TÉCNICO LISBOA

Optimization of the electrical and thermal microgrids for a nearly zero-energy building located in Lisbon

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ABSTRACT

This work is part of the European project IMPROVEMENT focusing on the challenge of renewable energy systems integration and energy efficiency improvement in public buildings for SUDOE region. The aim of the thesis is to develop a model for conducting optimization of operating costs for electrical grid using energy systems modelling tool for linear optimization OMEGAlpes. Additional objective is to minimize the imports from the heating network by maximizing self-consumption. In the work is described nZEB characteristics, review of technologies and nomenclature, the main characteristics of OMEGAlpes tool.

The model is developed with OMEGAlpes using Python programming language for a building located on the Lumiar campus of LNEG in Lisbon, Portugal for one week period in May. In the building there are installed electrical and thermal systems for self-production (PV and ST panels) together with energy storage units (battery and water tank). The whole system is supported by a heat pump that uses electricity from PV panels to back up the heat load. The building is also connected to electrical and heating grids in case the self-production is insufficient to cover the loads.

As a result of the optimization process, a decrease in the electricity costs of 58% is obtained. The optimal storage capacities for the considered system are also established equal 21 kWh for the electrical storage and 90 l for the thermal storage. Thermal load is entirely covered from self-production together with water tank and a heat pump. No additional heat imports from the network are necessary.

Keywords: nearly zero-energy building, microgrids, optimization, OMEGAlpes.

RESUMO

Este trabalho faz parte do projeto europeu IMPROVEMENT centrado no desafio da integração de sistemas de energias renováveis e melhoria da eficiência energética em edifícios públicos para a região SUDOE. O objetivo da tese é desenvolver um modelo para conduzir a otimização dos custos operacionais da rede elétrica utilizando a ferramenta de modelização de sistemas de energia para a otimização linear OMEGAlpes. O objetivo adicional é minimizar as importações da rede de aquecimento através da maximização do autoconsumo. No trabalho é descrito as características nZEB, revisão de tecnologias e nomenclatura, as principais características da ferramenta OMEGAlpes.

O modelo é desenvolvido com OMEGAlpes utilizando a linguagem de programação Python para um edifício localizado no campus Lumiar do LNEG em Lisboa, Portugal, por um período de uma semana em maio. No edifício estão instalados sistemas elétricos e térmicos para autoprodução (painéis PV e ST) juntamente com unidades de armazenamento de energia (bateria e reservatório de água). Todo o sistema é suportado por uma bomba de calor que utiliza eletricidade de painéis fotovoltaicos para suportar a carga térmica. O edifício está também ligado a redes elétricas e de aquecimento caso a autoprodução seja insuficiente para cobrir as cargas.

Como resultado do processo de otimização, obtém-se uma diminuição dos custos de eletricidade de 58%. As capacidades ótimas de armazenamento para o sistema considerado são também estabelecidas iguais a 21 kWh para o armazenamento elétrico e 90 l para o armazenamento térmico. A carga térmica é inteiramente coberta pela autoprodução juntamente com um tanque de água e uma bomba de calor. Não são necessárias importações adicionais de calor da rede.

Palavras-chave: Edifícios (Quase) Energia Zero, micro-redes, otimização, OMEGAlpes.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

+ZEB	Energy Plus Building
DOE	Department of Energy
EPBD	Energy Performance of Buildings Directive
EPS	Expanded Polystyrene
IoT	Internet of Things
LNEG	National Energy and Geology Laboratory Campus
MILP	Mixed-Integer Linear Program
nZEB	Nearly Zero-Energy Building
PCM	Phase Change Material
PEB	Positive Energy Building
PV	Photovoltaic panels
RES	Renewable Energy Sources
SIM	Super-Insulation Materials
ST	Solar Thermal collectors
VIP	Vacuum Insulation Panel
ZCH	Zero Carbon Home
ZEB	Zero Energy Building / Zero Emission Building

1 INTRODUCTION

Global energy sector is undergoing constant transition towards more sustainable, carbon-neutral system. In pursue of the reduction of the impact on the environment, the building stock has been identified as a sector that could significantly contribute to achieving the EU climate and energy targets. Buildings represent the largest sector in the final energy consumption in Europe, consuming about 40% of the total final energy, of which 27% constitutes residential buildings and 13% non-residential buildings [1]. The building stock in the EU Member States is relatively old, with 45% built pre-1970 and 75% built pre-1990, before widespread adoption of energy regulations [2]. The energy performance of a large share of the existing buildings is inadequate, as around 75% of the building stock is considered to be energy inefficient [3]. The rate of buildings renovation is estimated around 1.2%. In addition to the existing buildings, the current stock is expected to increase due to new constructions at a rate of 1% per year [4]. Consequently, reduction of the energy consumption in the building sector has become an important strategy in the European energy policies.

The Energy Performance of Buildings Directive (EPBD) 2010/31/EU sets the standards for new and already existing buildings across Europe. It introduces nearly Zero-Energy Building (nZEB) as the new construction target. The directive also establishes that all new buildings have to be nZEB buildings by December 31, 2020 and requires that new buildings owned by public authorities are nZEB buildings already after December 31, 2018 [5]. The amending Directive 2018/844 underlines the need for long-term measures to reduce the final energy consumption from the building sector and decarbonize the building stock, which is estimated to be responsible for around 36% of all greenhouse gas emissions in the Member States, by year 2050 [6].

While designing and constructing new buildings with high performance levels and in compliance with the nZEB requirements seems a pretty straightforward transition, it is the older, already existing buildings that pose a real challenge. As demolition and rebuilding is neither an economically viable nor an environmentally friendly solution at a large scale, introduction of the renovation and retrofitting strategies of the building stock is necessary. The existing buildings, which are predominantly of low energy performance, represent the vast majority of the building stock, therefore they have a great unrealized potential to deliver high energy and CO_2 savings, and benefit overall energy security throughout the EU.

Addressing the problem of buildings retrofitting is a European project IMPROVEMENT. This project focuses on the challenge of renewable energy systems integration and energy efficiency improvement in public buildings with critical loads (e.g. medical or scientific centers) and converting those buildings into nearly zero-energy public buildings by means of integration of combined cooling, heating and power microgrids under requirements of high power quality and continuity of service. The project is developed for typical climatic conditions of SUDOE region (Southwest of Europe), characterized by cold winters and extremely hot summers, which results in a highly seasonal dependent renewable energy generation.

