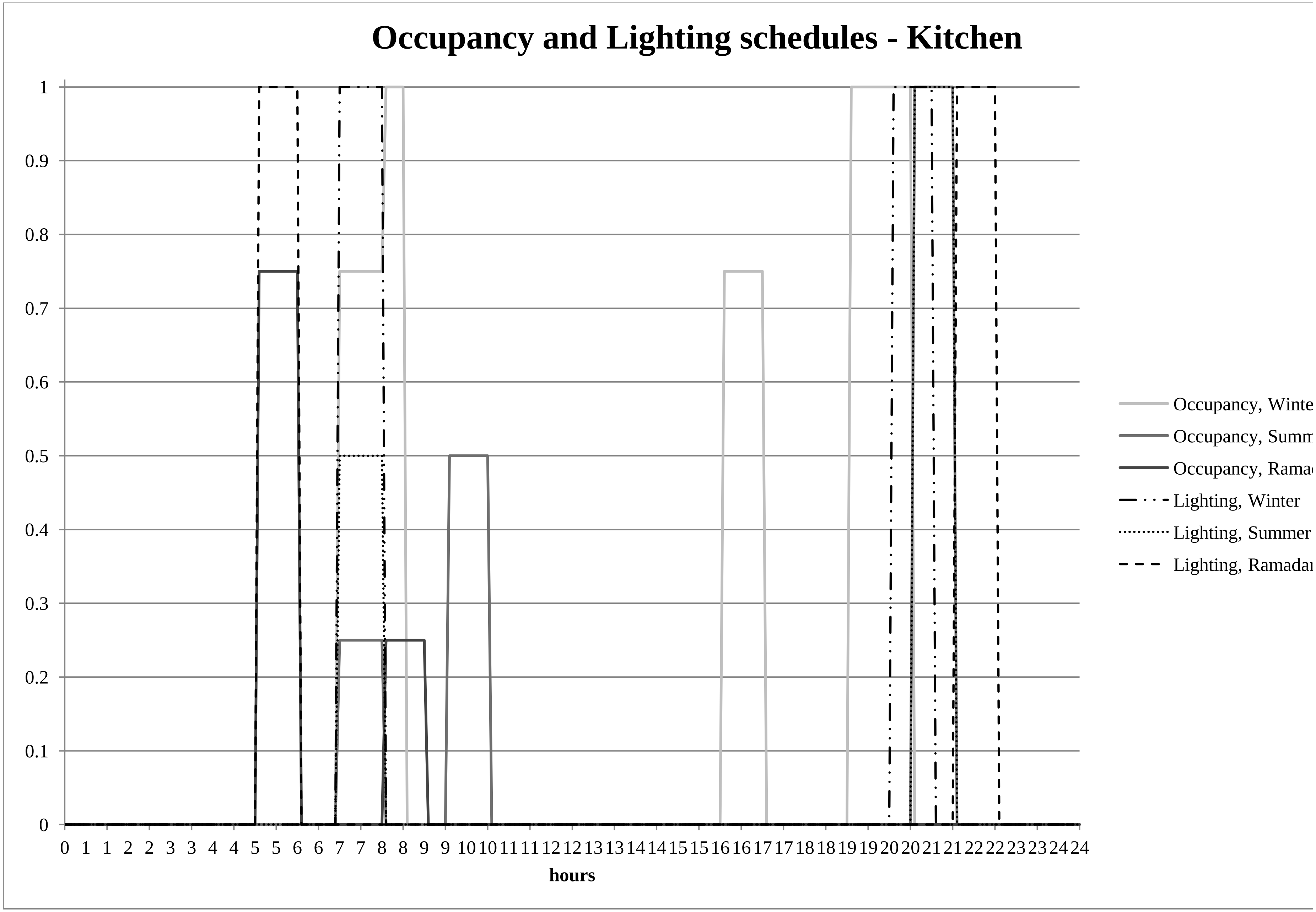

Occupancy and Lighting schedules - Bedroom
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 1 2 2 3 4 4 5 5 6 7 7 8 8 9 10 10 11 11 12 13 13 14 14 15 16 16 17 17 18 19 19 20 20 21 22 22 23 23 24
hours
Occupancy, Winter
Occupancy, Summer
Occupancy, Ramadan
Lighting, Winter
Lighting, SummeRamadan and -Ramad

Figure 7c



Occupancy and Lighting schedules - Kitchen
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 1 2 2 3 3 4 4 5 5 6 6 7 7 8 8 9 9 10 10 11 11 12 12 13 13 14 14 15 15 16 16 17 17 18 18 19 19 20 20 21 21 22 22 23 23 24 24
hours
Occupancy, Winte
Occupancy, Summ
Occupancy, Rama
Lighting, Winter
Lighting, Summer
Lighting, Ramadan

