Empowering local renewable energy communities for the decarbonisation of the energy systems

D3.2 – Technologies for sector coupling approach

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Executive summary

LocalRES is a Horizon2020 funded project with the objective of deploying innovative local energy systems driven by Renewable Energy Communities (RECs).

Within LocalRES project, the Work Package 3 (WP3) focuses on the new role and services that RECs will play in the energy landscape. To this purpose, innovative technology will be implemented to safely operate a community grid and assets. This will enable the RECs to maximise the value of their assets leading to a decrease in the overall cost of the community.

To correctly manage energy systems operation in REC, it is essential to know first how energy is used at both single building and REC level. With this objective, this deliverable focuses on understanding how energy, more specifically, thermal and electrical energy is used within the buildings.

In this work a time resolution of one hour has been used, as it allows a sufficiently detailed representation of the effects that influence thermal and electrical energy use patterns at both building and REC level.

One of the objectives of this work is to obtain realistic thermal and electrical energy use patterns at building and REC level that can be considered representative of realistic cases considering the EU context. For this purpose, a series of aspects that influence thermal and electrical energy use in buildings at EU level have been analysed. In particular, the building typology, the building status and the climate, and how they influence building thermal and electrical energy use have been assessed. From this analysis, 27 residential building cases have been identified, modelled and simulated in TRNSYS. The main focus in this work has been placed on residential buildings as they represent the wide majority of buildings that can be part of a REC in small context like those considered in LocalRES project. Nevertheless, also thermal and electrical energy use patterns for offices, schools and supermarkets have been analysed.

Regarding the technologies considered, in this work the focus has been placed on technologies that allow coupling different sectors, meaning that, for example, building thermal demand is covered through a heat pump system that consumes electrical energy. In addition, photovoltaic systems and batteries have been considered to assess their effects in determining how the electrical energy consumption is covered. Although heat pump systems, especially coupled with photovoltaic system and batteries represent the most suitable technologies for sector coupling purposes, this report presents also a simplified assessment of thermal and electrical energy use in buildings considering small cogenerators (sized based on the single building thermal needs).

To have a realistic evaluation of thermal and electrical energy use at building level it is important to model, with the due level of detail, not only the building but also the system devoted to cover building thermal energy needs. For this reason, in general, also the heating ventilation and air conditioning system has been modelled in TRNSYS. This allows obtaining building thermal and electrical energy use patterns representative of realistic cases, taking into consideration the effects associated to the presence of components like, for example, thermal storages that lead to a

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decoupling of thermal production and consumption sides. A simplified assessment that does not implies the development of a TRNSYS model has been performed in school and supermarket buildings.

Moreover, in this report two methods have been developed for the aggregation of thermal and electrical energy use at REC level. These methods are focused on residential buildings as they present not negligible variations in terms of thermal and electrical energy use patterns associated to different buildings' usage by the occupants. The results of these aggregation methods in terms of thermal and electrical energy use patterns at REC level are presented considering a simplified REC composed by 10 residential buildings as example. The results of this analysis highlight how different residential buildings are characterized by slight differences in terms of thermal and electrical energy use and how these differences influence the aggregated thermal and electrical energy use at REC level.

The results presented in this report, in terms of thermal and electrical energy use patterns at single building and REC level will be mainly used in task T3.3 and T3.4 for the development of the Multi Energy Virtual Power Plant and, more specifically, for its training. Moreover, the data in terms of hourly thermal and electrical energy use time series at single building level presented in this report will be made available to the public through the platform Zenodo (Zenodo, n.d.).

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List of acronyms and abbreviations

AWHP	Air-Water Heat Pump
BESS	Battery Energy Storage System
CDD	Cooling Degree Days
CHP	Combined Heat and Power
DCW	Domestic Cold Water
DHW	Domestic Hot Water
DR	Demand Response
GHI	Global Horizontal Radiation
HDD	Heating Degree Days
HVAC	Heating Ventilation and Air Conditioning
HP	Heat Pump
lMFH	large Multi-Family House
LP	Linear Programming
MEVPP	Multi Energy Virtual Power Plant
MILP	Mixed Integer Linear Programming
oemof	Open Energy system Modeling Framework
P&ID	Piping and Instrumentation Diagram
PR	Performance Ratio
PV	Photovoltaic
QTH	Thermal Energy
QEL	Electrical Energy
REC	Renewable Energy Community
SC	Space Cooling
SFH	Single Family House
SH	Space Heating
sMFH	small Multi-Family House
SoC	State of Charge
TES	Thermal Energy Storage
TSV	Thermostatic Valve

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1/ Introduction

1.1. Purpose of the report

The Horizon2020 funded project LocalRES aims at deploying local energy systems driven by RECs. The main objective of LocalRES is to contribute to a socially fair energy transformation that puts renewable energy into the hands of communities and people. For this purpose, LocalRES will deliver new digital tools that will boost the expected structural change in the current energy system.

Within LocalRES project, WP3 focuses on the new role and services that RECs will play in the energy landscape considering the implementation of innovative technology to safely operate a community grid and assets. This will enable the RECs to maximise the value of their assets leading to a decrease in the overall cost of the community. Specifically, the REC digitalisation requirements will be agreed, and the multi-market energy and flexibility trading and dispatching strategy through Peer-to-Peer (P2P) and Multi Energy Virtual Power Plant (MEVPP) will be developed, including users demand behaviour forecasting.

For the correct management of energy system operations in REC, the first step is to understand how energy is used first at single building level and second at REC level.

To this end, this deliverable reports an analysis of thermal and electric energy uses for a series of buildings. This analysis is developed in WP3 of the project, more specifically in task T3.2 with the aim of achieving a realistic representation of the thermal and electrical energy consumption patterns at building level, considering the various energy needs of a building and how they are covered. This analysis is performed on a series of buildings identified as representative of the EU building stock. The main focus has been placed on residential buildings as they represent the wide majority of the buildings that can be part of a REC in small context like those considered in LocalRES project. Nevertheless, also thermal and electrical energy use for a series of non-residential building types (office, school, supermarket) have been analysed.

An hourly time resolution is used in this analysis. This level of detail is necessary to have a realistic representation taking into due consideration a series of effects (e.g., the time needed for a heat pump (HP) to pass from start-up to full-load operation) that, if neglected, would result in oversimplified behaviours not representative of a real case.

To take into due account these effects that characterize building and system behaviours, a series of models in TRNSYS have been developed for residential and office buildings analysed. These models include the building and the Heating Ventilation and Air Conditioning (HVAC) system part. The HVAC system is composed by all the components (generation unit, thermal storages, distribution and emission system) part of the system responsible for the delivering of thermal energy to the building to cover building thermal needs. The modelling of building and HVAC system part with the due level of detail allows elaborating building energy uses time series representative of realistic cases, in which the HVAC operations are managed according to fixed and standard control logics. A more simplified approach without the development of a TRNSYS model has been followed to establish energy use patterns in school and supermarket buildings.

Regarding the covering of building's energy needs, the focus has been placed on technologies that allow the coupling of different sectors (where in this context the term sectors refer to thermal and electrical sectors). An example of technology for sector coupling approach is constituted by compression heat pump systems. This work has been mainly focused on this kind of system for the covering of buildings' thermal needs. In addition to compression heat pump systems, also the presence of a photovoltaic (PV) system and a battery energy storage system (BESS) is considered and a series of additional analyses regarding electric energy consumption, production, self-consumption over specific time periods for the various cases analysed is reported. The reason this report mainly focuses on HP system, eventually coupled also with PV systems and BESS is related to the fact that the integration of these technologies represents the most suitable solution for sector-coupling purposes. Nevertheless, also cogenerators have been considered as sector-coupling technology. More specifically, as cogenerator, a Combined Heat and Power (CHP) system, sized to cover single building thermal needs has been considered. A simplified assessment in terms of thermal and electrical energy use at building level considering this kind of technology is included in this report.

The last aspect analysed in task T3.2 and reported in this document regards the development of a methodology for the aggregation of different buildings energy use time series to elaborate a meaningful and realistic representation of energy uses at REC level. To this purpose, two methods for the aggregation of single building loads at REC level have been developed. These methods focus mainly on residential buildings as they present not negligible variations in terms of thermal and electrical energy use patterns due to the different usage of the building by the occupants. The two methods are applied and the results in terms of thermal and electrical energy use at REC level presented for a REC of 10 residential buildings used as example.

The results presented in this report in terms of thermal and electrical energy use time series at single building and REC level will be used within T3.3 and T3.4 for the development of the MEVPP, in particular, for the training of the MEVPP. This allows training the MEVPP using a variety of thermal and electrical energy use time series representative of meaningful and realistic cases that can be encountered in a future real application of the MEVPP.

In addition to share the data obtained in terms of thermal and electrical energy use time series for the buildings analysed within the LocalRES Consortium and, in particular with CENTRICA, partner responsible for the MEVPP development, the main results in terms of thermal and electrical energy consumption time series for the cases presented in this document will be made available through the platform Zenodo (Zenodo, n.d.).

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1.2. Relation to other activities of the project

As input for task T3.2 the information gathered in task T3.1 and reported in deliverable D3.1 about the available assets (mainly HP systems, PV systems and BESSs) in the four demo cases of the project have been used.

The output of task T3.2 in terms of energy use time series will be used mainly within T3.3 and T3.4 for the development of the MEVPP and more specifically for its training. This allows training the MEVPP using meaningful data representative of a series of building cases that can be encountered in a future application of the MEVPP in a real REC. Moreover, the same outputs of task T3.2 could be beneficial also for task T3.5.

1.3. Structure of the report

This report is structured as follows:

- Section 1/: Introduction

This section includes a brief explanation of the purpose of the report, the relation with other activities, the structure of the report and the contribution of partners.

- Section 2/: Methodology

This section reports the methodology considered in this work. More specifically, first a general description of the procedure used is reported, while the second and third parts describe the methodology used to identify the 27 residential cases and the other non-residential cases considered. The fourth part presents the HVAC, the PV system and BESS considered for this analysis. Finally, the fifth part reports two methods to aggregate building energy loads at REC level.

- Section 3/: Results

This section reports first the results of TRNSYS simulation in terms of thermal and electrical energy use time series at building level. These results are reported for one of the 27 residential cases identified, while the main results for all the cases considered are reported in section 7/. Second, this part reports with an example the evaluation of thermal and electrical energy use time series at REC level obtained aggregating single buildings' thermal and electrical energy use time series. In this section the results are divided in subsections presenting results over two weeks, considered for the purpose of this work representative of winter and summer period respectively, and over the entire year.

- Section 4/: Conclusions

This section reports the main conclusion of the work.

- Section 5/: Next steps:

This section reports an overview of the possible future developments.

- Section 6/: Bibliography

This section includes the bibliographic references used in the report.

- Section 7/: Appendix

This section reports the main results for all cases considered.

1.4. Contribution of partners

The partners that contributed to this task are CARTIF and CENTRICA. The collaboration with CENTRICA mainly concerned the definition of the needed inputs from this task for the development of the MEVPP within task T3.3, and receive feedbacks as work package leader. The collaboration with CARTIF, instead, mainly concerned the evaluation of possible use of the outputs of this task in task T3.5. Finally, TECNALIA and AIT were responsible for the internal review of this deliverable.

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2/ Methodology

2.1. General methodology used

The identification of **thermal and electrical energy uses** at building level is the starting point to then aggregate the various time series to obtain thermal and electrical energy use time series at REC level.

In this work, thermal energy use is associated to the thermal energy delivered to the building by the HVAC system to cover Space Heating (SH), Space Cooling (SC) and Domestic Hot Water (DHW) demand.

Considering that, as stated in section 1.1, the focus of this task is on technologies that allow **sector coupling**, the thermal and electrical energy uses are related. In other words, the focus is, for example, on technologies (like compression Heat Pumps (HPs)) that, as part of the HVAC system, allows delivering thermal energy to the building to cover its thermal needs using electrical energy to run the system. This allows using renewable electrical energy produced locally within the REC to run the HVAC system and cover building thermal needs.

This implies that the identification of electrical energy use in the considered building does not account for only the electrical energy consumption to run the typical electrical devices present inside the building, but must consider also the electrical energy used for the covering of building's thermal energy demand in case a HP system is considered.

In this regard, a specification must be introduced at this stage. This specification is about the differences and relations between building thermal energy demand and building thermal energy consumption. In this context, thermal energy demand represents the amount of thermal energy required to ensure the comfort conditions in the building as defined by the user, while thermal energy consumption is the amount of energy consumed by a realistic HVAC system to cover the same thermal energy demand.

This specification must be introduced as, in many analyses, the thermal energy demand of a building can be used to extrapolate, with the right assumptions, the energy consumption of a building. This is particularly valid for relatively long period energy analyses (e.g., monthly or yearly energy analyses), where the focus is on the calculation of monthly or yearly energy consumption starting from the respective energy demand, and taking into account fixed parameters like, in the most simplified case, an overall system efficiency.

This kind of calculation does not consider in detail the dynamic effects associated to the presence of system components like thermal storages or to the control of the HVAC system. In fact, both thermal storages and system control lead to a decoupling of building thermal demand and system consumption to cover the same demand. Moreover, also the time needed by a HP to pass from start-up to full load operation, if neglected would results in an oversimplified and not realistic electrical energy use pattern.

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Contrarily to energy analyses over long periods (e.g., monthly or yearly energy analysis), in this task the focus is on a more granular time horizon. In fact, the objective is **to evaluate building energy use time series with a time resolution of 1 hour**. With this time resolution, it is not possible to extrapolate realistic building energy consumption patterns starting from building energy demand and simply applying fixed (i.e. static) parameters like an overall system efficiency, especially if HP systems are considered.

It is instead necessary to develop a dynamic model of the building with its HVAC system and, to this purpose, in this work, TRNSYS (Klein, S.A. et al, 2017, TRNSYS 18: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA, n.d.) has been used as the software environment for the development of the dynamic models to simulate residential and office buildings.

Simplified analysis without the development of a specific TRNSYS model but using different methods to elaborate energy use patterns have been applied only for school and supermarket buildings. More specifically, energy use patterns in schools have been elaborated following the method reported in (UNI/TS 52016:2018), while the energy use patterns for a supermarket have been elaborated based on a series of boundary conditions presented in (CommONEnergy D2.1).

At this point it is useful to introduce a specification about the time resolution used in this work. As already stated, the time resolution used to evaluate building energy use time series is 1 hour. On the other hand, TRNSYS simulation time step has been fixed equal to 5 minutes. This shorter time step used in TRNSYS simulations allows taking into consideration all effects due to system components (e.g., thermal storages) and system controls (e.g., thermostatic control of building internal temperature, or the time needed by a HP to pass from start-up to full load operation). The building energy use time series with 1-hour time resolution are obtained resampling the TRNSYS simulation results with a 5 minutes timestep. In this way, the building energy use time series at 1-hour time resolution include the effects associated to the presence of thermal storages and system control that lead to a decoupling of thermal demand and consumption. The consideration of all the previous aspects allows simulating the operation of a realistic HVAC system, having as result a realistic estimation of its energy use according to the time resolution considered in this analysis (1 hour).

The time resolution of 1 hour is selected as it is a good balance between an enough precise representation of realistic building energy uses, taking into consideration the effects associated to the presence of thermal storages and system control, and a limited calculation effort. This is particularly true for the building thermal energy use, while, in some cases, data with more granular time resolution could be needed for the assessment of electrical energy use. In this work, the results in terms of building and REC energy uses are presented considering 1-hour time resolution. However, in case this time resolution is not suitable for the development of the MEVPP it is possible to deliver the same TRNSYS simulation results also with a 5-minute time resolution.

Based on the previous considerations, the steps reported below have been followed to obtain realistic hourly thermal and electrical energy use time series at building level in residential and office buildings, where a TRNSYS model has been developed for each case considered. On the contrary,

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as previously mentioned, a simplified approach has been followed for schools and supermarket buildings.

- Starting from the building energy demand time series, a typical HP system has been sized according to what reported in iNSPiRe (R. Fedrizzi) and BuildHeat (C. Dipasquale) project.
- A dynamic simulation in TRNSYS has been run to simulate the behaviour of the HVAC system and extrapolate its electrical energy consumption with an hourly time resolution.
- The HVAC system electrical energy consumption is summed with the electrical energy consumption of the other electrical appliances present inside the building to determine the overall building electrical energy consumption. It is important to specify that the electrical consumption associated to other electrical appliances present inside the building has been considered in the TRNSYS simulations. This allows correctly accounting for the internal heat gain associated to this electrical consumption. Moreover, the thermal energy delivered to the building for SH, SC and DHW is analysed.

Also, the presence of a PV system and a BESS has been considered to assess how the building electrical energy consumption is covered considering these technologies. To perform this analysis the following steps have been followed:

- A PV + BESS has been sized accounting for the available area on the roof for PV installation.
- PV production has been calculated based on PV size, the irradiation data for the considered reference location and performance ratio (PR).
- Electrical energy flows have been elaborated by applying the Open Energy system Modelling Framework (oemof), a toolbox for the dispatch of energy flows following the predefined rule-based priorities. In this context, actually, oemof is used at single building level, meaning that the management of electrical energy flows accounts for single building electrical energy consumption, production and the presence of a BESS. This kind of use of the oemof is a simplification associated to the kind of analysis performed in this work. Nevertheless, oemof will be used accounting also for the possibility of exchanging energy between different buildings belonging to the same REC as reported in section 5/ and in (V. Casalicchio, 2022)].

Regarding the case that considers a cogenerator, in this work the modelling of the cogenerator has not been performed using a specific TRNSYS type but a more simplified assessment has been done. In particular, the considered cogenerator has been sized to cover building thermal needs and a series of fixed parameters have been used to define the thermal and electrical energy produced. The self-consumption of the electrical energy produced by the cogenerator is prioritized, yet allowing in any case sending the eventual electrical energy production surplus to the grid. The HVAC system that considers a cogenerator differs from the one that consider a HP only for the generation unit in terms of HVAC system layout and control. In other words, the other parts of the HVAC system visible in Figure 3, as well as the control logics used are the same in the two cases.

One of the main objectives of this work is to obtain building energy use patterns that can be considered meaningful and realistic in general for the EU context. For this purpose, it is essential to assess the factors that could influence the results obtained previously from simulations. In this

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regard, three factors that can affect building energy consumption time series have been identified and described in section 2.2. Based on the considerations reported in section 2.2, 27 residential buildings and 9 office buildings have been defined and the procedure presented in the previous points applied for each of them.

Finally, in task T3.2 a methodology to **aggregate** different energy use time series at building level has been elaborated. This allows aggregating single building energy use time series resulting in energy use time series at REC level. To this purpose, two aggregation methods have been developed. The difference between the two methods is related to the consideration of slight differences in building usage by the occupants.

As already mentioned in previous sections, the results in terms of thermal and electrical energy use time series at single building and REC level represent the most important and exploitable result from this work. These energy use time series constitute a valuable input for task T3.3 and T3.4 that will address the development of the MEVPP using these time series for the MEVPP training. Moreover, the energy use time series for the cases reported in this report will be made available to the public trough the platform Zenodo (Zenodo, n.d.).

2.2. Identification of the building types to be considered in the REC

RECs group together a series of buildings that could be characterized by important differences in terms of thermal and electrical energy uses.

In this work, the main focus has been placed on residential buildings as, especially in the context of small REC, and in the project demo sites, they represent the wide majority of the buildings. Moreover, residential buildings not only represent the wide majority of the buildings that can be potentially part of a REC, but are also the buildings in which there is more room to apply demand response (DR) strategies. This allows in general to partly modify building thermal and electrical loads providing at the end the possibility to exploit optimization and flexibility within the REC. Other building types, like offices, schools and supermarket, are instead characterized by less variability in the building energy use patterns due to the fact that the usage of this kind of buildings is almost the same within the specific building type.

Nevertheless, evaluations related also to offices, schools and supermarkets in terms of energy use time series have been done for the sake of completeness in this work.

To have a realistic representation of thermal and electrical energy uses associated to a REC from numerical models, it is essential to model, with the right level of detail, building energy uses. For this reason, in this task a series of characteristics have been analysed and a total of 27 residential buildings have been defined as the minimum number to have a sufficient and enough general representation of the possible residential buildings combinations that can be found in a REC in the EU context.

These 27 residential cases derive from the considerations reported in the following.

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One aspect that influences thermal and electrical energy uses at building level is related to the building type considered. In other words, the thermal and electrical energy consumption patterns of a Single-Family House (SFH) are different from the thermal and electrical energy consumption patterns of a Multi-Family House (MFH). Generally, the thermal and electrical energy consumption of a MFH are higher in comparison to those of a SFH due to the higher volume to be conditioned and to the higher number of electrical devices present in a MFH. To take in due consideration the influence of the building type on thermal and electrical energy uses, three residential building types have been considered in this work: SFH, small Multi-Family House (sMFH) and large Multi-Family House (lMFH). More details about geometrical characteristics of the three residential building types considered are reported in section 2.2.1.

Another aspect that influences thermal and electrical building energy uses is related to the status of the building. In fact, an old building generally exhibits high thermal energy consumption due to the low performance of thermal envelope[1] and HVAC system. The low performance of thermal envelope is associated to the limited insulation layer thickness (if present) that generally characterized this kind of buildings. On the contrary, new or deep renovated buildings are characterized by more insulated and hence more performant thermal envelope and more efficient HVAC system that lead to lower thermal and electrical energy consumption. Between old and new (or deep renovated) buildings it could be defined an additional building status that, here, is called "renovated". The renovated building status aims to represent those buildings that have undergone a partial renovation (e.g., replacement of windows only, replacement of the HVAC system only) or, in any case, a building with thermal and electrical energy uses that are in between the values typical for an old and a new building. Based on these considerations, to take into due account the influence of the building status on the definition of thermal and electrical energy uses, three building status have been considered in this work: old, renovated and new. Section 2.2.2 reports more details about the thermal properties, in particular, the thermal transmittance of the main envelope components of old, renovated and new buildings.

The thermal and electrical energy uses, as well as building envelope characteristics are also dependent on the considered climates. In fact, the same building located in Stockholm or in Rome presents important differences in thermal and electrical energy uses. At the same time the same building type in Stockholm and Rome typically presents also important differences in terms of thermal envelope characteristics. For these reasons, to have a sufficient representativity of the climatic conditions of the EU context, three EU climates have been considered: Nordic, Continental and Mediterranean. For each climate, a reference location has been identified and its climatic conditions used in the models. The three locations identified are Stockholm for the Nordic climate, Stuttgart for the Continental climate, Rome for the Mediterranean climate. The three reference locations and climates identified are part of the climates used also in FP7 iNSPiRe project (R. Fedrizzi). The considered reference locations are also well aligned in terms of climatic conditions with the project demo sites located respectively in Berchidda (ITA), Ispaster (ESP), Ollersdorf (AUT),

[1] The thermal envelope of a building is the set of structures that separate the conditioned space (subject to being heated and/or cooled) of the building from outside or from other parts of the building that are not conditioned.

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and Kokar (FIN). More specifically, Berchidda (ITA) and Ispaster (ESP) climatic conditions can be considered, for the purpose of this work, enough aligned to those in Rome, the climatic conditions in Ollersdorf (AUT) can be considered aligned to those in Stuttgart and the climatic conditions in Kokar (FIN) can be considered aligned to those in Stockholm. In comparison to the work performed in iNSPiRe project, where the EU region was divided in seven climates, here only three climates have been considered. This is motivated by the fact that, as reported in (Dipasquale C.), buildings located in colder climates are generally characterized by more performant thermal envelope and this results in limited variations in terms of building yearly thermal energy consumption.

As mentioned previously, the combination of three residential building types, three building status and three EU climates leads to a total of 27 residential cases. Table 1 summarizes these 27 residential cases.

Table 1: 27 residential cases of climates (with also the reference locations considered), building types and building status considered

Climate	Reference location	Building type	Building status
Nordic	Stockholm	SFH	Old
			Renovated
			New
		sMFH	Old
			Renovated
			New
		lMFH	Old
			Renovated
			New
Continental	Stuttgart	SFH	Old
			Renovated
			New
		sMFH	Old
			Renovated
			New
		lMFH	Old
			Renovated
			New

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Mediterranean	Rome	SFH	Old
			Renovated
			New
		sMFH	Old
			Renovated
			New
		lMFH	Old
			Renovated
			New

Regarding non-residential buildings, in this work thermal and electrical energy use time series of offices, schools, and supermarkets have been assessed.

Regarding offices, an office building has been modelled in TRNSYS. More specifically, one office building in terms of geometry has been modelled in the same three climates (Nordic, Continental, Mediterranean) and considering the same three building status (Old, Renovated, New) presented above for residential buildings. This results in nine TRNSYS simulations of office buildings (three office building status in three climates). The main characteristics in terms of geometry and thermal transmittance of the office building considered are reported in section 2.2.1 and 2.2.2, respectively.

The general statement already exposed that the building models developed in TRNSYS and used in this work, and therefore their results in terms of building thermal and electrical energy use are representative of realistic cases is supported by the fact that these building models have been developed within different EU projects like FP7 iNSPiRe (Dipasquale C.) and H2020 BuildHeat (C. Dipasquale). In these projects, specific efforts have been dedicated to analysing and setting realistic boundary conditions in terms of building wall constructions, occupancy schedules, electrical appliances usage, infiltration and ventilation. These analyses have been performed versus literature and monitored data.

Regarding schools and supermarket, a more simplified approach has been followed without using TRNSYS as mentioned in section 2.1.

For school buildings, hourly thermal and electrical energy use time series have been obtained for one school building in terms of geometry having a floor area of 4,700 m^2 and for a total of nine different cases considering the three climates and three building status used and presented previously for residential and office buildings using the standard (UNI/TS 52016:2018). The main assumptions in terms of heating and cooling schedule and internal gains due to presence of occupants, electrical appliances and lights are taken from standard (UNI/TS 16798-1:2019). Moreover, for the school building only SH is considered as building thermal demand as SC is

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generally limited or not present in schools and DHW demand is negligible in comparison to SH thermal demand for the purpose of this work.

Regarding supermarket, food shop category has been considered. The choice of the food shop is motivated by the fact that this kind of building presents high specific values of electrical energy consumption (in the range of 500 – 1,000 kWh/m²/y as reported in (CommONEnergy D2.1)). Moreover, in this work, in supermarket building, only assessment related to the electrical energy use has been performed. This is because in this kind of buildings the electrical consumption represents the highest building energy consumption. More specifically, the electrical energy consumption is due 50% to refrigeration, 25% to lighting system, 20% to HVAC system, 5% to other electrical consumptions as reported in (CommONEnergy D2.1). The considered supermarket is a small one (with a floor area of 800 m²) and can be considered representative of small supermarkets having a floor area up to 20,000 m² according to what is reported in (CommONEnergy D2.1). The assumptions considered to define supermarket electrical loads are:

- 12 occupancy hours, from 8 a.m. to 8 p.m.
- Refrigeration, constant load equal to peak load during occupancy hours, reduction of 40% during closing hours (data from a real food shop).
- Lighting, constant load equal to peak load during occupancy hours, no load during closing hours.
- Heating and cooling, load equal to peak load during occupancy hours, reduction of 50% during closing hours.
- Other electrical consumptions, load equal to peak load during occupancy hours, no load during closing hours.

2.2.1. Geometrical features of the residential and office buildings considered

This section reports in more detail a series of geometrical features of the residential and office buildings considered in this work. In particular, Table 2 reports a series of geometrical features for SFH, while Table 3 reports the main geometrical characteristics for both sMFH and lMFH. In fact, sMFH and lMFH are identical for a series of geometrical parameters (e.g., number of dwellings per floor, living area per dwelling, living area per floor), while the main difference is related to the number of floors (3 for the sMFH, 7 for the lMFH) that influences other geometrical parameters (total number of dwellings, total living area). The model used to simulate sMFH and lMFH is almost the same and, with the right modifications, can be used to simulate a MFH with a number of floors from 3 to 7. For this reason, the sketch and the picture reported in Table 3 are for a generic MFH, in this case with 5 floors. In Table 3 the values for the lMFH, where different from sMFH, are reported in brackets. Finally, Table 4 summarizes the main geometrical characteristics of the considered office building. All the information reported in this section are taken from (Dipasquale C.).

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Table 2: SFH main geometrical characteristics. Source: (Dipasquale C.)

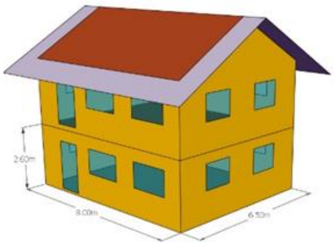
SFH	
Sketch and picture	 
Number of floors	2
Number of dwellings	1
Living area per floor	50 m²
Total living area	100 m²
Ceiling/floor height	2.5 / 3.0 m
Building width / depth	6.5 / 8.0 m
Roof type and materials	Tilted (30°)
Glazing ratio	20%
S/V ratio	0.78

Table 3: sMFH and lMFH main geometrical characteristics (the values for lMFH, where different from the value for sMFH, are reported in brackets). Source: (Dipasquale C.)

sMFH (lMFH)	
Sketch and picture	 
Number of floors	3 (7)
Number of dwellings per floor	2
Number of dwellings tot	6 (14)
Living area per dwelling	50 m²

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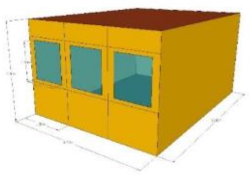
Living area per floor	100 m^2
Total living area	300 (700) m^2
Ceiling/floor height	2.5 / 3.0 m
Building width / depth	16.3 / 7.6 m
Roof type and materials	Flat concrete roof
Glazing ratio	20%
S/V ratio	0.65 (0.52)

Table 4: Office main geometrical characteristics. Source: (Dipasquale C.)

OFF		
Sketch and picture		
Zone height/width/depth	3.0 / 4.5 / 6.0 m, Ceiling height = 2.8 m	
Zone floor area / volume	27 m^2	
Number of zones per floor	6	
Office area per floor	162 m^2	
Number of floors	5	
Total living area	810 m^2	
Roof type	Flat concrete roof	

2.2.2. Thermal transmittance values of the residential and office buildings considered

As stated in section 2.2, building type and status, as well as climatic conditions are factors that influence thermal performances and consequently energy uses of a building.

This section reports the thermal transmittance (U value) of the main thermal envelope components for the considered residential and office buildings. For the sake of simplicity, it is useful to remind here that the thermal transmittance is basically proportional to the thermal losses of the envelope. The following Table 5, Table 6 and Table 7 summarize the thermal transmittance of main thermal envelope components for respectively an old, a renovated and a new SFH in the three considered climates, while Table 8, Table 9 and Table 10 report the same quantities for MFH (value valid for both sMFH and lMFH for the reasons presented in section 2.2.1). Table 11, Table 12 and Table 13

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report instead the thermal transmittance of main envelope components for respectively an old, a renovated and a new office in the three considered climates.

The thermal transmittance values used are taken mainly from the work performed in the FP7 iNSPiRe project and reported in (Dipasquale C.). In particular, the U values used for old buildings are those that can be found generally in buildings built in the period 1970-1980 in the considered climates. On the contrary, for new buildings, the U values considered are in accordance with the limits imposed by the respective national regulation. As can be noted from the tables and as expected, passing from Mediterranean to Nordic climate the performance of the thermal envelope tends to increase. The same trend can be noted also passing from old to new buildings. There are not important differences instead based on the considered building type.

Table 5: Thermal transmittance values for old SFH in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.36	0.32	0.32	2.83
Continental	Stuttgart	0.87	0.76	1.47	2.83
Mediterranean	Rome	1.33	1.40	1.47	2.83

Table 6: Thermal transmittance values for renovated SFH in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.28	0.26	0.29	1.40
Continental	Stuttgart	0.43	0.44	0.43	1.40
Mediterranean	Rome	0.65	0.66	1.47	1.40

Table 7: Thermal transmittance values for new SFH in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.14	0.14	0.14	0.59
Continental	Stuttgart	0.18	0.18	0.18	1.40
Mediterranean	Rome	0.28	0.26	0.26	1.40

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Table 8: Thermal transmittance values for old sMFH and lMFH in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.41	0.31	0.33	2.83
Continental	Stuttgart	0.88	0.96	1.37	2.83
Mediterranean	Rome	1.21	1.51	1.37	2.83

Table 9: Thermal transmittance values for renovated sMFH and lMFH in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.29	0.29	0.31	1.40
Continental	Stuttgart	0.56	0.59	1.37	1.40
Mediterranean	Rome	0.74	0.85	1.37	2.83

Table 10: Thermal transmittance values for new sMFH and lMFH in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.22	0.14	0.15	0.59
Continental	Stuttgart	0.23	0.15	0.16	0.59
Mediterranean	Rome	0.29	0.26	0.26	1.40

Table 11: Thermal transmittance values for old office in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.34	0.29	0.41	2.83
Continental	Stuttgart				
Mediterranean	Rome	1.21	1.39	0.62	5.29

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Table 12: Thermal transmittance values for renovated office in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.29	0.20	0.31	1.40
Continental	Stuttgart	0.38	0.33	0.41	1.40
Mediterranean	Rome	0.74	0.67	0.62	2.83

Table 13: Thermal transmittance values for new office in the three considered climates

Climate	Reference location	U_{walls}	U_{roof}	$U_{ground\ floor}$	U_{window}
		[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]	[W/(m²·K)]
Nordic	Stockholm	0.20	0.17	0.28	0.59
Continental	Stuttgart	0.22	0.19	0.21	0.59
Mediterranean	Rome	0.29	0.26	0.26	1.40

2.3. Climates considered

The energy performances of the considered buildings are assessed in three different EU climates: Nordic, Continental, Mediterranean. These three climates aim to be representative of the climatic conditions in the EU context. Based on the considered climate, one country belonging to this climate is selected as representative of the climatic conditions and thermal envelope properties. Moreover, for each country considered as representative of the respective climate, a city belonging to the country is selected and its climatic conditions used in the simulations. The weather files of the three reference cities are obtained from Meteonorm software v7 (Meteonorm Software, 2023).

Table 14 reports the three considered climates, with the respective city selected as references locations, as well as the Heating Degree Days (HDD), Cooling Degree Days (CDD), and yearly average external temperature. The HDD and CDD are calculated using the free online software (Custom Degree Day Data, n.d.) as the average value over the last three years (2020, 2021, 2022) and considering 18 °C (C. Dipasquale) and 24 °C (Eurostat - Heating and cooling degree days - statistics, n.d.) as base temperature for HDD and CDD calculation respectively.

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Table 14: HDD and yearly average temperature for the three cities considered as reference locations for the three climates identified

Climate	City	Heating Degree Days	Cooling Degree Days	Yearly average temperature
Unit	-	-	-	[°C]
Nordic	Stockholm	3,541	10	7.9
Continental	Stuttgart	2,784	42	10.0
Mediterranean	Rome	1,299	187	15.8

Figure 1 shows the external temperature cumulative distribution along the year for the three cities selected. As expected, Stockholm is characterized by the lowest external temperature, while Rome shows the highest one and Stuttgart presents values in between. In general, higher differences between the various climates are visible for what regards the minimum external temperature, where a difference in the range of 15 °C can be identified comparing Stockholm and Rome yearly minimum external temperature, while the difference decrease moving towards maximum external temperature, where a difference in the range of 3-4 °C can be observed comparing the same locations. Figure 2 reports instead the cumulative distribution of global solar radiation on the horizontal. According to expectations, Stockholm shows the lowest values, while Stuttgart is characterized by slightly higher ones and Rome by the highest.