The project develops technology for two pilot buildings: LNEG in Lisbon, Portugal and Hospital Axarquia in Spain, to be used as prototypes for future integration in public buildings, where sensible high-tech equipment is predominant, in the SUDOE region. For buildings with sensitive loads, power quality and continuity of supply are fundamental aspects, e.g. for sanitary reasons in hospitals, scientific considerations in universities and technological centers or security reasons in banks and airports. Those buildings require large amounts of electricity, steam for space heating and hot water, and energy for ventilation and cooling. They also often operate equipment with extreme sensibility to power disturbances.

IMPROVEMENT project aims to increase energy efficiency of public buildings by switching from fossil fuels based energy generation to direct production using solar power. The intermittency of renewable resources is to be solved by introduction of hybrid energy storage systems. Incorporation of Internet of Things (IoT) power quality sensors constitutes a key solution to solve the power quality issues introduced by renewable energies in the system. The project improves the energy reliability, security and autonomy of existing buildings which loads may be considered challenging, and provides energy and CO_2 savings. The developed technology may be expanded to other regions of the world and adapted to different climatic conditions.

1.1 Objectives

This work is part of the European project IMPROVEMENT and will develop, validate and demonstrate a system for the modernization of existing public buildings, converting them into nZEB buildings by integrating micro-networks of combined heat, cold and electricity generation with storage systems in a system designed for typical climatic conditions of SUDOE regions.

Specifically, the thesis will focus on optimization of operating costs for electrical microgrid in a public building located on the Lumiar campus of LNEG in Lisbon using energy systems modelling tool for linear optimization called OMEGAlpes.

1.2 Structure of the thesis

This work focuses on the optimization of the work of a microgrid for a nearly zero-energy office building located in Lisbon using OMEGAlpes tool. The first section describes nZEB building characteristics, reviews technologies and nomenclature. Additionally, the main characteristics of OMEGAlpes, structure and graphical representation are detailed. The next section focuses on the optimization model developed with OMEGAlpes modelling tool using Python programming language, together with discussion of results.

2 LITERATURE REVIEW

2.1 Nearly Zero-Energy Building (nZEB)

The already mentioned EPBD Directive 2010/31/EU, which introduces the nZEB as a construction target, also provides a general definition of the term. It states that nearly Zero-Energy Building means a building with a very high energy performance, requiring nearly zero or very low amount of energy which should be covered to a significant extent by energy produced on-site or nearby from renewable sources [5]. The referenced definition presents no unified standard and can be subject to different interpretations, as the EPBD indicates that there cannot be a single performance level for the nZEBs across Europe. Flexibility is essential to account for the impact of climate, renewable energy sources (RES), heating and cooling needs, building stock, financial conditions, etc. Therefore Member States are required to draw up National Plans towards nZEBs reflecting regional conditions. All Member States have to formulate their own definitions, detail intermediate targets, develop measures and policies to stimulate the transformation into nZEBs, as well as ensure that new and renovated buildings meet minimum energy performance requirements.

Starting from an integrated design approach, which should take into account all the factors like location, climate or resources, and involves careful selection of materials, components, and a complete set of installations, it is possible to realize very high performance buildings. On the very first design stages for a new building, some features should be considered to reach the nZEB target, like the building position and orientation to help control the solar radiation contributions on the transparent envelope but also ensure a rational use of daylight to reduce lightning, as well as the wind exposition or the building thermal mass, which allows to reduce the temperature variations due to the outdoor conditions [7]. Measures should also strongly consider climatic conditions, as insulation and building tightness appear most important in colder climates, while in warmer locations main focus should be on efficient appliances and lightning [8].

With increasing number of buildings undergoing retrofits towards nZEB, different levels of renovation started to be described, depending on the range of improvements and savings obtained. The most often used terms are: minor, major, deep and nZEB renovations. Minor renovation is referred by BPIE as a small intervention involving application of one to three simple, low cost measures. Typically, it allows to obtain the energy savings of up to 30% [1]. Major renovation is defined in EPBD as an intervention that either reaches a total cost over 25% of the value of the building, or covers more than 25% of the surface of the building envelope [5]. The European Parliament introduced a definition for deep renovation as a refurbishment reducing both the delivered and the final energy consumption of a building by at least 80% in comparison to the initial levels [9]. Finally, the so-called nZEB renovation involves the replacement or upgrade of all elements which have an influence on energy use, together with installation of renewable energy technologies. It also implies a new concept of renovation, having a holistic approach, taking into account the building's lifecycle and impact on the environment [10]. In general, the European Commission indicates that Member States should encourage renovations of buildings leading to efficiency improvements of more than 60% [11].

Reduction of the energy consumption in the buildings undergoing renovation can be accomplished through passive and active measures. Passive measures include refurbishment of the façade, introduction of insulation or windows replacement. Active measures involve overall building envelope and energy systems (heating, ventilation, air conditioning, lighting) and installation of renewable technologies.

Introduction even only of passive approaches can significantly reduce energy consumption of a building, as they directly affect the loads put on the building's mechanical and electrical systems. The envelope of a construction is a crucial element to dynamically balance the interaction between indoors and outdoors. Installation of insulation contributes to decreasing the heat transfer through the envelope minimizing winter heat losses and summer heat gains, improving the thermal comfort. Insulation can be implemented within the whole or only a part of a building, both on external and internal walls, as well as on floors, ceilings or roofs [8]. Besides traditional insulation materials, like rock wool or Expanded Polystyrene (EPS), some new solutions emerged, such as Phase Change Material (PCM). PCMs have the capability to limit temperature fluctuations by retaining thermal energy in the form of latent heat and releasing it successively in a correspondence with a solid-liquid/liquid-solid phase change. Among the advantages of this solution is the reduction of energy requirement and a phase shift of the summer and winter thermal load peaks. Other advanced material is Vacuum Insulation Panel (VIP), which together with aerogel belong to the family of Super-Insulation Materials (SIM), characterized by high thermal insulating properties and small thickness [7].