Figure 8

Click here to download high resolution image

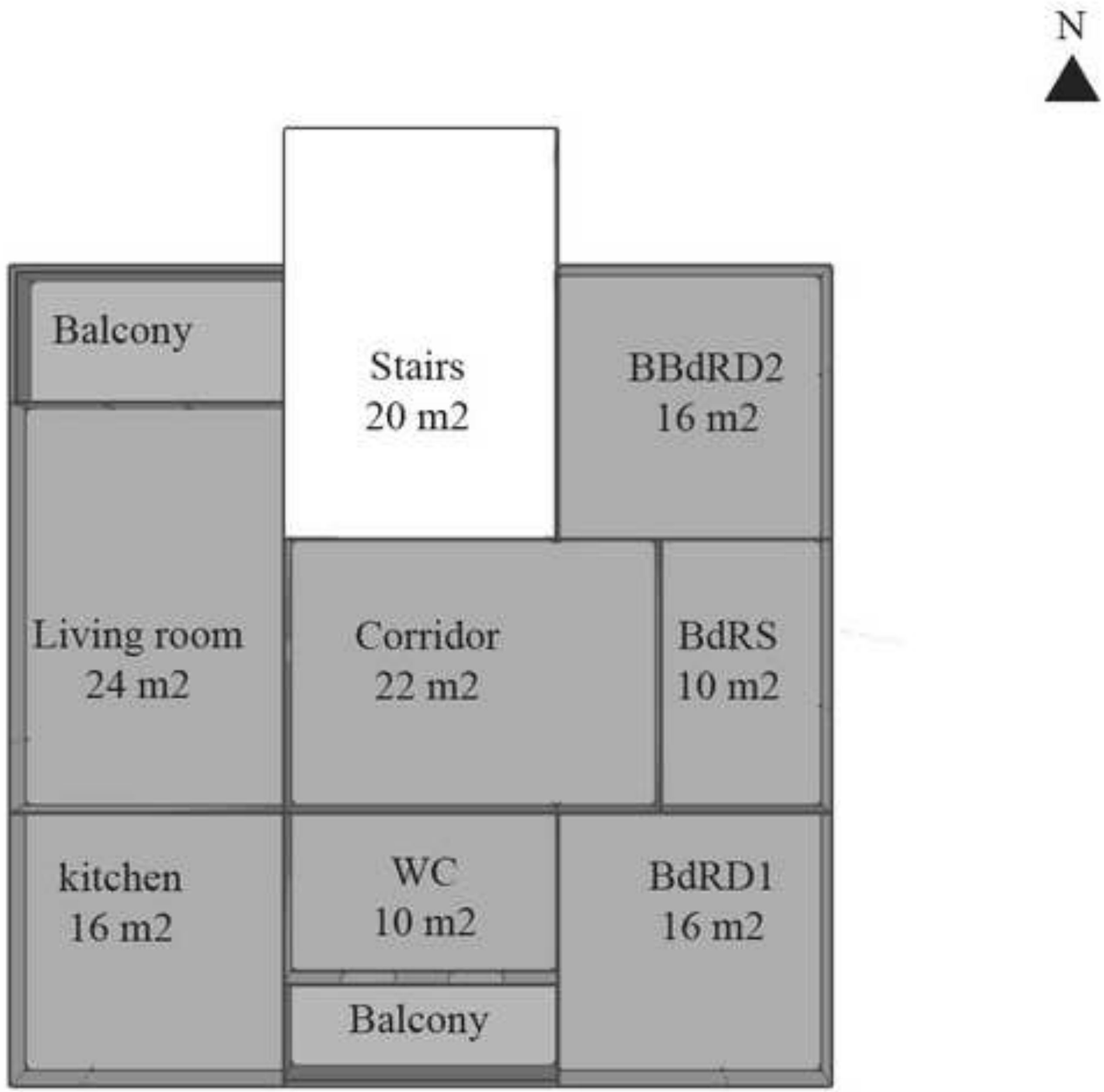