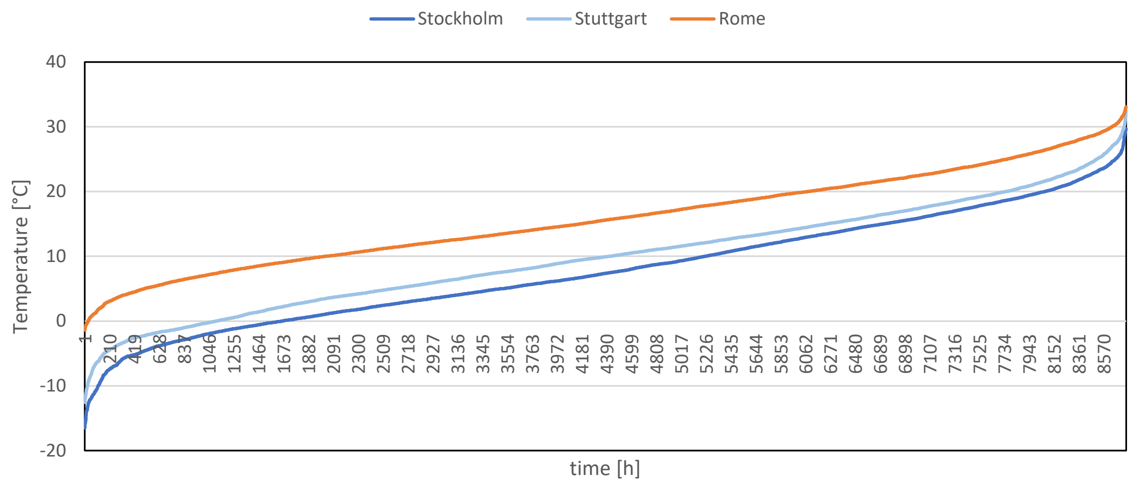

Figure 1: External temperature distribution in the three considered locations. Source: (Meteonorm Software, 2023)

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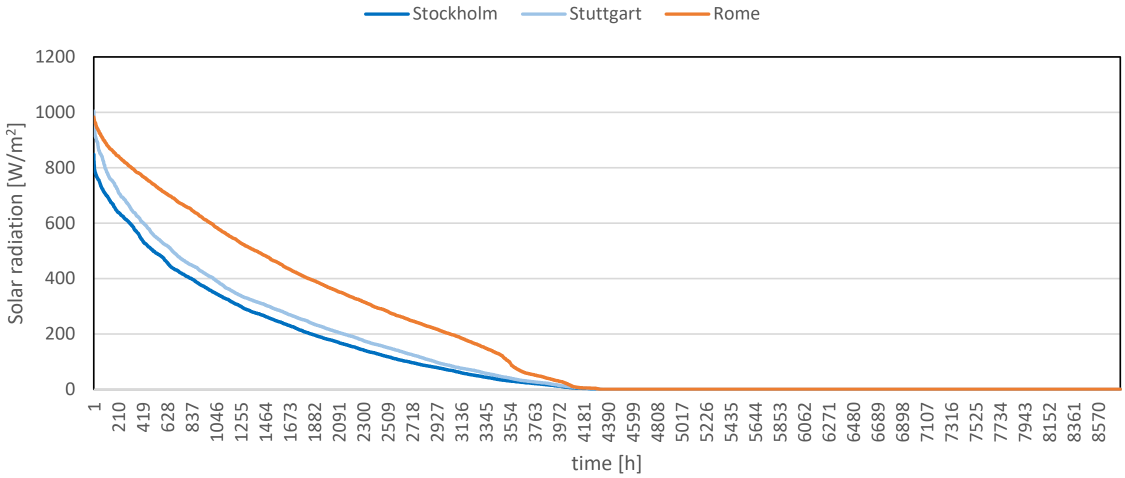

Figure 2: Solar radiation (on the horizontal) distribution in the three considered locations. Source: (Meteonorm Software, 2023)

To conclude this section about considered climates, Table 15, Table 16 and Table 17 summarize, for each climate, monthly values of maximum global solar radiation on the horizontal, average, minimum and maximum external temperature of the respective reference location.

Table 15: Climatic characteristics for the reference location of the Nordic climate (Stockholm). Source: (Meteonorm Software, 2023)

	Max solar radiation on horizontal	Average external temperature	Min external temperature	Max external temperature
Unit	[W/m^2]	[°C]	[°C]	[°C]
JAN	142	-1.1	-16.5	7.8
FEB	328	-1.6	-14.2	7.7
MAR	597	1.1	-10.9	12.9
APR	673	6.6	-3.3	19.5
MAY	816	11.8	0.3	23.5
JUN	849	15.6	3.2	27.2
JUL	791	18.9	8.9	29.7
AUG	747	17.8	7.1	26.4
SEP	644	12.8	2.3	23.0
OCT	418	7.7	-2.8	16.4
NOV	245	3.5	-7.3	12.4
DEC	115	0.8	-12.9	9.6

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Table 16: Climatic characteristics for the reference location of the Continental climate (Stuttgart). Source: (Meteonorm Software, 2023)

	Max solar radiation on horizontal	Average external temperature	Min external temperature	Max external temperature
Unit	[W/m²]	[°C]	[°C]	[°C]
JAN	417	0.8	-12.6	12.5
FEB	588	2.3	-9.4	14.2
MAR	755	5.5	-5.3	19.9
APR	850	9.8	-3.2	22.2
MAY	963	14.4	3.2	28.7
JUN	1004	17.6	5.5	30.4
JUL	902	18.9	8.3	32.4
AUG	923	18.7	9.3	31.5
SEP	795	14.1	4.1	26.7
OCT	611	10.2	0.1	20.9
NOV	465	5.1	-3.0	16.5
DEC	320	1.6	-8.0	11.5

Table 17: Climatic characteristics for the reference location of the Mediterranean climate (Rome). Source: (Meteonorm Software, 2023)

	Max solar radiation on horizontal	Average external temperature	Min external temperature	Max external temperature
Unit	[W/m²]	[°C]	[°C]	[°C]
JAN	498	7.8	-1.4	17.5
FEB	586	8.3	0.1	18.2
MAR	817	11.0	1.8	20.6
APR	878	13.5	5.0	23.2
MAY	984	18.4	8.8	29.0
JUN	975	21.8	11.9	32.0
JUL	983	24.3	15.5	33.1

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AUG	925	24.6	16.3	32.9
SEP	845	20.4	11.3	30.1
OCT	740	17.3	8.1	25.7
NOV	516	12.7	2.7	23.4
DEC	417	9.3	-0.3	18.9

2.4. Identification of the technologies for sector coupling

As briefly reported in section 1.1, in this work the focus has been placed on technologies that allows sector coupling. The term "sector coupling" identifies, for example, technologies that can cover a building demand (e.g., building thermal demand for SH) using as input a different energy vector (e.g., electricity). The use of technologies that allow sector coupling enables to increase self-consumption and management of energy produced within the REC.

A compression HP system, that delivers thermal energy for covering building thermal needs using as input electric energy, is one example of technology that allows sector coupling. Moreover, the installation of a HP system coupled also with a PV system and a BESS allows increasing self-consumption and management of energy produced within the REC even more. For the previous reasons, in this work, the main focus for what regards sector coupling technologies has been put on compression HP systems, coupled also with PV systems and BESSs.

Although in principle also cogeneration units are devices that allow sector coupling, in general less attention is put on this kind of devices in comparison to HP systems eventually coupled with a PV system and a BESS. This is basically due first to the generally higher maintenance costs of cogeneration units at single building application if compared to other generation units for the same application (gas boiler, HP system) (M. Kegel, 2014). Second, actual standard cogeneration units cannot efficiently exploit the renewable electrical energy locally produced from a PV system and eventually temporarily stored in a BESS. Third there is an important growth expected in the deployment of PV systems, BESSs and HP systems (L. Lyons) in the years to come. The synergic operation of these three technologies represents one of the most promising developments to couple thermal and electrical sectors, allowing to exploit renewable energy produced locally within a REC. Nevertheless, in this work also cogenerators have been considered as sector coupling technologies for the covering of building thermal and electrical energy use. This has been done through a simplified assessment better described in the following.

In the following sections, first the main parts of the HVAC system modelled in TRNSYS are presented also explaining briefly how the system is managed. Second, the PV and BESS models used in this work are presented, with a brief description on their characteristics.

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2.4.1. HVAC system

Figure 3 shows the Piping and Instrumentation Diagram (P&ID) of the HP system modelled in TRNSYS to cover SH, SC and DHW (DHW only in residential buildings) building thermal demand. The description of the main parts of the system is presented in the following according to their role as generation, thermal storage, distribution, emission devices. In the case in which cogenerators are considered as generation units the schematic reported in Figure 3 remains the same except for the different generation unit. Moreover, next also a specific part describes the indoor temperature control considered in the different buildings.

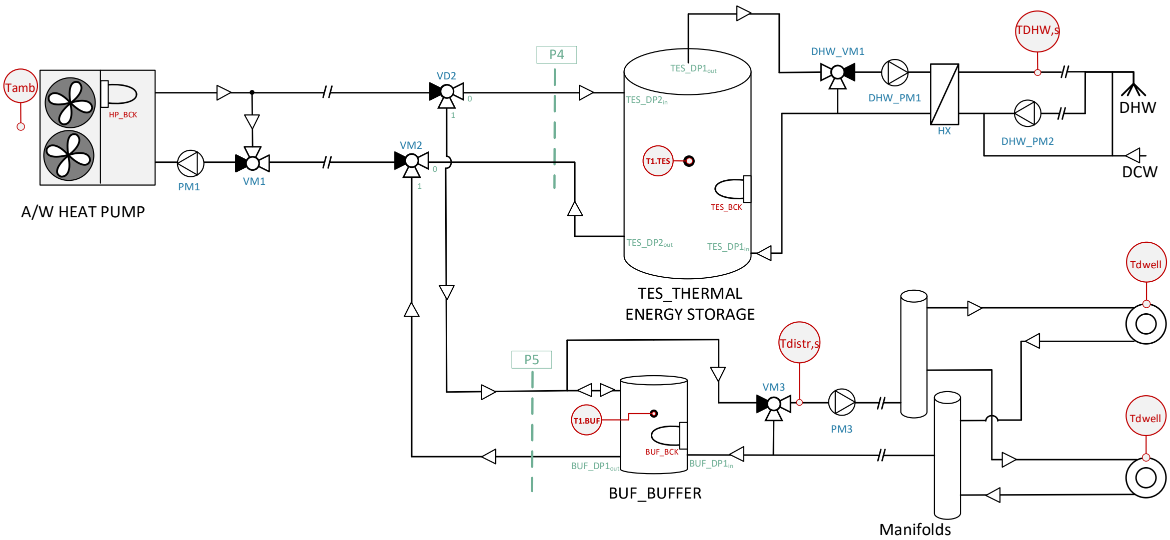

Figure 3: P&ID of the HP system considered

GENERATION

The HP considered in this work is an air-to-water (A/W) HP and is modelled using a TRNSYS type specifically developed within EURAC to simulate operations of variable speed HPs. This TRNSYS type relies on two performance maps (one for the heating mode and one for the cooling mode). These performance maps include information about thermal power delivered by the HP and HP electrical consumption based on a series of input variables (inlet temperature and mass flowrate at source and load side and compressor speed). Moreover, to be more aligned to a real case, the HP TRNSYS type used also includes a series of constraints in terms of maximum variations of compressor speed over time. These constraints have been verified in HPs' laboratory tests. As result, the use of this HP TRNSYS type allows simulating realistic HP operations based on real performances measured from laboratory tests. The sizing of the HP in terms of nominal thermal power has been done according to the procedure followed also in iNSPiRe project and reported in (R. Fedrizzi). Sections P4 and P5 visible in Figure 3 represent the sections where the thermal energy for respectively DHW and SH/SC is measured.

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THERMAL STORAGE

The thermal Energy Storage (TES) is a water tank used for DHW preparation. In this kind of system DHW is prioritized to SH and SC. The TES allows hydraulically decoupling DHW production and demand sides. The temperature sensor T1.TES, placed at 60% of TES height and visible in Figure 3 is used to monitor the temperature inside the TES and to control the charging of the TES ensured by the HP. More specifically, the TES charging starts when the temperature measured by the sensor T1.TES reaches 45 °C and ends when the same temperature reaches 50 °C.

The buffer tank is a smaller water storage designed for two main objectives. Firstly, this storage is useful to hydraulically decouple the generation side and the distribution side (working as a hydraulic junction). Secondly, it is used to provide thermal inertia (thermal flywheel, thermal mass), smoothing the operation of the HP and providing the heat required during de-icing cycles. In winter, the temperature inside the buffer tank is set according to a climatic curve defined in Figure 4 and dependent on the emission system considered. More specifically, in the cold season, the HP is activated to charge the buffer tank if the temperature measured by sensor BUF.T1, placed at 60% of buffer tank height as visible in Figure 3, is 3 °C lower than the SH set point temperature. The buffer tank charge ends when the temperature measured by sensor BUF.T1 reaches the SH set point temperature. During summer, instead, if a radiant floor system is considered, the buffer tank is maintained between 12 and 15 °C by the HP to cover building SC demand.

Both TES and buffer tank are equipped with an electrical resistance (TES_BCK and BUF_BCK in Figure 3) used as back-up element. These electrical resistances are activated if the HP is not able to ensure the desired temperature level in the TES and buffer tank respectively to avoid discomfort at user side.

DISTRIBUTION

The DHW distribution system consists of a heat exchanger (HX in Figure 3) sized in a way that guarantees the supply of the DHW load. The function of the HX is to separate the user side with the TES allowing to maintain the TES at temperature lower if compared to a typical case (where TES temperature in the range 55 – 60 °C are used) and in the range 45 – 50 °C without Legionella problems. Maintaining the TES at lower temperature is beneficial for HP performances in terms of HP Coefficient of Performance (COP) due to the lower HP outlet water temperature needed for TES charging. The mixing valve DHW_VM1 and the circulating pumps DHW_PM1 and DHW_PM2 visible in Figure 3 operate to ensure the delivering of the DHW to the user at the right temperature level. In this context the DHW set point temperature at user side (measured by the sensor TDHW,s in Figure 3) is fixed equal to 42 °C, slightly higher than what is prescribed in standards (UNI/TS 11300-2:2019) to ensure the comfort conditions. In the TRNSYS model, distribution pipes are implemented to take into consideration the thermal losses of the DHW distribution circuit.

The SH/SC distribution system is modelled with a mixing valve (VM3 in Figure 3) that keeps the distribution temperature (measured by sensor Tdistr,s in Figure 3) equal to the set temperature and one circulating pump (PM3 in Figure 3). The SH set temperature is defined by a climatic curve different based on the considered emission system (radiators or radiant floor system) visible in

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Figure 4. The SC set temperature delivered to the radiant floor system is instead fixed and equal to 18 °C. Between the circulating pump PM3 and the emission devices, distribution pipes are implemented to take into consideration the thermal losses of the distribution circuit.

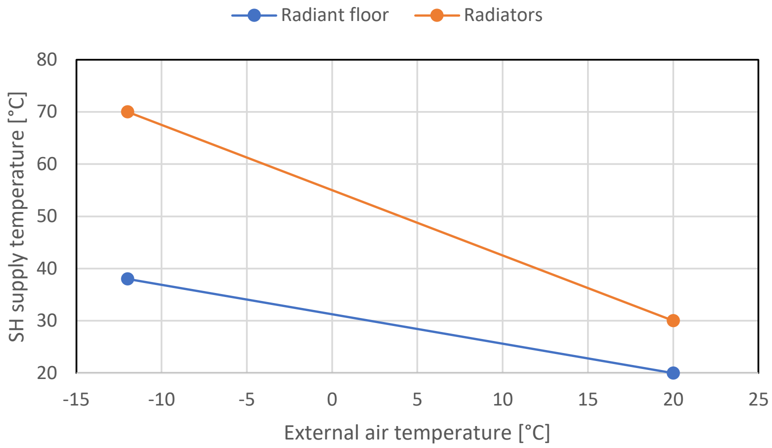

Figure 4: Climatic curve for the definition of SH set point temperature

EMISSION DEVICES

In this work radiators are considered as emission units for the delivering of SH thermal energy in old and renovated residential buildings, while a radiant floor system is considered for the covering of both SH and SC demand in new residential buildings. The SC demand in old and renovated buildings is covered by split units modelled in TRNSYS but not reported in Figure 3 for the sake of simplicity. In office buildings, instead, the SH and SC demand is covered by fan coils.

INDOOR TEMPERATURE CONTROL

The indoor building temperature at dwelling level is measured by sensors Tdwell in Figure 3. In old MFHs the SH is delivered only in some predefined periods of the day to be aligned to the operation of realistic centralized HVAC systems in this kind of buildings. In this work the period in which SH is delivered to old MFHs is considered from 6 a.m. to 12 p.m. and from 2 p.m. to 10 p.m. from October 15th to April 15th. Moreover, no thermostat at dwelling level is considered and the SH thermal energy is always delivered in the periods defined previously. However, the effect of Thermostatic Valves (TSVs) placed on the single radiators are considered. When the indoor dwelling temperature exceeds 20 °C the water circulating in the radiators of that dwelling is reduced simulating the effect of TSVs. This reduction reduces also the thermal power delivered by the radiators of the dwelling considered. The indoor temperature during summer season is instead maintained at 26 °C by the dwelling split unit. In this case the control presents a hysteresis of ±0.25 °C i.e., during summer the indoor temperature is maintained in the range 25.75 – 26.25 °C.

The indoor temperature control at dwelling level in renovated and new residential buildings in general and in old SFHs is instead based on a thermostat at dwelling level and no limitations in terms of periods for the delivering of SH are applied. The considered set point temperature for the residential building are 20 °C and 26 °C in winter and summer season respectively. The control

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presents also in this case a hysteresis of ±0.25 °C. The values of set point temperature used for SH, SC and DHW, as well as the hysteresis dead band are the same used in iNSPiRe project and reported in (Dipasquale C.).

The indoor setpoint temperature in office buildings has been considered equal to 20.5 and 25 °C for winter and summer season respectively. These set points are valid in the hours in which the office is considered occupied, hence from 8 a.m. to 5 p.m., while a set-back temperature equal to 18 and 27 °C is considered in the unoccupied hours for winter and summer season respectively. All these values in terms of temperature set point, set-back, office occupied and unoccupied hours are reported in (Dipasquale C.).

The indoor set point in school buildings has been fixed equal to 20 °C in the occupied hours that in this work are considered from 8 a.m. to 5 p.m., while a temperature set-back of 17 °C is used outside the occupied hours.

No specific considerations have been done for supermarket for what regards indoor set temperature as the consumption of HVAC system in this kind of buildings represents a minor contribution to the overall building consumption as already explained in section 2.2.

COGENERATOR SYSTEM

Although cogenerators can be considered generation units, they are reported here to distinguish them from the various components modelled in TRNSYS. As stated above, also cogenerators can be considered technologies for sector coupling as they deliver both thermal and electrical energy. In this work, small cogeneration units sized to be used within the single buildings have been analysed. However, contrarily to the more detailed analysis over HP systems, in this case only a simplified analysis has been performed. This is mainly associated to the limited number of cogenerators available on the market for this kind of applications. Moreover, each cogeneration unit is characterized by some peculiarities in terms of operation. For these reasons, in this work the cogenerator has been modelled considering that it operates to ensure the covering of building thermal demand. At the same time, the electrical energy produced is first used to cover building electric needs and, in case of electrical energy production surplus, this is sent to the grid.

The cogenerator has been modelled as an element characterized by thermal, electrical and overall efficiency. Table 18 reports these three efficiencies considered and the value representing the thermal losses.

Table 18: Characteristics of the considered cogenerator

Characteristic	Value
	[-]
Thermal efficiency	0.60
Electrical efficiency	0.30
Overall efficiency	0.90
Thermal losses	0.10

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With respect to Figure 3, the case in which a cogenerator is considered differs only for the generator part (cogenerator to be considered in substitution of the HP) and for the possibility to deliver SC to the building that is not considered for cogeneration units. In fact, the cogenerator accounted for in this work delivers only electrical energy and thermal energy to cover building SH and DHW demand.

2.4.2. PV and BESS

The part of this work - more focused on photovoltaic and battery energy storage systems - is developed by applying the Open Energy System Modelling Framework (oemof) and pvlib-python (W. M. Holmgren, 2018), a tool for the simulation of photovoltaic system production.

Oemof (open energy modelling framework, n.d.) is a free, open-source toolbox developed in Python, designed as a framework with a modular structure, based on pyomo (W. M. Holmgren, 2018), (W. E. Hart J.-P. W., 2011) and used to solve linear (LP) and mixed integer linear (MILP) programming optimization models. By default, oemof allows performing hourly base dispatch optimization to supply the demand minimizing the annual costs. However, here it is exploited differently, and it is tailored to the needs of this work as follows. First, the simulation is not optimized over the year or period under consideration, but it has been considered only the state of the individual timestep, in order to prioritize according to pre-defined rules. In this work oemof provides valuable support for modeling the different components/modules and managing and analyzing the different energy flows. This procedure has been followed as the development of the control algorithms to optimally dispatch energy in a REC is not within the scope of this task. This issue will be addressed in Task 3.3 of LocalRES project.

The structure of the electrical system with its modules is shown schematically in Figure 5.

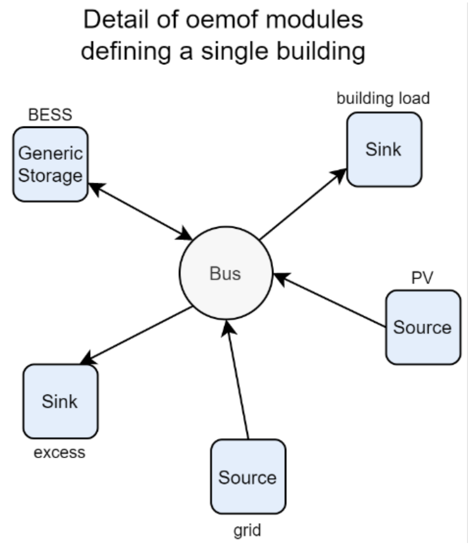

Figure 5: Simplified diagram of the building model according to oemof modules

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At each timestep, oemof recreates the system in Figure 5, by changing the inputs according to the previous timestep results - therefore updating the state of the storage systems - and then it manages the energy flows of the current timestep and the system load requirements.

Figure 5 shows the components defining each building. These components represent:

- the electric load;
- the *grid*, from which energy is purchased;
- the *excess* sink, which accounts for the not consumed production, fed into the grid;
- the PV *energy system*
- the *BESS*
- the *Bus*, which represents the element used in oemof to connect all previous parts

The arrows directions indicate how the energy flows among the components.

Regarding the operation of PV+BESS system, in this context the self-consumption is prioritized, meaning that the PV production is first, if possible, used within the building to cover building electrical energy demand. If there is a PV production higher than the building electric consumption the PV surplus is first stored in the BESS and, if this is not possible, it is sent to the grid. Moreover, in this context, BESS can be charged only using energy from PV. Although in principle BESS can be charged using energy from the grid (for example in periods along the day in which the electricity price is particularly low) this condition has not been considered in this work as this kind of operation implies an optimized control that is outside the scope of this task and will be addressed in T3.3.

The following sub-sections provide a further description of the PV energy system and of the BESS modules.

PV MODEL

The PV production profile is obtained using pvlib-python (W. M. Holmgren, 2018) and then integrated into the oemof Source component for the modelling of the PV system module.

The chosen pvlib transposition model is *pvlib.irradiance.get_total_irradiance*, (pvlib irradiance, n.d.) which determines the total in-plane irradiance, its beam, sky diffuse, and ground reflected components, through the specified sky diffuse irradiance model (isotropic is the default model).

Pvlib-python requires the following inputs:

- the global horizontal radiation (GHI),
- the direct horizontal radiation (DHI),
- the direct normal radiation profiles (DNI),
- the geographic location (latitude, longitude, altitude) to download the solar position parameters which are necessary for the application of the solar decomposition technique,
- the PV panel nominal power (Pn_{PV}),
- the tilt and azimuth,
- the surface area of a 1 kW PV panel ($active\_area_{PV}$),
- the performance ratio (PR).

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Once calculated the total irradiance (poa_{global}) based on the plane transposition, using pvlib-python (for further details please refer to the manual (W. E. Hart C. D.-P.)), the following equation calculates the production profile of the PV system.

$$production_{PV} = Pn_{PV} \cdot poa_{global} \cdot PR \cdot active\_area_{PV}$$

This pvlib simplified model for photovoltaic power estimation has been demonstrated to be enough accurate for simulation with hourly time resolution in (Barchi G) where it has been demonstrated how the model power estimation choice does not impact significantly even on the state variable electrical quantities (i.e. voltage and phase angle) in distribution grid.

BESS MODEL

The BESS module is modeled by the GenericStorage component of oemof: an object designed for one input and one output.

Here are the parameters on which the module is based, relevant to the work:

- absolute nominal capacity of the storage E_{nom} [kWh],
- relative storage content in the previous timestep (between 0 and 1) E(t-1),
- relative loss of the storage content per time unit β(t),
- efficiency associated with the inflow $E_i(t)$ and outflow $E_o(t)$ of the storage $\eta_i(t)$ $\eta_o(t)$,
- minimum and maximum storage content as a fraction of the nominal capacity (between 0 and 1)

The following equations respectively govern the storage system functioning and balance and the lower and upper bound constraint for the storage content.

$$E(t) = E(t-1) \cdot \big(1 - \beta(t)\big) - \frac{E_o(t)}{\eta_o(t)} + E_i(t) \cdot \eta_i(t)$$

$$E_{nom} \cdot c_{\min} \leq \mathrm{E(t)} \leq E_{nom} \cdot c_{\max}$$

Where:

- E(t) = current storage content
- c_{min} = normed minimum value of storage content
- c_{max} = normed maximum value of storage content

In addition, each energy flow involved is defined by the cost parameter, which is associated with one unit of the flow and is added to the objective expression of the optimization problem. The variable cost is the priority mechanism through which the battery storage system is managed. This cost is 0 when a rule-based behavior maximizing self-consumption is chosen as in this work.

Consequently, to charge the battery at timestep t, a high outflow cost and a low inflow cost are set; on the contrary, to discharge the battery, a high inflow cost and a low outflow cost are set. This is valid, provided that it is possible to charge or discharge energy according to the state of charge of the battery. Therefore, at each timestep, the input relative to the storage content at the previous timestep will be updated and also the relative loss of the storage content per time unit will be taken into account.

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Table 19, Table 20 and Table 21 provide an overview of main data of the PV and BESS. Table 20 reports the chosen tilt surface and azimuth surface according to the optimal values provided by PVGIS (T. Huld, 2012) and the PR. The PV system has been dimensioned according to the typical size for a SFH and to the available rooftop area for sMFH and lMFH. The BESS system has been dimensioned according to the typical commercial solutions in combination with a PV system having as reference (Impianto fotovoltaico per una casa ecosostenibile e all'avanguardia, n.d.) and (Fotovoltaico e sistemi di accumulo, n.d.).

Table 19: PV power and BESS capacity for SFH and sMFH (and also lMFH)

	SFH	sMFH (lMFH)
PV [kWp]	4.5	10
BESS [kWh]	6.0	15

Table 20: PV main characteristics

Climate	Reference location	Tilt	Azimuth	PR
Unit		[°]	[°]	
Nordic	Stockholm	34	0	0.85
Continental	Stuttgart	39	3	
Mediterranean	Rome	36	-5	

Table 21: BESS main characteristics

β(t)	Round trip η	c_{min}	c_{max}
4.2E-6	0.97	0.2	0.8

2.5. Aggregation of building loads at REC level

In the previous sections the focus was on the methodology used and the assumptions made for the evaluation of thermal and electrical energy uses at single building level for a series of building cases identified.

A REC considers instead several buildings, with the objective to optimize specific quantities (e.g., maximize energy self-consumption within the REC) or provide specific service to the grid (e.g., reduce REC peak consumption during certain periods, provide flexibility service, etc). To understand

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the correct amount of energy available for this kind of services at REC level, first, the energy use patterns at REC level, with the due level of detail, should be identified.

The first method to identify energy use patterns at REC level is to define the type and number of buildings belonging to the considered REC and simply sum the energy use time series of the specific building for a number equal to the number of buildings considered part of the REC. In other words, with the hypothesis of a REC composed by 10 buildings in total, 7 SFHs and 3 sMFHs, this first method implies that the energy use at REC level is calculated as the sum of the energy use of the SFH multiplied by 7 and of the energy use of the sMFH multiplied by 3. The following formula explains, for each hour of the year (i) and for a specific energy vector (j) this first method considering as building types SFHs, sMFHs, lMFHs, offices, schools and supermarkets.

$$E\ REC_{i,j,method\ 1} = (n_{SFH} \cdot E_{SFH} + n_{sMFH} \cdot E_{sMFH} + n_{lMFH} \cdot E_{lMFH} + n_{OFF} \cdot E_{OFF} + n_{SCHOOL} \cdot E_{SCHOOL} + n_{SUPERMARKET} \cdot E_{SUPERMARKET})|_{i,j}$$

Where:

- $E\ REC_{i,j,method\ 1}$ is the energy use at REC level for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j) obtained with the first method;
- n_{SFH} is the number of SFHs in the considered REC (equal to 7 in the previous example);
- E_{SFH} is the SFH energy use for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j);
- n_{sMFH} is the number of sMFHs in the considered REC (equal to 3 in the previous example);
- E_{sMFH} is the sMFH energy use for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j);
- n_{lMFH} is the number of lMFHs in the considered REC (equal to 0 in the previous example);
- E_{lMFH} is the lMFH energy use for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j).
- n_{OFF} is the number of offices in the considered REC (equal to 0 in the previous example);
- E_{OFF} is the office energy use for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j).
- n_{SCHOOL} is the number of schools in the considered REC (equal to 0 in the previous example);
- E_{SCHOOL} is the school energy use for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j).
- $n_{SUPERMARKET}$ is the number of supermarket in the considered REC (equal to 0 in the previous example);
- $E_{SUPERMARKET}$ is the supermarket energy use for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j).

However, generally, different residential buildings of the same building type do not present exactly the same energy use patterns due to the different habits of the occupants, and, consequently, different usage of the various buildings. This, as said, is valid for residential buildings, while non-residential buildings belonging to the same building type are instead generally used basically in the same way. For this reason, the previous method that does not consider any difference between energy use of different residential buildings of the same type (e.g., different energy use patterns for

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the 7 SFHs in the previous example) would result in an oversimplified calculation of the energy use pattern at REC level.

To overcome this issue, a second method has been defined. In this second method, for each residential building type, multiple thermal and electrical energy consumption time series have been obtained from TRNSYS simulations. These time series are always representative of realistic energy consumption time series of the building type considered, but with small differences that are representative of the differences in occupants' habits and usage of the building. For the sake of clarity, Figure 6 shows the main inputs to the building model considered, grouping them in three categories:

- Fixed inputs related to weather conditions (e.g., external ambient temperature and Global Horizontal Radiation, GHI)
- Fixed inputs for the HVAC system (e.g., SH set point temperature). Although the SH and SC set point temperature can be considered in principle a variable input defined by the users, in this context they are considered fixed inputs to obtain a series of building energy use time series in which the comfort conditions to be respected are always the same.
- Variable inputs dependent on occupants' behaviours (occupant presence inside the building, use of electrical appliances and lights, users' DHW demand).

Moreover, the same figure shows also the TRNSYS model outputs used in this work. These are the building thermal and electrical energy uses.

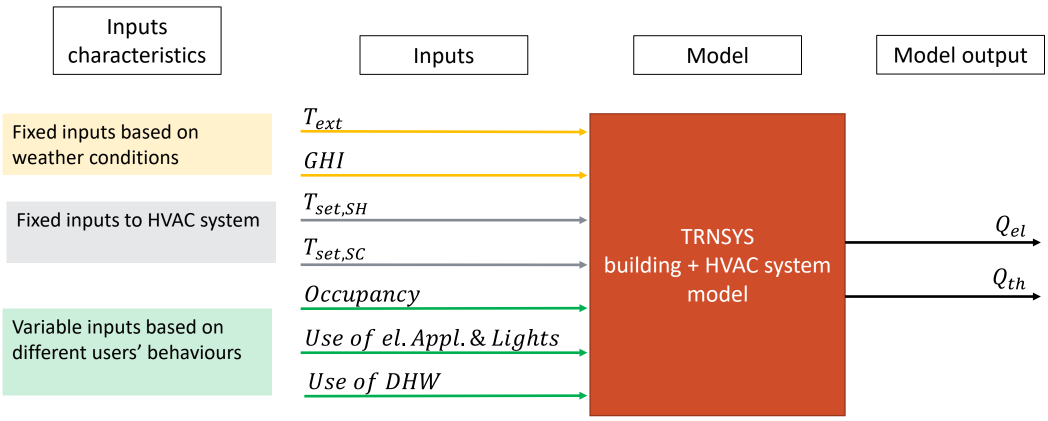

Figure 6 Building model inputs, inputs characteristics and outputs

To obtain a number of building energy use time series, slightly different, but always representative for the considered building type, the variable inputs have been changed from one simulation to another. To be more precise, different occupancy profiles, electrical appliances and lights use profiles, users' DHW demand profiles have been prepared and used as input in the different simulations. 10 different occupancy, appliances and lights profiles have been obtained as representative of occupants' usage of 10 different SFHs. Those profiles are taken from the work done in FP7 iNSPiRe project and reported in (Dipasquale C.). The same procedure has been followed to obtain 20 different occupancy, appliances and lights profiles at dwelling level that are

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used in the sMFH and lMFH TRNSYS simulations. Again, these profiles have been taken from the work done in FP7 iNSPiRe project and reported in (Dipasquale C.). Regarding DHW user demand profiles, a specific software (DHWCalc) (U. Jordan, 2005) has been used. DHWCalc distributes DHW user demand according to a probability function allowing to set the higher/lower probability of having DHW user demand around specific hours of the day and in specific days of the week. In this way it is possible to obtain different DHW user demand profiles representative of a specific building type but with slight differences due to the application of the probability function.

In this work 10 different occupancy, appliances, lights and DHW user demand profiles have been prepared for the simulation of up to 10 different SFHs. Moreover, 20 different occupancy, appliances, lights and DHW user demand profiles at dwelling level have been prepared and then randomly combined to simulate different sMFHs and lMFHs.

As an example, Figure 7, Figure 8 and Figure 9 show respectively the occupancy, appliances and DHW demand profiles for the 7 SFHs considered part of the REC used as example previously for one day as example.

As can be noted in Figure 7, people are present in their SFHs during night, while during the day they are generally not at home. The presence of occupants is especially variable between 8 a.m. and 8 p.m. to consider the different possible occupants' habits and presence in their SFH. Considering the total living area of the SFH (100 m^2) and the occupancy index defined in (UNI 10339:1995) (0.04 m^2/pers), 4 occupants are considered in the SFH.

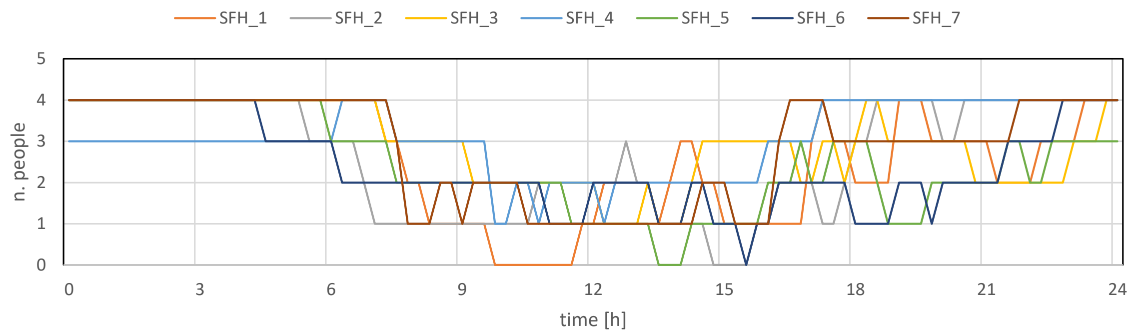

Figure 7: Occupancy profile for 7 SFHs in a typical day (Jan 1st)

Regarding the electrical consumption due to appliances and lights in different SFHs, as Figure 8 shows, there is a quite uniform electrical consumption during nights, while the electrical consumption from 6 a.m. to 8 p.m. is generally more variable. The uniform consumption during night is associated to the devices generally present in a SFH that continues to run also during night (e.g., fridge) and to the stand-by consumption of the electric devices. From 6 a.m. to 8 p.m., instead, the variability in the electrical energy consumption is higher due to the different usage of the electric devices based on occupants' presence and behaviours.

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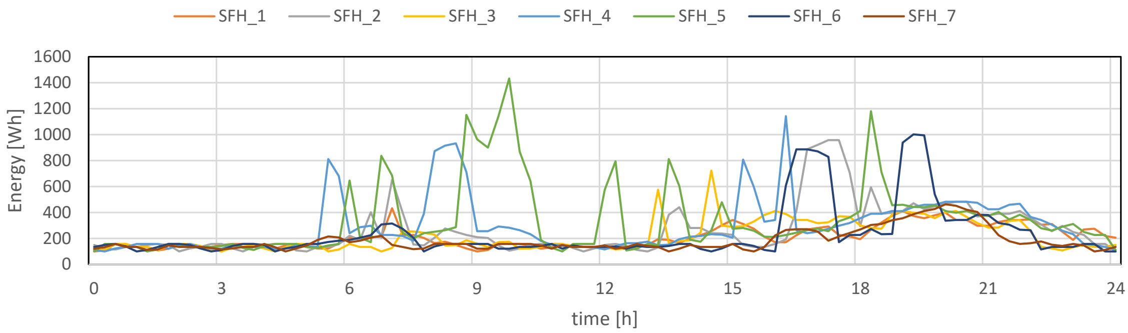

Figure 8: Electrical appliances and light consumption profile for 7 SFHs in a typical day (Jan 1st)

Figure 9 shows instead the users' DHW draw-off profile for different SFHs obtained from DHWCalc (U. Jordan, 2005). As can be noted, DHW usage is generally concentrated first in the morning, especially from 6 a.m. to 9 a.m., with some draw-offs also around noon and, second, in the evening, between 6 p.m. and 9 p.m.