Another important aspect in a building is glazing. It is considered the weakest link in the building envelope when it comes to thermal insulation [12]. A large window-to-wall ratio affects the energy performance of the building, increases both heating and cooling energy demand, and the peak power. On the other hand, using daylight supplies can possibly lower the use of electricity for lightning. A frequent measure is an installation of a high-performance solar shading system on the windows. Another solution is to improve thermal resistance of the transparent components. It can be achieved, for example, by introduction of multilayer glass (double or triple glazed windows), optimization of the spacing between the glass sheets, filling the gap with a participating gas or aerogel, or applying vacuum in the slabs, and also by coating the glass surfaces with low-emissivity materials. There is also an advanced type of glazing, like electrochromic glazing, which allows to increase the window-to-wall ratio without a negative impact on the energy performance of the building. PCMs can also be incorporated in the glass structure, absorbing part of the solar radiation for the storage of thermal energy, letting the visible radiation enter [7] [13].

Once all the building envelope optimization measures, feasible from a techno-economic point of view, have been implemented, and the reduction of primary energy is obtained through low-energy technologies (like insulation, daylighting, natural ventilation, evaporative cooling), the renewable sources should be added to the system to balance the demand for residual energy. Depending on the availability, RES can be on-site or off-site. Control automation and smart metering devices can also contribute to a building energy performance. They allow the control of the energy demand/supply through Information and Communication Technologies (ICT), decreasing energy consumption. They also allow data collection for performance calculations and dynamic simulation modelling. Control over heating, cooling, ventilation, but also lightning can be applied [8].

Besides nZEBs, many different terms and building categories emerged in recent years. This testifies there exists a visible interest in buildings with reduced impact on the environment and new ideas and technologies are constantly developed. Among them there are: Zero Energy, Zero Emission, Zero Carbon, Energy Plus, Positive Energy and others. There are also used labels like: net zero, off-grid, self-sustainable or autonomous. Even though the topic of zero energy buildings has gained a growing attention in the last decade, no general agreement is reached on technical meaning common definition of these buildings across Europe [14]. The multiplicity of different terms may lead to confusion and uncertainty, so in order to distinguish other building types from nZEB, a general distinction between some other types.

US Department of Energy (DOE) gives a definition of a Zero Energy Building (ZEB) as an energy-efficient building producing enough renewable energy to meet its own annual energy consumption requirements. In ZEBs cost effective measures are used to greatly reduce energy usage by means of efficiency gains with the remaining energy needs supplied from renewable energy systems. [15] However, ZEB can also be used to denote Zero Emission Building, which refers to a building that produces at least an equivalent amount of emission-free energy in relation to the consumed fossil-fuel based energy [16]. As both Zero Energy Building and Zero Emission Building share the same acronym, they are often used and understood synonymously, when in reality their definitions differ fundamentally. The first refers to the energy a building consumes in its everyday operation, the second to the carbon emissions discharged to the environment as a result of its day-to-day operation [17]. Similar concept to Zero Emission Building is developed in the UK under name Zero Carbon Home (ZCH). It was defined by the Government as a building, which net carbon emissions from all energy used would be zero over a year [18]. Another identical approach can be also found under name Zero Carbon Building developed by the International Energy Agency [19].

There can be also found a wording 'Net' used in relation to the Zero Energy Buildings. Net ZEB is defined as an energy neutral building that delivers as much energy to the grid as it draws from it over a period of time, usually one year. Net ZEB indicates that the building is connected to the grid [20]. The opposite of the net ZEB is an autonomous ZEB, which is not connected to the grid. This is a standalone building that supplies its own energy needs and has a possibility to store energy for night or winter time use. Such constructions can also be referred to as off-grid or self-sustainable. Usually it indicates that not only there is no connection to the electrical grid, but also to the other utilities like water, gas or sewer system [17].

In case a building produces more energy from renewable sources than it imports over a year, then it is called an Energy Plus Building (+ZEB) [17]. Similar concept exists under a name Positive Energy Building (PEB) as a further evolution of the nZEB design. PEB is an efficient building producing more energy than necessary to it needs, generating an energy surplus that can be utilize in a number of ways. In contrast to the net ZEB, which in some periods produces excess energy but takes it back from the grid later, PEB should produce surplus energy all over the year. The extra energy from a PEB could be shared with the grid, but could also be used to supply infrastructures in the vicinity, e.g. public lightning. Even more beneficial approach is when instead of considering an individual building, a concept of a Positive Energy District is developed, composed of a mix of existing buildings and PEBs connected with one another. In this way PEBs could contribute to the energy support of other buildings linked to it, balancing the energy needs [7].

2.1.1 Solar XXI as an example of nZEB building

A demonstration project towards Net Zero-Energy Building called Solar XXI was developed at National Energy and Geology Laboratory Campus (LNEG) in Lisbon, Portugal. The building started operating in 2006 with an energy balance to approach the "zero" goal. It is a low energy office building that integrates many passive strategies to reduce energy use for heating, cooling and lighting, introducing also PV panels in the façade and at the parking lot for the on-site production of electricity. Solar XXI building energy performance is about 10 times the energy performance of a standard new office building in Portugal. Solar proves to be highly efficient, close to a Net Zero-Energy Building [21].

The passive concepts include thermal insulation of the building envelope in order to reduce the thermal loads and provide good thermal comfort. All the building walls and the roof are externally insulated, as well as the ground floor. The direct gain concept is applied, so all the windows in the south façade were enlarged, constituting 46% of this area. In this way the building benefits from winter solar energy gains during daytime, cutting down on demand for natural lighting and heating. The important aspect is providing the windows are properly shaded during summer season to minimize the direct solar incidence and diminish the cooling loads, in spite of decrease in natural lighting access. In the building external blinds were installed for the south-facing windows and the windows in other facades are shaded by internal blinds and light roller shades. In the middle of the building there is a light well, providing natural lighting in the central rooms, but also serving as a natural ventilation with a stack effect. Natural ventilation is also provided due to cross wind via openings in the façade. The building has no air conditioning system, so ground cooling option was introduced to reduce the summertime heat load. The ground cooling system uses the soil as a cooling source, as its temperature varies from 13˚C to 19˚C throughout the year. The pre-cooled air due to soil high thermal inertia is injected into the building rooms by natural convection or forced convection using fans providing better thermal comfort for the users [21] [22].

When it comes to energy dependency, the photovoltaic panels with heat recovery integrated in the south façade and on the adjacent parking lot cover about 67% of the primary energy and 70% of total electricity used in the building with a production of around 20 MWh/year. As for an additional energy source Solar XXI uses natural gas, mainly for a natural gas boiler for heating purposes [21].