Figure 9
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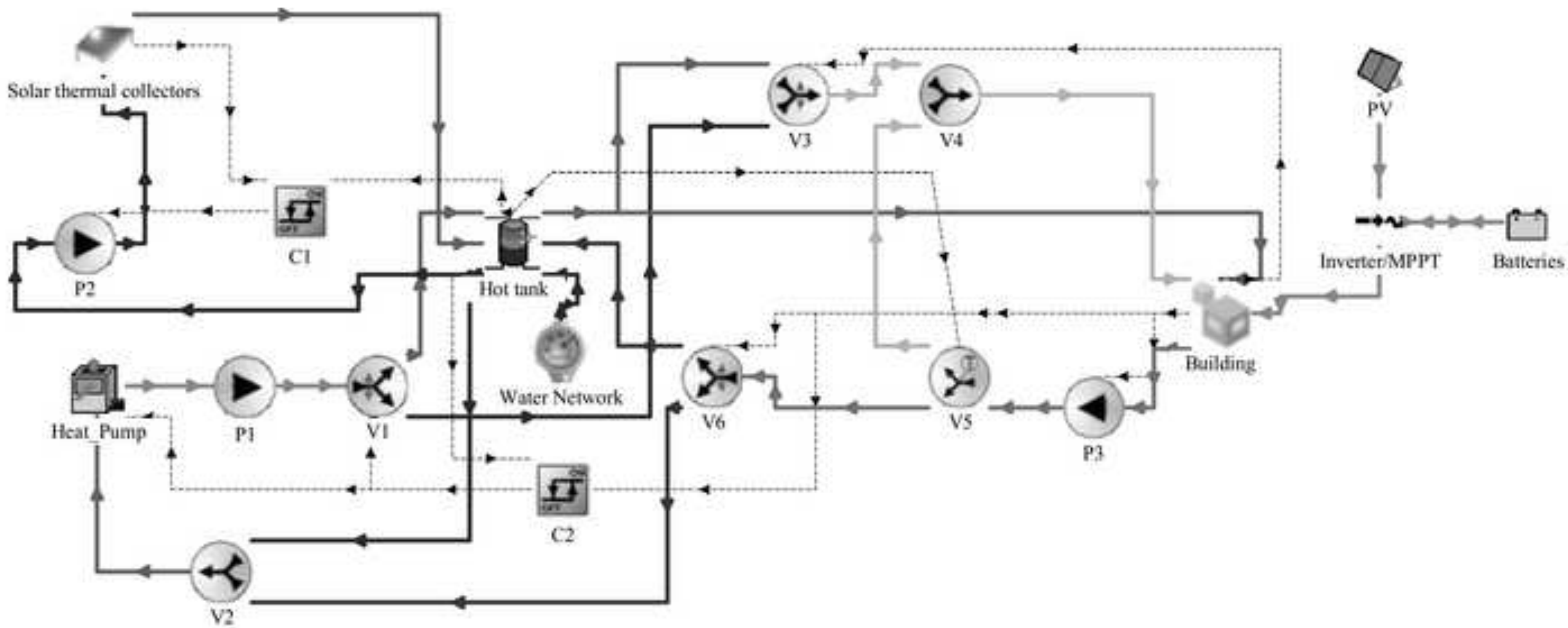