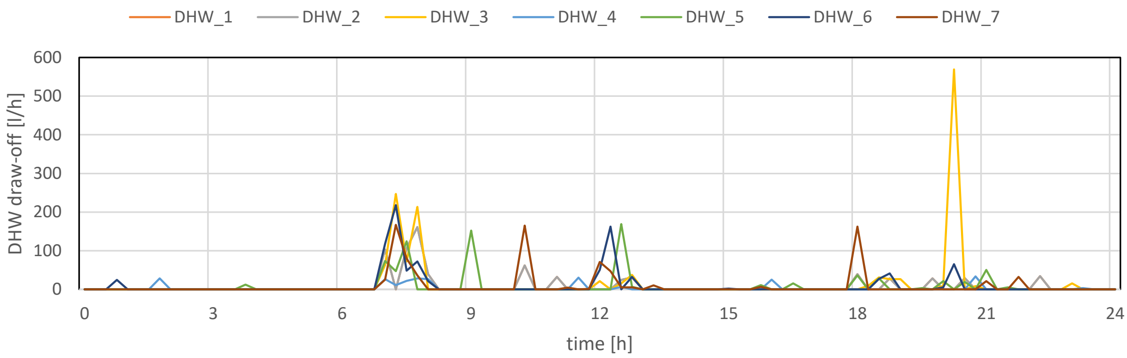

Figure 9: Users' DHW draw-off profile for 7 SFHs in a typical day (Jan 1st)

Based on the previous analysis over Figure 7, Figure 8 and Figure 9 it can be stated that this second method allows considering the differences in terms of building energy use time series between residential buildings of the same type, that are associated to the differences in the occupant's behaviours and usage of the buildings.

This also allows obtaining a more meaningful and realistic energy use time series at REC level through the aggregation of energy consumption time series of slightly different residential buildings.

The following formula summarizes how the energy use at REC level, for each hour of the year and for each energy vector is calculated according to this second method. As can be noted, the differences regard the assessment of residential building energy consumption at REC level to consider the differences associated to the different usage of the residential buildings by the occupants. On the other hand, considering that the usage of non-residential buildings is basically the same within the considered non-residential building type, the contribution to energy use at REC level from non-residential buildings is calculated in the same way reported in the first method.

$$E\ REC_{i,j,method\ 2} = (\sum_{k=1}^{l} E_{SFH,k} + \sum_{m=1}^{n} E_{sMFH,m} + \sum_{o=1}^{p} E_{lMFH,o} + n_{OFF} \cdot E_{OFF} + n_{SCHOOL} \cdot E_{SCHOOL} + n_{SUPERMARKET} \cdot E_{SUPERMARKET})\Big|_{i,j}$$

Where:

- $E\ REC_{i,j,method\ 2}$ is the energy use at REC level for the considered hour of the year (i) and the considered energy vector (e.g., electricity) (j) obtained with the second method;
- E_{SFH} is the SFH energy use for the considered SFH (k), in the considered hour of the year (i) and for the considered energy vector (e.g., electricity) (j);
- k is the index that identifies the specific SFH considered;
- l is the number of SFH in the considered REC (equal to 7 in the previous example);
- E_{sMFH} is the sMFH energy use for the considered sMFH (m), in the considered hour of the year (i) and for the considered energy vector (e.g., electricity) (j).
- m is the index that identifies the specific sMFH considered;
- n is the number of sMFH in the considered REC (equal to 3 in the previous example);
- E_{lMFH} is the lMFH energy use for the considered lMFH (o), in the considered hour of the year (i) and for the considered energy vector (e.g., electricity) (j).
- o is the index that identifies the specific lMFH considered;
- p is the number of lMFH in the considered REC.

The number of buildings and the building types belonging to a REC are variable parameters depending on the specific REC. Although each REC could be quite peculiar in terms of number and type of buildings included, in this work a series of rules have been defined to allow modelling a REC characterized by different construction density. This allows considering as REC, group of buildings built in zone characterized by different construction density. To have a sufficient general representation of various construction densities, three different levels of construction density have been defined:

- Low construction density: 70% of the buildings are SFH, 30% of buildings are sMFH;
- Medium construction density: 15% are SFH, 70% are sMFH, 15% are lMFH;
- High construction density: 30% of the buildings are sMFH, 70% of the buildings are lMFH.

Table 22 summarizes the three construction density levels considered.

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Table 22: Density of different building types for the various construction density levels considered

Building type	Construction density		
	Low	Medium	High
SFH	70 %	15 %	0 %
sMFH	30 %	70 %	30 %
lMFH	0 %	15 %	70 %

In addition, considering that the building status is generally related to envelope and system thermal performances, and this has an important influence on energy uses in buildings, three building stocks, with different building status densities have been defined:

- Old building stock: all buildings are old (built before 1970-1980);
- Renovated building stock: building stock composed by 15% of old buildings, 70% of renovated buildings and 15% of new buildings;
- New building stock: all buildings are new or deep renovated.

Table 23 summarizes the three buildings stocks considered.

Table 23: Density of the different building status considered for the various building stocks

Building status	Building stock		
	Old	Renovated	New
Old	100 %	15 %	0 %
Renovated	0 %	70 %	0 %
New	0 %	15 %	100 %

The combination of the three construction density levels and three building stocks allow having nine possible combinations that ensure a sufficient representation of a series of generic REC in terms of construction density level and building types included. These considerations include only residential buildings as they represent the wide majority of the buildings part of a REC in small context like those considered in LocalRES project. If non-residential buildings are included in the considered REC they are assessed separately and on top of this analysis.

Knowing the exact number and type of the building included in a specific REC would results in a more detailed simulation of the REC. However, if no information about construction density and building types belonging to the REC are available, the most similar condition in Table 22 and Table 23 can be used as starting point.

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3/ Results

This section reports in the first part the results in terms of thermal and electrical energy use time series at single building level obtained from TRNSYS simulations, while, in the second part, a REC is defined as example to assess the results in terms of thermal and electrical energy use time series. The thermal and electrical energy use time series at REC level are obtained aggregating single buildings energy use time series according to the second method reported in section 2.5.

All the analyses reported below focus first on limited periods to assess thermal and electrical energy uses at single building and REC level. For this purpose, the analyses have been performed over two weeks considered representative of the winter and summer period system operation respectively. Subsequently, thermal and electrical energy uses at single building and REC level are analysed also over the entire year.

3.1. Identification of thermal energy use for DHW, SH, SC at building level

This section reports the results in terms of thermal energy use for DHW, SH and SC at building level.

The following sections 3.1.1 and 3.1.2 report an analysis over one week (1-7 Jan) of the winter period and one week (25 Jun – 1 Jul) of the summer period respectively. In this context, these weeks are used as representative of typical behaviours during the winter and summer season respectively. In these sections results are presented considering first a HP as generation unit in the HVAC system and second a cogenerator.

Section 3.1.3 reports instead an analysis of building thermal energy use for DHW, SH and SC over the entire year. In this section, the results presented consider solely a HP as generation unit in the HVAC system.

For the sake of simplicity, all the results reported in the following parts refer to one of the 27 residential cases identified and reported in Table 1, i.e. the old sMFH in the Continental climate.

The main results in terms of building thermal energy use for all the cases analysed are instead reported in section 7/.

3.1.1. Identification of thermal energy use for DHW and SH in winter period (1 – 7 Jan)

As already mentioned in section 2.1 the simulations performed in TRNSYS allow obtaining realistic thermal energy use time series that considers the effects associated to the presence of thermal storages and to the control of the system. Figure 10 shows in yellow line the SH thermal energy delivered by the HVAC system to the building in one week of the winter period taken as example of the cold season (period 1-7 Jan). The yellow line takes into account the boundary conditions assumed representative of the operation of a realistic HVAC system in the considered building. The same Figure 10 shows also in green line the amount of thermal energy needed to always ensure the comfort temperature (considered in this context equal to 20 °C) in the building, hence, without considering constraints associated to the realistic operation of the HVAC system as, for example the limitations in terms of periods along the day in which SH can be delivered to the building. As can be noted in Figure 10, thermal energy needed to maintain the winter set point temperature and thermal energy effectively delivered to the building from a realistic HVAC system show important differences associated, in the case of old buildings, mainly to HVAC system control. In fact, to be aligned to typical operation of centralized HVAC systems in old buildings, the SH system is considered operative only in limited periods along the day. In this case these periods are between 6 a.m. and 12 p.m. and from 2 p.m. to 10 p.m. Finally, the black dashed line in Figure 10 shows the external temperature trend highlighting its correlation with thermal energy delivered from a realistic HP system.

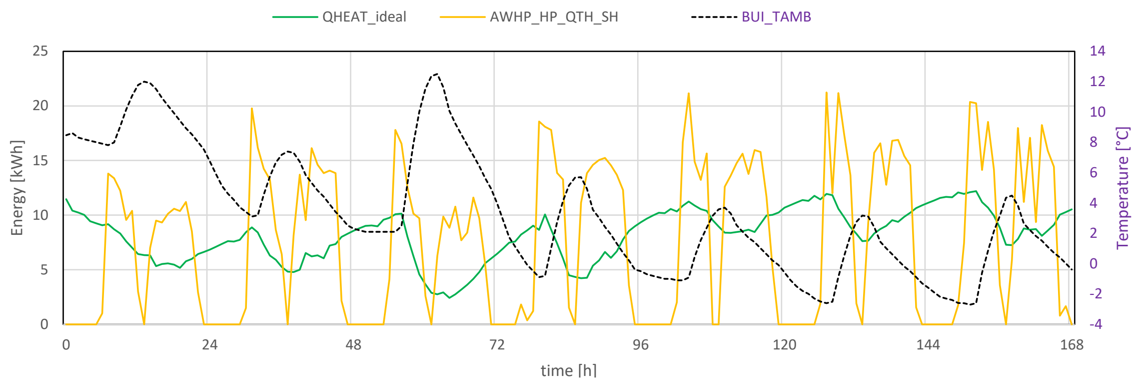

Figure 10: SH thermal energy demand (green), thermal energy delivered for SH by the HP (yellow) and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

Figure 11 shows instead, for the same week considered previously (period 1-7 Jan), the thermal energy delivered from the HP to charge the DHW tank. The shape of the profile, representing from 3 to 6 charging events per day is typical of the kind of system considered, in which a DHW tank is present to allow a partial decoupling of DHW demand and production sides with the advantages already described in section 2.4. Regarding the DHW user demand time series accounted for, these are obtained, also in this case, from DHWCalc (U. Jordan, 2005). More specifically, different DHW user demand time series at dwelling level are used for the different dwellings belonging to the considered building.

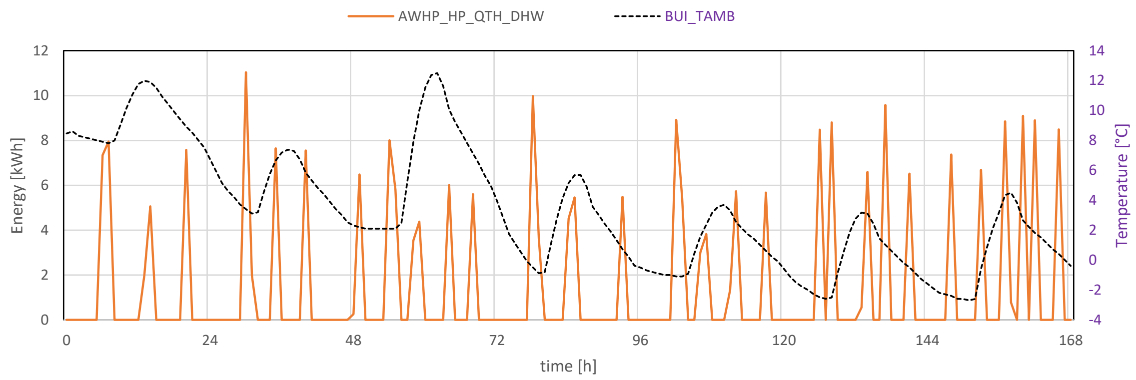

Figure 11: Thermal energy delivered from the HP to charge DHW tank (orange) and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

The thermal energy delivered by the HP for SH and DHW and presented in previous Figure 10 and Figure 11 are summed together in Figure 12 for the same period (1-7 Jan) showing the overall thermal energy delivered to the building (red line) in the considered week of the winter season. Figure 12 highlights that, as expected, SH constitutes the main building thermal need in an old building in which the thermal envelope is generally characterized by low performances and high U values as reported in section 2.2.2.

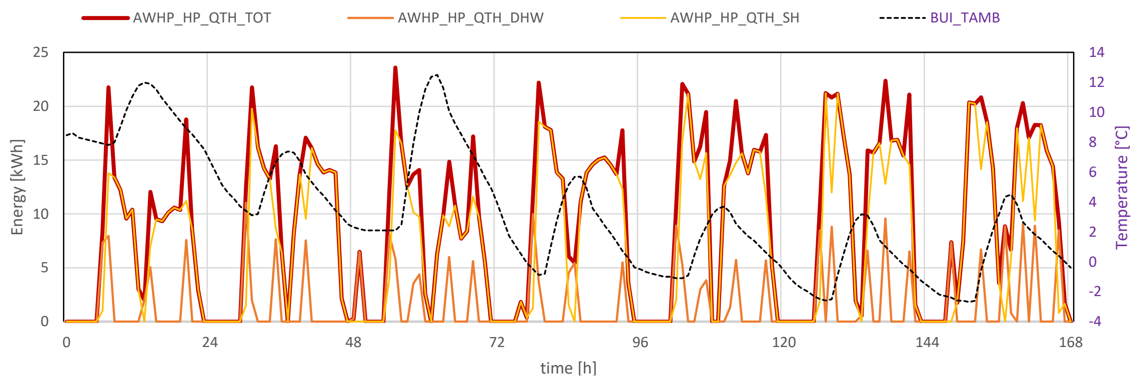

Figure 12: Thermal energy delivered for DHW (orange) and SH (yellow) by the HP, their sum (red) and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

It is important to highlight that, in systems where the generation unit is constituted by a HP like the one considered here, the thermal energy delivered from the HP is responsible of an electric consumption of the HP itself. Figure 13 presents the total thermal energy delivered by the HP (red line) and the associated HP electric consumption (blue line). As can be noted looking at the trends of thermal energy delivered by the HP and HP electric consumption in Figure 13, the two trends are not directly proportional. To highlight this aspect the HP COP (calculated as the ratio between overall thermal energy delivered by the HP and the HP electric consumption) is reported in Figure 14 for the winter week considered (period 1-7 Jan). As can be noted in Figure 14, the HP COP presents, in the analysed period, values in the range 1.5 – 4, with, as expected, a strong relation to

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external temperature that in the considered HP (air-to-water HP) constitute the source temperature.

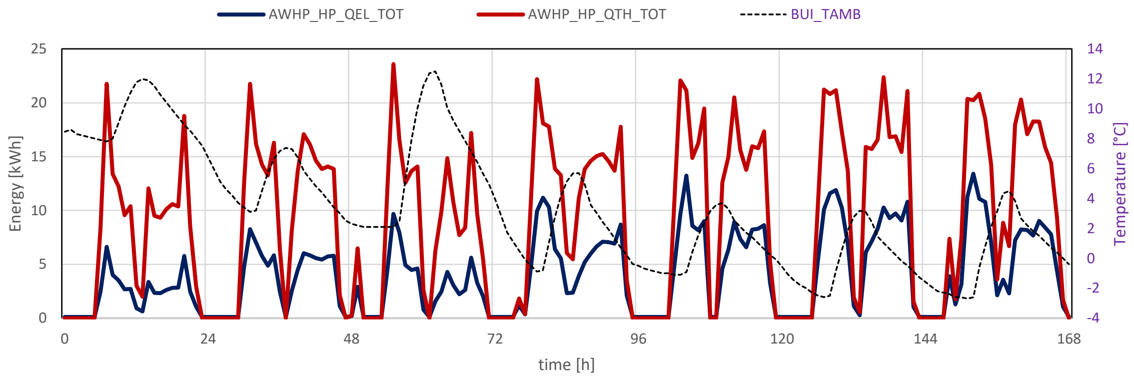

Figure 13: Overall thermal energy delivered by the HP (red), HP overall electric consumption (blue) and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

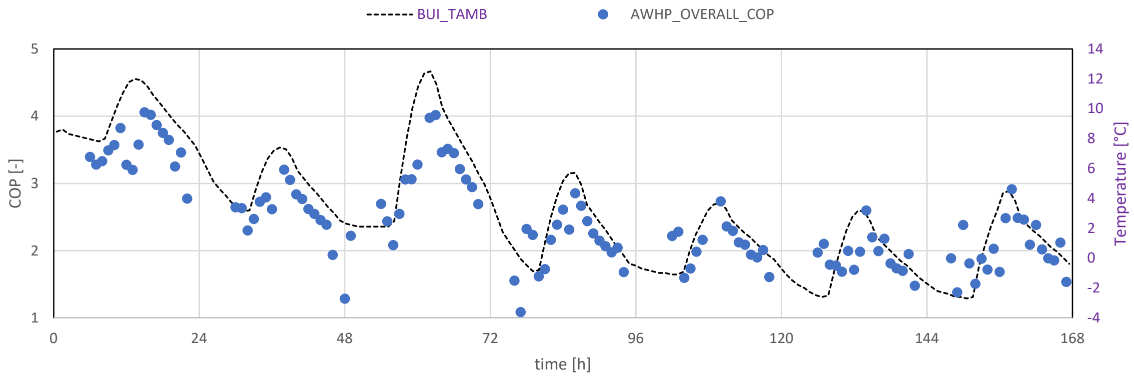

Figure 14: HP COP (blue) and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

The analysis reported in this section, in particular regarding the differences between thermal demand for SH and thermal energy delivered for SH by a realistic HVAC system, and the variability of HP COP based on operative conditions, confirms that it is essential, to obtain realistic hourly energy consumption time series at building level, to simulate with the due level of detail system operations. A method that considers thermal demand for SH and a fixed HP COP for the system would results in oversimplified and not realistic hourly energy uses trends at building level.

Finally, if a cogenerator is considered as generation unit, the delivering of the same thermal energy needed to cover building thermal needs results in a thermal energy consumption dependent on the cogenerator thermal efficiency. Figure 15 shows the thermal energy delivered to the building (the same reported in Figure 13) and the cogenerator thermal energy consumption in the considered week representative of the winter period. As already stated, in this work the cogenerator has been managed to cover building thermal energy demand for SH and DHW.

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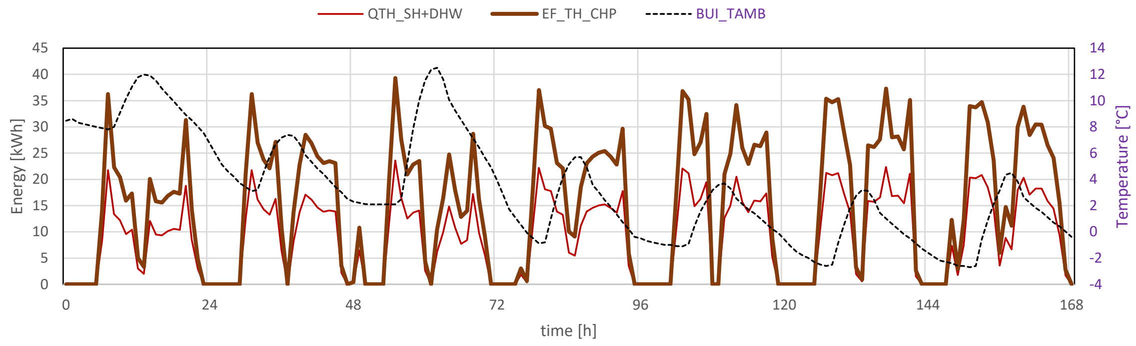

Figure 15: Overall thermal energy delivered by the cogenerator (red), cogenerator thermal energy use (brown) and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

3.1.2. Identification of thermal energy use for DHW and SC in summer period (25 Jun – 1 Jul)

An analysis similar to what explained before has been performed for one week of the summer season (period 25 Jun – 1 Jul) taken as example of the summer conditions. In the analysed case (an old sMFH in the Continental climate) as reported in section 2.4.1, split units are used to cover SC demand. Figure 16 shows, for the considered period, the energy delivered to the building by split-units. As can be noted in Figure 16, the SC thermal energy delivered to the building is very limited. This is in accordance with expectations considering that we are analysing a building in the Continental climate.

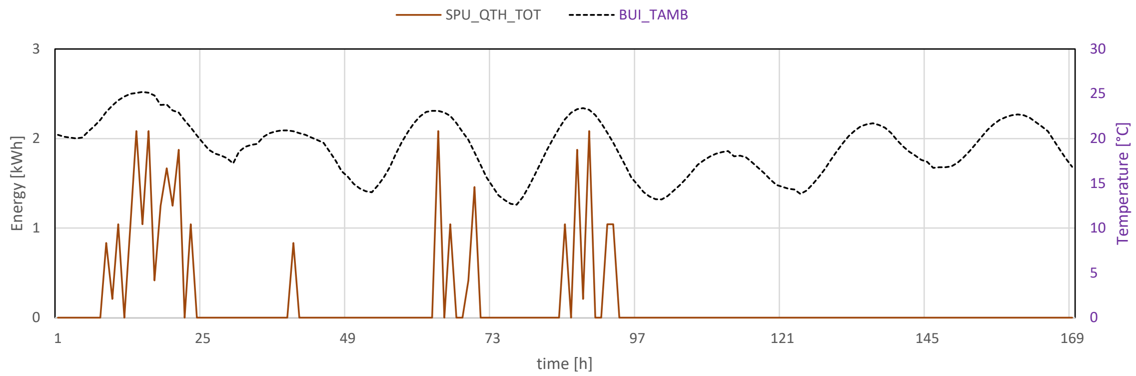

Figure 16: SC thermal energy delivered by the split unit (brown) and external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun – 1 Jul

Figure 17 represents, instead, the thermal energy delivered by the HP to charge the DHW tank in the analysed summer week. As can be noted comparing Figure 11 and Figure 17, the patterns are similar, confirming that, the DHW thermal demand from the users, and hence the DHW thermal energy delivered by the HP to charge the DHW tank is basically independent from the season considered.

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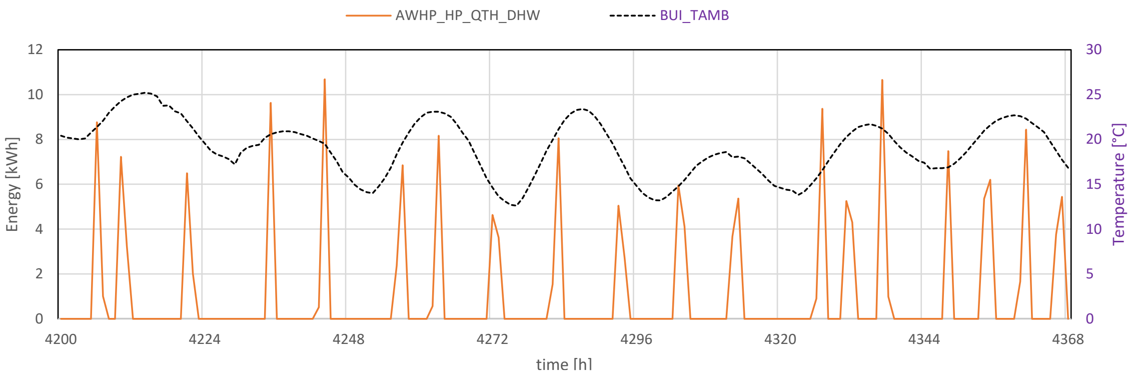

Figure 17: Thermal energy delivered from the HP to charge DHW tank (orange) and external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun – 1 Jul

As reported previously, in a HP system electrical energy is used to deliver thermal energy to the building. This is valid for HP but also for split-units. Figure 18 shows overall thermal energy delivered by the HP that, in this case and in summer season, is only associated to the thermal energy for DHW tank charging, and the related HP electric consumption. Figure 19 presents instead the HP COP in the same period. The HP COP values are generally in the range 3- 4.5 with occasionally values around 2 – 3 that can be associated to the start-up phase of the HP. These lower values associated to the start-up phase of the HP are visible although the time resolution of the data visible in Figure 19 is 1 hour as these are obtained resampling data from TRNSYS simulations that, as stated in section 2.1, are obtained using a simulation timestep of 5 minutes.

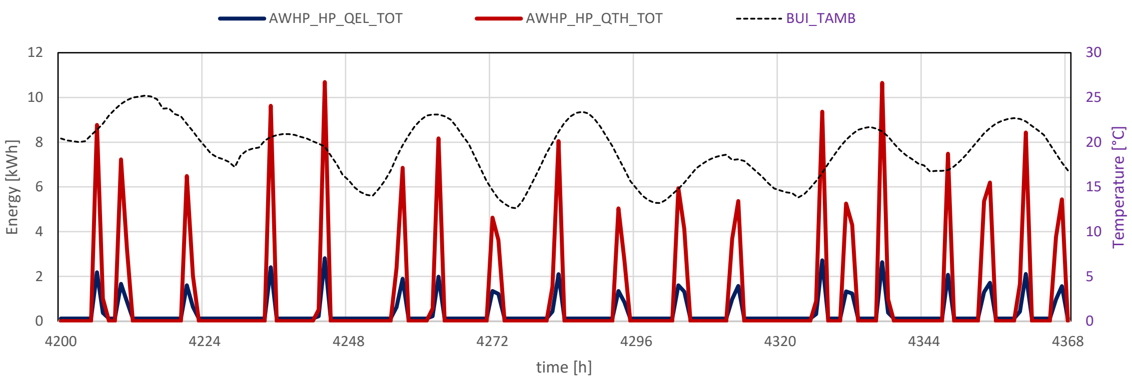

Figure 18: Overall thermal energy delivered by the HP (red), HP overall electric consumption (blue) and external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun – 1 Jul

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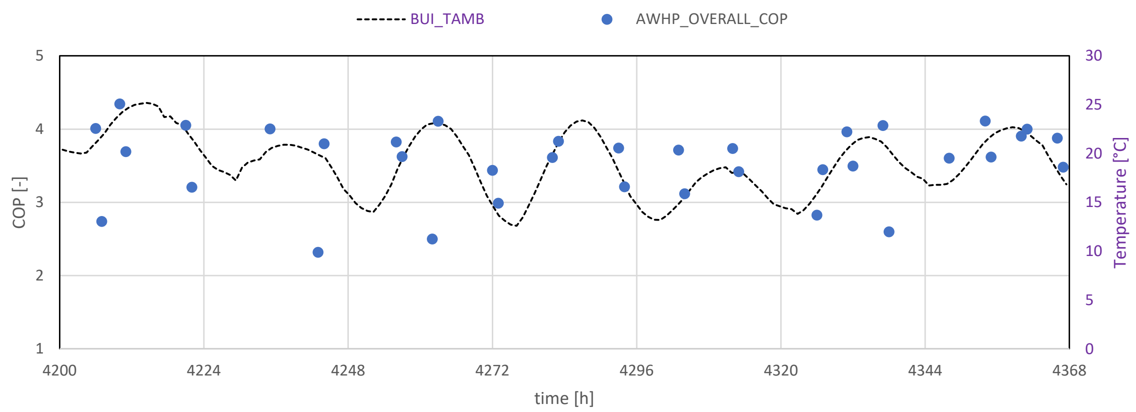

Figure 19: HP COP (blue) and external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun – 1 Jul

Finally, also in the system that consider a cogenerator the SC building demand is covered by split units and the cogenerator is only used for the charging of the DHW tank. The thermal energy needed for DHW tank charging, in this case, results in a thermal energy consumption of the cogenerator dependent on the cogenerator thermal efficiency. Figure 20 presents the thermal energy delivered for DHW tank charging (the same shown in Figure 17) and the cogenerator thermal energy consumption in the week considered representative of the summer period.

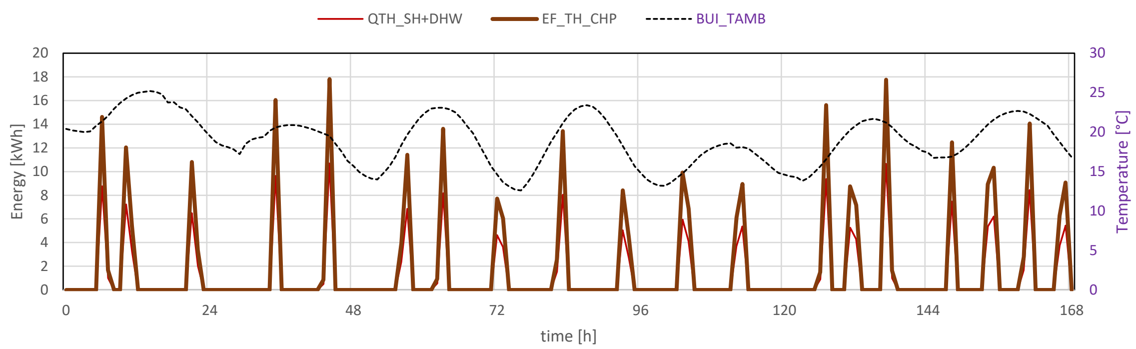

Figure 20: Overall thermal energy delivered by the cogenerator (red), cogenerator thermal energy consumption (brown) and external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun – 1 Jul

3.1.3. Identification of thermal energy use for DHW, SH, SC over the entire year

In addition to the evaluations over two weeks of the year considered as representative of respectively winter and summer period, the following Figure 21, Figure 22 and Figure 23 show the thermal energy delivered by the HP for respectively DHW, SH and SC for the various hours of the day (y axis) and along the days of the year (x axis). With this kind of plot, it is possible to have a visual impression of specific period of the year, or hours of the day, characterized by particularly high or low values of the analysed variable.

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As can be seen in Figure 21, the thermal energy delivered by the HP for DHW tank charging presents a peak in the early morning (generally between 6 a.m. and 9 a.m.). The high values in this period of the day are basically replicated over the entire year. This behaviour is due to the high DHW users' demand in this period as reported in Figure 9 that cause the discharge of the DHW tank and, consequently, the need of HP operation to charge the DHW tank again. On the contrary, after 9 a.m. the thermal energy delivered by the HP to charge the DHW tank does not presents peaks over other specific hours of the day or days of the year. The lowest values of thermal energy delivered by the HP for DHW tank charging are generally associated to the night period (from 10 p.m. to 6 a.m.). In this period the users' DHW demand is generally very limited.

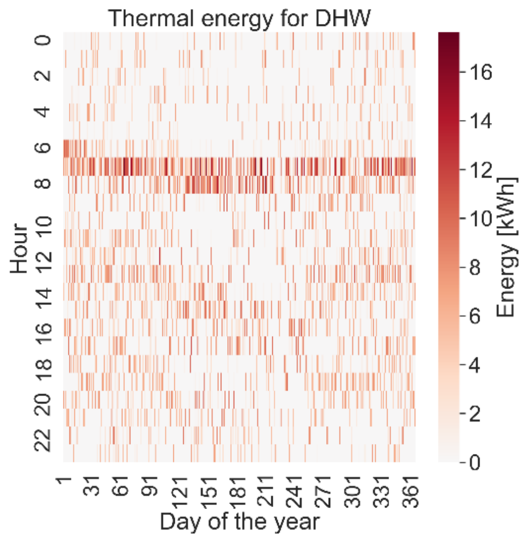

Figure 21: Heat map reporting hourly thermal energy for DHW

The thermal energy delivered by the HP for SH is reported for the various hours of the year in the following Figure 22. As can be noted in this figure, the variability of thermal energy delivered for SH is limited between hours of the same day when the system is operating, while a general decreasing trend can be seen moving from periods characterized by colder weather conditions (January, December, at the left and right extremes of the figure), characterized by dark red colour in Figure 22, to milder ones (March, October, more at the centre of the figure), characterized by lighter red colour in Figure 22.

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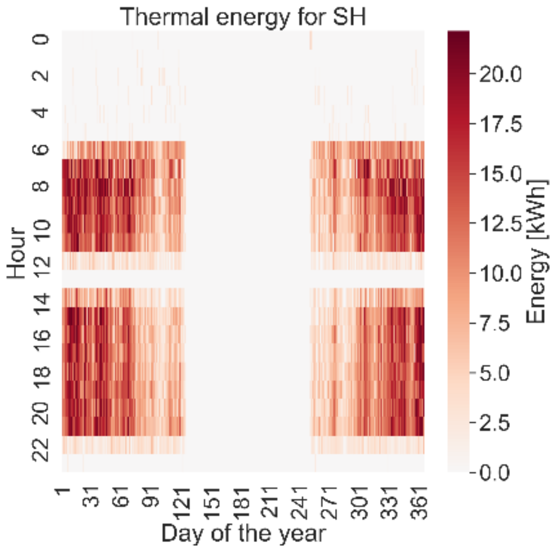

Figure 22: Heat map reporting hourly thermal energy for SH

Figure 23 shows instead the thermal energy delivered by the split unit to the building to cover building SC thermal demand. As can be noted in Figure 23, SC thermal energy delivered in the considered case is very limited and, when present, concentrated mostly in the period from 12 p.m. to 8 p.m.

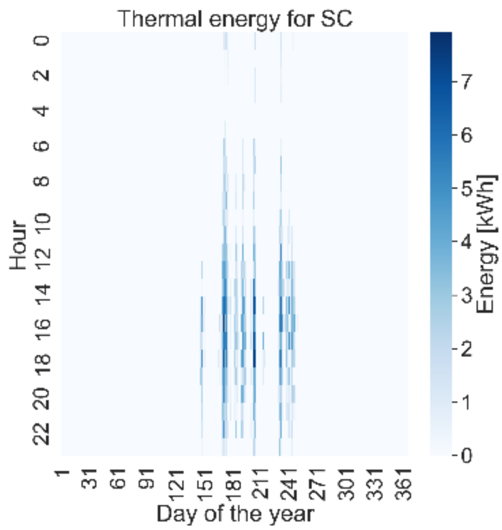

Figure 23: Heat map reporting hourly thermal energy for SC

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3.2. Identification of electrical energy use at building level

Complementary to section 3.1, this section reports the analyses and results regarding electrical energy use at building level.

In this analysis, first, the overall building electrical energy consumption has been evaluated summing up the various electrical energy consumption contributions in the building.

Secondly, in the case that considers a HP system for the covering of building thermal needs, it has been considered the possibility to cover this electrical energy use, at least partially, with a PV system + BESS, evaluating how these systems modify the way in which building electrical energy consumption is covered.

The following, sections 3.2.1 and 3.2.2 reports an analysis over one week (1-7 Jan) of the winter period and one week (25 Jun – 1 Jul) of the summer period respectively. In this context, these weeks are used as representative of typical behaviours during the winter and summer season respectively. In these sections results are presented considering first a HP as generation unit in the HVAC system and second a cogenerator.

Section 3.2.3 reports instead an analysis of PV production and electrical energy self-consumed within the building over the entire year. In this section, the results presented consider solely a HP as generation unit in the HVAC system.

As done in section 3.1, for the sake of simplicity, also here the results are presented for one of the 27 residential cases identifies and reported in Table 1, i.e. the old sMFH in the Continental climate, while the main results in terms of building electrical energy use for all the cases analysed are reported in section 7/.

3.2.1. Identification of electrical energy use, winter period (1 - 7 Jan)

As already described in section 2.1, from TRNSYS simulations the electrical energy use at building level has been elaborated. This electrical energy use accounts for different contributions. The mains, in the winter period, are the HP electric consumption to cover building SH and DHW demand, the electrical consumption due to appliances and the one associated to lighting system.

Figure 24 shows, for the period 1-7 Jan, the building overall electric consumption (red line) and the various electrical consumption contributions associated to HP (dark blue), electrical appliances (light blue) and lights (green. As highlighted in Figure 24, in the considered winter period, the main contribution to overall building electrical energy use is associated to the HP to deliver thermal energy to cover building DHW and SH thermal demand. This is mainly due to the fact that the considered building (old sMFH in the Continental climate) presents a high building thermal SH demand, associated to the low performances of the thermal envelope.

Moreover, the HP electric consumption, and therefore the overall building electrical consumption, presents important variability along the various hours. This is mainly due to the considered HVAC

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system control that, to be aligned to a realistic case in an old building, considers HVAC system operation for SH only in defined periods of the day during winter season.

As can be noted in Figure 24, the electrical use due to appliances and lights is limited compared to the HP electrical consumption in the considered building and in the analysed winter week. In particular, the electrical consumption due to appliances is basically always present and is characterized by small variations during the various hours of the day, while the electrical consumption associated to the lights is mainly present, as expected, in the evening.

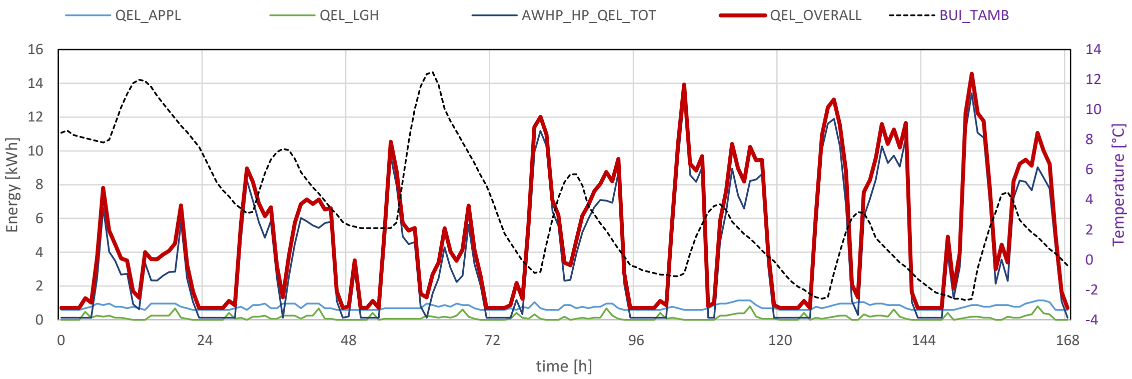

Figure 24: Overall electrical energy use (red) and main contributions due to HP (dark blue), electrical appliances (light blue), lights (green). The graph shows also external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

Figure 25 reports instead the electrical energy flows in the case in which a PV+BESS is considered. The starting point is the overall building electrical energy consumption (red line) that is the same reported in Figure 24. The PV production (yellow area) allows covering part of this electric consumption. It is important to note in Figure 25 that, also in winter, period with generally low PV production due to the low solar radiation and high electrical energy consumption due to the high consumption of the HP to cover building DHW and SH demand, there are periods in which there is PV surplus. This surplus can be stored in the BESS (dark green area) and used in a second moment when the electric consumption is higher than the PV production (light green area). Figure 25 also shows the BESS SoC (green line), highlighting the periods in which the BESS is charged or discharged. The part of electrical energy consumption that cannot be covered by PV+BESS is covered by electricity coming from the grid (red area). For the reasons associated to the low PV production and high HP consumption during the winter period, most of the electrical energy use is covered using electricity coming from the grid.