The main south-oriented façade of Solar XXI building with enlarged windows for direct gain and PV panels covering the wall in nearly equal proportions, as well as the PV panels introduced in the parking lot are presented in Figure 1.

Figure 1 South façade of Solar XXI building and a parking lot located at LNEG campus [23].

2.2 Optimization modelling tools

The shift from centralized to district level production creates new challenges to design an energy project optimal from ecological and financial point of view. In order to answer the complexity in the district energy projects, numerous decision support tools have been developed. Among the multi-carrier energy project optimization modelling tools can be listed proprietary (closed source, preventing contributions from third parties) tools like HOMER, REopt, Artelys or DER-CAM, and open source tools including FICUS, oemof, and OMEGAlpes. They are all shortly described below.

HOMER stands for The Hybrid Optimization of Multiple Energy Resources and is a commercial software for microgrid modelling based on a techno-economic analysis. It helps to design and plan cost-effective and reliable micropower systems that combine traditional and renewable generation sources. HOMER evaluates thousands of variables and compares value streams, assesses system options, and provides cost reduction or risk-mitigation strategies [24].

REopt: Renewable Energy Integration and Optimization is a commercial techno-economic decision support platform. It is used for optimization of energy generation, storage and controllable loads to maximize the value of integrated distributed energy systems for buildings, campuses and microgrids. REopt aims to recommend the optimally sized mix of renewable energy, conventional generation and energy storage technologies to meet energy performance goals, as well as cost savings [25].

Artelys Crystal Energy Planner is a commercial software that enables optimal management of energy production assets for the entire value chain, so including generation, consumption, storage, transport, emissions, etc.

Modelling techniques together with advanced forecasting and planning algorithms allow to perform a techno-economic optimization of an entire energy system [26].

DER-CAM stands for The Distributed Energy Resources Customer Adoption Model and is a free decision support tool that serves the purpose of finding optimal distributed energy resource investments for buildings or multi-energy microgrids. It can be used to find the optimal portfolio, sizing, placement and dispatch of a wide range of distributed energy resources while co-optimizing multiple stacked value streams like load shifting, peak shaving or power export agreements [27].

FICUS is an open-source optimization modelling tool developed for local energy systems. It aims to find the minimum cost energy system to satisfy given demand time-series. It is based on Excel for the model definition, making it more difficult to integrate more complex energy projects [28].

Oemof (Open Energy Modelling Framework) is a modular open-source framework to model energy supply systems. The internal library Solph provides a toolbox with basic energy units and a few specific energy components to build energy system model [29].

OMEGAlpes stands for Generation of Optimization Models As Linear Programming for Energy Systems. It aims to build Mixed-Integer Linear Program (MILP) to design and manage multi-carrier energy system models. It allows to solve quickly big optimization problems at a district scale. OMEGAlpes is open-source with permissive license for a non-restrictive contribution, and is written in Python programming language [30].

2.2.1 Solving optimization problems in OMEGAlpes

There are a few case studies developed using OMEGAlpes showing its functionality. Further described will be a study concerning a demand-side management which is helpful to better understand the possibilities OMEGAlpes brings and uses a similar approach as used in this work.

The problem formulated describes demand-side management in order to maximize self-consumption from the PV generation by shifting the energy consumption of a washing machine and a dryer, with heat storage into a water tank. The generation from PV panels is used to run the electrical appliances, and the surplus is either exported to the grid, or directed to water heater to cover the domestic hot water demand, supported by a water tank.

The case is formulated using OMEGAlpes, which detailed specification is further described in chapter 3.1. The washing machine and the dryer are described using class ShiftableConsumptionUnit, because their consumption profiles are known and their operation can be shifted in time, so that the imports of electricity from the grid are minimized. Electric production from the PV panels is described with FixedProductionUnit class, the generated power that is exported to the grid is modeled as consumption with VariableConsumptionUnit, and the power imported from the grid is represented as production with VariableProductionUnit. As these power profiles are not fixed, variable class units are used. The water heater’s electrical consumption and heat production is represented by ElectricalToHeatConversionUnit, with efficiency 90%. Beside the domestic hot water, the heated water can also be stored in the water tank of capacity 6000 kWh. Additionally, a constraint is added to avoid simultaneous importing and exporting of the electricity from the grid, and a constraint to prevent launching the dryer before washing cycle is finished.

The objective is specified to minimize the imports from the electrical grid, in this way maximizing the self-consumption. After specification of the problem the optimization is launched yielding 53% of self-consumption compared to 3% without the demand-site management strategy [28].

3 METHODOLOGY

This thesis is a part of the project IMPROVEMENT and is realized for an existing building located in Lisbon, Portugal that aims to become a nZEB. In the building there are installed electrical and thermal systems for self-production together with energy storage units. For electricity generation purposes 3 photovoltaic (PV) panels are mounted with total power of 4 kW, assisted by a battery with capacity of 31.68 kWh. For space heating, 2 solar thermal (ST) collectors are used, assisted by a water tank with capacity of 300 l. The whole system is supported by a heat pump that uses electricity from PV panels to back up the heat load. The building is also connected to electrical and heating grids in case the self-production is insufficient to cover the loads. The scheme of the system is presented in Figure 2 and the picture of the considered building is showed in Figure 3.