Figure 10

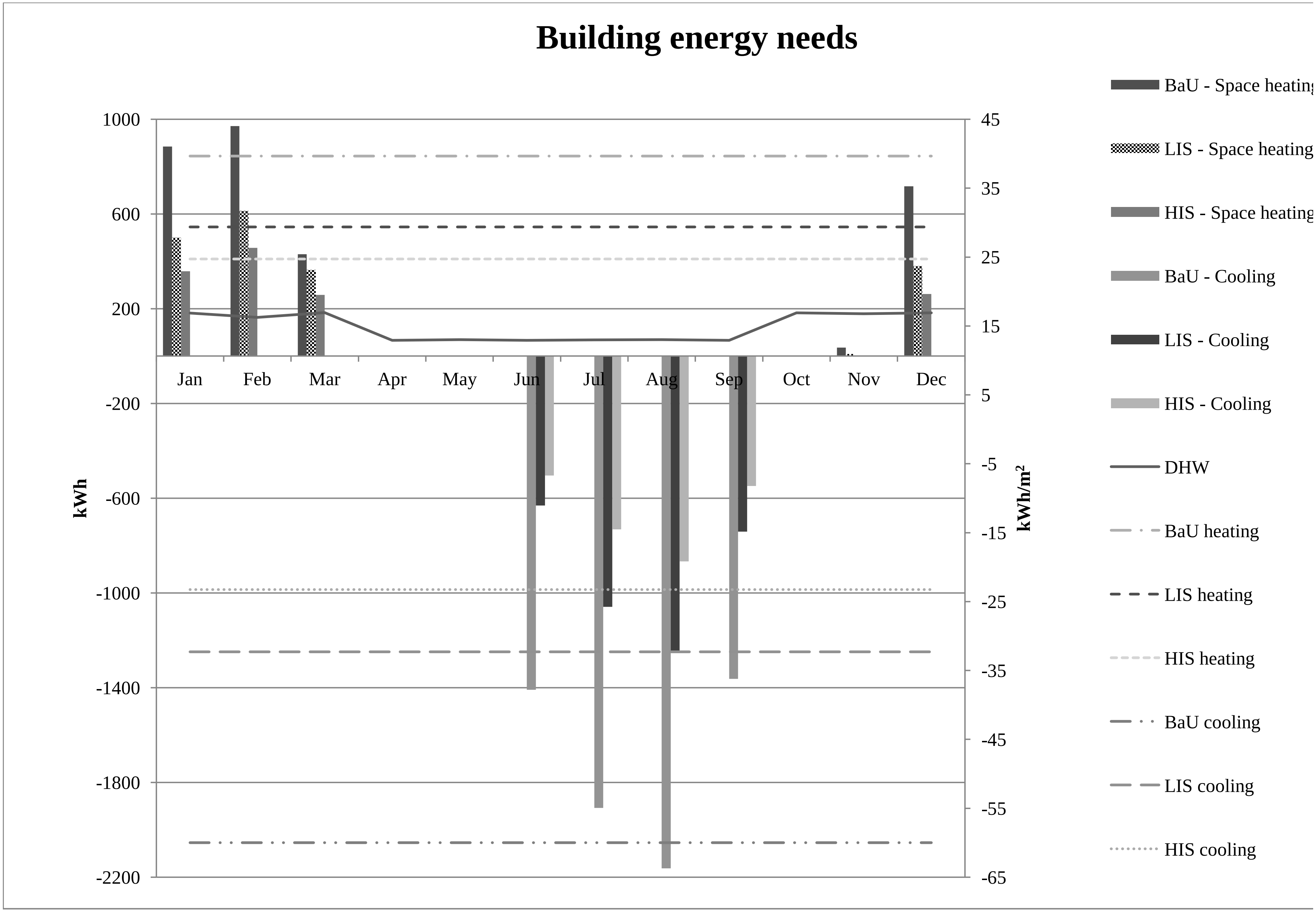