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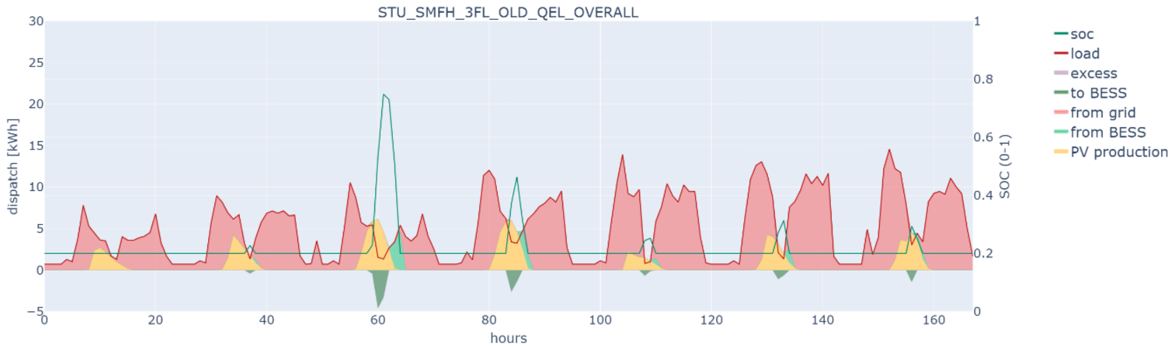

Figure 25: Electrical energy flows; Old sMFH in the Continental climate, period 1-7 Jan

Finally, if a cogenerator is considered as generation unit, the electrical energy produced is dependent on the cogenerator electrical efficiency. Moreover, being in this work the cogenerator managed to always ensure the covering of building thermal demand for SH and DHW and considering that constant cogenerator thermal and electrical efficiencies have been assumed, the electrical energy production of the cogenerator is strongly related to the building SH and DHW thermal needs. Figure 26 shows the electrical energy produced by the cogenerator (orange) and the building electrical energy consumption (yellow) in the week considered representative of the winter period. As can be noted comparing Figure 26 and Figure 24, in this case the building electrical energy consumption is much lower due to the fact that the electrical consumption associated to the HP is not present. As visible comparing the cogenerator electrical energy production and the building electrical energy use shown in Figure 26, during the considered winter week for most of the time there is a surplus of cogenerator electric production that cannot be used within the building and is therefore sent to the grid. The amount of electrical energy sent to the grid is reported in Figure 26 in green. There are, however, also periods along the day in which the cogenerator is not working and in these periods the energy is taken from the grid. The energy taken from the grid to cover building electrical energy needs is shown in Figure 26 in blue. The fact that the cogeneration is considered in operation only in some periods of the day is associated to the limited periods in which SH is delivered to the building in the considered case.

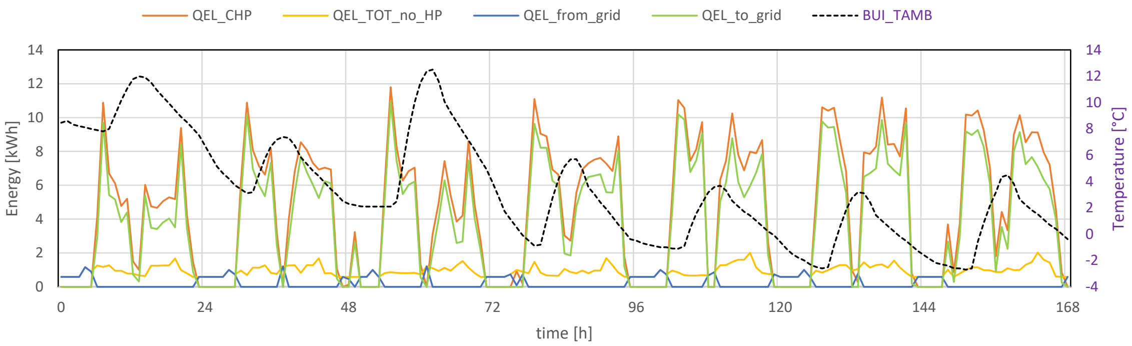

Figure 26: Cogenerator electrical energy produced (orange), overall electrical energy use (yellow), electrical energy sent (green) and taken (blue) to/from the grid and external temperature (black, dashed); Old sMFH in the Continental climate, period 1-7 Jan

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3.2.2. Identification of electrical energy use, summer period (25 Jun – 1 Jul)

In the considered building (old sMFH in the Continental climate), for the reasons reported in section 2.4.1, a split unit is considered for the covering of SC building thermal energy demand. As for HP systems, also split units consume electricity to deliver thermal energy (in this case thermal energy for SC).

Figure 27 shows the overall building electrical energy use in the analysed week representative of the summer period, also highlighting the various contributions. In general, as can be seen comparing Figure 27 and Figure 24, during summer the overall building electrical energy use is smaller in comparison to the winter period. In the analysed summer week, the main contributions to overall building electric energy use are associated to HP operation to charge the DHW tank (dark blue) and to electrical appliances (blue). Smaller electrical energy consumption contributions are instead associated to lights (green) and split unit (orange). As can be noted in Figure 27, there is a minimum electrical consumption associated to the HP (around 120 W) that represents the stand-by consumption of the device.

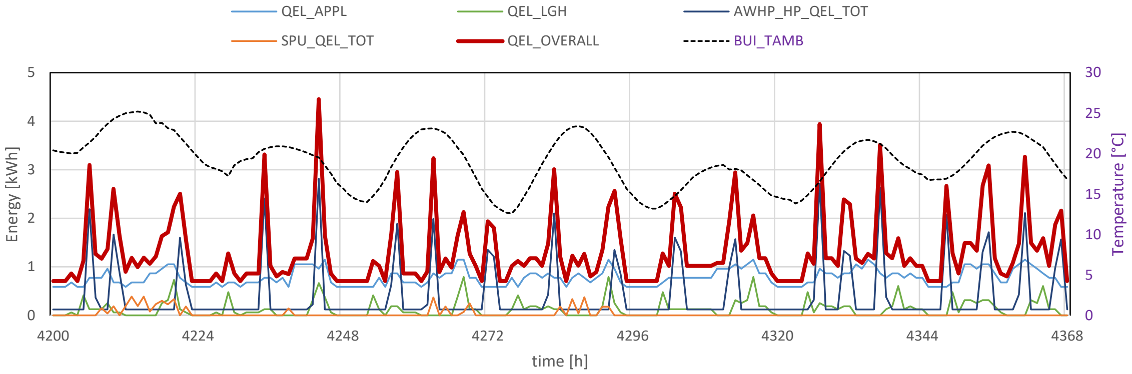

Figure 27: Overall electrical energy use (red) and main contributions due to HP (dark blue), electrical appliances (light blue), lights (green) and split unit (orange). The graph shows also external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun-1 Jul

Figure 28 shows instead the electrical energy flows in the analysed summer week considering also a PV+BESS. As for the winter period analysed in section 3.2.1, the starting point is the overall building electrical energy consumption (red line) that is the same reported in Figure 27. In the analysed summer period, the overall electrical energy consumption is limited due to the low building thermal demand associated to the covering of DHW and SC thermal needs. On the other hand, if compared to the winter period, the PV production is higher in summer period, due to the high availability of solar source in summer season in the considered climate. These two opposite effects result in a higher fraction of the overall building electrical energy consumption covered directly by PV and in a higher PV surplus that can be used to charge the BESS (dark green area). With more PV surplus available for BESS charging, consequently, also the contribution of BESS in covering part of the electrical consumption is higher (light green area). Figure 28 also shows the BESS SoC (green line), highlighting periods in which BESS is charged or discharged. As can be noted in Figure 28, in summer sunny days, generally, one complete charging/discharging cycle occurs per

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day. Although a PV+BESS is considered, also in the analysed summer week there are periods basically in all days in which the PV+BESS cannot cover the building electrical energy consumption (red area). These periods are generally associated to the nights, where the PV is not producing anymore and the BESS has already been fully discharged. In these periods the electrical energy needed is taken from the electrical grid. On the other hand, in summer sunny days, as can be seen in Figure 28, there is a part of the PV surplus that cannot be instantaneously self-consumed or stored in the BESS as the BESS is already fully charged. This PV surplus (purple area in Figure 28) is sent to the grid. This condition generally occurs in the first hours of the afternoon, after the complete charging of the BESS.

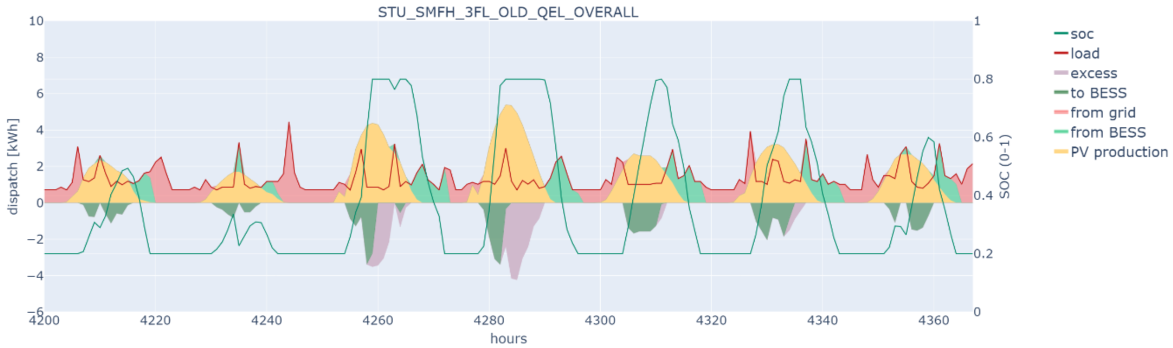

Figure 28: Electrical energy flows; Old sMFH in the Continental climate, period 25 Jun-1 Jul

Finally, Figure 29 presents the electrical energy production if a cogenerator is considering and how this relates with the building electrical energy consumption during the week considered representative of the summer period. As can be noted in Figure 29 and as already mentioned, the considered cogeneration is managed to ensure the covering of the building thermal energy demand for DHW and SH. During summer season, the only building thermal need covered by the cogenerator is represented by the DHW and this results in discontinuous cogenerator operation for the DHW tank charging. The electrical energy produced by the cogenerator is shown in Figure 29 in orange. The building electrical consumption, in the considered period, accounts for the electrical consumption of appliances, lights and split units and is shown in yellow in Figure 29. As can be noted in Figure 29, due to the discontinuous operations of the cogenerator during the considered summer representative week, the building electrical energy consumption is covered for most of the time using electrical energy from the grid (blue), while there is a surplus of electrical energy produced by the cogenerator when it works to charge the DHW tank and this surplus is sent to the grid (green).

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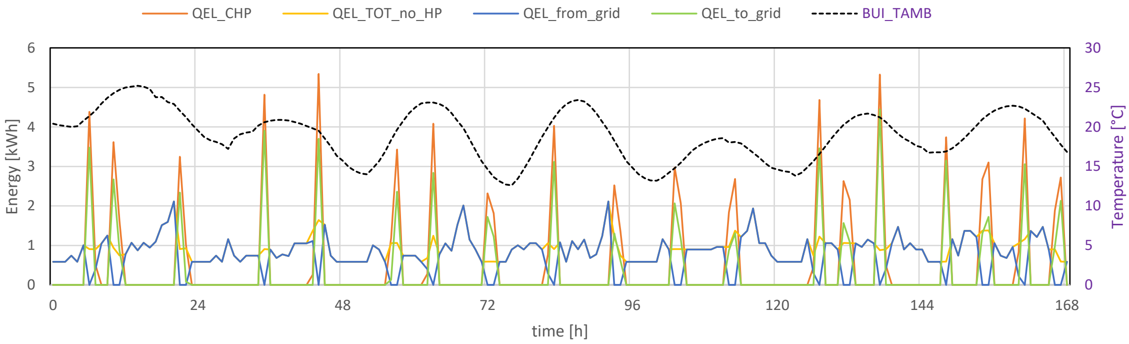

Figure 29: Cogenerator electrical energy produced (orange), overall electrical energy use (yellow), electrical energy sent (green) and taken (blue) to/from the grid and external temperature (black, dashed); Old sMFH in the Continental climate, period 25 Jun-1 Jul

3.2.3. Identification of building electrical energy use over the entire year

As reported in section 3.1.3 for building thermal energy use for DHW, SH and SC, also in this case an analysis over the entire year has been elaborated. The analysis shown in Figure 30, Figure 31 and Figure 32 aims to evaluate, for the various hours of the day (y axis) and along the days of the year (x axis) building electrical energy use, PV production and percentage of energy produced by PV and self-consumed[2]. This kind of plot allows highlighting specific hours along the day or specific periods along the year characterized by particularly high or low values of the analysed variable.

Figure 30 shows the overall building electrical energy use. As can be noted, the trend is similar to the one presented in Figure 22, highlighting that the main contribution to overall building electrical energy use is associated to the HP electric consumption, in particular to cover building SH demand. This motivates the highest values visible in Figure 30 during first and last days of the year, typically characterized by the coldest climatic conditions. In the summer period, instead, from Figure 30 it can be noted that the highest electrical energy consumption occurs in the period between 6 a.m. and 9 a.m. and this trend is basically repeated for all days of the summer period. This trend is associated to the HP consumption for DHW tank charging that, as already presented in Figure 27 constitutes the main electrical consumption during summer.

[2] In this context the energy self- consumed (or simply self-consumption) is calculated, for every hour of the year, as the ratio between the energy consumed that is covered by PV or BESS and the PV production

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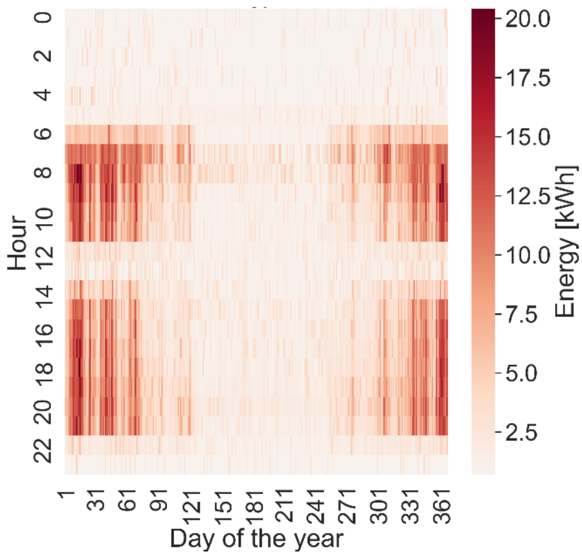

Figure 30: Heat map reporting hourly overall building electrical energy use

Figure 31 shows instead the PV production for the various hours of the year. As can be noted in Figure 31 the PV production reaches its maximum (both in terms of absolute power and number of operating hours per day) during summer for the higher availability of the solar source in the climate considered in this period. As can be noted comparing Figure 30 and Figure 31 overall building electrical energy use and PV production show, in the considered case, almost opposite trends, with winter period characterized by high electrical energy use and low PV production, while, in summer, the highest PV production is reached and, at the same time, the electrical energy use is generally low. The comparison of Figure 30 and Figure 31 motivates the importance given to energy storages in general that enable the possibility to exploit renewable energy locally produced for the covering of building energy consumptions. In this context, in addition to thermal storages already accounted for and included in the TRNSYS models developed, also BESS have been considered as already stated in section 2.1.

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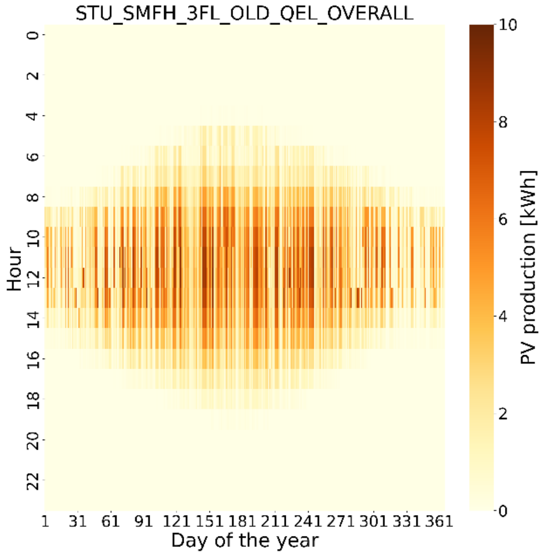

Figure 31: Heat map reporting hourly PV production

Figure 32 puts together the information reported in Figure 30 and in Figure 31 giving a visual impression of the energy self-consumed over the entire year. The figure on the left accounts for the presence of a BESS, while the figure on the right accounts for only a PV system. As can be noted in the figure on the left, the self-consumption is equal to 100 % in the first and last hours of the day in which there is PV production. This is mainly due to the fact that the PV production in these periods is limited and is basically entirely instantaneously consumed within the building. Moreover, the self-consumption hourly values are equal to 100 % in the winter period, due to the sum of multiple effects: the generally low PV production, the high overall building electrical consumption and the presence of a BESS to store the eventual limited PV surplus that can occur during short periods along the day. The self-consumption values tend do decrease in the central hours of the day during summer season as, in this period, typically, there is a high PV production, a low overall building electrical energy consumption and the BESS electric capacity is limited. In this period the PV production that cannot be instantaneously self-consumed or stored into the BESS is sent to the electrical grid decreasing the self-consumption value. The figure on the right shows instead that, if a BESS is not considered, first, there are moments also in winter days in which there is a PV surplus that is sent to the grid and, second, for a high number of hours during the summer period there is PV surplus that is injected into the electrical grid. The difference with the case that considers a BESS is more evident during morning hours of the summer period. In these periods, generally, the battery is empty as it has been fully discharged during evening or night of the previous day, hence there is electrical capacity available to store the PV surplus in the first hours of the day in which the PV production becomes greater than the building electrical energy consumption as visible also in Figure 28.

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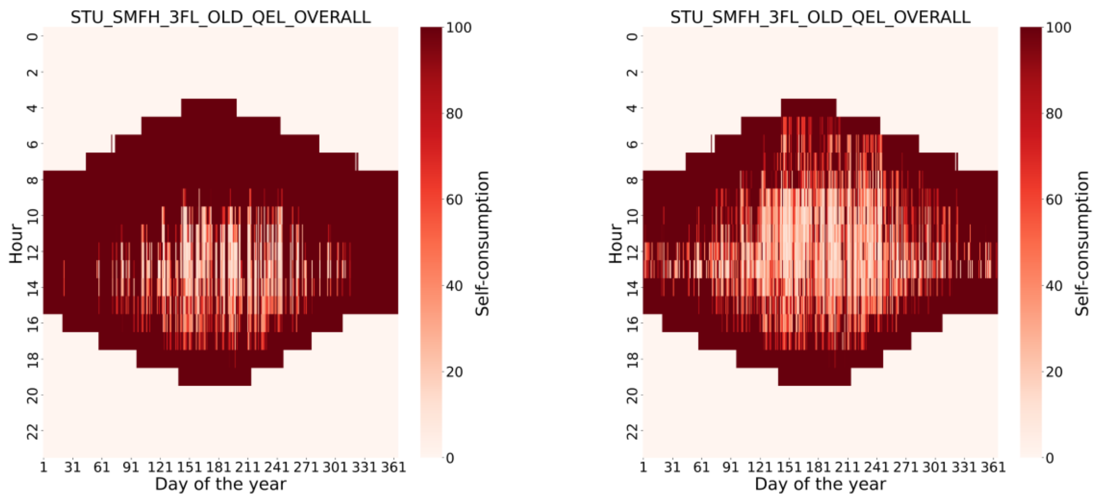

Figure 32: Heat maps reporting hourly self-consumption (in percentage) considering PV and BESS (left) and PV only (right)

3.3. Identification of thermal energy use for DHW, SH and SC at REC level

This section reports the analysis of thermal energy use for DHW, SH and SC at REC level for a REC defined as example.

The scope of this section is to assess the results in terms of thermal energy use for DHW, SH, SC elaborated aggregating the single buildings' thermal energy use time series according to the second method reported in section 2.5. This also allow assessing the effects on REC thermal energy use of different usage of residential buildings by the occupants.

Contrarily to sections 3.1, in which the thermal energy for SH and DHW are treated separately, in the following sections, for the sake of simplicity, only the aggregated thermal energy use for DHW and SH is presented.

For this evaluation, first, a series of assumptions have been made to define the considered REC. These are reported in the following.

- The considered REC is composed by 10 residential buildings
- All the considered buildings are equipped with a HP system.
- A low construction density is considered (70 % of the buildings belonging to the REC are SFHs, 30 % are sMFHs).
- An old building stock is considered (100 % old buildings).
- The Continental climate is considered.

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Based on the previous assumptions, the considered REC is composed by 7 old SFH and 3 sMFH in the Continental climate.

As done in sections 3.1.1 and 3.1.2, also the following sections 3.3.1 and 3.3.2 report an analysis over one week (1-7 Jan) of the winter period and one week (25 Jun – 1 Jul) of the summer period respectively. In this context, these weeks are used as representative of typical behaviours during the winter and summer season, respectively.

Section 3.3.3 reports instead an analysis of thermal energy use for DHW, SH and SC at REC level over the entire year.

3.3.1. Identification of thermal energy use for DHW and SH in winter period (1 – 7 Jan)

As described in section 2.5, to obtain a realistic aggregated thermal energy use at REC level it is important to consider the effects associated to the different occupants' behaviours and usage of the buildings in the considered REC. To this purpose, 7 old SFHs in the Continental climate, different in terms of occupant's behaviours as reported in section 2.5, have been modelled in TRNSYS and simulated. Figure 33 shows the thermal energy use for DHW and SH (the aggregated values) for these 7 cases over the winter week considered as representative of the winter period (1-7 Jan). As can be noted in Figure 33, the general thermal energy use for DHW and SH is similar for all the SFHs considered but with differences that represent the different occupant's behaviour and usage of the different SFHs. In particular, the differences in thermal energy use are mainly associated to the different users' DHW demand time series considered as variable input as shown in Figure 6.

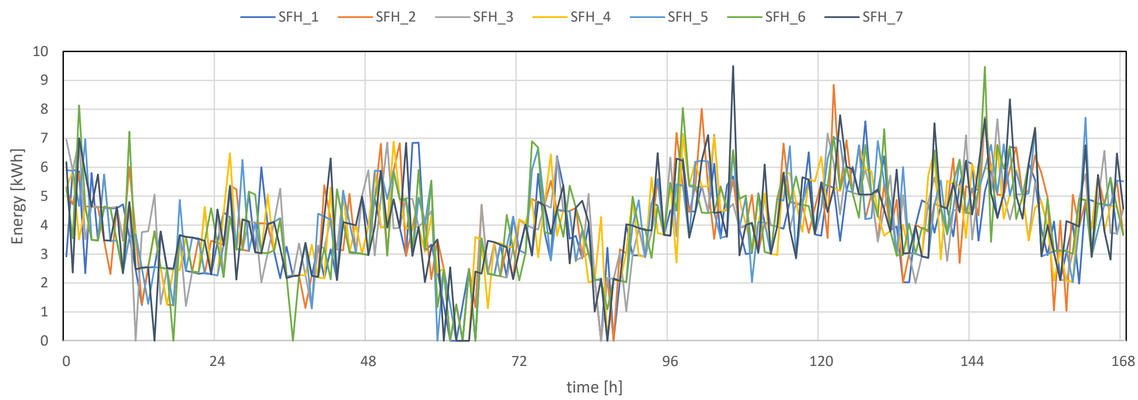

Figure 33: DHW and SH thermal energy use for the 7 SFHs part of the REC considered; Old SFHs in the Continental climate, period 1-7 Jan

The same analysis reported previously for the 7 old SFHs belonging to the considered REC has been performed also for the 3 old sMFH. Figure 34 shows the thermal energy use for DHW and SH (the aggregated values) for the 3 sMFH considered in the analysed winter week (period 1-7 Jan). As can be seen in Figure 34 the thermal energy use profiles of the 3 sMFHs are similar mainly due to the fact that SH thermal energy use is the main building thermal energy need in the considered case and the variations associated to the variable inputs presented in Figure 6 are very limited. The differences between the 3 profiles reported in Figure 34 are instead associated also in this case mainly to the different users' DHW demand time series considered as variable input to the models. The values reported in Figure 34 are higher in absolute terms if compared to those visible in Figure 33 and this is mainly due to the higher volume to be heated in the sMFH considered.

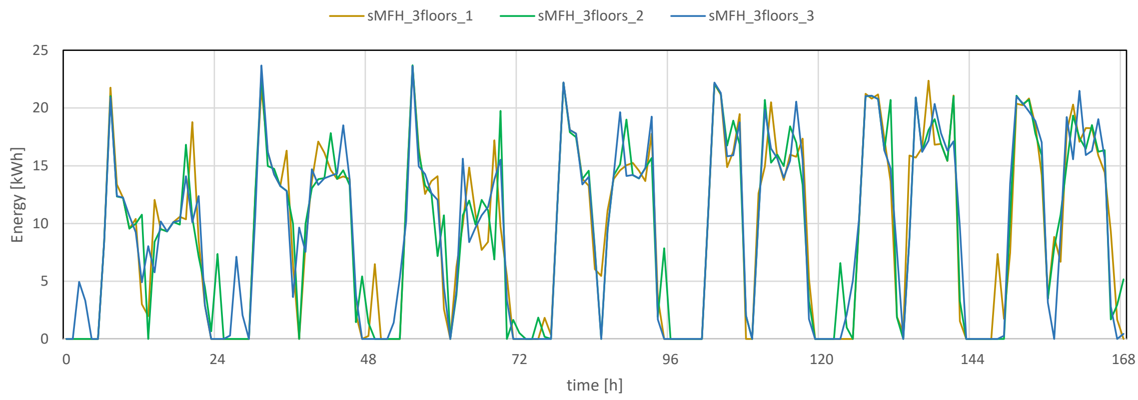

Figure 34: DHW and SH thermal energy use for the 3 sMFHs part of the REC considered; Old sMFHs in the Continental climate, period 1-7 Jan

The thermal energy use for DHW and SH at REC level has been obtained summing up the different hourly thermal energy use for DHW and SH of the 7 SFHs and the 3 sMFHs considered part of the REC. Figure 35 shows the thermal energy use for DHW and SH of all 7 SFHs, all 3 sMFHs and the total value at REC level. As can be noted, the thermal energy use for DHW and SH at REC level presents a trend similar to the typical thermal energy use profile for DHW and SH of a sMFH, highlighting the importance of the contribution of sMFHs in the considered REC. Nevertheless, Figure 35 shows also that the aggregation of thermal energy use for DHW and SH of different buildings tends to flatten the thermal energy use profile for DHW and SH at REC level in comparison to the typical trend of a sMFH visible in Figure 34. Figure 35 also present in blue dashed line the thermal energy use at REC calculated aggregating the profile according to the first method presented in section 2.5, hence summing up the same time series typical for a SFH and the one typical for a sMFH based on the number of SFHs and sMFHs belonging to the considered REC. As can be noted in Figure 35, the thermal energy use general pattern obtained using the first method described in section 2.5 is quite similar to the one obtained using the second method described in section 2.5. Nevertheless, it can be noted that the peaks obtained considering only one thermal energy use time series for each building type (method 1) tends to overestimate peaks thermal energy use. From Figure 35 this overestimation can be in the range of 20%.

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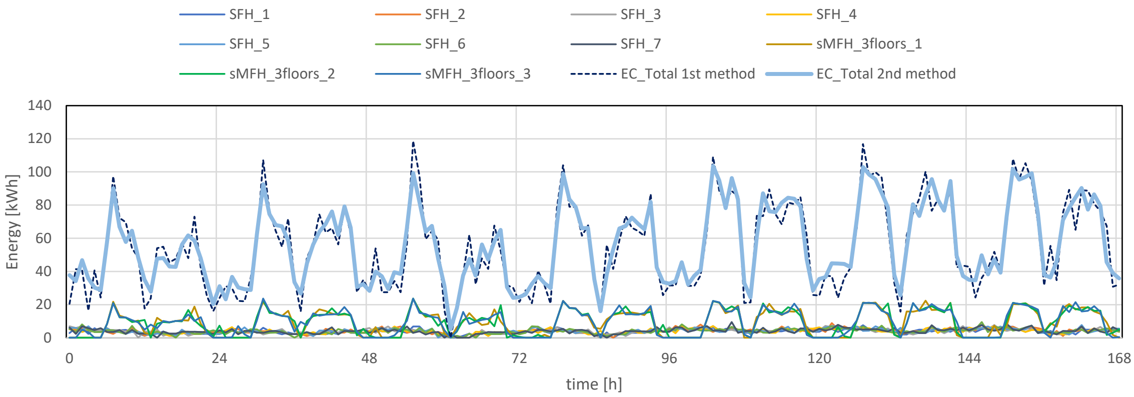

Figure 35: DHW and SH thermal energy use for the 7 SFHs, the 3 sMFHs and the total quantity at REC level calculated with both methods of section 2.5; Old buildings in the Continental climate, period 1-7 Jan

3.3.2. Identification of thermal energy use for DHW and SC in summer period (25 Jun – 1 Jul)

This section reports an analysis of the thermal energy use at REC level in one week considered, in this context, representative of the summer period (25 Jun – 1 Jul). In this case DHW and SC thermal energy use are reported separately as they are delivered, in the considered case, using two different units (HP system for DHW and split units for SC). Figure 36 represents the thermal energy use for DHW of the 7 SFHs that are part of the considered REC. The thermal energy use for DHW is associated to the thermal energy needed to charge the DHW tank. For this reason, as can be noted in Figure 36, the trends reported are characterized by similar shape, indicating that, in general, the amount of thermal energy delivered to the DHW tanks in the various SFHs for their charging is similar, but differently distributed over time. The peaks are associated to events in which the specific DHW tank is being charged and at the same time discharged on the users' side. This effect results in an increment of the thermal energy needed to ensure the complete charging of the DHW tank.

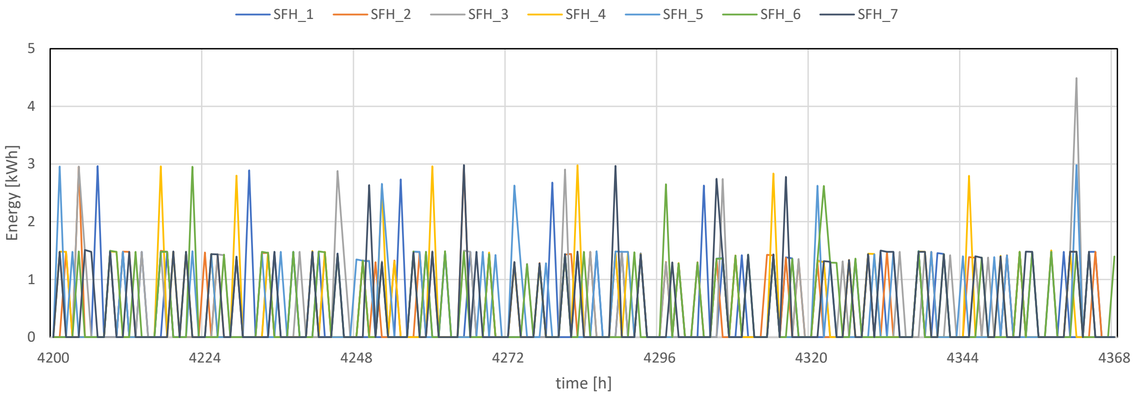

Figure 36: DHW thermal energy use for the 7 SFHs part of the REC considered; Old SFHs in the Continental climate, period 25 Jun – 1 Jul

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The same analysis reported in Figure 36 has been performed also for the 3 sMFHs part of the considered REC and these results are shown in Figure 37. Comparing Figure 36 and Figure 37, it can be noted that the thermal energy needed for the DHW tank charging in sMFH is higher due to the higher volume of the DHW tank, sized based on the number of occupants of the building. The variability in the amount of thermal energy needed for a specific charging of a DHW tank depends on the simultaneous DHW demand at users' side. In fact, being the sMFH constituted by 6 dwellings the DHW users' demand is more uniformly distributed along the day in comparison to the DHW demand typical of a SFH that presents instead DHW usage concentrated around a limited number of moments along the day.

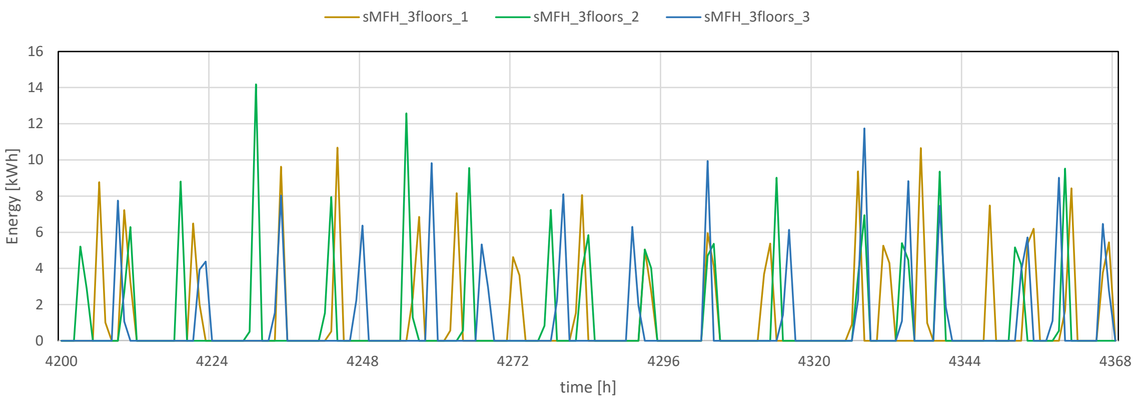

Figure 37: DHW thermal energy use for the 3 sMFHs part of the REC considered; Old sMFHs in the Continental climate, period 25 Jun – 1 Jul

Figure 38 shows the thermal energy for DHW for the 7 SFHs and the 3 sMFHs part of the considered REC and their sum representing the thermal energy for DHW at REC level. Although the aggregation of loads generally leads to a flattening of the total load at REC level, this is less valid for the thermal energy use for DHW as can be seen in Figure 38. This is due to the typically discontinuous operation that characterized DHW tank charging. In addition to that, Figure 38 presents also the thermal energy use for DHW during the analysed summer week calculated according to the first method presented in section 2.5. Contrarily to the analysis over the considered winter week reported in the previous section, here, the differences between the thermal energy use at REC level obtained from the two methods described in section 2.5 presents important differences. In fact, to not consider the differences in terms of thermal energy use at building level for the different buildings of the same building type belonging to the considered REC would result in an overestimation of the thermal energy use for DHW in the considered period. This assumption would result in very high peaks in thermal energy use as shown by the blue dashed line in Figure 38.

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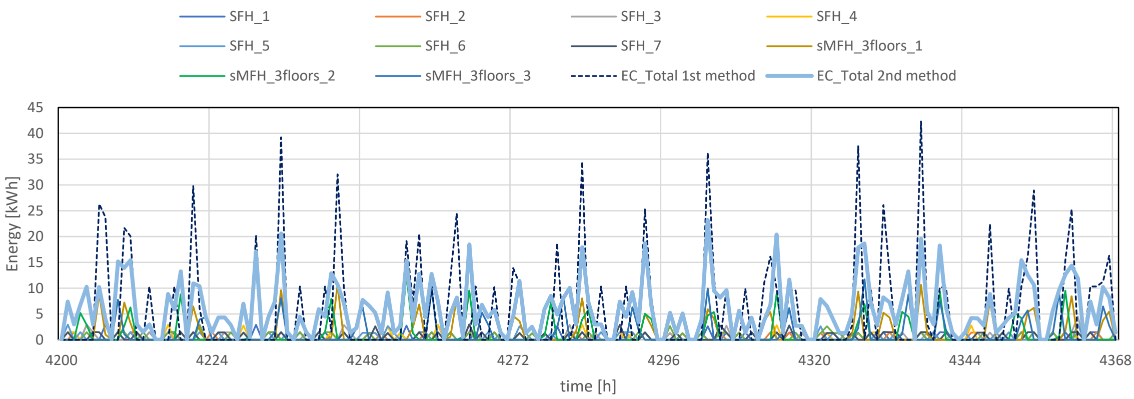

Figure 38: DHW thermal energy use for the 7 SFHs, the 3 sMFHs and the total quantity at REC level calculated with both methods of section 2.5; Old buildings in the Continental climate, period 25 Jun – 1 Jul

The other buildings' thermal need in addition to DHW during summer period is SC. In the buildings part of the considered REC (old SFHs and sMFHs in the Continental climate) the SC thermal demand is considered covered by split units. Figure 39 shows the thermal energy use for SC of the 7 SFHs part of the considered REC. As can be noted, SC represents, in the buildings and climate considered, a very limited thermal energy use concentrated in short periods over the summer analysed week (period 25 Jun – 1 Jul).