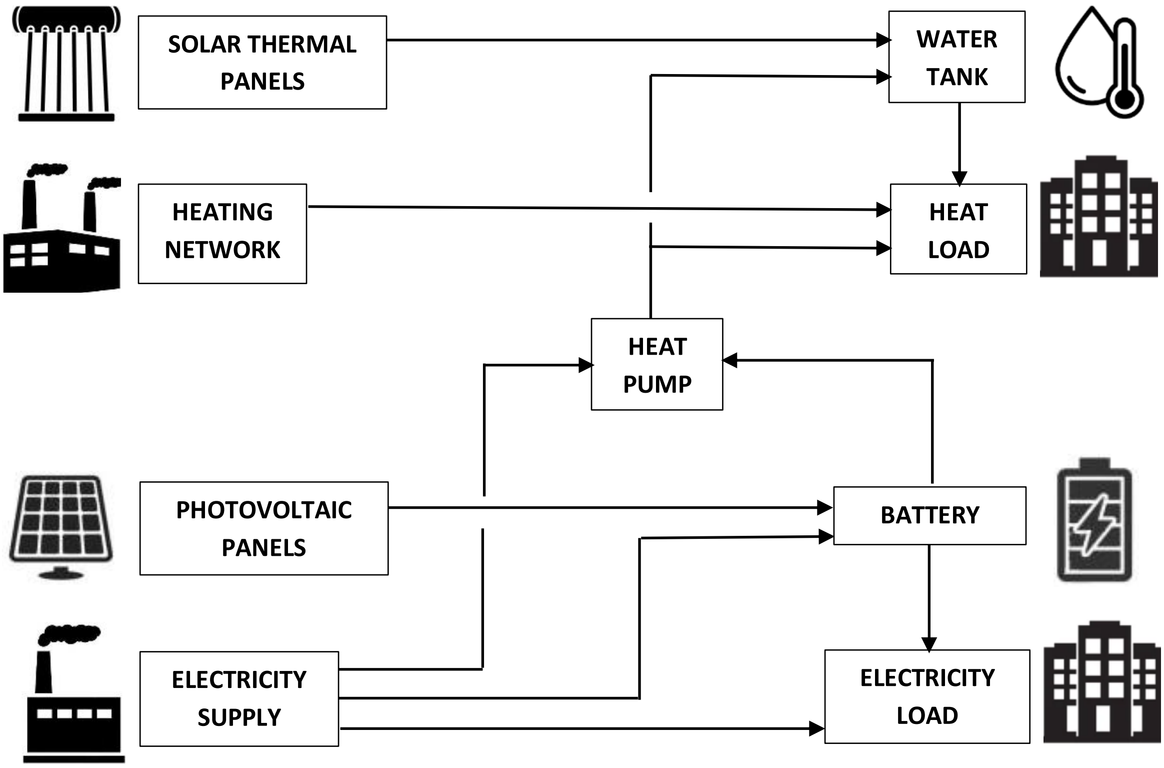

Figure 2 Schematic representation of the energy system installed in the considered building.

Figure 3 Picture of the interior of the considered building.

In this work a few case studies will be developed. First two cases consider only the electrical and thermal microgrids separately, with the aim to maximize self-production and size an optimal storage unit. Third case is developed for electrical and thermal systems together with storage units and a heat pump to minimize the heat imports from the heating network. Last and main case of this study concerns the system from the previous case with additional aim to minimize the operating cost of the electrical grid.

3.1 OMEGAlpes specification

For the purposes of this thesis OMEGAlpes platform is chosen to develop a model and conduct an optimization, as it is a free, open-source tool based on Python, a widely used high-level programming language. OMEGAlpes stands out for being intuitive and easy to operate, and for providing an additional function of model graphical representation creation.

OMEGAlpes library aims to generate MILP optimization models. The most basic form of an optimization problem is adjusting a set of decision variables in order to minimize an objective function (1).

$$Minimize\ F = f(x_1, x_2, \ldots, x_n) \tag{1}$$

The optimization problems have to respect physical laws that bound the values of some decision variables. The problems are denoted as constrained optimization problems (2).

$$\begin{cases} Minimize & F = f(x)\ for\ x \in E^n \\ Subject\ to: & a_i(x) = 0\ for\ i \in (1, 2, \ldots, p) \\ & c_j(x) \geq 0\ for\ j \in (1, 2, \ldots, q) \end{cases} \tag{2}$$

As only MILP formulations are considered, an optimization problem should take the following form to be classified as linear (3).

$$\begin{cases} Minimize & f(x) - c^T x \\ Subject\ to: & Ax = b \\ & x \geq 0 \end{cases} \quad (3)$$

Many energy systems problems include not only continuous variables (e.g. power, costs, etc.), but also integer variables are necessary for formulation of some constraints (e.g. system on/off), and then MILP formulation is required (4), with either continuous variables ($x \epsilon R^n$) or integer variables ($y \epsilon Z^m$).

$$\begin{cases} Minimize & f(x) - c^T x - h^T y \\ Subject\ to: & Ax + Gy \leq b \\ & x \geq 0\ for\ x\ in\ R^n \\ & y \geq 0\ for\ y\ in\ Z^m \end{cases} \quad (4)$$

3.1.1 Structure

OMEGAlpes is based on an intuitive object-oriented library that provides a panel of pre-built energy units with predefined operational options, associated constraints and objectives. The models are based on 'general', 'energy' and 'actor' packages. The structure of the library is described on a class diagram in Figure 4.

The 'general' sub-package gathers all the classes needed to formulate an optimization problem, including Unit (representing the elementary object of an optimization problem), TimeUnit (describing the dynamic of the case, like duration and time step), Quantity (defining a variable or a parameter), Objective (providing objective of the optimization problem), Constraint with DynamicConstraint (time-dependent) and ExternalConstraint (not reflecting a physical equation).

The 'energy' sub-package provides all the models used to describe an energy system in OMEGAlpes. It contains ProductionUnit, which can be then specified as VariableProductionUnit (used for unknown production profiles), FixedProductionUnit (used for known production profiles), ShiftableProductionUnit (used for profiles that can be shifted in time) and SquareProductionUnit (used for a defined square power profile). The next unit is ConsumptionUnit, which can be divided into VariableConsumptionUnit (used for unknown consumption profiles), and FixedConsumptionUnit (used for known consumption profiles). Another class in this package is StorageUnit, which allows to introduce energy storage to the system. ConversionUnit enables modelling of a heat pump. Lastly, EnergyNode class allows to link all the energy units of the same energy type while ensuring the power balance.

The 'actor' sub-package was developed to make possible taking into account stakeholders' objectives and constraints in the design process. This package is divided into two modules: operator_actors and regulator_actors. First module focuses on stakeholders who operate the energy units and have responsibility on these units. It includes classes of Prosumer, Consumer and Producer. The second module focuses on stakeholders who do not operate the energy units but influence final decisions and resource regulation [28]. It contains

StateAuthority and LocalAuthority. This package gives more modelling possibilities, but a model can be generated without integrating the actor modelling.