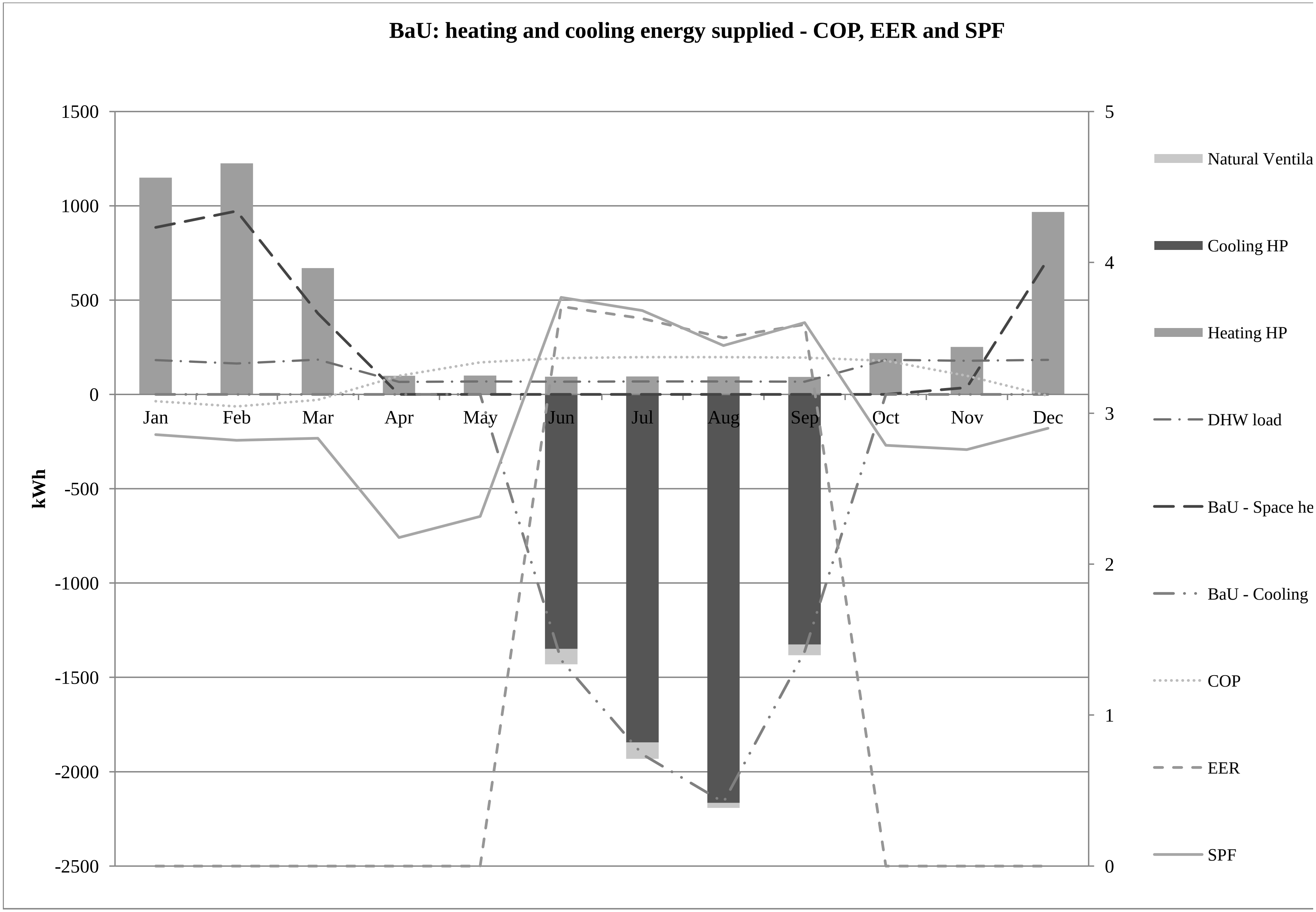
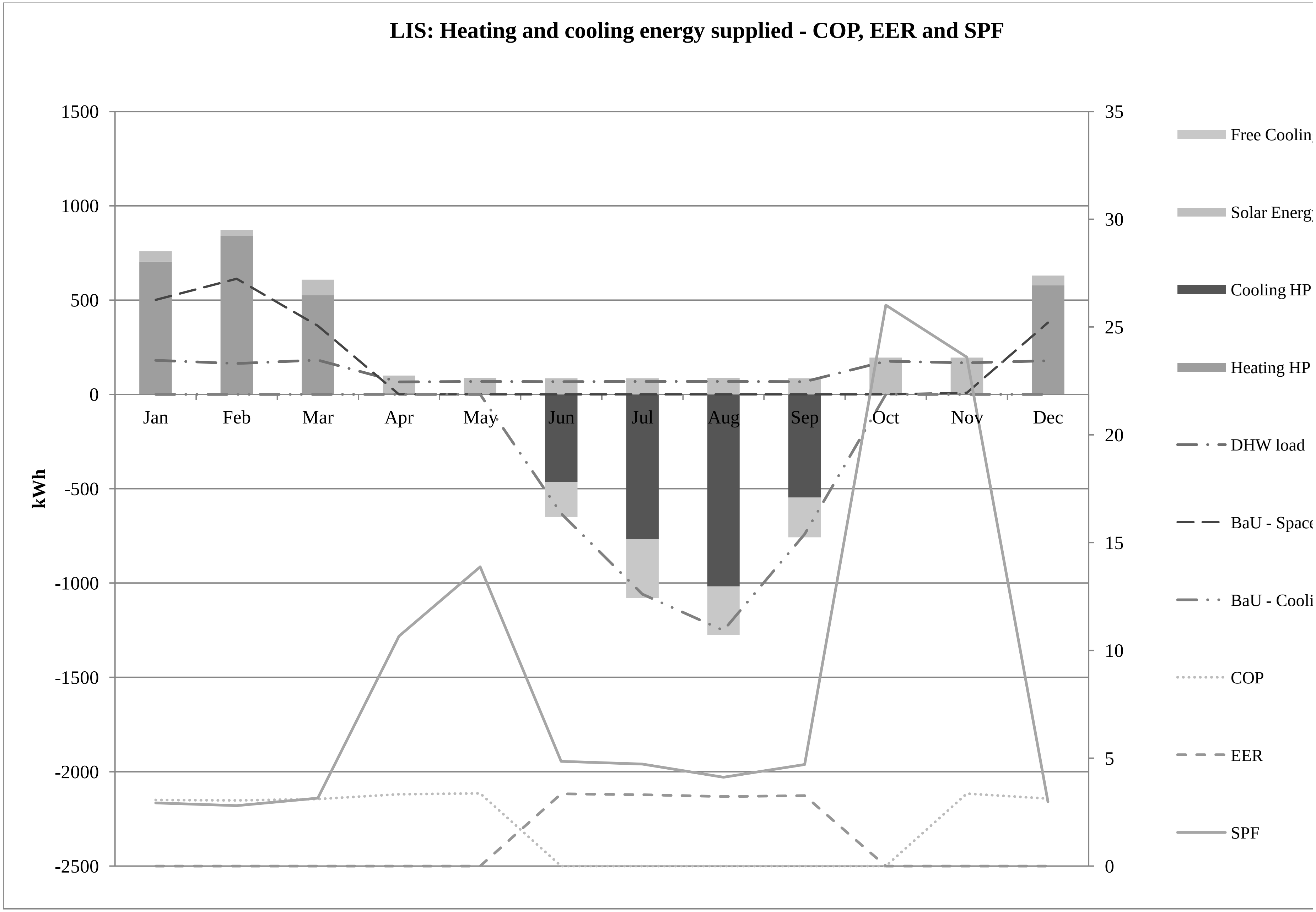