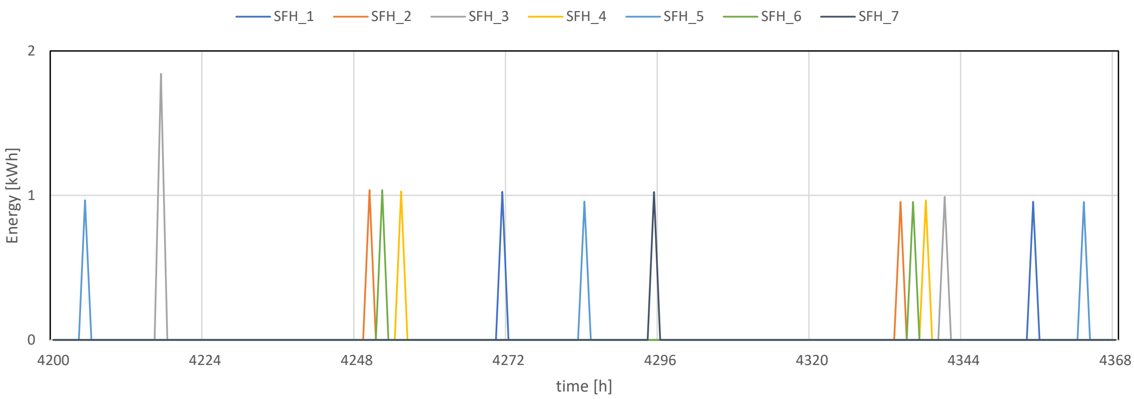

Figure 39: SC thermal energy use for the 7 SFHs part of the REC considered; Old SFHs in the Continental climate, period 25 Jun – 1 Jul

The same analysis reported in Figure 39 for the 7 SFHs has been performed also for the 3 sMFHs part of the considered REC and this is shown in Figure 40. Also, in sMFHs the thermal energy for SC is very limited in absolute terms and slightly more distributed over longer periods of the day in comparison to SFHs.

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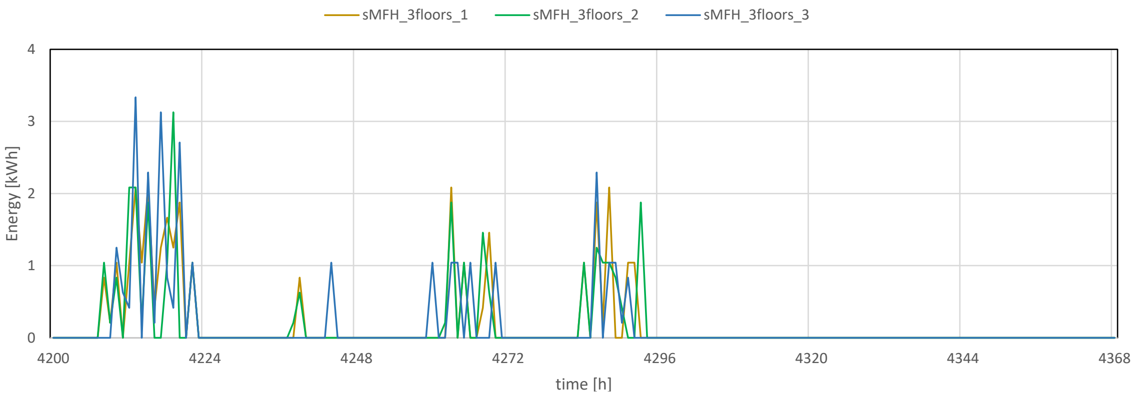

Figure 40: SC thermal energy use for the 3 sMFHs part of the REC considered; Old sMFHs in the Continental climate, period 25 Jun – 1 Jul

Figure 41 presents the thermal energy for SC of the 7 SFHs and the 3 sMFHs as well as the thermal energy for SC at REC level calculated using the first (blue dashed line) and the second (green line) method reported in section 2.5. As highlighted in Figure 41 also at REC level the thermal energy use for SC is very limited in the considered case with a trend constituted mainly by different peaks distributed over the considered summer period. The aggregation of thermal energy for SC at REC level according to the first method described in section 2.5, also in this case, would result in a thermal energy use at REC level characterized by high peaks less representative of the real thermal energy use pattern for SC at REC level in comparison to the results obtained using the second method presented in section 2.5.

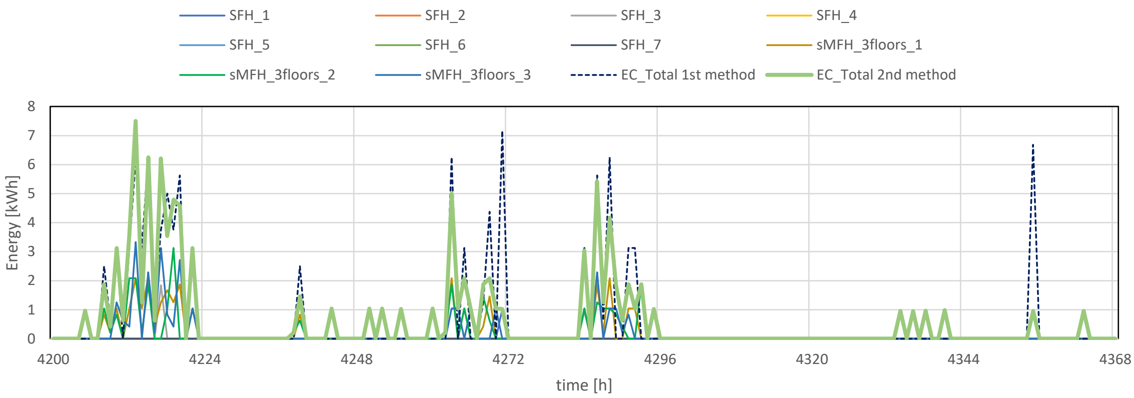

Figure 41: SC thermal energy use for the 7 SFHs, the 3 sMFHs and the total quantity at REC level calculated with both methods of section 2.5; Old buildings in the Continental climate, period 25 Jun – 1 Jul

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3.3.3. Identification of thermal energy use for DHW, SH and SC over the entire year

In addition to the evaluations over two weeks considered representative of the winter and summer period respectively, this section reports the hourly thermal energy use for DHW and SH (the aggregated value) and SC at REC level over the entire year.

Figure 42 shows the thermal energy use for DHW and SH (the aggregated values) for the various hours of the year. As highlighted in Figure 42 the highest values are associated to the first and last days of the year, days generally characterized by the coldest conditions in terms of external temperature. Moreover, the highest values occur in the period from 6 a.m. to 10 p.m., hence, when in the sMFHs belonging to the considered REC the SH system is in operation. In the nights of the winter period the main contribution to thermal energy use is instead associated to the SH thermal energy delivered in SFHs and to the thermal energy used for DHW tanks charging in all the considered buildings. During summer period the only thermal energy use visible in Figure 42 is due to the thermal energy used to charge the DHW tanks in the various buildings and, as can be noted in Figure 42 this is concentrated in the period 6 a.m. – 9 a.m., period generally characterized by high users' DHW demand.

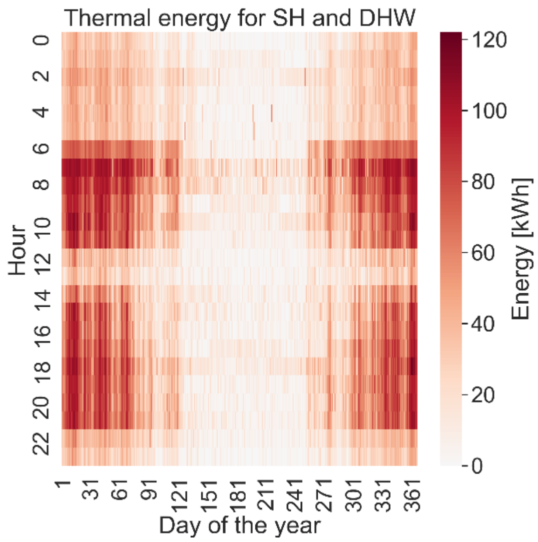

Figure 42: Heat map reporting hourly thermal energy use for DHW and SH at REC level

Figure 43: shows instead the thermal energy use for SC at REC level. As highlighted in Figure 43 the thermal energy use for SC in the considered REC is very limited and distribute over a limited number of days during the summer period, generally in the period 12 p.m. – 8 p.m.

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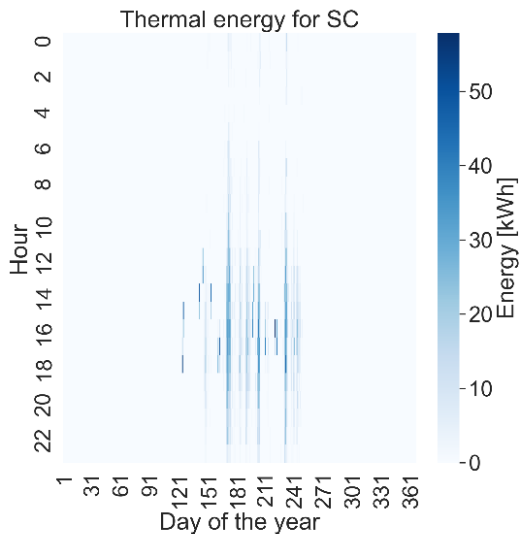

Figure 43: Heat map reporting hourly thermal energy use for SC at REC level

3.4. Identification of electrical energy use at REC level

Complementary to section 3.3, this section reports the evaluation of electrical energy use at REC level for the REC considered as example. The electrical energy consumption at REC level is obtained aggregating single buildings electrical energy use time series according to what is reported in section 2.5. In particular, the second method reported in section 2.5 has been considered.

The following sections 3.4.1 and 3.4.2 report an analysis over two weeks (1-7 Jan and 25 Jun – 1 Jul) considered, in this context, representative of the winter and summer period respectively. Moreover, section 3.4.3 reports an evaluation of electrical energy use at REC level over the entire year.

For the sake of simplicity, in this example about aggregation of thermal and electrical energy use at REC level, PV and BESS have not been considered as this example wants only to present one application of the methodology developed for the aggregation of thermal and electrical energy uses for different buildings to obtain thermal and electrical energy uses at REC level as described in section 2.5.

3.4.1. Identification of electrical energy use in winter period (1 – 7 Jan)

As stated in section 3.3, HP systems have been considered in this context to cover DHW and SH demand in the buildings belonging to the REC used as example. Considering also that, if present, the HP represents the main electrical consumption contribution in the building as visible in Figure 24, it is expected an electrical energy use pattern similar to the thermal energy use for DHW and SH one in the analysed winter week.

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Figure 44 shows the electrical energy use of the 7 SFHs belonging to the considered REC, highlighting the similar trend but also the slight differences between different time series due to the differences in occupants' behaviours and usage of the various SFHs. Comparing Figure 44 and Figure 33 it can be noted that, as stated before, thermal energy use for DHW and SH, and electrical energy use are related in the analysed winter week. Moreover, differently from thermal energy use for the 7 SFHs for DHW and SH reported in Figure 33, the electrical energy use time series shown in Figure 44 present always a base consumption to account for the stand-by consumption of the electrical devices present in the building (mainly HP). This minimum electrical consumption is represented by the minimum values visible in limited moments in Figure 44.

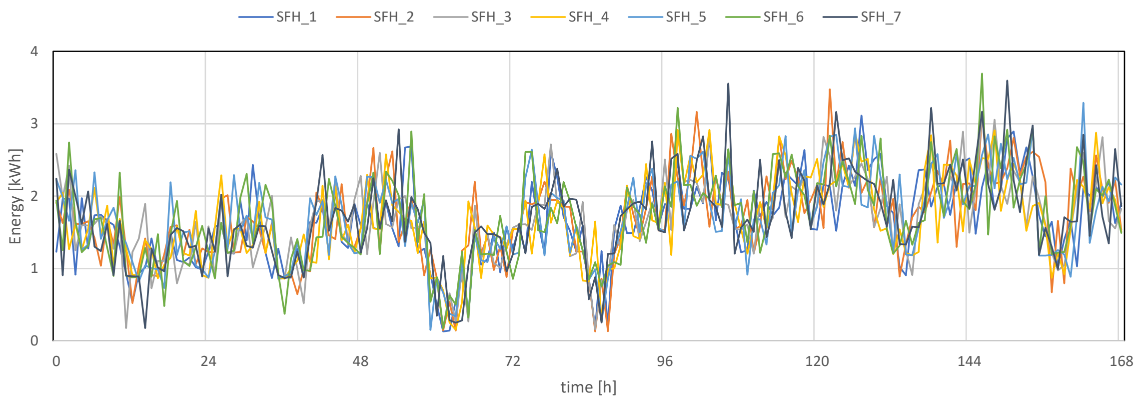

Figure 44: Electrical energy use for the 7 SFHs part of the REC considered; Old SFHs in the Continental climate, period 1 -7 Jan

Figure 45 presents instead the electrical energy use for the 3 sMFHs part of the considered REC. Also, in this case it is possible to see the relation between thermal energy use for DHW and SH, and electrical energy use in the analysed winter week due to the consideration of a HP system for the covering of building DHW and SH thermal demand. This relation can be noted comparing Figure 45 and Figure 34. Moreover, Figure 45 highlights the peaks that constitute the main difference between the electrical energy use time series of the 3 sMFHs. These peaks are associated to the charging of DHW tank that occurs in different moments in the 3 sMFHs. This is mainly due to the differences in the DHW usage of the occupants. As already reported for the 7 SFHs, also sMFHs are characterized by base electrical consumption that accounts for the stand-by consumption of the electrical devices present in the building. The typical stand-by consumption of a sMFH is higher in comparison to the typical stand-by consumption of a SFH due to the high nominal power of the HP, (needed to cover a higher building thermal demand) and to the high number of electrical appliances. This can be noted comparing the minimum values visible in Figure 44 and Figure 45, respectively. Differently from Figure 44, the electrical energy use in the 3 sMFHs part of the considered REC present longer periods characterized by the minimum electrical consumption. This is because the main electrical consumption is due to the HP for the covering of SH building thermal demand and, in the sMFH, the SH is delivered only in specific periods of the day; more specifically from 6 a.m. to 12 p.m. and from 2 p.m. to 10 p.m. On the contrary, this limitation is not applied in SFH as visible in Figure 44.

This motivates the higher building electrical energy consumption during night periods visible in Figure 44.

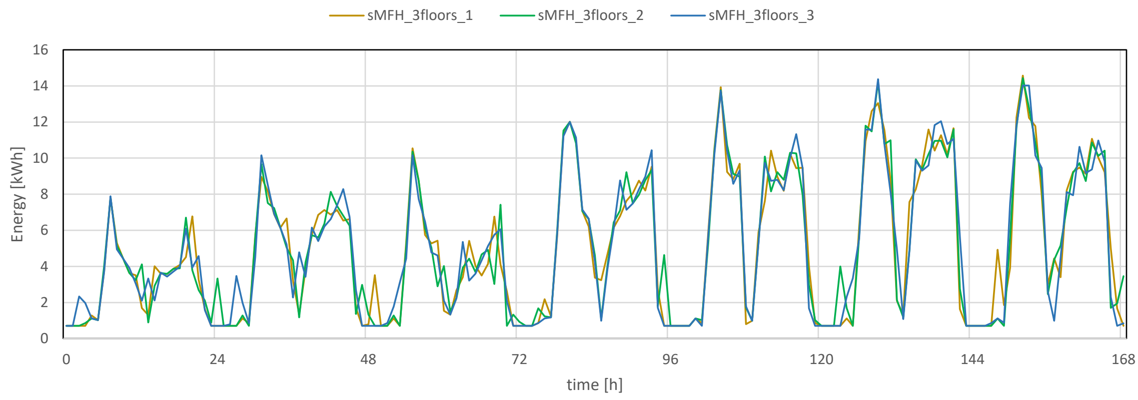

Figure 45: Electrical energy use for the 3 sMFHs part of the REC considered; Old sMFHs in the Continental climate, period 1 -7 Jan

Figure 46 shows the electrical energy use at REC level calculated with the first (blue dashed line) and the second (blue line) method reported in section 2.5, as well as the single electrical energy use of the 7 SFHs and 3 sMFHs part of the considered REC. As can be noted in Figure 46, the electrical energy use at REC level presents peaks mainly associated to the consumption of the HP systems in the 3 sMFHs to cover buildings' SH thermal demand. Moreover, the aggregation of electrical energy use of different buildings, characterized by similar patterns but with slight differences in the distribution over time, leads to a base electrical energy consumption at REC level that, in this case and in the analysed winter week, is in the range 15 – 30 % of the peak electrical energy use. Regarding instead the electrical energy use at REC obtained from the two methods described in section 2.5, in Figure 46 it can be noted that, although the general trend is similar, the first method tends, as reported in the previous sections, to overestimate the peak electrical energy consumption at REC in certain moments.

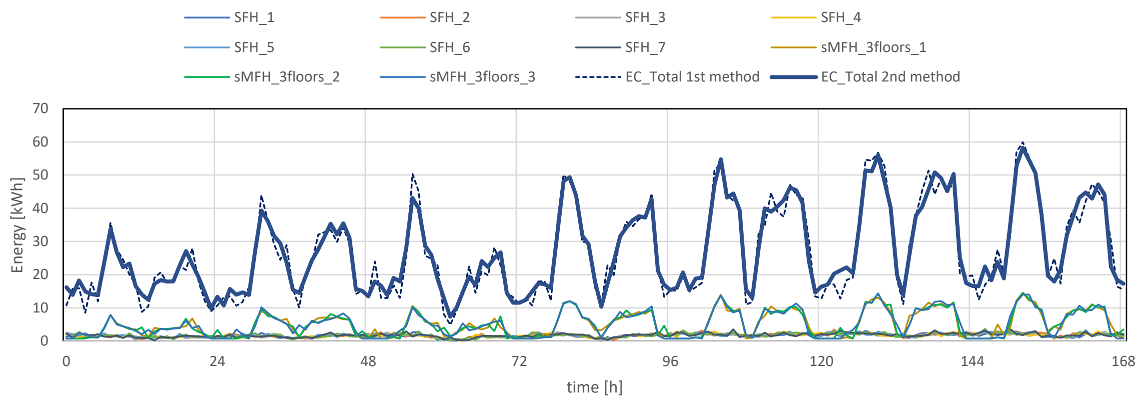

Figure 46: Electrical energy use for the 7 SFHs, the 3 sMFHs and the total quantity at REC level calculated with both methods of section 2.5; Old buildings in the Continental climate, period 1-7 Jan

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3.4.2. Identification of electrical energy use in summer period (25 Jun – 1 Jul)

This section reports an analysis of the electrical energy use at REC level, as well as the electrical energy use at single building level for the 7 SFHs and the 3 sMFHs part of the considered REC during the week considered representative of the summer period (25 Jun – 1 Jul). In this case, in addition to the electrical consumption due to appliances and lighting system, this analysis considers, for the assessment of building electrical energy use, the electrical energy consumption associated to split units to cover building SC thermal demand and electrical energy consumption due to HP system to cover building' DHW thermal demand.

Figure 47 presents the electrical energy use for the 7 SFHs part of the considered REC during the analysed summer week. As can be noted from the figure, the electrical energy use in the analysed case is very limited and characterized by a limited number of peaks associated to the electric consumption of the HP system to charge the DHW tank in the various SFHs as visible also in Figure 27. The DHW tank charging events are differently distributed over time for the various SFHs considered. This is mainly associated to the different DHW users' demand time series used as variable input in the different SFHs' TRNSYS models as reported in Figure 9. Figure 47 highlights also the base electrical energy use, equal for all SHFs, that accounts for the stand-by consumption of electrical devices present in the considered buildings.

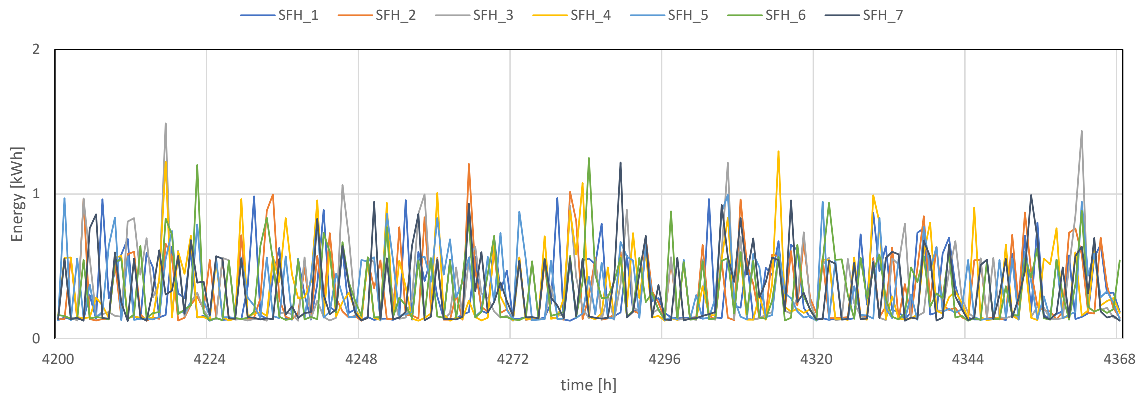

Figure 47: Electrical energy use for the 7 SFHs part of the REC considered; Old SFHs in the Continental climate, period 25 Jun – 1 Jul

The electrical energy use for the 3 sMFHs part of the considered REC is instead reported in Figure 48 for the analysed summer week. Also in this building type, the electrical energy use is very limited in absolute terms and associated to a limited number of peaks along the day. These peaks are differently distributed over time for the 3 sMFHs and are associated to the electric consumption of the HP system to charge the DHW tank in the various sMFHs.

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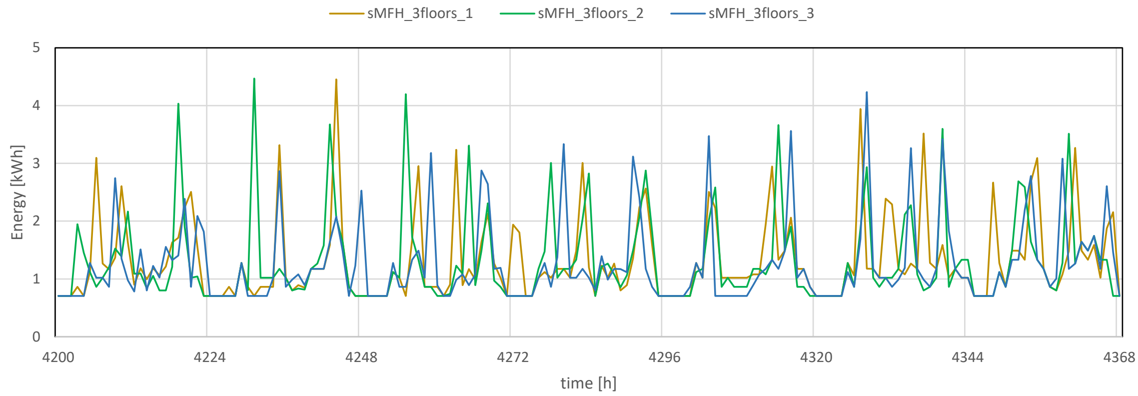

Figure 48: Electrical energy use for the 3 sMFHs part of the REC considered; Old sMFHs in the Continental climate, period 25 Jun – 1 Jul

Figure 49 shows the electrical energy use at REC level obtained using first (dark blue dashed line) and second method (dark blue line) reported in section 2.5, as well as the electrical energy use of the 7 SFHs and the 3 sMFHs belonging to the considered REC. As can be noted in Figure 49, during the analysed summer week, the electrical energy use at REC level is characterized by lower values in absolute terms if compared to the electrical energy use during the analysed winter period reported in Figure 46. Figure 49 highlights also that the electrical energy use trend at REC level is characterized by peaks distributed along the days of the analysed period and mainly associated to the HP system electric consumption for the DHW tank charging in the various sMFHs. As visible in Figure 49 there is always a base electrical energy use at REC level equal to around 30% of the peak electrical energy use in the considered period. Moreover, the electrical energy use time series at REC level obtained using the first method described in section 2.5 is characterized by high peaks that are not representative of a realistic electrical energy use pattern at REC level.

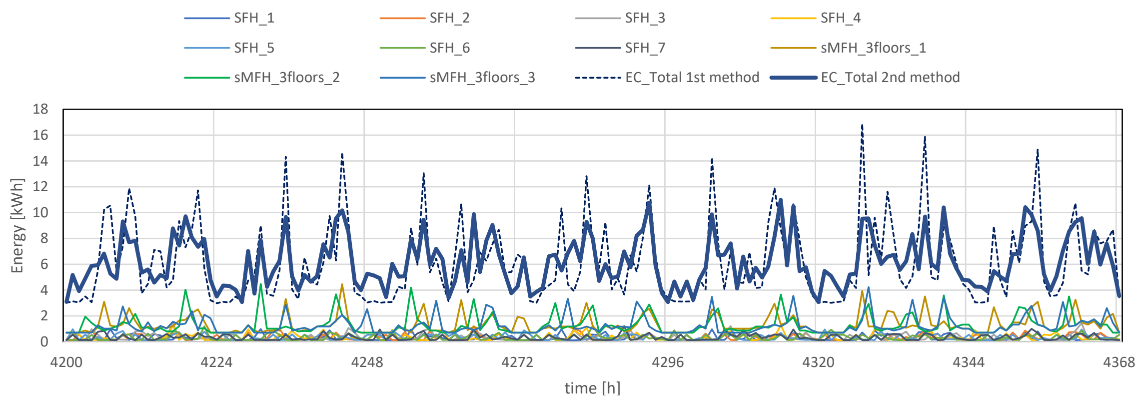

Figure 49: Electrical energy use for the 7 SFHs, the 3 sMFHs and the total quantity at REC level calculated with both methods of section 2.5; Old buildings in the Continental climate, period 25 Jun – 1 Jul

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3.4.3. Identification of electrical energy use over the entire year

Finally, complementary to what is reported in section 3.3.3 for the thermal energy use at REC level, this section aims to analyse the hourly electrical energy use at REC not over limited time periods (one week) but considering the entire year.

For this reason, Figure 50 shows the hourly electrical energy use at REC level over the entire year. As can be noted comparing Figure 42 and Figure 50 the trends are similar, highlighting the fact that the main electrical energy use, also at REC level, is associated to the electrical consumption of the HP system in sMFHs for the covering of buildings' SH thermal demand. This explains the highest values visible in Figure 50 in the first and last period of the year, generally characterized by the coldest external temperature, and in the period 6 a.m. – 10 p.m., period in which the HP systems in the sMFHs work to cover building SH thermal demand. The electrical energy use during night hours of the winter period is instead associated to the electrical consumption of HP systems in sMFHs for the charging of the DHW tanks and to the electrical consumption of HP systems in SFHs for both DHW and SH as, generally, the rules in terms of limited periods for SH operation do not apply in such building type.

As already mentioned in previous sections, the electrical energy use at REC level is lower during summer period in comparison to winter period. In particular, during summer, a slightly higher electrical energy use at REC level can be seen in Figure 50 in the period 6 a.m. to 9 a.m. This is associated to the charging of the DHW tanks that occurs frequently in this period of the day to counterbalance the high users' DHW demand in the same period as visible in Figure 9.

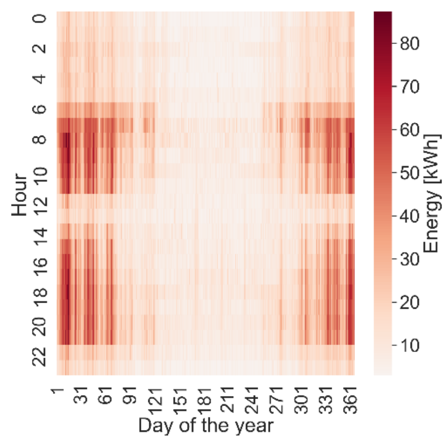

Figure 50: Heat map reporting hourly electrical energy use at REC level

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4/ Conclusions

In this report, realistic thermal and electric energy use time series at building level for 27 residential cases and for a series of non-residential buildings have been elaborated.

Each of the 27 residential cases and of the 9 office buildings have been identified ensuring a sufficiently wide representation of the energy uses in the EU building stock, taking in due consideration the variety of building typologies, aging and geographical distribution.

Simulations in TRNSYS with an hourly time resolution have been elaborated starting from the work developed within FP7 iNSPiRe (R. Fedrizzi) and H2020 BuildHeat (C. Dipasquale) projects, where models results have been validated versus literature and monitoring data.

A simplified approach based on standard (UNI/TS 52016:2018) has been used to assess energy uses of a school in the different EU climates considered, considering different thermal envelopes associated.

Finally, energy uses of a reference supermarket have been modelled starting from real buildings monitored, and the results in terms of hourly electricity consumed have been compared with openly available literature from the project FP7 CommONEnergy (Galvez Martos).

The technologies considered for covering thermal and electric loads span across the most common solutions enabling sector coupling, i.e., air-to-water heat pumps and cogeneration systems integrating TES and PV+BESS solutions.

The thermal and electrical energy uses identified at single building levels represent reference electric loads in their respective building categories, and can be aggregated at REC level. The work presented here also includes a simple method to account for a superposition of the effects that is not a simple mathematical addition of single building loads, rather it accounts for a statistical distribution of the buildings' use, hence of the energy uses; this allows obtaining a more realistic distribution of thermal and electrical energy use patterns across the REC.

The energy use time series are being used for training the LocalRES MEVPP, allowing to consider a wide variety of possible building loads possibly be faced in a real application of the MEVPP. All the relevant time series will be published on the platform Zenodo.

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5/ Next steps

These time series reported in this report have been obtained using TRNSYS as simulation environment. Although TRNSYS allows modelling the physical phenomena influencing the thermal behaviour of the building and HVAC system considered for the covering of buildings' thermal needs with a high level of detail, it also poses some limitations to the use of the models.

Indeed, it is not possible to integrate more than one building model in a TRNSYS environment. This makes it impossible to use TRNSYS for dynamic simulation of a community of buildings. Moreover, even in case of a co-simulation environment is set up to run multiple TRNSYS environments in parallel, TRNSYS detailed models require high computational effort for simulation. This results in an unsuitable simulation running time, when it comes to use the environment for training a MEVPP platform.

This implies that TRNSYS can only be used to elaborate "static" thermal and electric energy use time series, which cannot account for dynamic aspects like thermal discomfort or eventual rebound effects following the implementation of demand response (DR) measures.

Dynamic reactions to DR measures are particularly relevant to the development of MEVPP as they can identify relevant barriers to the DR measures eventually deployed; simplified models allowing to account for the dynamic response of a building with its HVAC system with as low computational effort as possible, nonetheless with accurate enough energy performance prediction are needed.

To this end, simplified models are being developed with the purpose of modelling building thermal and electrical loads, HVAC systems (including HPs and thermal storages), PV and BESS systems to be coupled with building loads. The final objective is to develop a dynamic simulation environment that allows including and simulating several buildings interacting in a virtual energy community in short time enough as to be coupled with a MEVPP platform during the development phase, before deployment in a real environment.

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7/ Appendix A

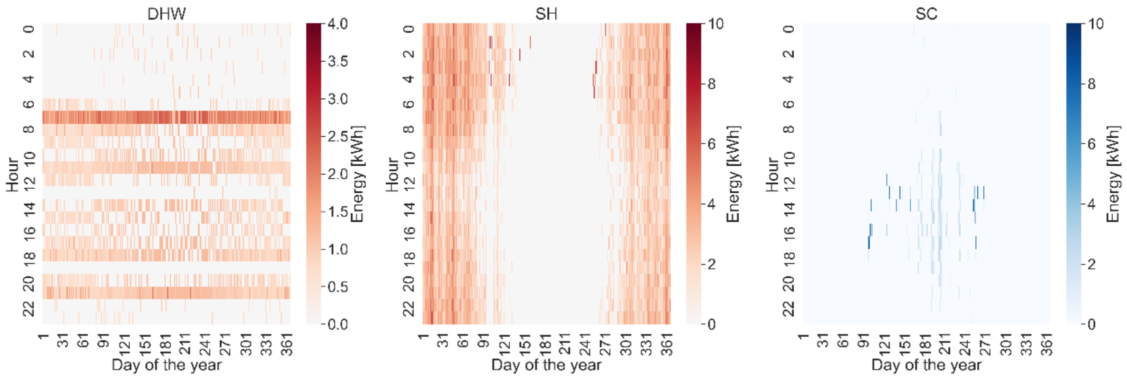

Figure 51: DHW, SH and SC hourly energy consumption; old SFH in the Nordic climate

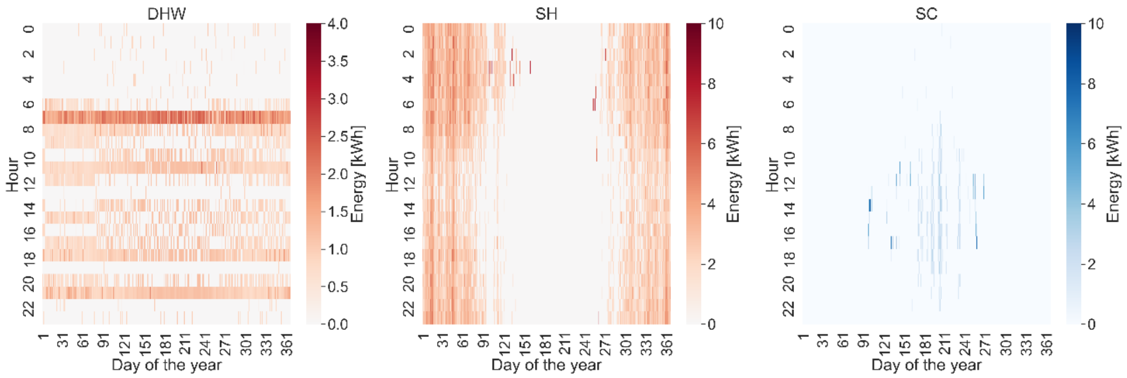

Figure 52: DHW, SH and SC hourly energy consumption; renovated SFH in the Nordic climate

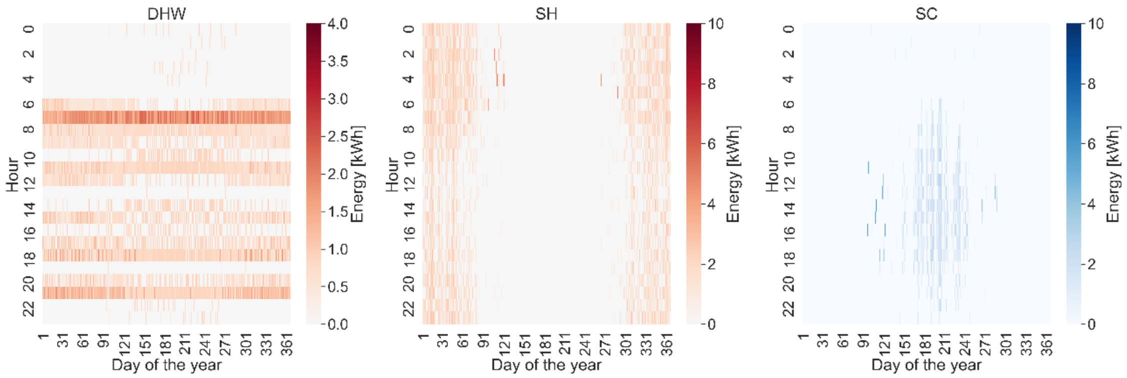

Figure 53: DHW, SH and SC hourly energy consumption; new SFH in the Nordic climate

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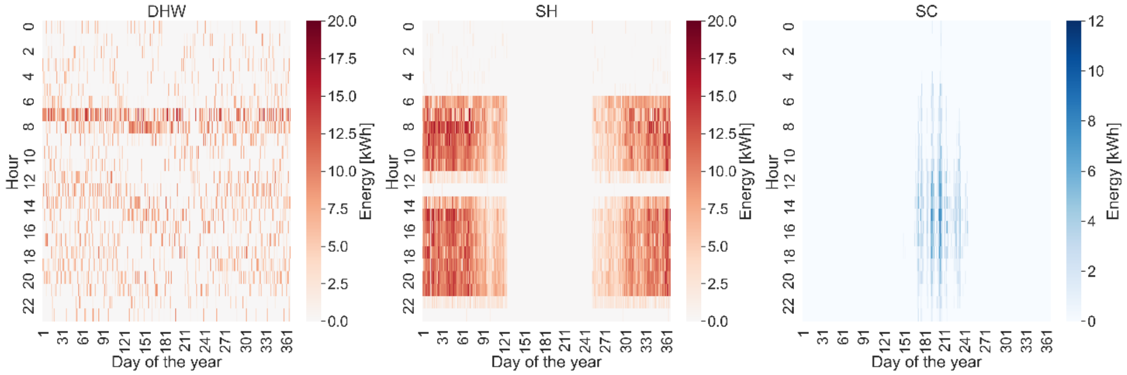

Figure 54: DHW, SH and SC hourly energy consumption; old sMFH in the Nordic climate