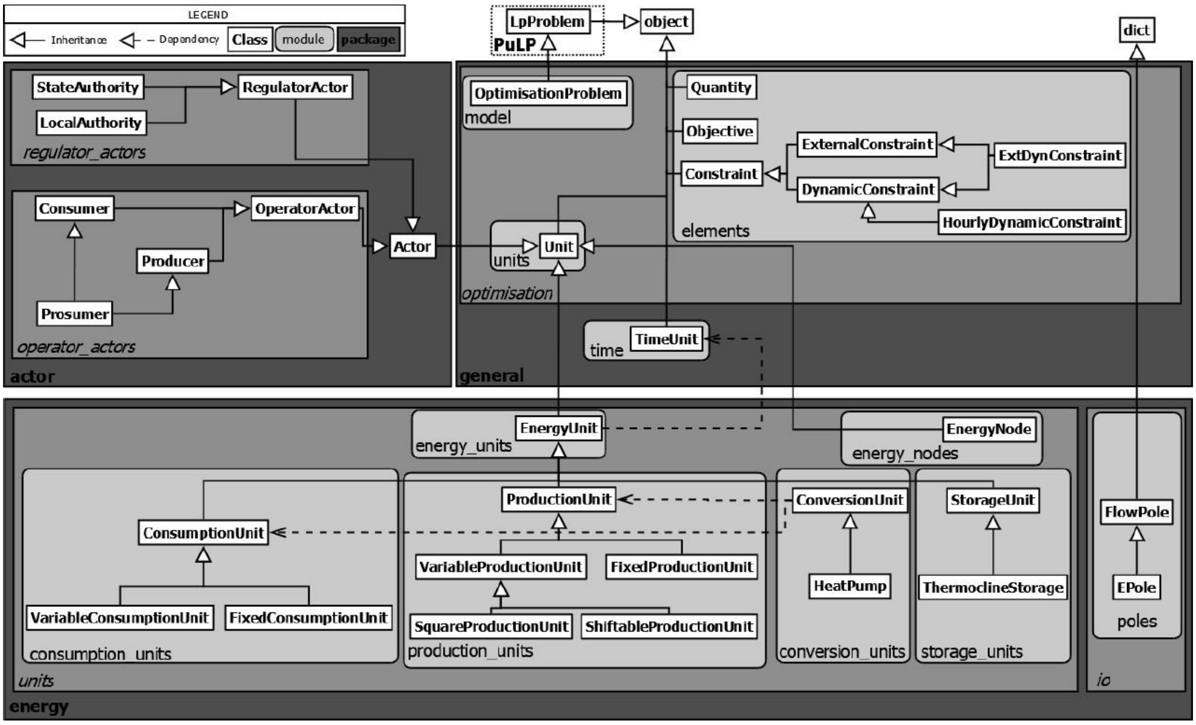

Figure 4 OMEGAlpes class diagram [31].

3.1.2 Graphical representation

For OMEGAlpes a web interface is available to make creating models and generating scripts easier. The graphical representation allows to build an energy system model using ready elements, introducing given parameters and constraints, and setting optimization objective. The basic interface layout is presented in Figure 5.

Figure 5 OMEGAlpes web interface layout.

The latest version omegalpes 0.4.0 introduces the possibility of creating model using graphical interface, however this function is still under development and the available options are limited. Currently it is possible to introduce the following elements: Production Units (with Variable, Fixed, Shiftable and Square Production Units), Consumption Units (with Variable, Fixed, Shiftable and Square Consumption Units), Storage Units and Nodes. Elements like HeatPump or ElectricalToHeat conversion unit are not available in the web interface version yet. However, they can be added and modelled directly in the script. The model in OMEGAlpes can be created using web interface, or partly based on the script generated using web interface and later expanded using Python, or developed in Python from the beginning without using the graphical representation.

The graphical model is built by selecting required units and connecting them accordingly. The system can be developed for electrical, gas or thermal energy type, each depicted by different color. The energy units graphical representation is presented in Figure 6 and the specified energy carrier representation in Figure 7.

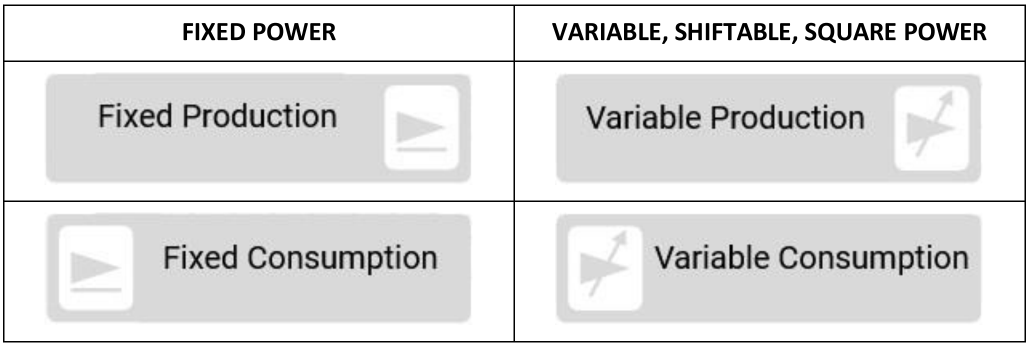

Figure 6 OMEGAlpes energy units graphical representation.

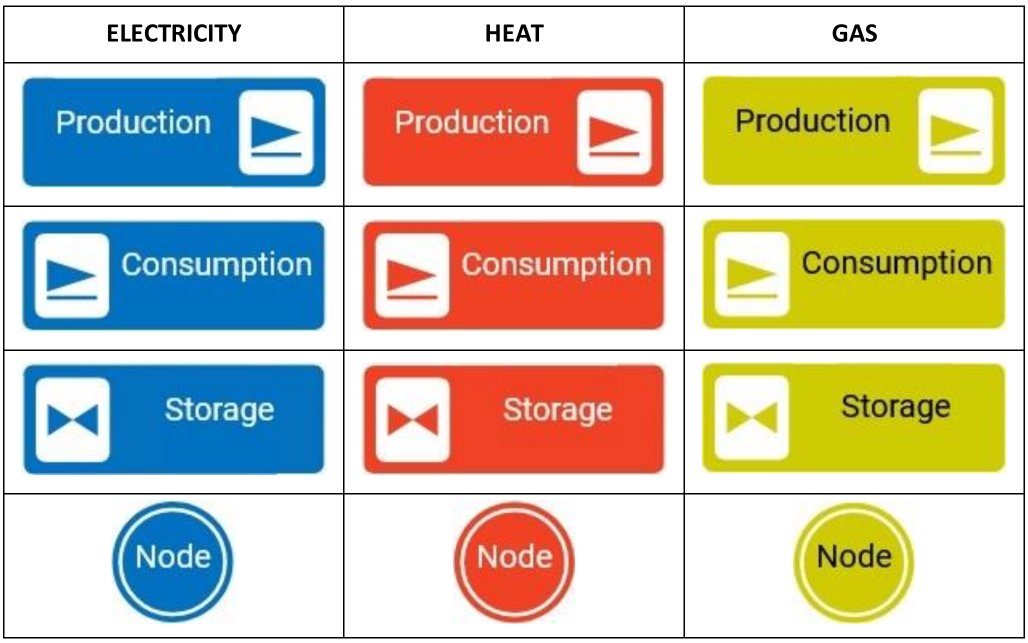

Figure 7 OMEGAlpes specified energy carrier graphical representation.