Building energy needs
kWh
kWh/m²
1000
600
200
-200
-600
-1000
-1400
-1800
-2200
45
35
25
15
5
-5
-15
-25
-35
-45
-55
-65
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BaU - Space heating
LIS - Space heating
HIS - Space heating
BaU - Cooling
LIS - Cooling
HIS - Cooling
DHW
BaU heating
LIS heating
HIS heating
BaU cooling
LIS cooling
HIS cooling

Figure 11



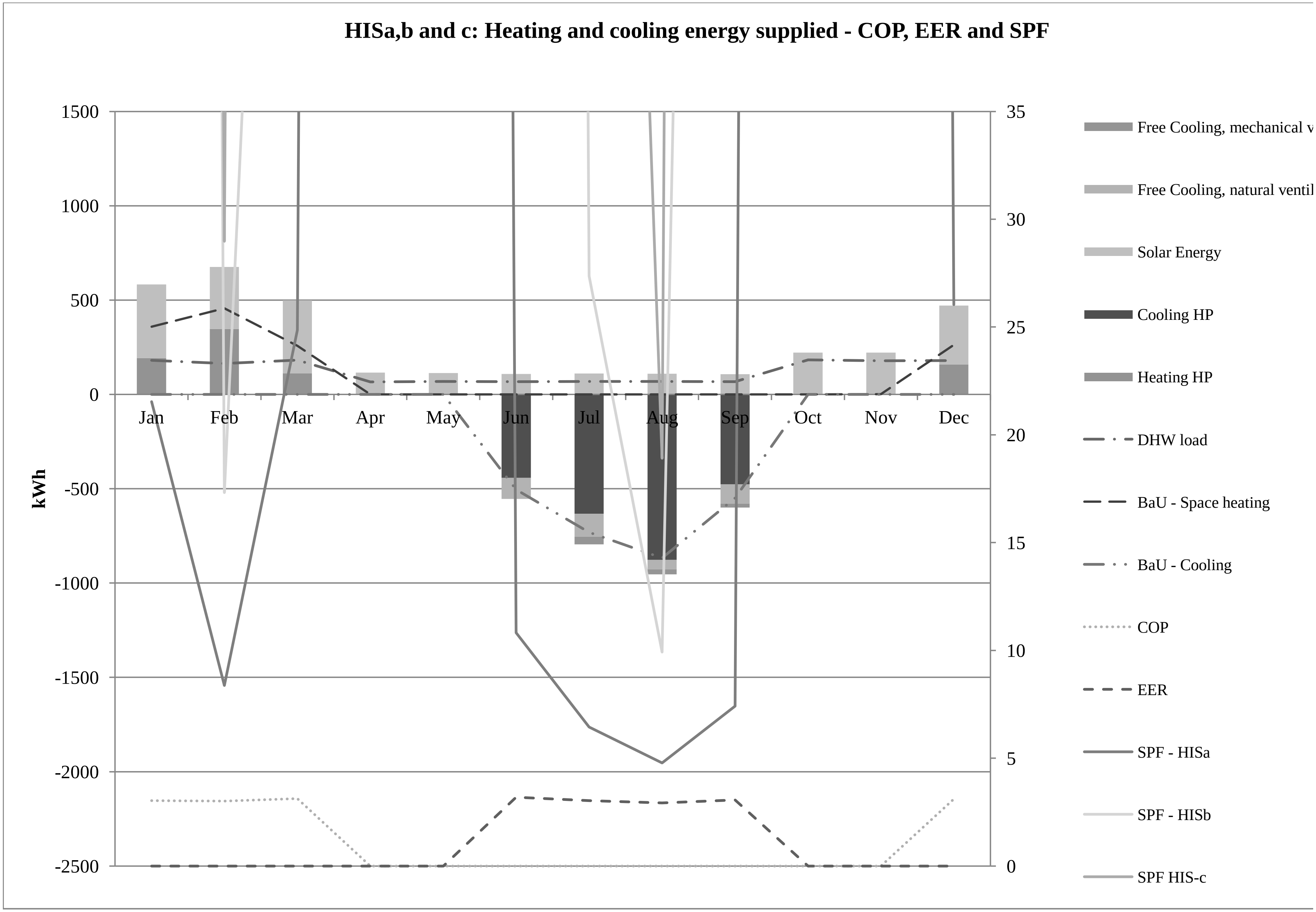
BaU: heating and cooling energy supplied - COP, EER and SPF
kWh
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
5
4
3
2
1
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Natural Ventila
Cooling HP
Heating HP
DHW load
BaU - Space he
BaU - Cooling
COP
EER
SPF