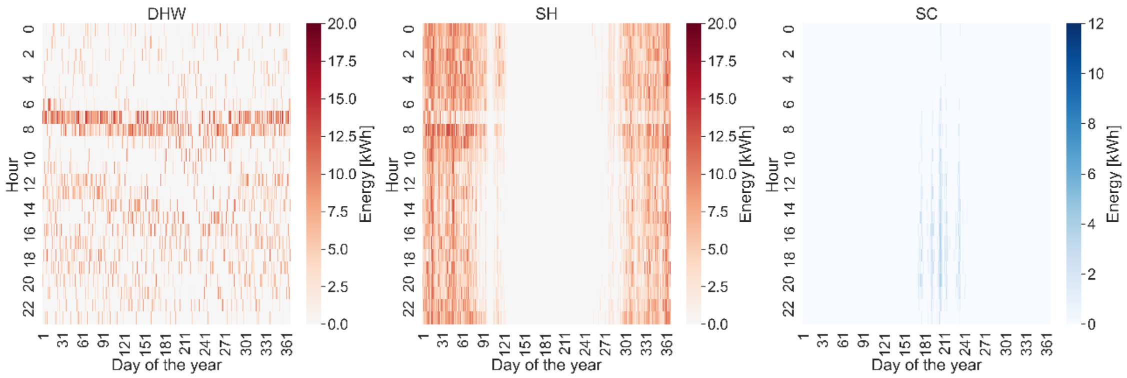

Figure 55: DHW, SH and SC hourly energy consumption; renovated sMFH in the Nordic climate

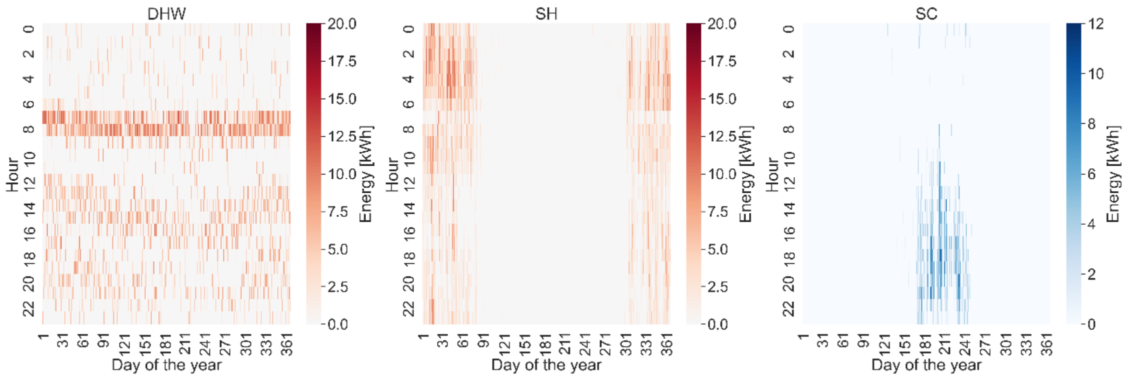

Figure 56: DHW, SH and SC hourly energy consumption; new sMFH in the Nordic climate

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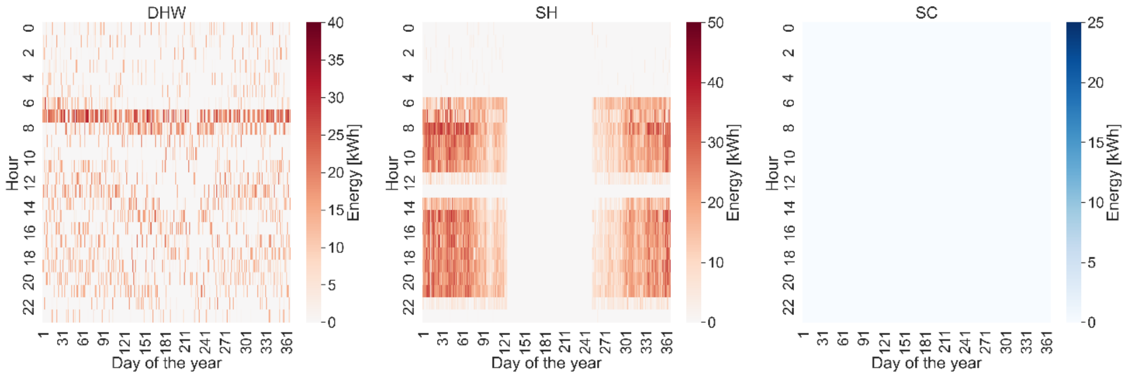

Figure 57: DHW, SH and SC hourly energy consumption; old IMFH in the Nordic climate

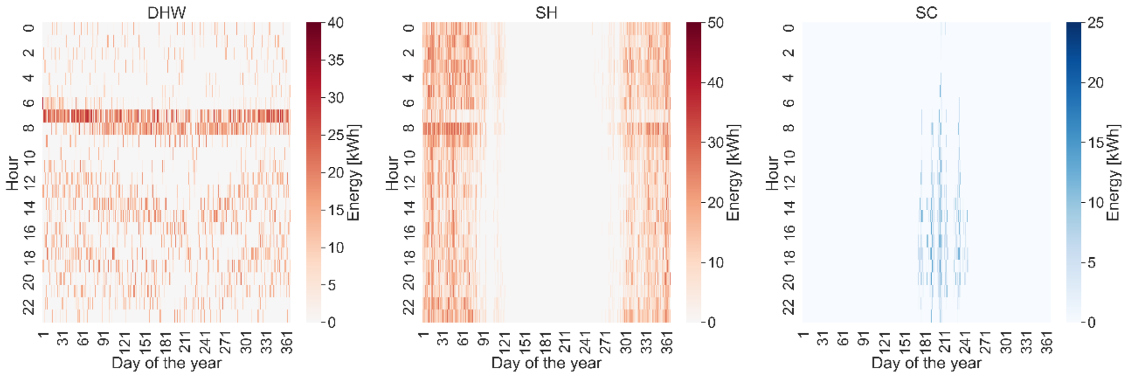

Figure 58: DHW, SH and SC hourly energy consumption; renovated IMFH in the Nordic climate

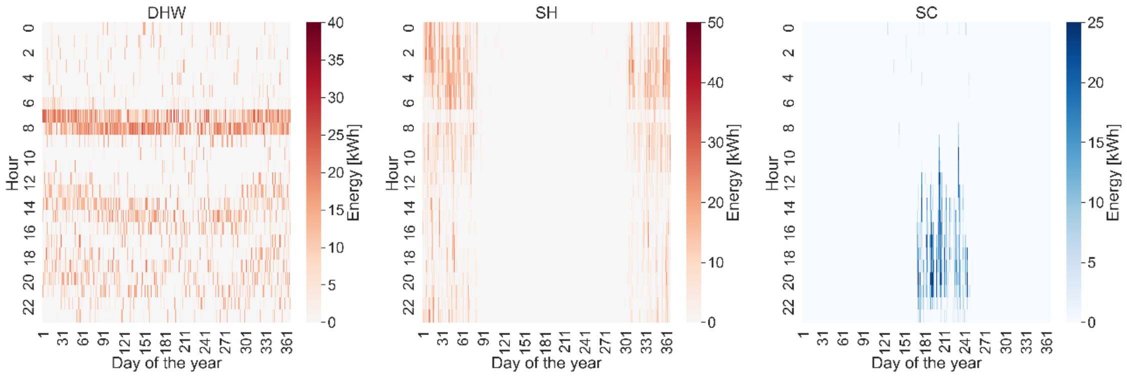

Figure 59: DHW, SH and SC hourly energy consumption; new IMFH in the Nordic climate

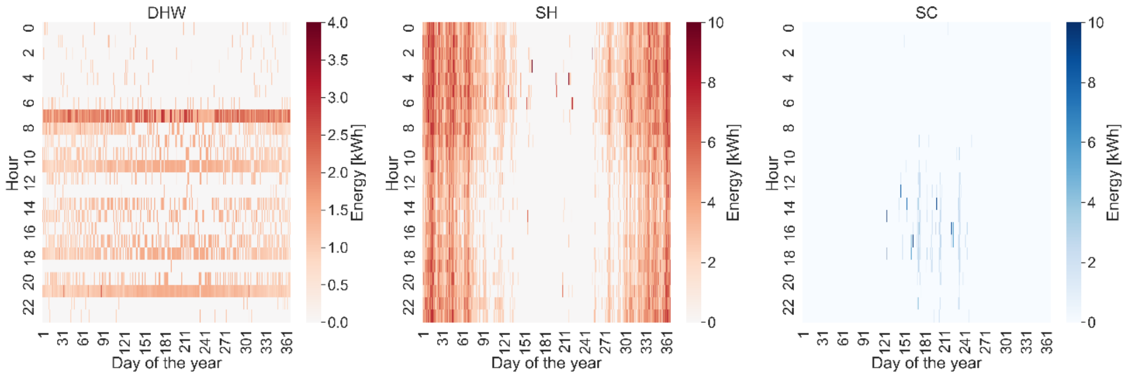

Figure 60: DHW, SH and SC hourly energy consumption; old SFH in the Continental climate

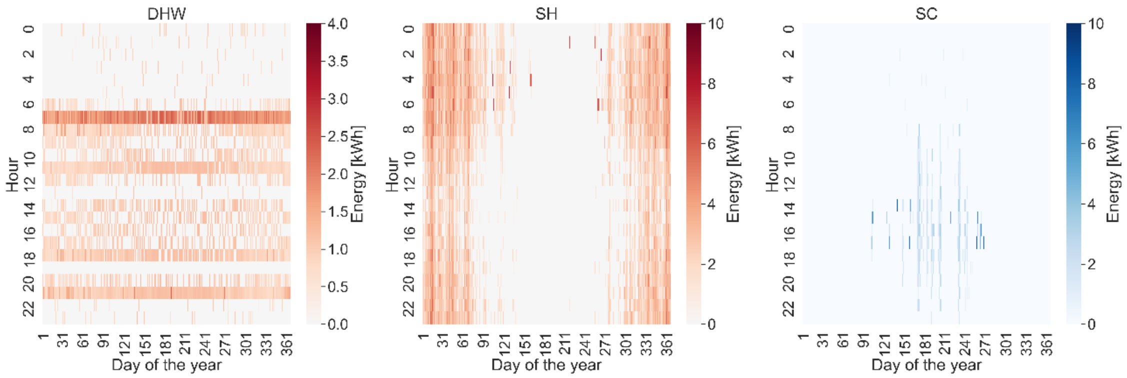

Figure 61: DHW, SH and SC hourly energy consumption; renovated SFH in the Continental climate

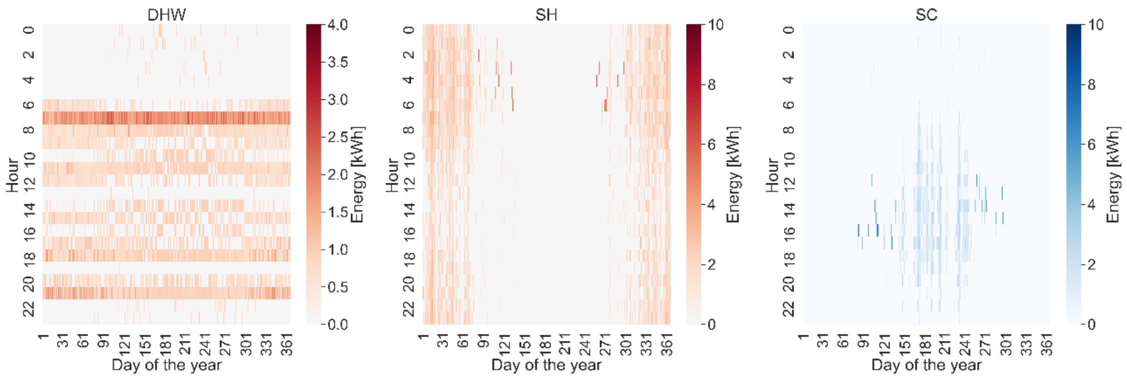

Figure 62: DHW, SH and SC hourly energy consumption; new SFH in the Continental climate

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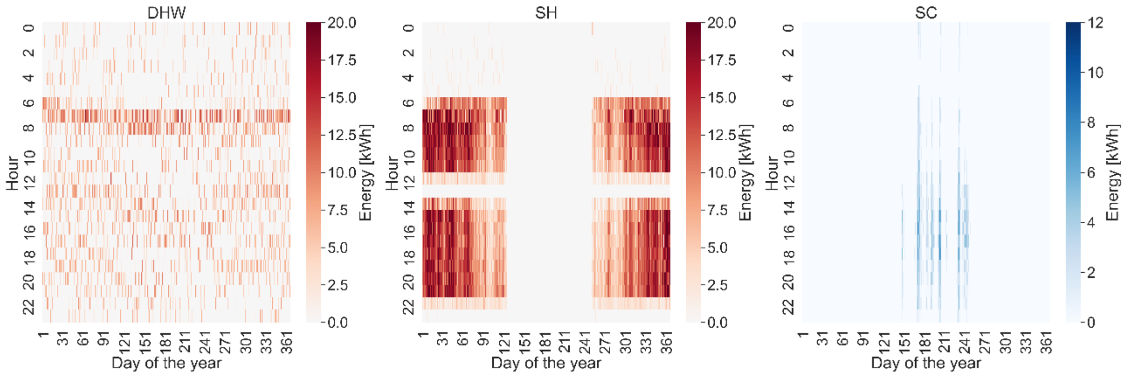

Figure 63: DHW, SH and SC hourly energy consumption; old sMFH in the Continental climate

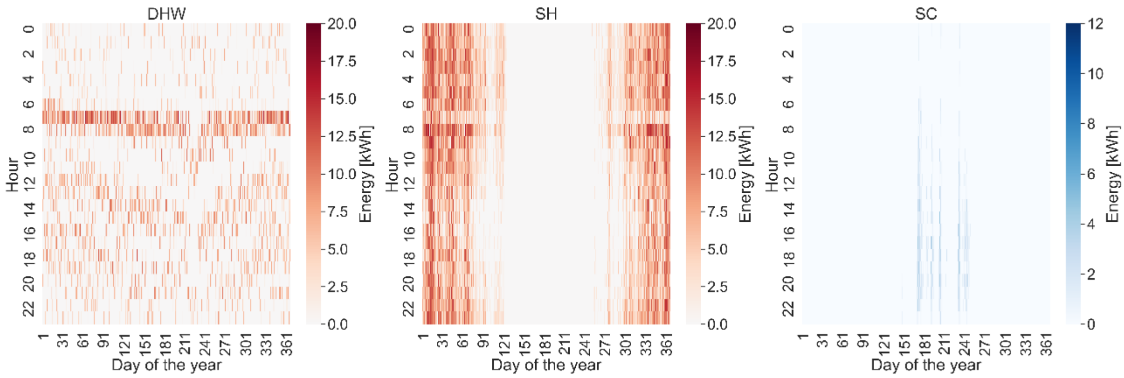

Figure 64: DHW, SH and SC hourly energy consumption; renovated sMFH in the Continental climate

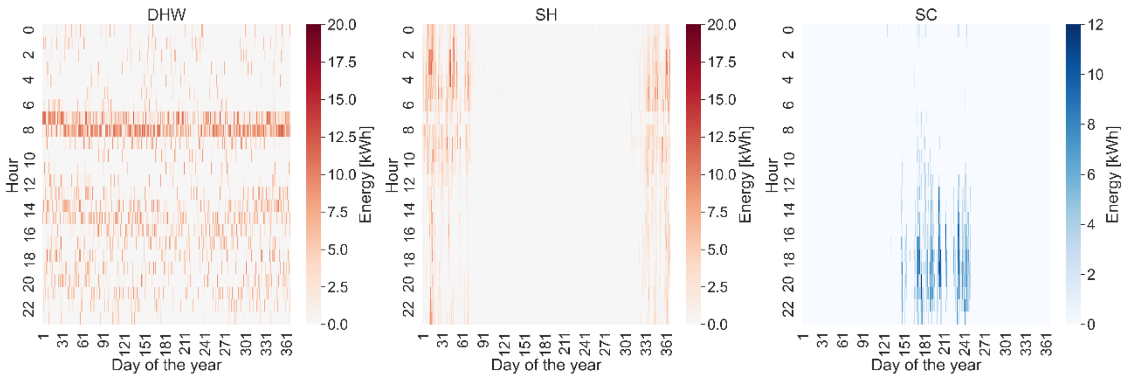

Figure 65: DHW, SH and SC hourly energy consumption; new sMFH in the Continental climate

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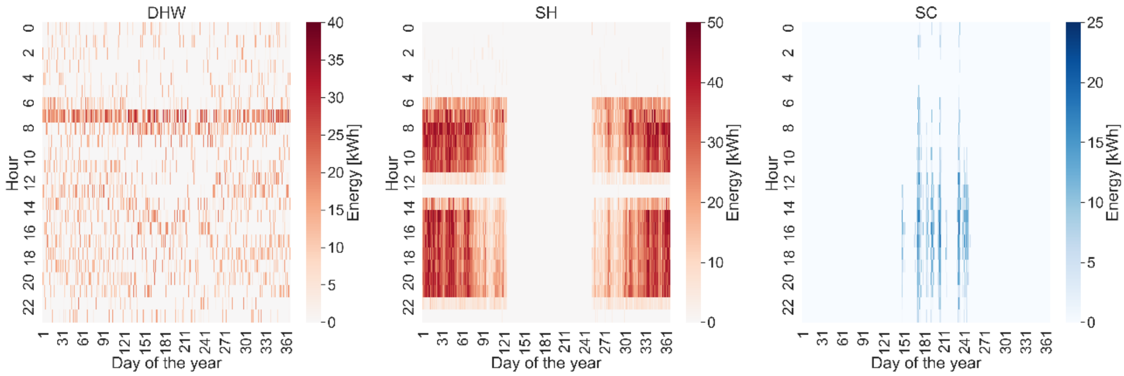

Figure 66: DHW, SH and SC hourly energy consumption; old IMFH in the Continental climate

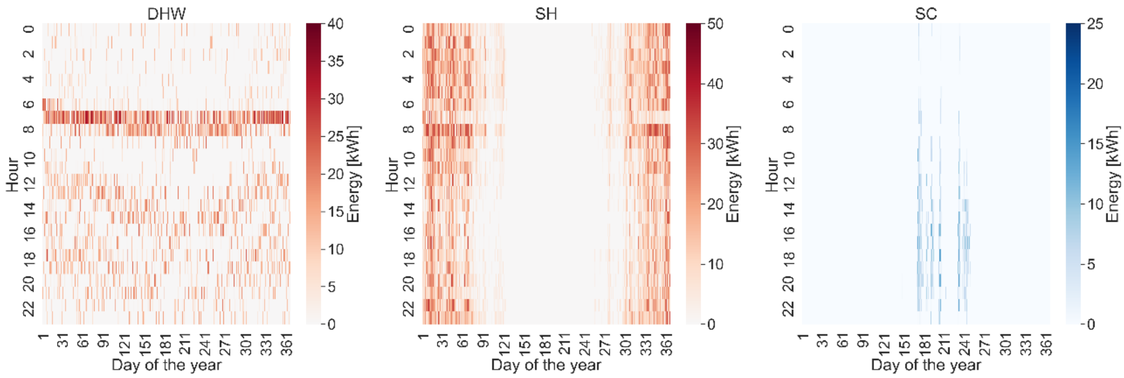

Figure 67: DHW, SH and SC hourly energy consumption; renovated IMFH in the Continental climate

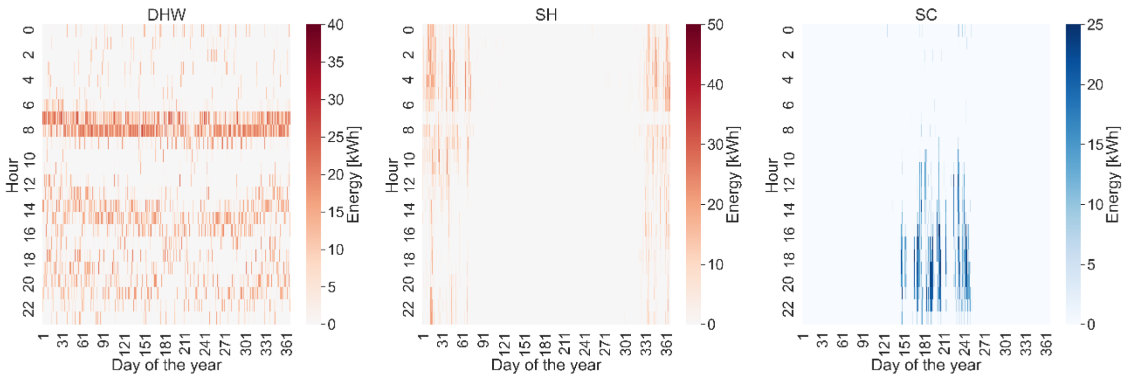

Figure 68: DHW, SH and SC hourly energy consumption; new IMFH in the Continental climate

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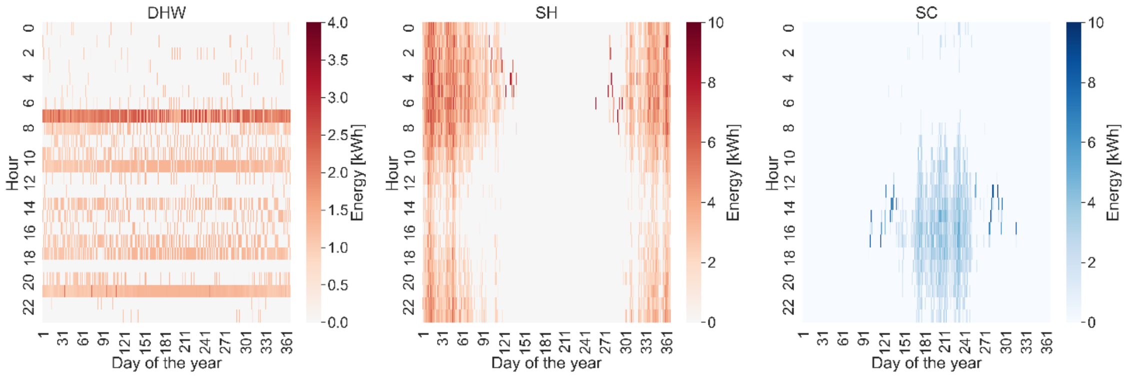

Figure 69: DHW, SH and SC hourly energy consumption; old SFH in the Mediterranean climate

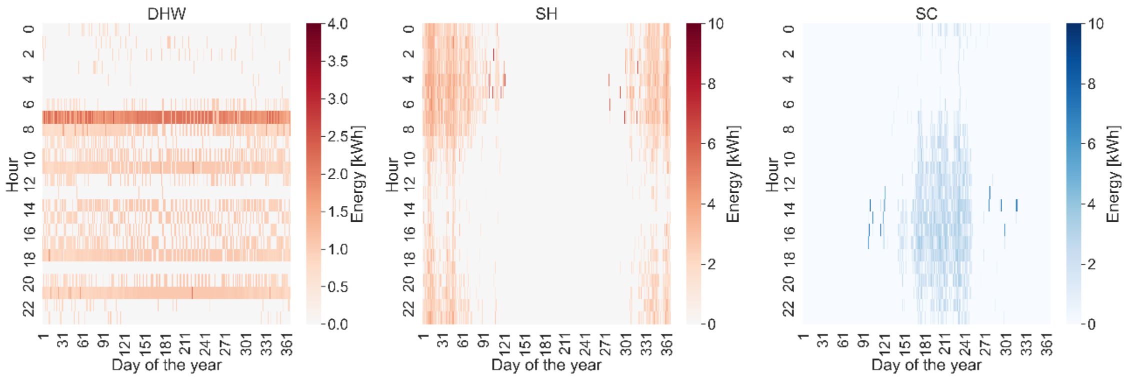

Figure 70: DHW, SH and SC hourly energy consumption; renovated SFH in the Mediterranean climate

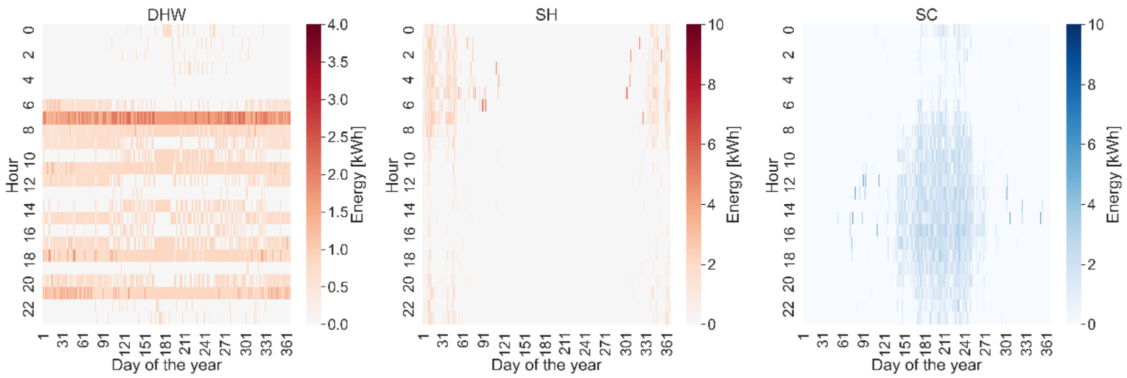

Figure 71: DHW, SH and SC hourly energy consumption; new SFH in the Mediterranean climate

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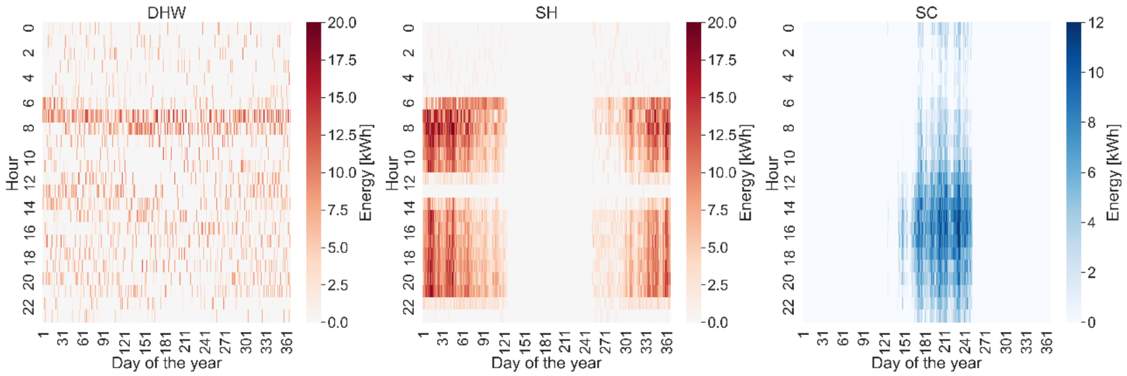

Figure 72: DHW, SH and SC hourly energy consumption; old sMFH in the Mediterranean climate

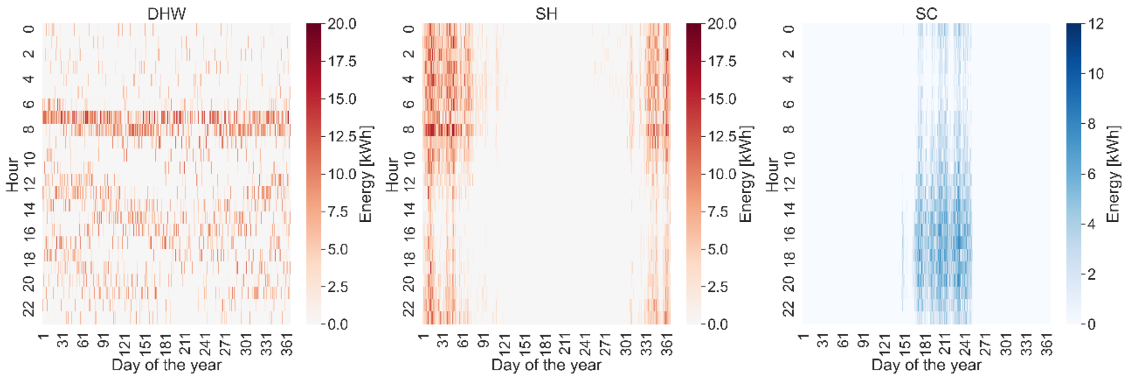

Figure 73: DHW, SH and SC hourly energy consumption; renovated sMFH in the Mediterranean climate

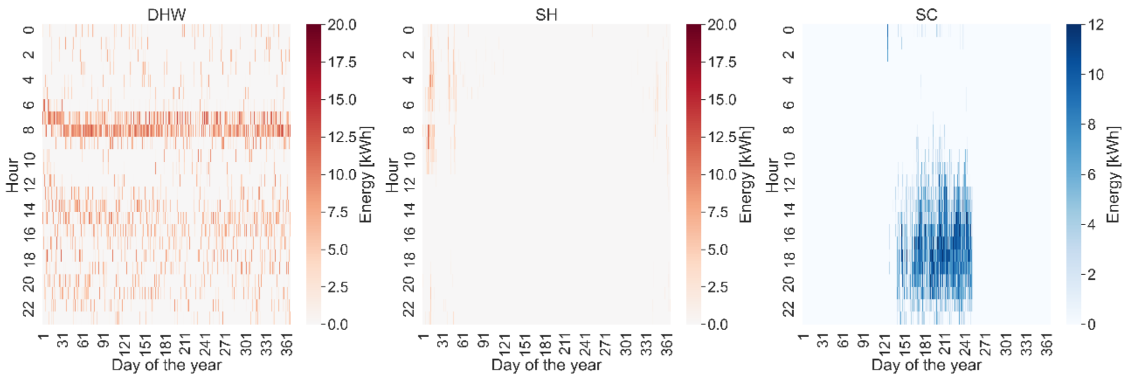

Figure 74: DHW, SH and SC hourly energy consumption; new sMFH in the Mediterranean climate

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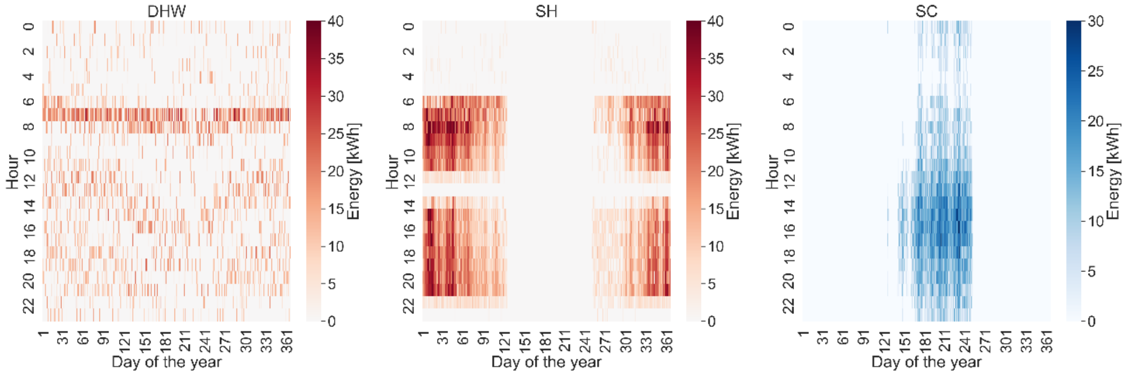

Figure 75: DHW, SH and SC hourly energy consumption; old lMFH in the Mediterranean climate

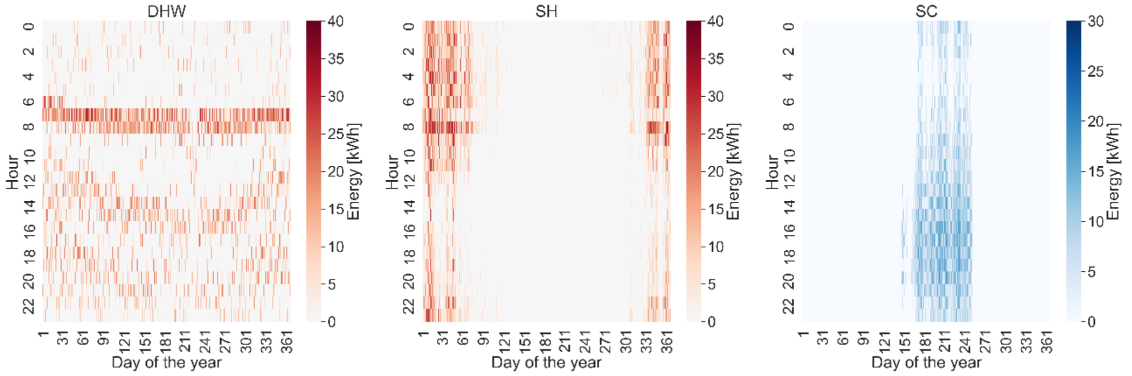

Figure 76: DHW, SH and SC hourly energy consumption; renovated lMFH in the Mediterranean climate

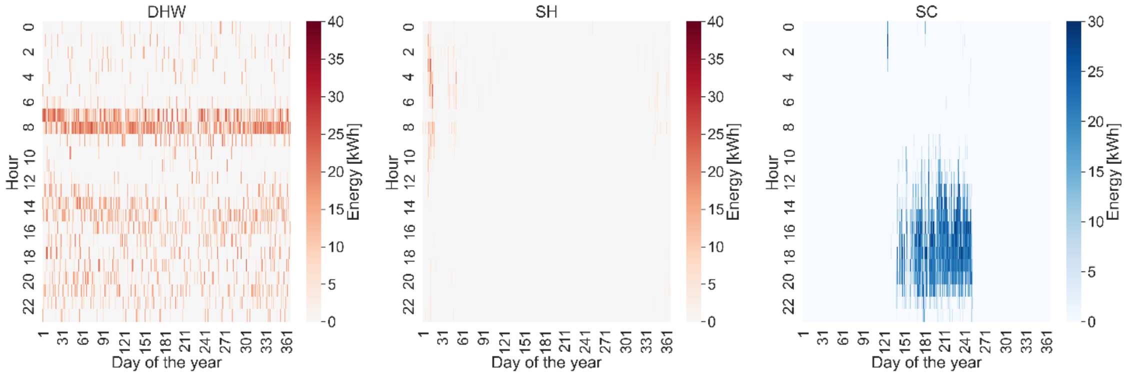

Figure 77: DHW, SH and SC hourly energy consumption; new lMFH in the Mediterranean climate

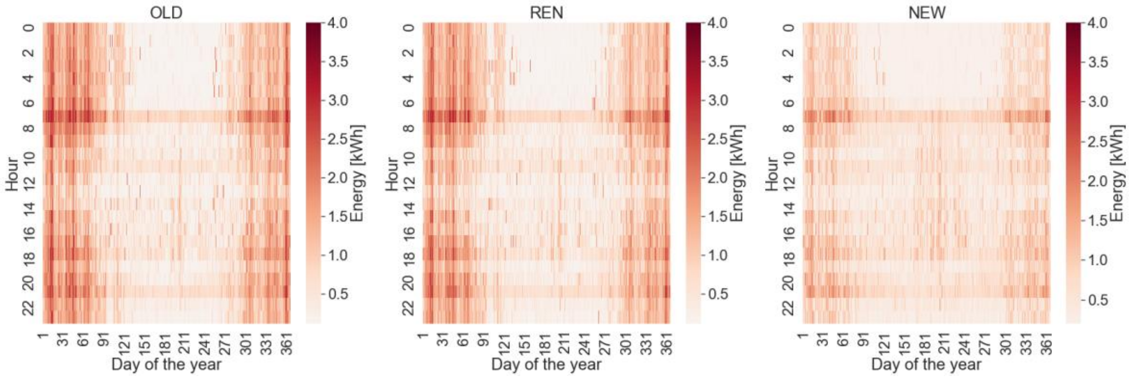

Figure 78: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) SFH in the Nordic climate

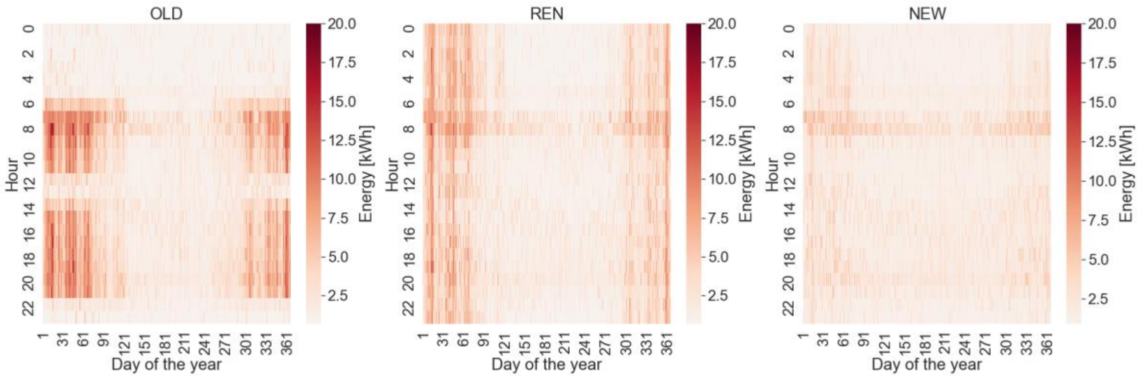

Figure 79: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) sMFH in the Nordic climate