After selecting a given unit, a properties menu is expanded where the user should introduce parameters necessary to conduct an optimization, specify all the constraints and formulate an optimization objective. Each unit has its own list of possible parameters that can be introduced and they are all listed in Table 1.

When a graphical representation is created, and all parameters and objectives are introduced, a script can be generated exporting the model, its image, and a code. Using web interface, the model can be created, but it does not solve the problem and display the results. To obtain the optimization results, the user needs to open and run the file.

Table 1 Units parameters, constraints and objectives available in the OMEGAlpes web interface.

	PRODUCTION UNIT	**CONSUMPTION UNIT**	**STORAGE UNIT**
PARAMETERS	• Minimal power demand • Maximal power demand • Instantaneous power demand • Minimal energy • Maximal energy • CO_2 emissions • Starting cost • Operating cost • Minimal time on • Minimal time off • Maximal ramp up • Maximal ramp down	• Minimal power demand • Maximal power demand • Instantaneous power demand • Minimal energy • Maximal energy • CO_2 emissions • Starting cost • Operating cost • Minimal time on • Minimal time off • Maximal ramp up • Maximal ramp down	• Minimal charging power • Maximal charging power • Minimal discharging power • Maximal discharging power • Capacity • Initial level of energy • Final level of energy • Minimal state of charge • Maximal state of charge • Charging efficiency • Discharging efficiency • Capacity self-discharging • Energy self-discharging
UNIT OBJECTIVES	• Minimize production • Maximize production	• Minimize consumption • Maximize consumption • Minimize consumption cost	• Minimize capacity
ENERGY UNIT OBJECTIVES	• Minimize starting cost • Minimize operating cost • Minimize cost (starting and operating) • Minimize time of use • Minimize CO_2 emissions • Minimize energy	• Minimize starting cost • Minimize operating cost • Minimize cost (starting and operating) • Minimize time of use • Minimize CO_2 emissions • Minimize energy	• Minimize starting cost • Minimize operating cost • Minimize cost (starting and operating) • Minimize time of use • Minimize CO_2 emissions
ENERGY UNIT CONSTRAINTS	• Time range (range of hours during which the unit can be operated) • Energy limits (minimal and maximal energy set during given time period)		

3.1.3 Limitations

OMEGAlpes allows to easily study complex problems, but it has some limitations. In general, the available options and possibilities in OMEGAlpes are constrained when compared to other software, for example DER-CAM. Commercial software usually allows to develop more complex problems, e.g. finding optimal distributed energy resource solution that would minimize costs while ensuring resiliency targets, like reliable supply of energy, continuity of service and ability to withstand disturbances, or finding where in the microgrid the distributed energy resources should be installed and how should they be operated to ensure voltage stability [27]. The possibilities OMEGAlpes gives are more restricted, but as it is still under development and being an open-source tool, with time available functions may be expanded and adapted to users' needs. It should be however mentioned that OMEGAlpes is designed mainly for pre-studies and does not integrate very detailed models that are required for real-time management.

When it comes to web interface, as already mentioned, it is not possible to introduce and model units like heat pump or water heater, so energy conversion and connection into a single model is not possible. All the values for energy units have to be introduced by hand, it is not possible to load files with data, which is problematic especially for units with fixed load that may contain thousands of values. The actor package is not available for the web interface and can be added only directly in the code, however information about possibilities this tool brings and examples of use are limited. There are also still some errors emerging when using the software, for example after generating the script there is sometimes a problem with loading the libraries properly, and have to be corrected manually.

In current shape the web interface may be mainly used to create a base for a model that would be further developed and improved by editing the generated code. The graphical interface, together with OMEGAlpes documentation and a few examples and articles available on the OMEGAlpes website make it easier for the user to get familiar with this software.

4 RESULTS AND DISCUSSION

4.1 Case 1: electrical storage

First case concerns a simplified model of the electrical part of the system with electricity demand covered by generation from PV panels together with energy storage in a battery, supported by imports from the electrical grid in case the production is insufficient.

For this case, PV production profile, as well as corresponding load profile are known. The data is collected for time period of one week in May in 15-minute time steps. The storage unit has got maximal charging and discharging powers, equal to 5 kW for both values, losses connected to self-discharging, equal to 1% per hour, and is constrained by minimal and maximal state of charge of the storage, equal to 20% and 90%, respectively. The initial state of the storage unit is set to be empty, so it reaches the minimal state of charge constraint at the starting period.

The objective of this case is to minimize the imports from the grid in order to maximize self-consumption and find an optimal storage capacity.

The graphical representation of the system is generated using OMEGAlpes web interface (Figure 8). The electrical grid is represented by a Variable Production Unit, as its production profile is unknown, the PV panels generation and electricity consumption are represented using Fixed Units, as both profiles are known. The code created for this model is available in Appendix A.