Figure 12



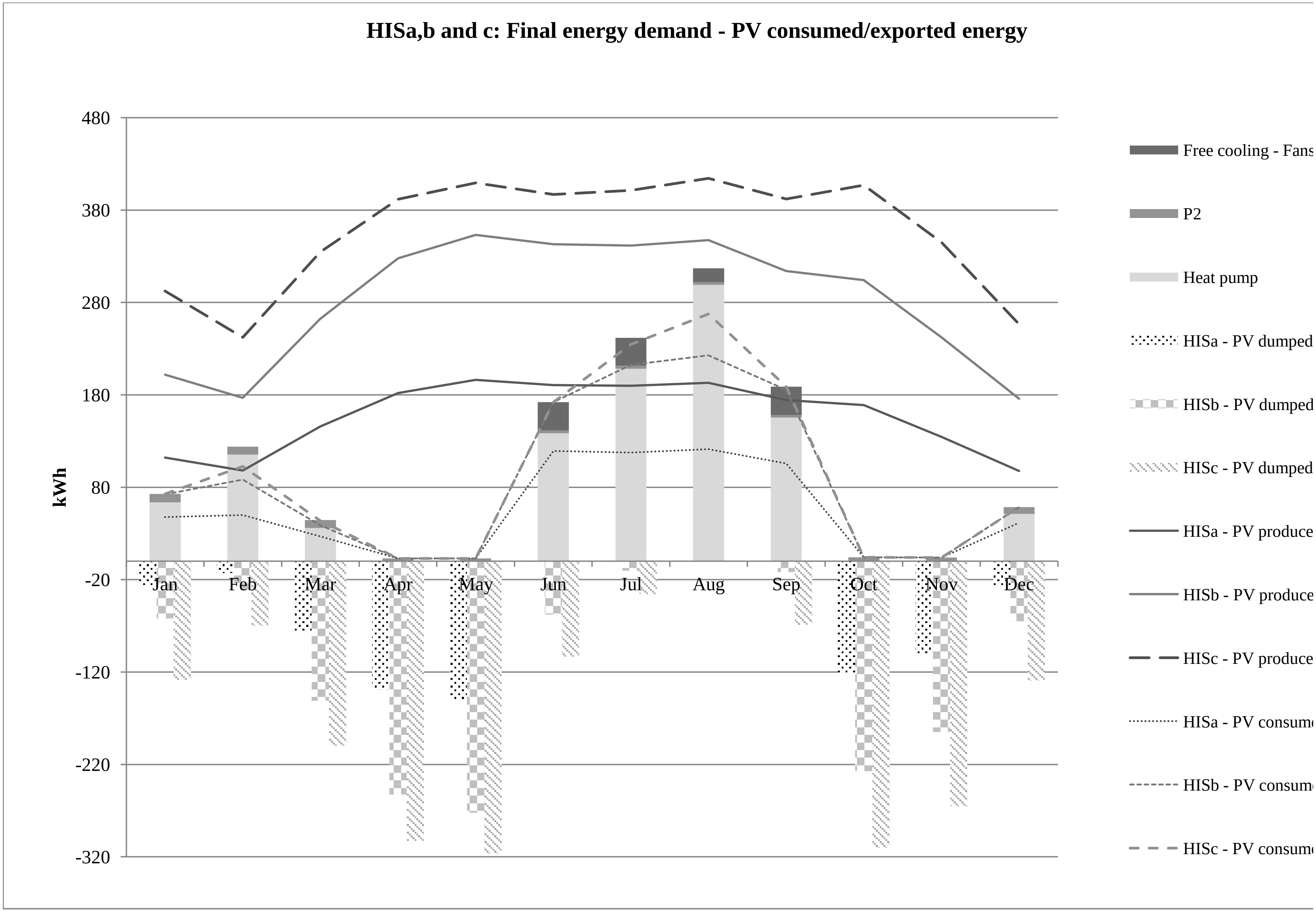
LIS: Heating and cooling energy supplied - COP, EER and SPF
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
kWh
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
35
30
25
20
15
10
5
0
Free Coolin
Solar Energ
Cooling HP
Heating HP
DHW load
BaU - Space
BaU - Cooli
COP
EER
SPF