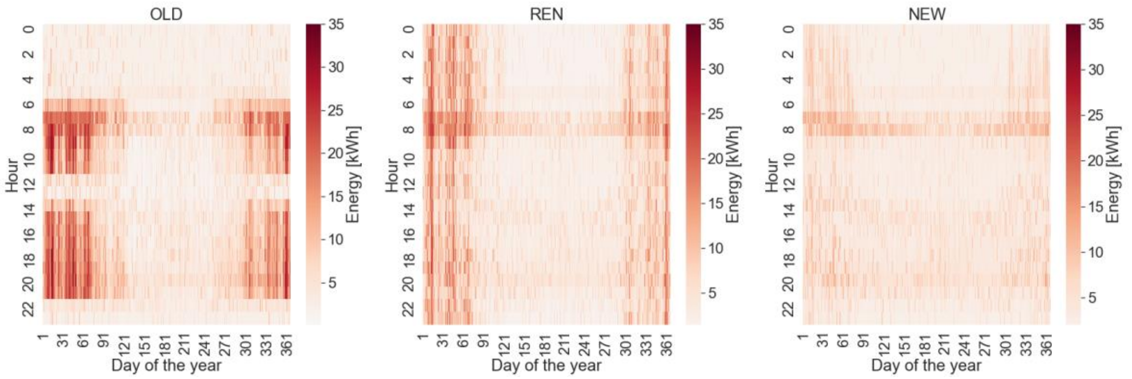

Figure 80: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) lMFH in the Nordic climate

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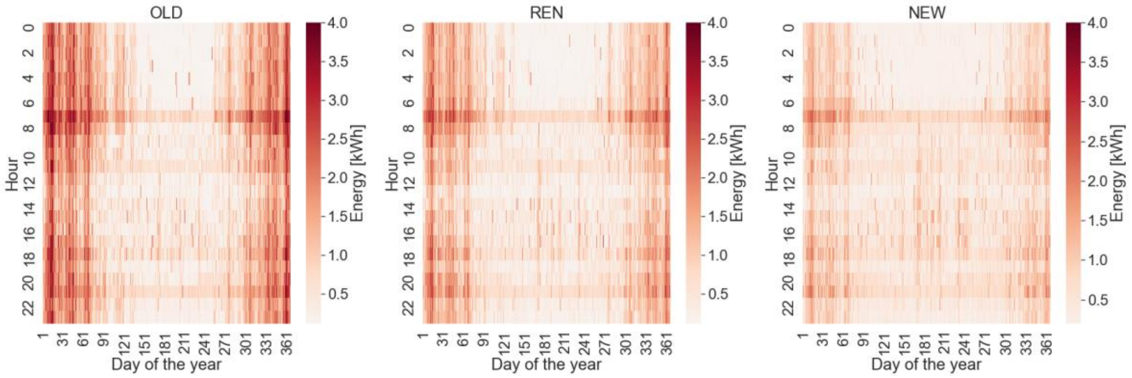

Figure 81: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) SFH in the Continental climate

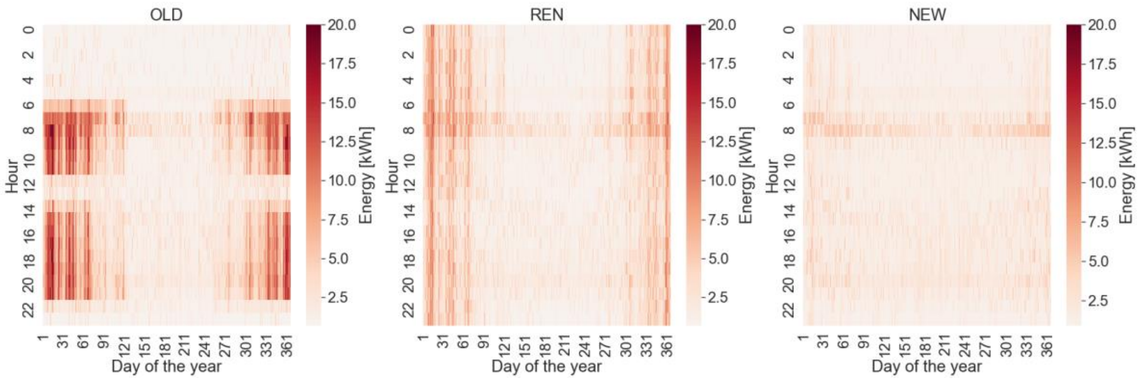

Figure 82: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) sMFH in the Continental climate

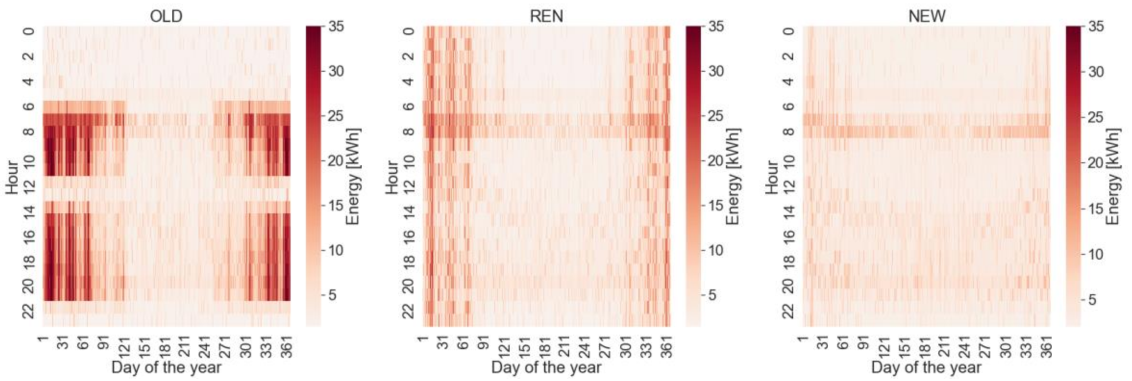

Figure 83: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) lMFH in the Continental climate

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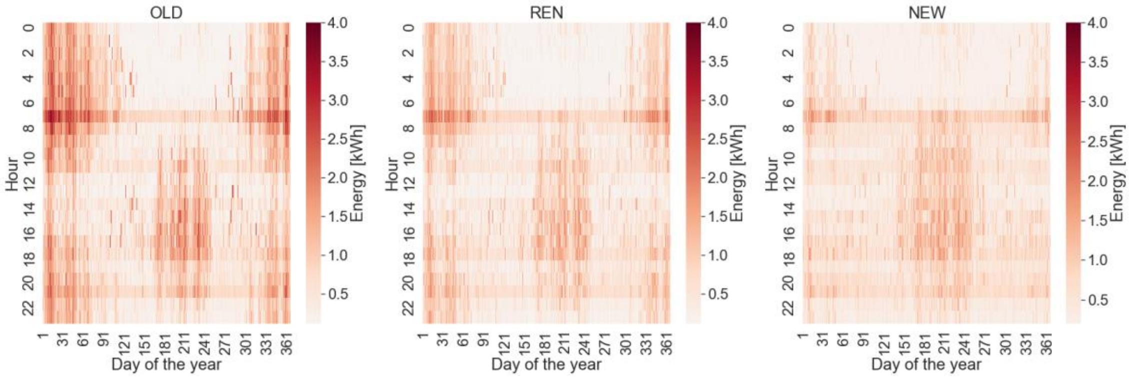

Figure 84: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) SFH in the Mediterranean climate

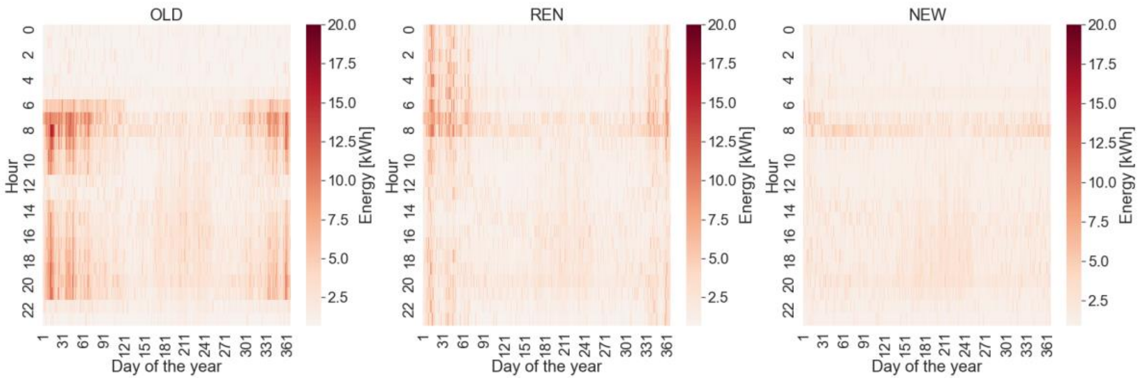

Figure 85: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) sMFH in the Mediterranean climate

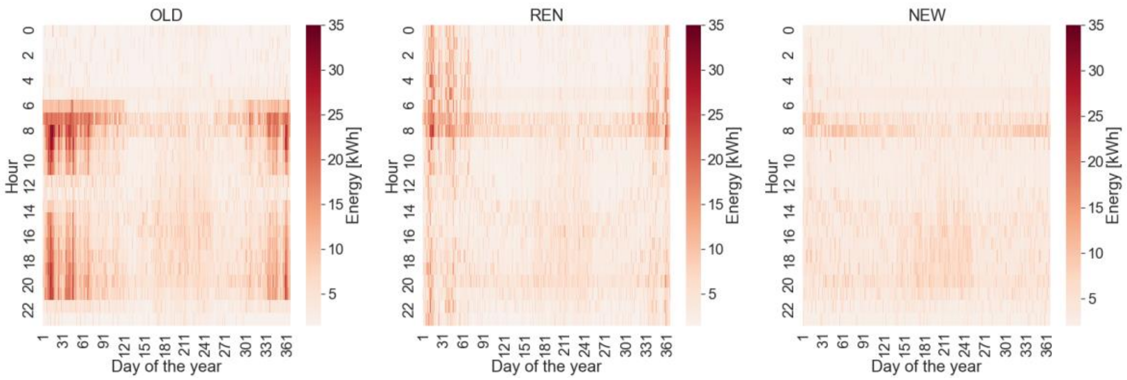

Figure 86: Hourly electrical energy consumption for old (left) renovated (centre) and new (right) lMFH in the Mediterranean climate

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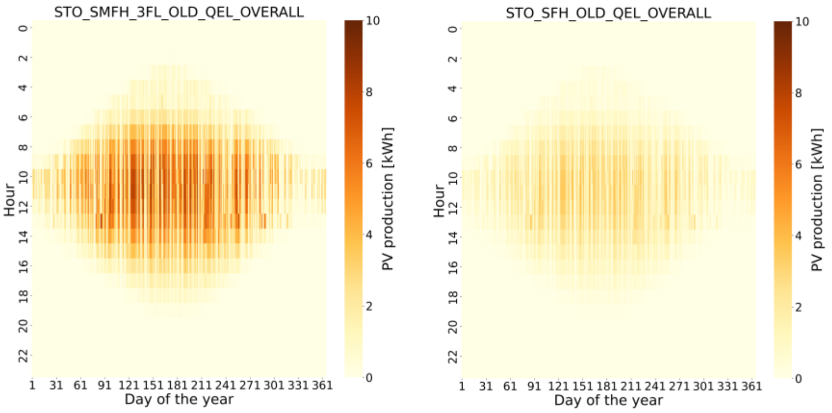

Figure 87: Hourly PV production for sMFH and lMFH (left) and SFH (right) in the Nordic climate

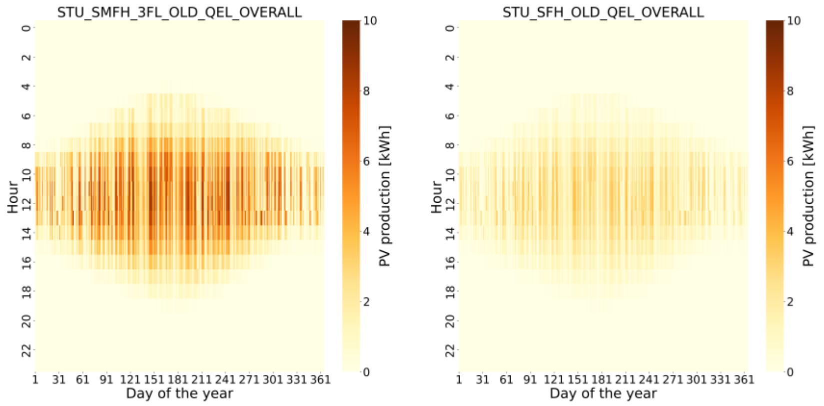

Figure 88: Hourly PV production for sMFH and lMFH (left) and SFH (right) in the Continental climate

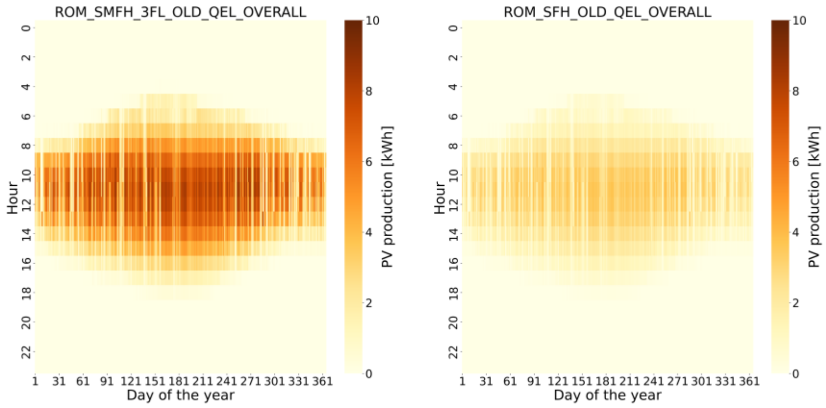

Figure 89: Hourly PV production for sMFH and lMFH (left) and SFH (right) in the Mediterranean climate

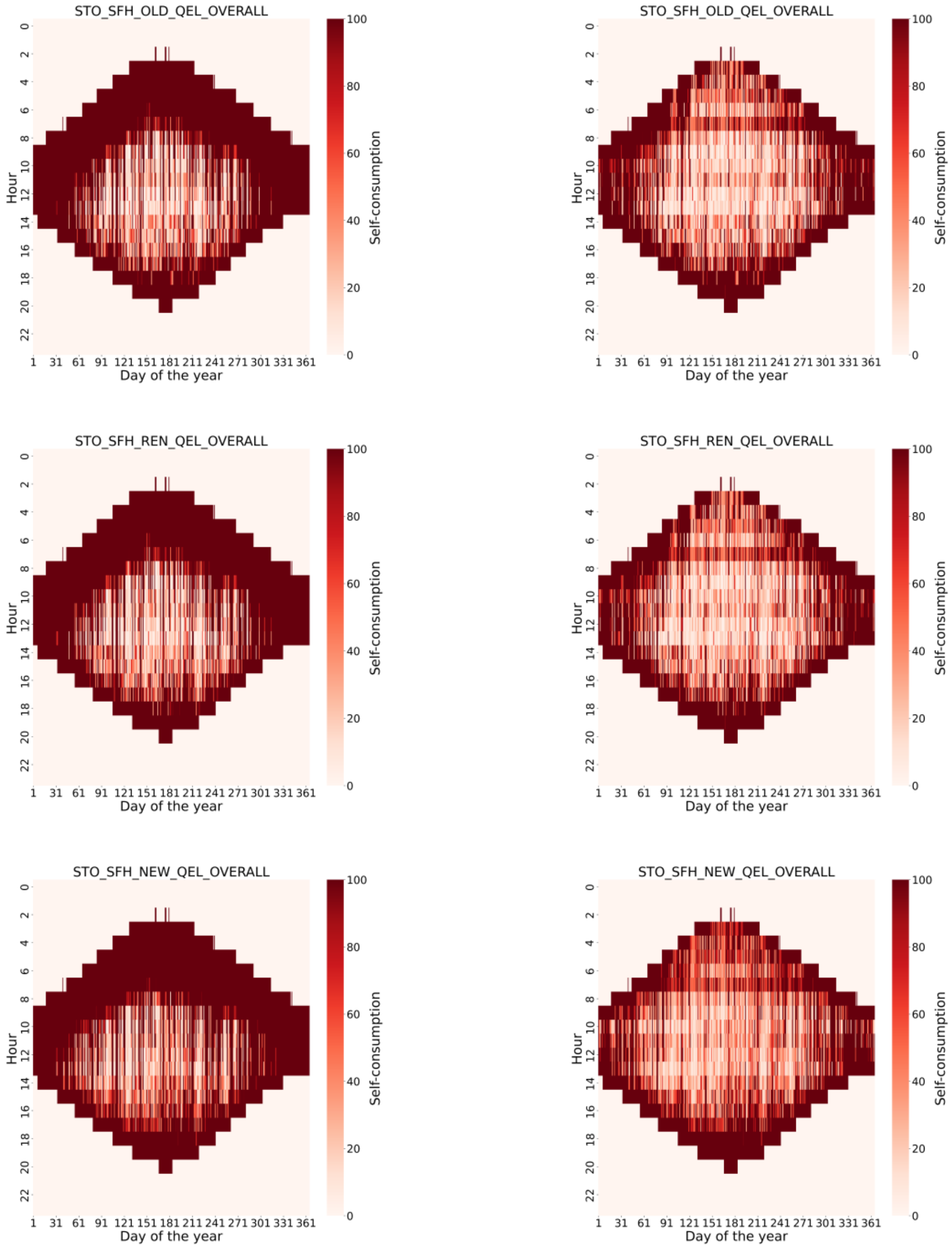

Figure 90: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) SFH in the Nordic climate

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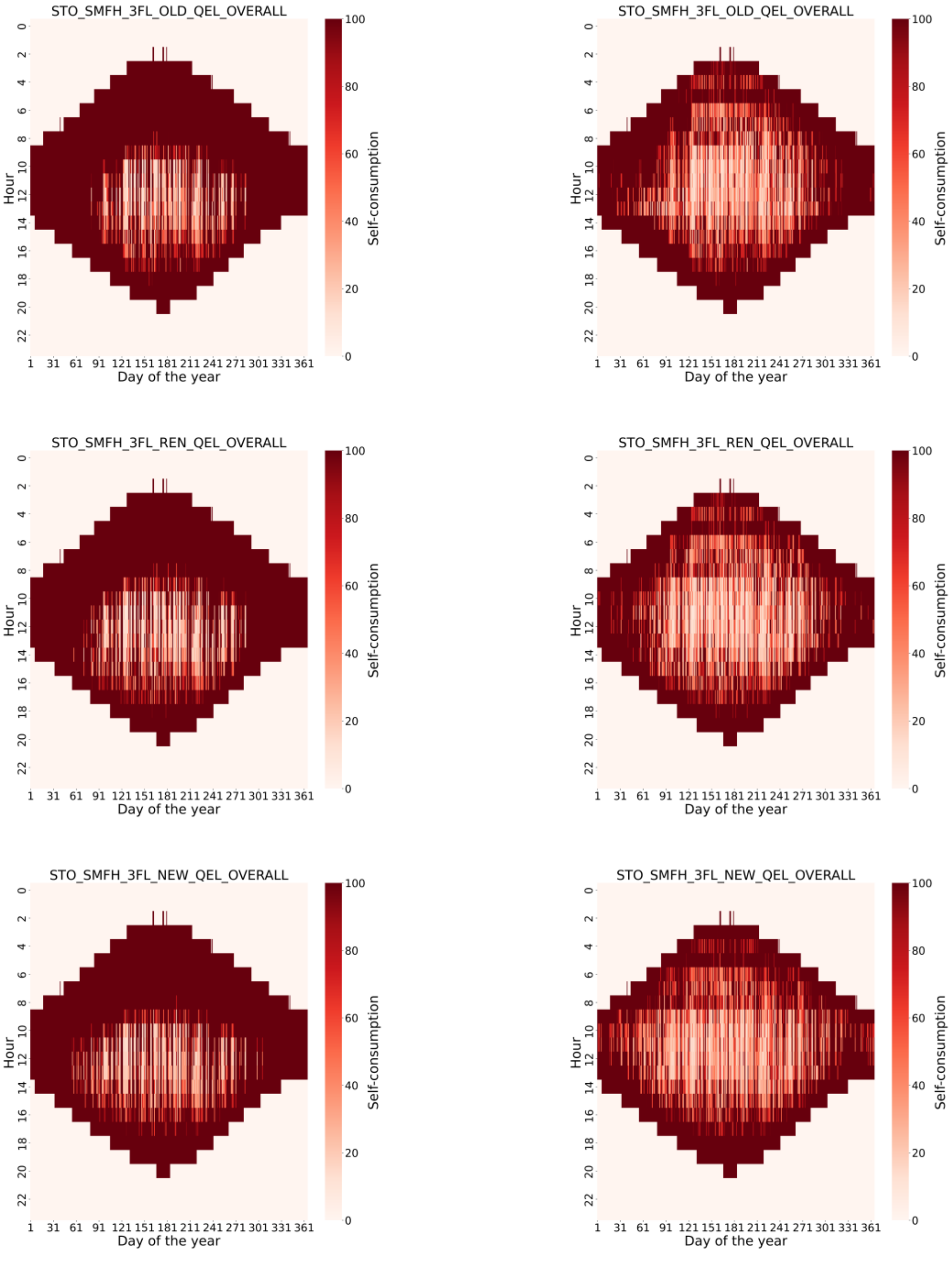

Figure 91: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) sMFH in the Nordic climate

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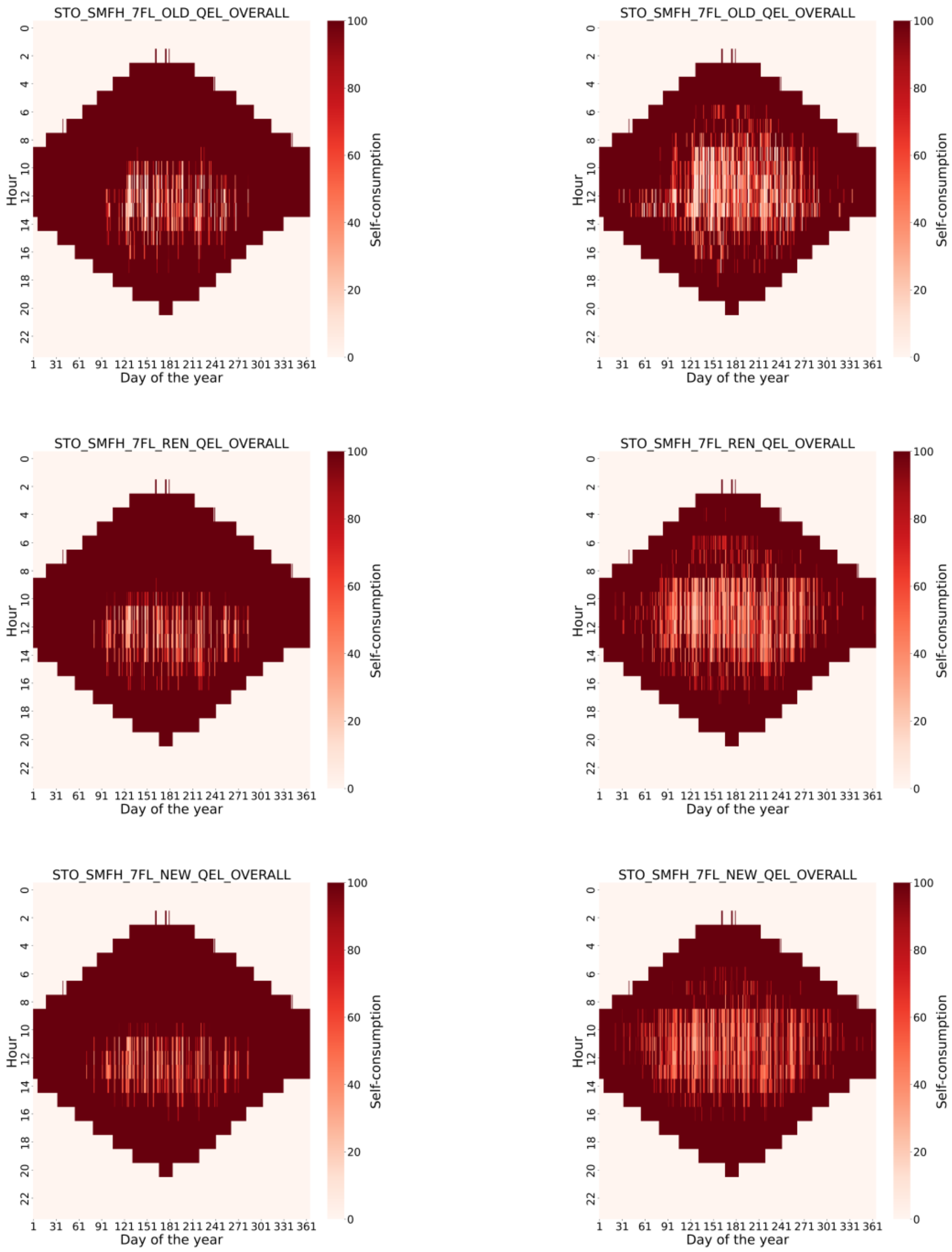

Figure 92: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) lMFH in the Nordic climate

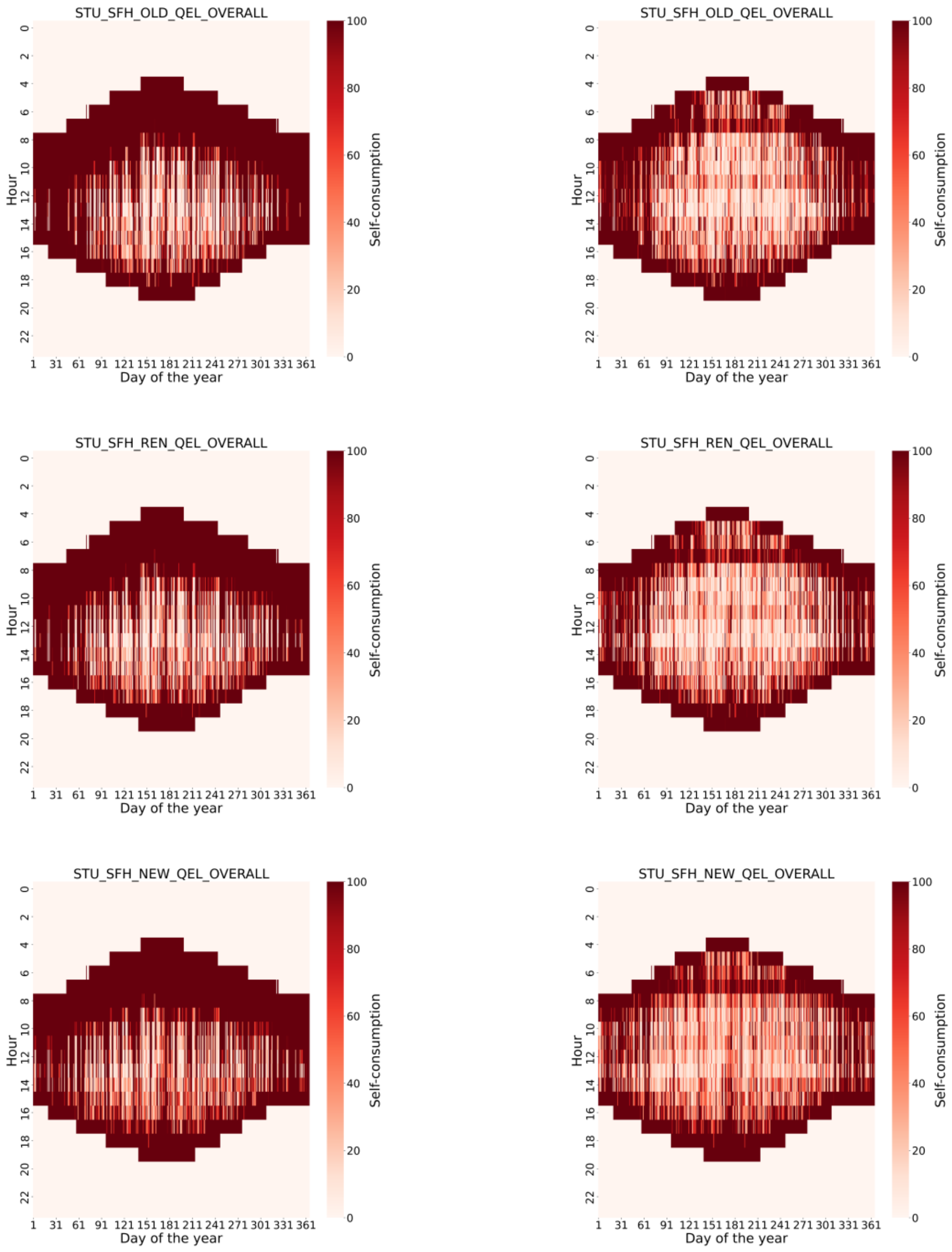

Figure 93: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) SFH in the Continental climate

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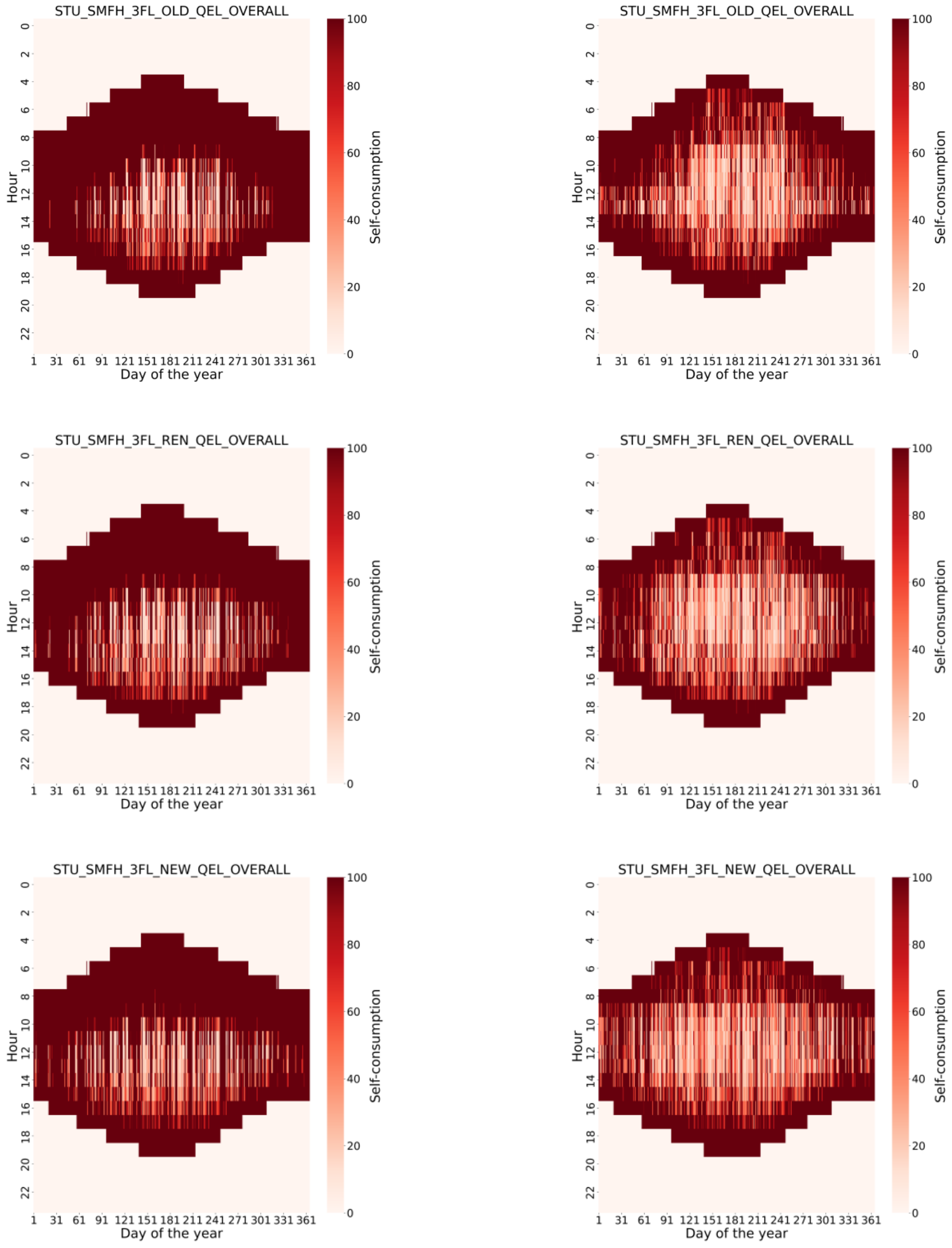

Figure 94: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) sMFH in the Continental climate

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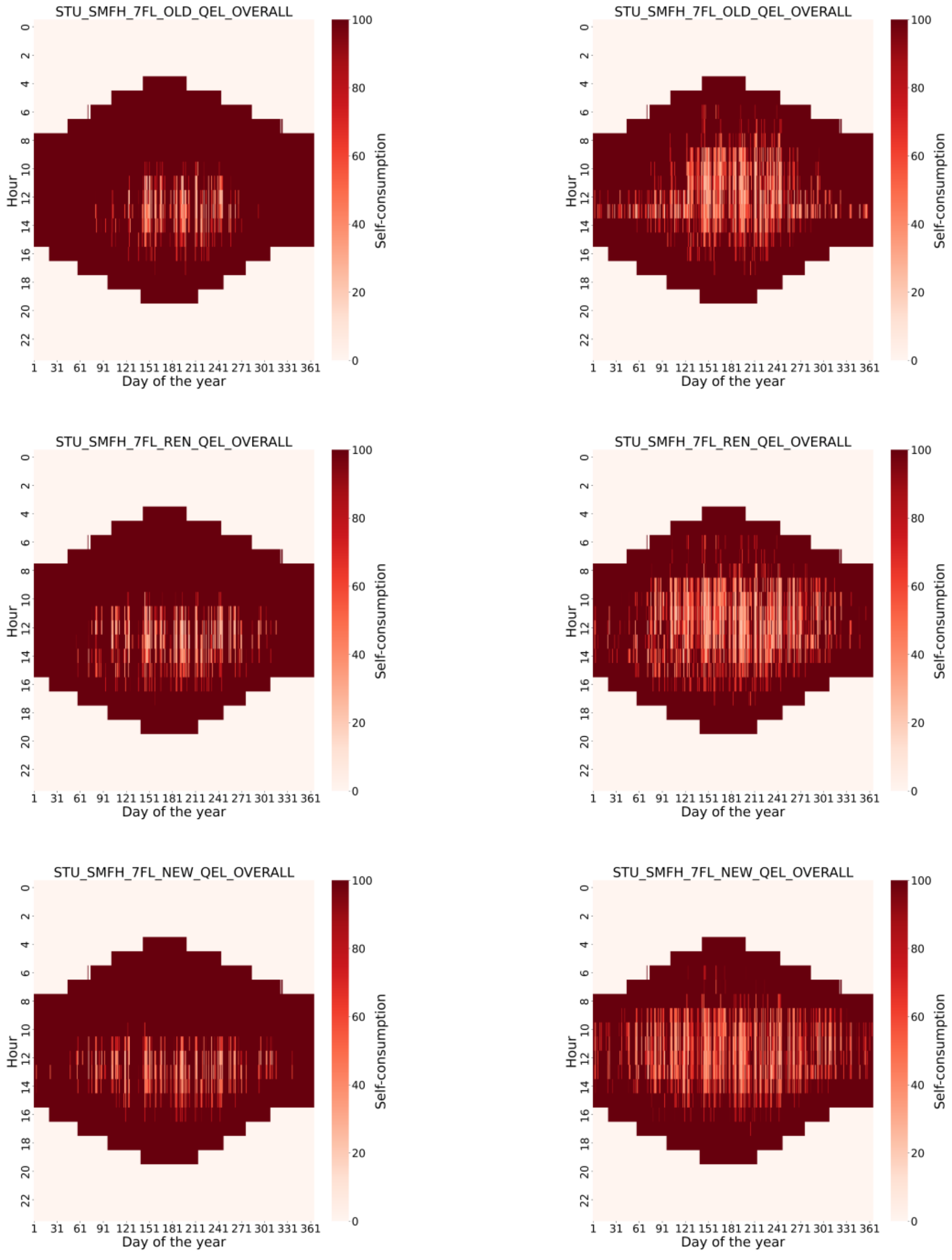

Figure 95: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) lMFH in the Continental climate