Figure 13



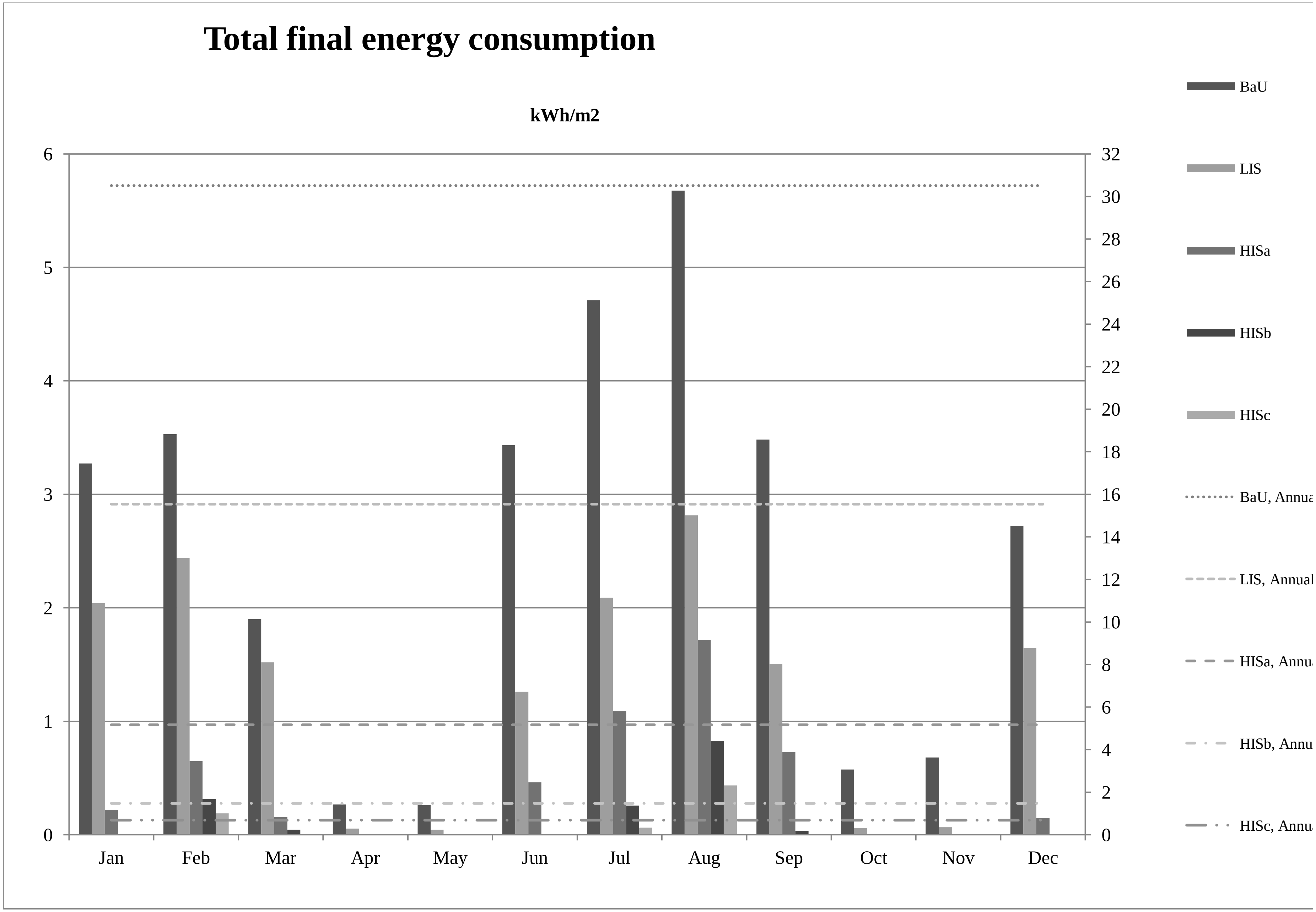
HISa,b and c: Heating and cooling energy supplied - COP, EER and SPF
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
kWh
35
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Free Cooling, mechanical v
Free Cooling, natural ventil
Solar Energy
Cooling HP
Heating HP
DHW load
BaU - Space heating
BaU - Cooling
COP
EER
SPF - HISa
SPF - HISb
SPF HIS-c

Figure 14



HISa,b and c: Final energy demand - PV consumed/exported energy
kWh
480
380
280
180
80
-20
-120
-220
-320
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Free cooling - Fans
P2
Heat pump
HISa - PV dumped
HISb - PV dumped
HISc - PV dumped
HISa - PV produce
HISb - PV produce
HISc - PV produce
HISa - PV consum
HISb - PV consum
HISc - PV consum

Figure 15


Total final energy consumption
kWh/m2
6
5
4
3
2
1
0
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BaU
LIS
HISa
HISb
HISc
BaU, Annua
LIS, Annual
HISa, Annu
HISb, Annu
HISc, Annu