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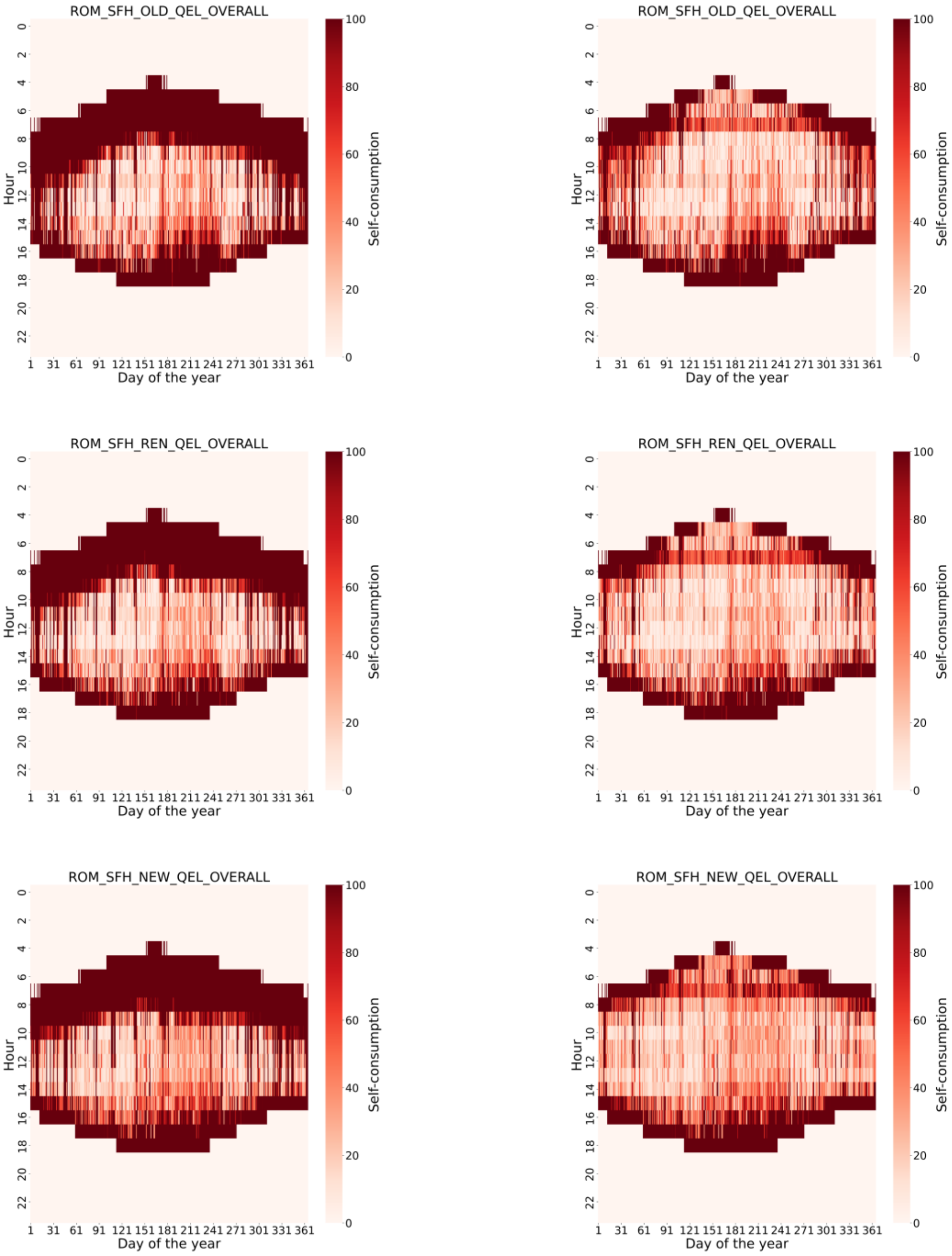

Figure 96: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) SFH in the Mediterranean climate

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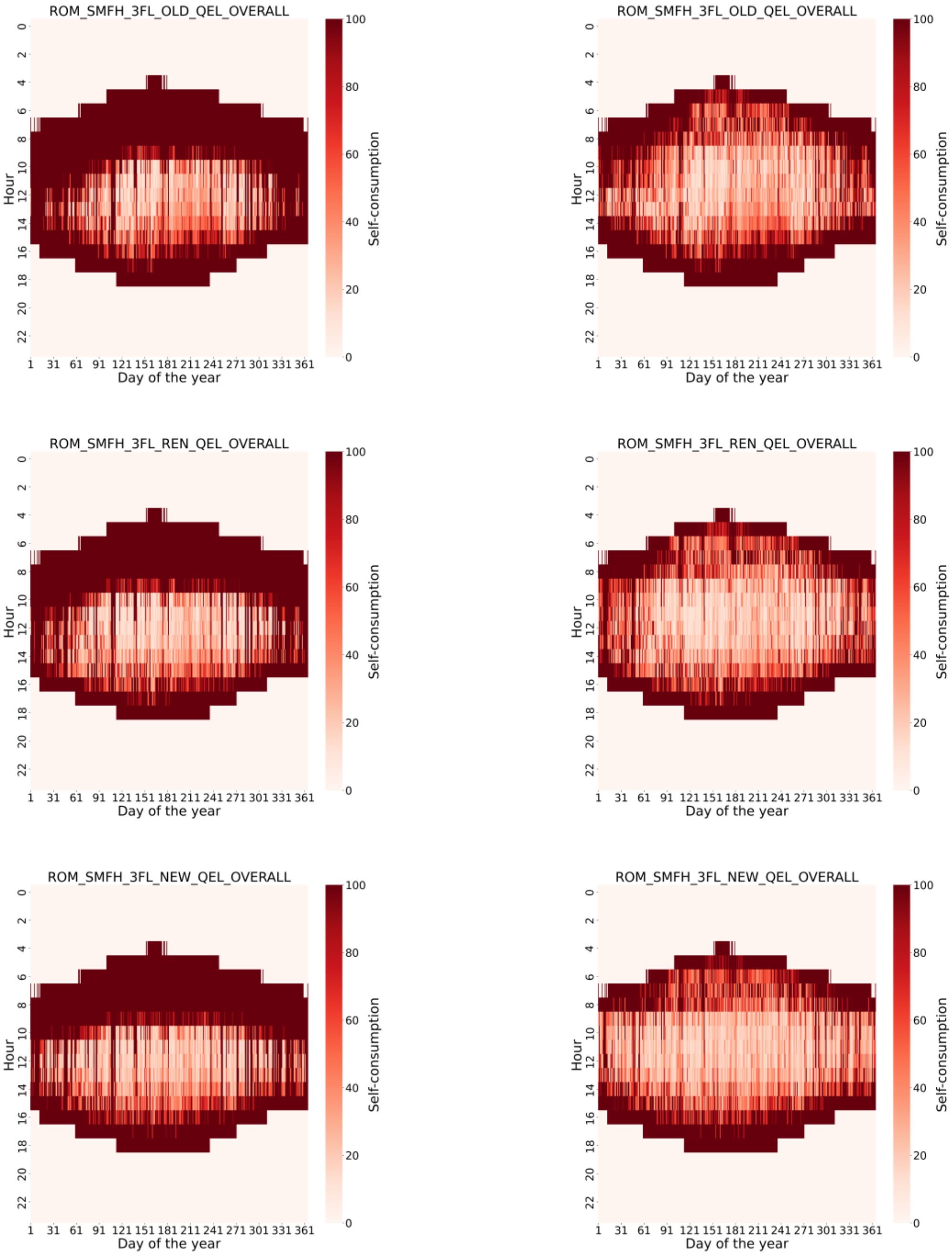

Figure 97: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) sMFH in the Mediterranean climate

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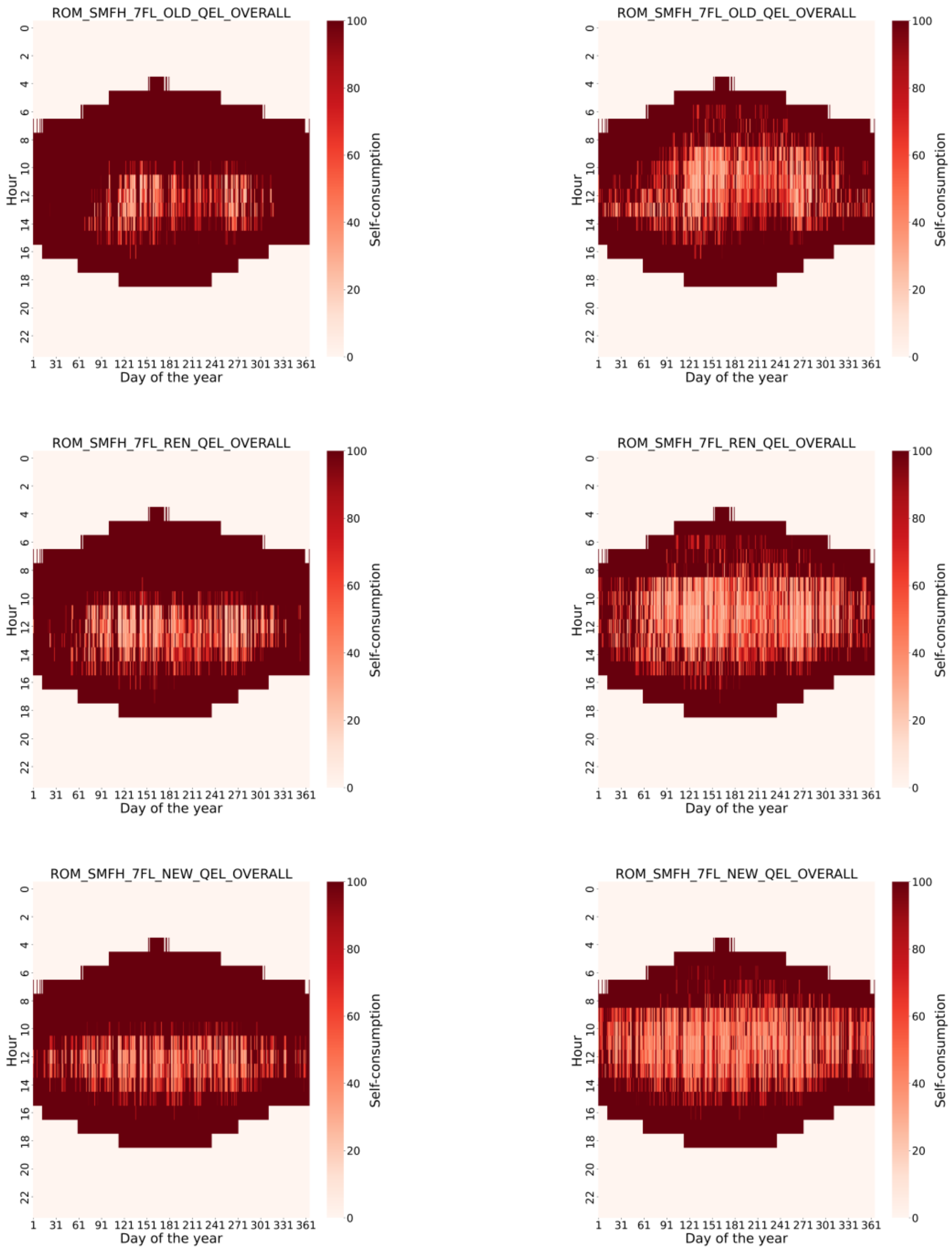

Figure 98: Hourly self-consumption considering PV+BESS (left) and PV only (right); old (top), renovated (centre) and new (bottom) lMFH in the Mediterranean climate

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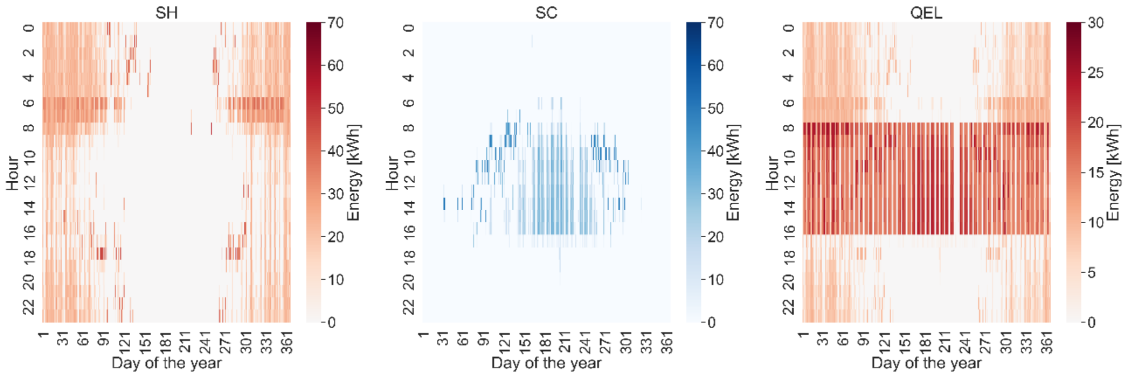

Figure 99: Hourly SH, SC and electrical energy consumption; old office in the Nordic climate

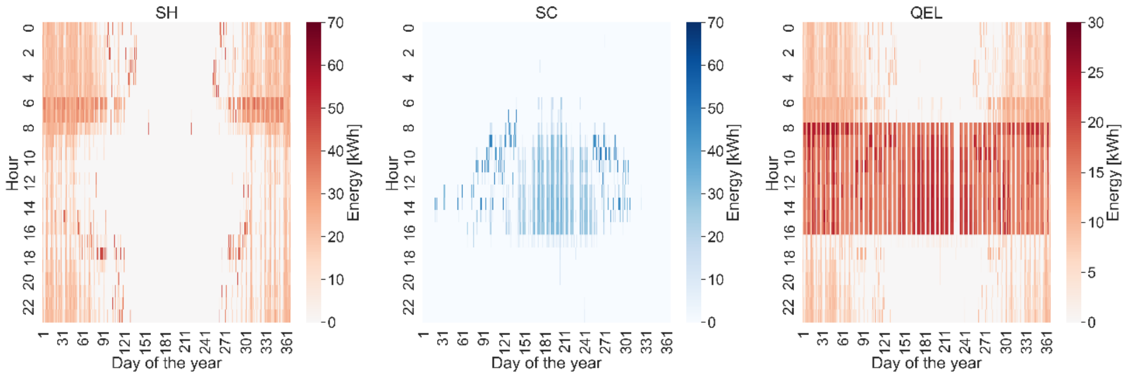

Figure 100: Hourly SH, SC and electrical energy consumption; renovated office in the Nordic climate

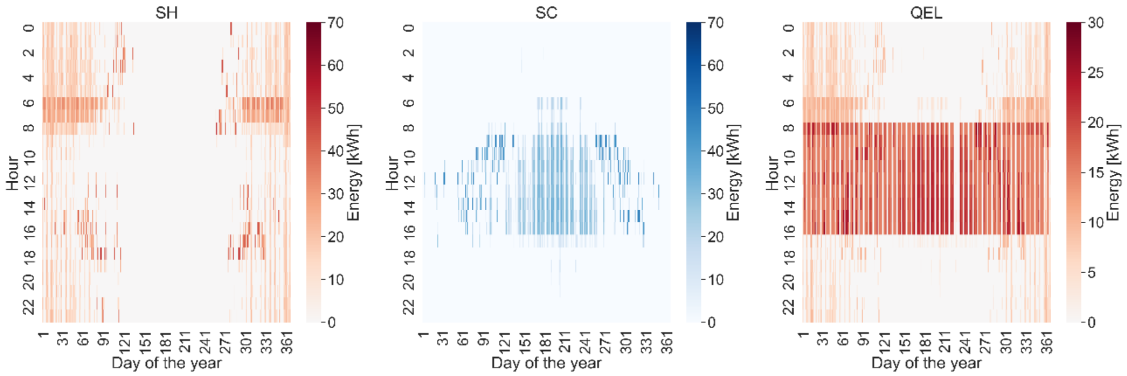

Figure 101: Hourly SH, SC and electrical energy consumption; new office in the Nordic climate

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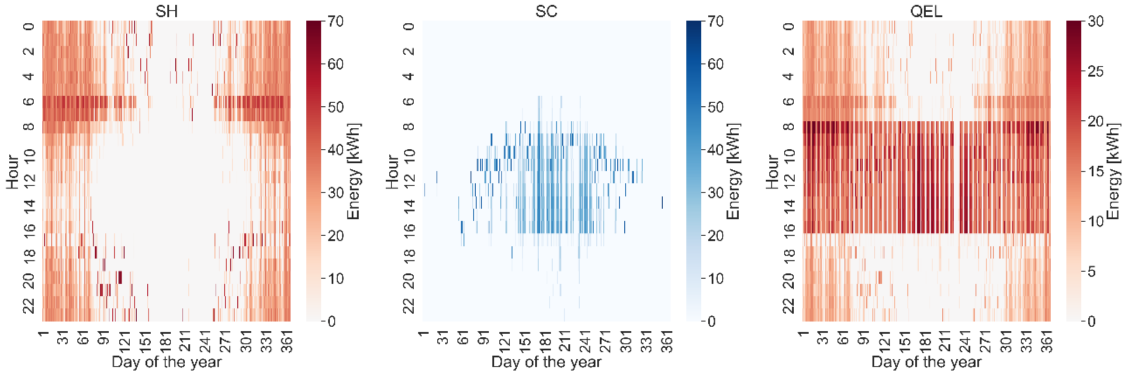

Figure 102: Hourly SH, SC and electrical energy consumption; old office in the Continental climate

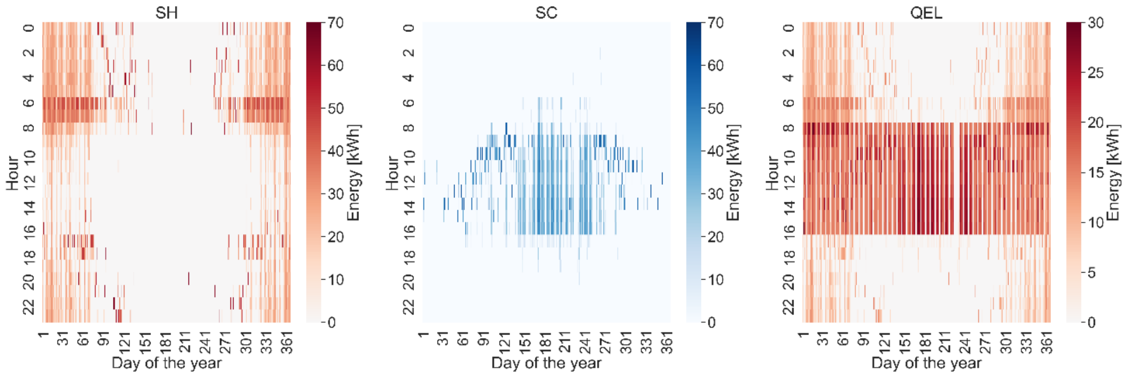

Figure 103: Hourly SH, SC and electrical energy consumption; renovated office in the Continental climate

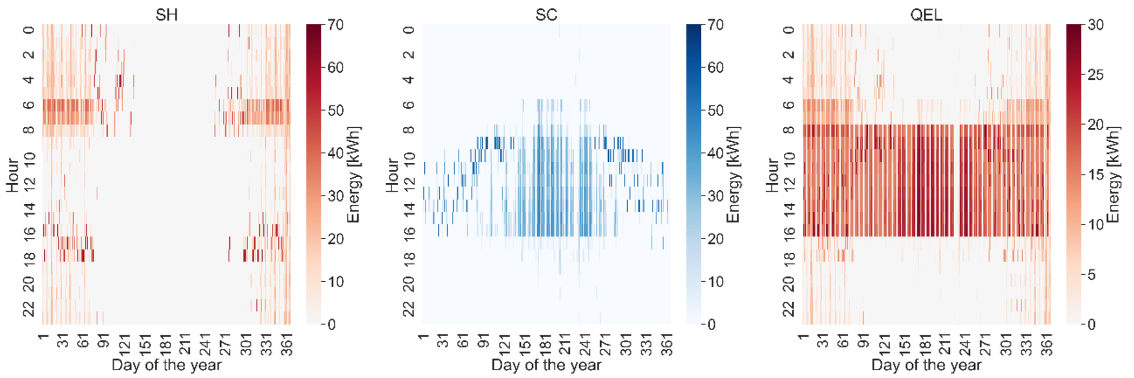

Figure 104: Hourly SH, SC and electrical energy consumption; new office in the Continental climate

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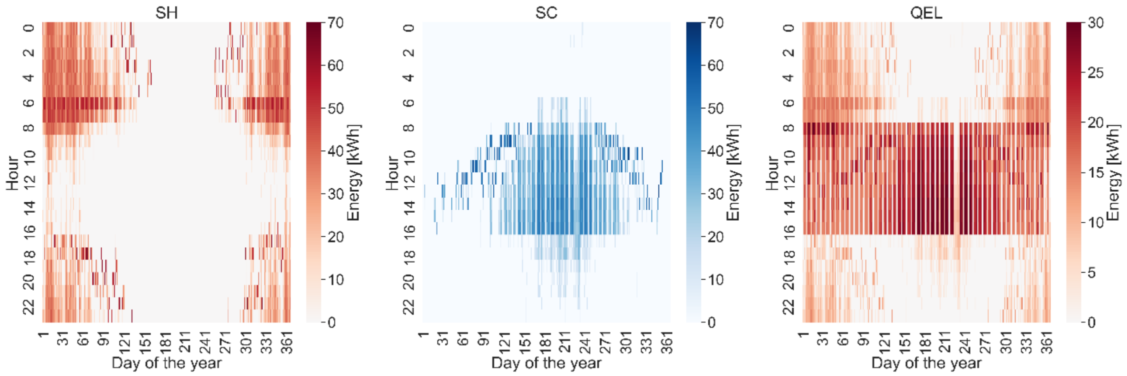

Figure 105: Hourly SH, SC and electrical energy consumption; old office in the Mediter. climate

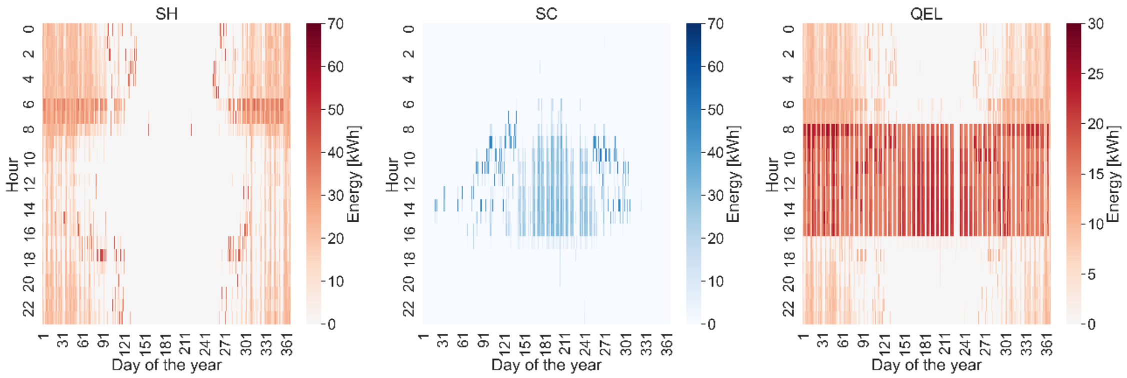

Figure 106: Hourly SH, SC and electrical energy consumption; renovated office in the Mediter. climate

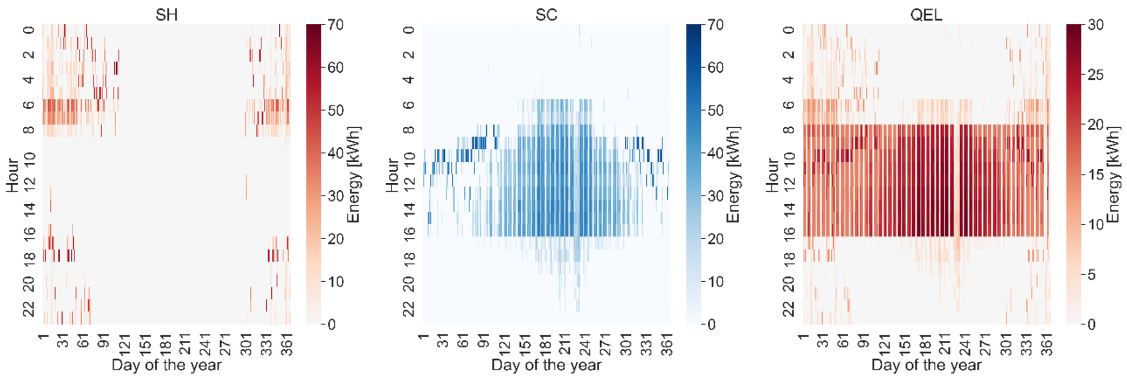

Figure 107: Hourly SH, SC and electrical energy consumption; new office in the Mediter. climate

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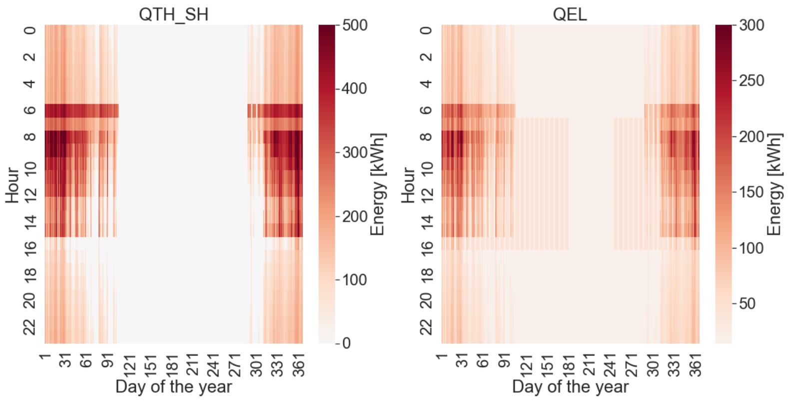

Figure 108: Hourly SH and electrical energy consumption; old school in the Nordic climate

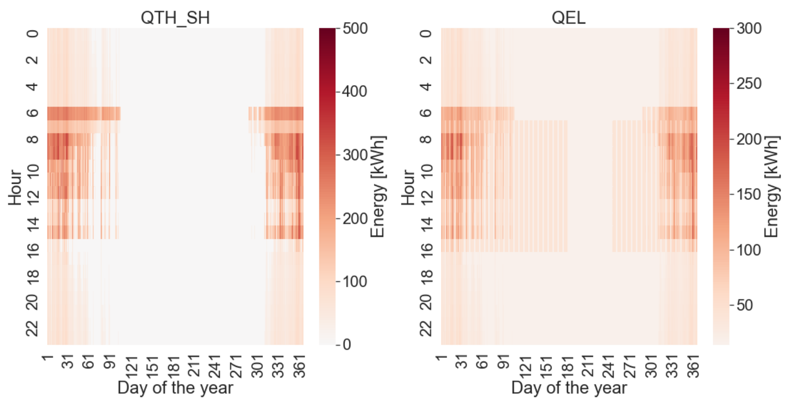

Figure 109: Hourly SH and electrical energy consumption; renovated school in the Nordic climate

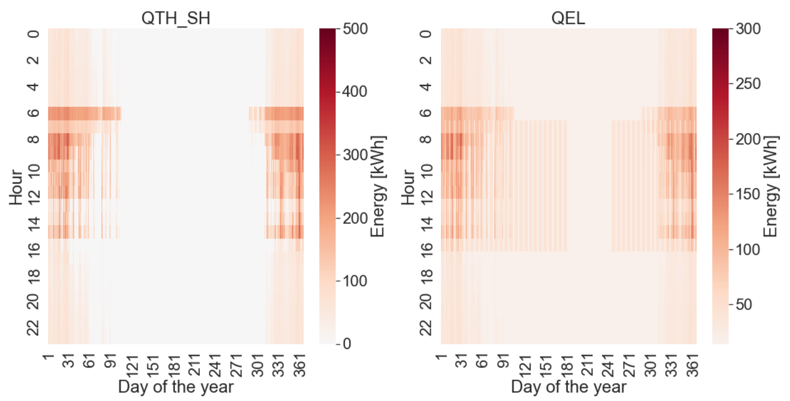

Figure 110: Hourly SH and electrical energy consumption; new school in the Nordic climate

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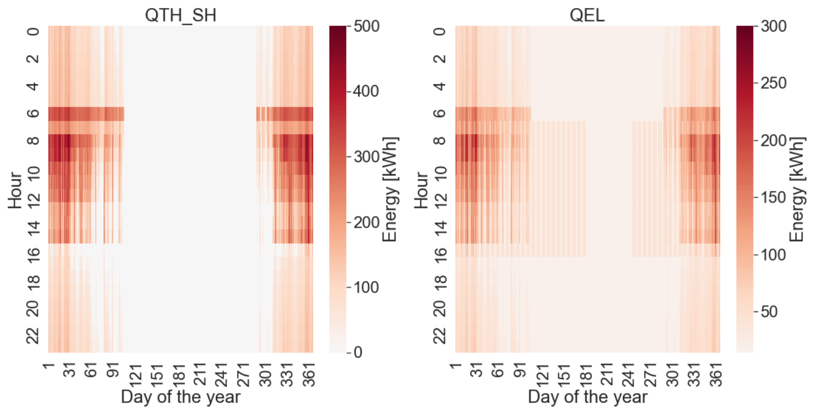

Figure 111: Hourly SH and electrical energy consumption; old school in the Continental climate

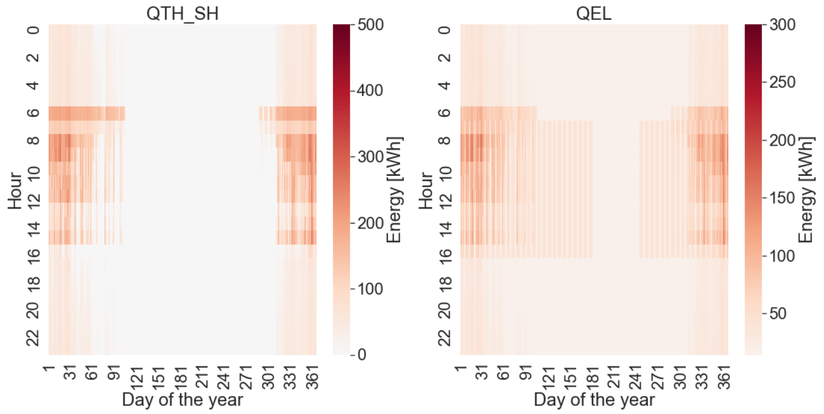

Figure 112: Hourly SH and electrical energy consumption; renovated school in the Continental climate

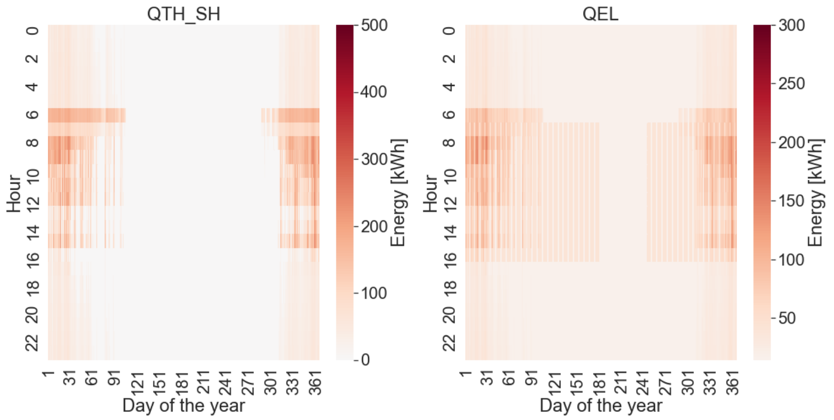

Figure 113: Hourly SH and electrical energy consumption; new school in the Continental climate

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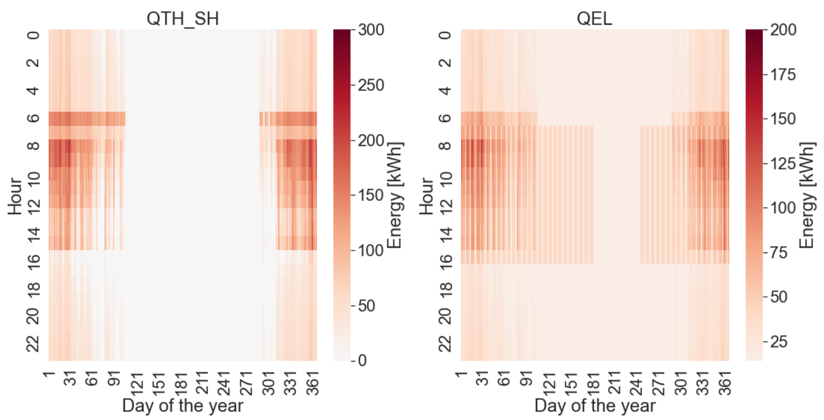

Figure 114: Hourly SH and electrical energy consumption; old school in the Mediterranean climate

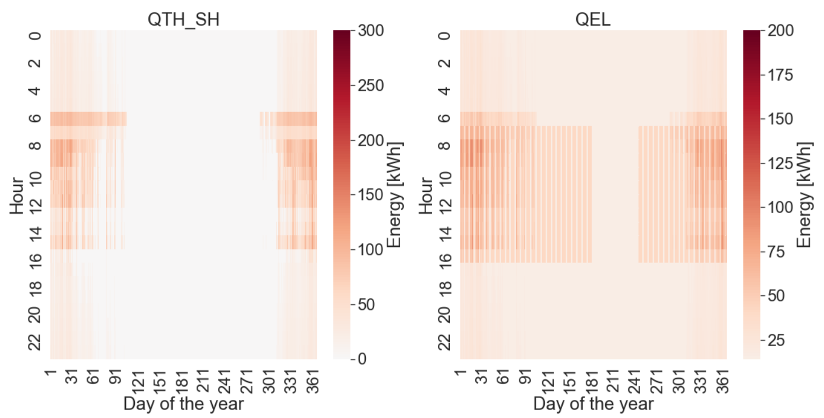

Figure 115: Hourly SH and electrical energy consumption; renovated school in the Mediterranean climate

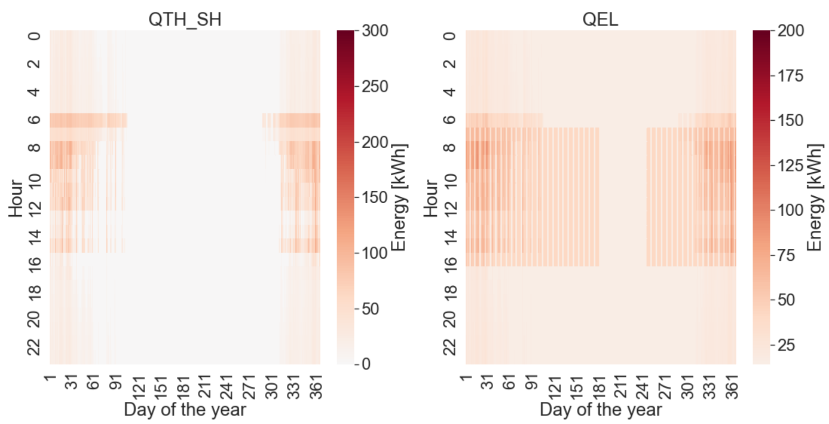

Figure 116: Hourly SH and electrical energy consumption; new school in the Mediterranean climate

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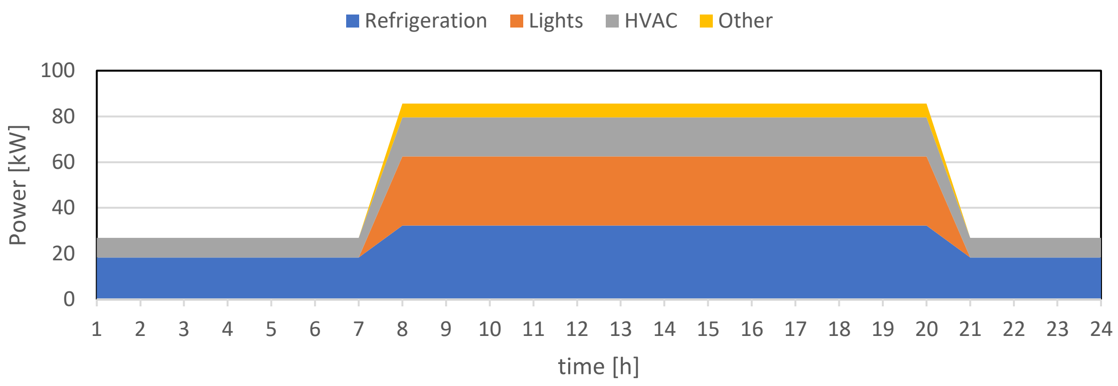

Figure 117: Electrical consumption contributions due to refrigeration, lights, HVAC system and other electrical consumptions in a supermarket in a typical day

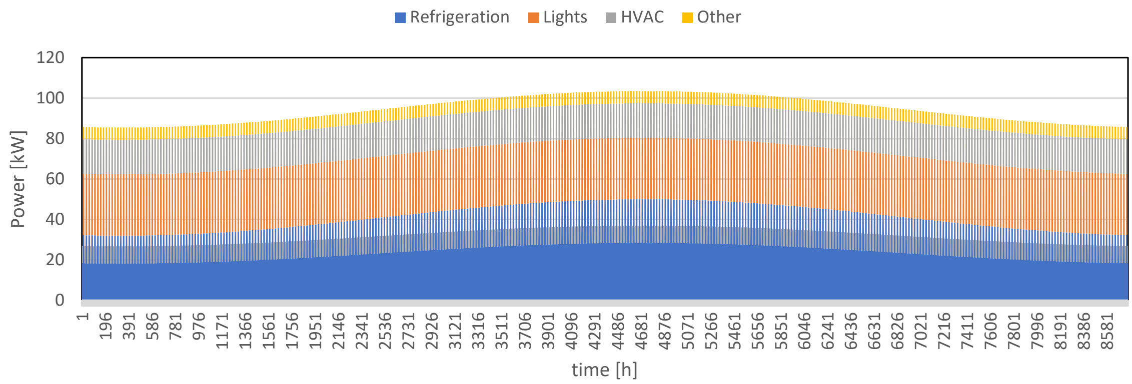

Figure 118: Electrical consumption contributions due to refrigeration, lights, HVAC system and other electrical consumptions in a supermarket along the year

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