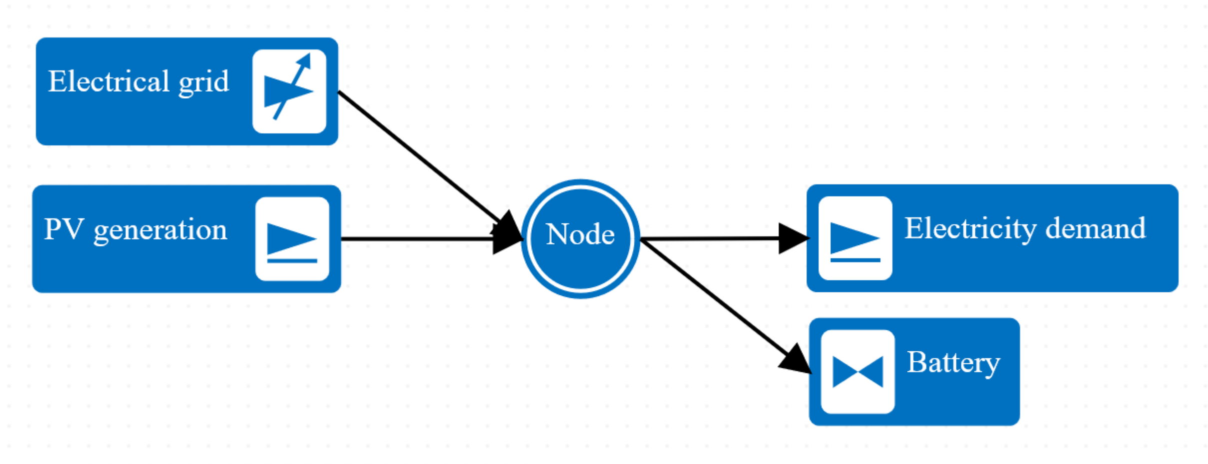

Figure 8 OMEGAlpes graphical representation of the basic electrical system with energy storage.

Figure 9 Power flow for the units connected to the electrical node over 1 week period for case 1 concerning electrical storage.

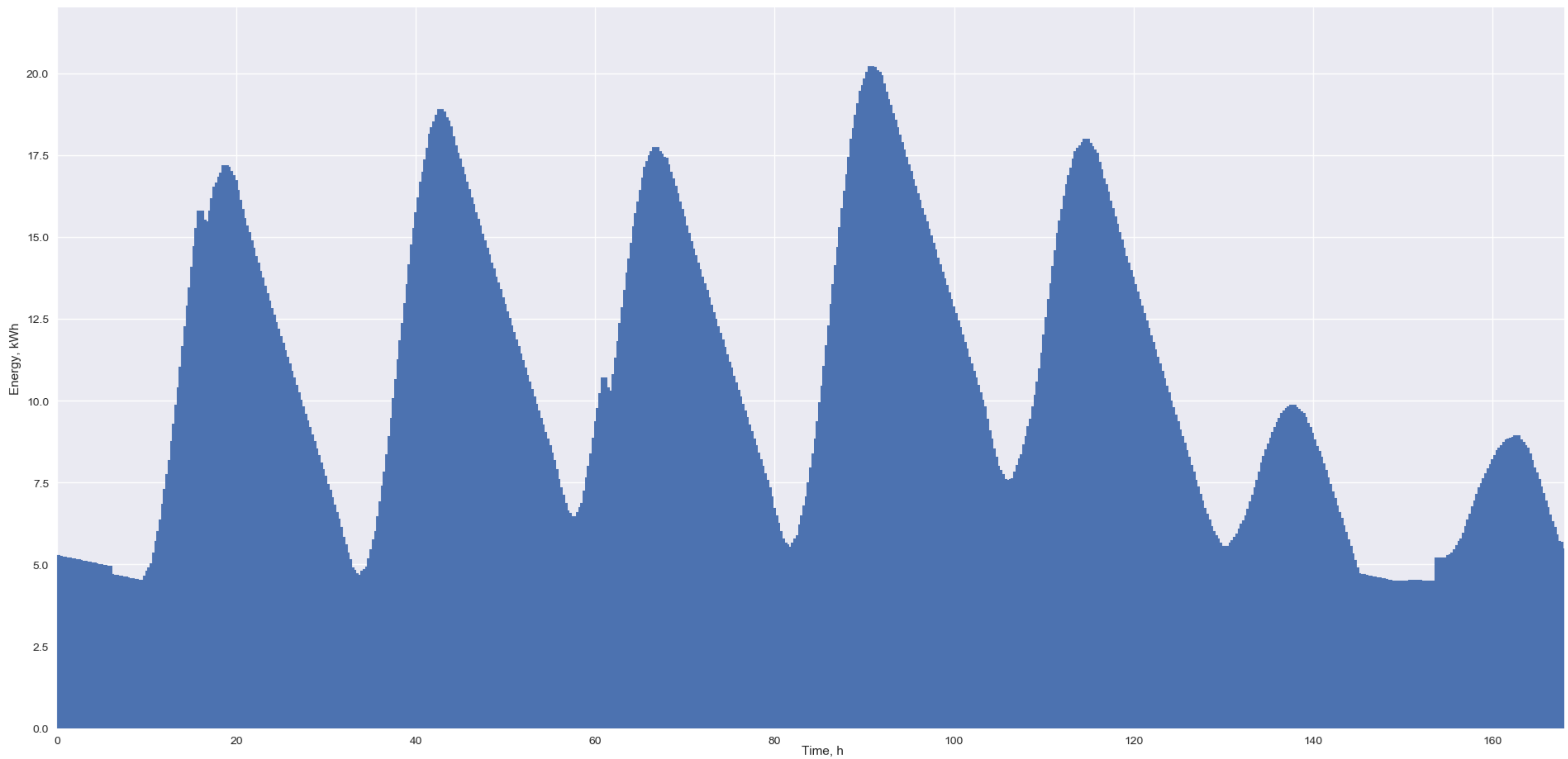

Figure 10 State of charge of the battery over 1 week period for case 1 concerning electrical storage.

Table 2 Results of the simulation for case 1 concerning electrical storage.

Electricity imports from the grid	15 kW
Electricity production from PV panels	153 kW
Electricity consumption	158 kW
Optimal electrical storage capacity	**22.5 kWh**

As a result of the optimization process conducted using OMEGAlpes tool, the optimal storage capacity is found to be 22.5 kWh. The overall electricity consumption equals 158 kW, production from PV panels is equal to 153 kW and the imports from the electrical grid are equal 15 kW. All the results are presented in Table 2.

Figure 9 presents distribution of the electricity load, PV production and imports from the grid, together with charging and discharging of the storage, and Figure 10 presents state of charge of the battery, both figures over one week period. It can be noticed that the week starts with covering demand from the grid, as there is given the constraint to start with an almost empty storage (20% charged). The decrease in the state of charge during this period is caused only by the losses connected with self-discharging, equal 1% an hour. Then the production from PV panels begins and the load starts being covered entirely by means of self-production. The PV generation during the day surpasses the demand, so the battery storage starts being charged. The battery usage has a priority before the grid imports, so when self-production drops significantly for a moment around 16 hour, probably due to a short change in the weather conditions, a part of load is covered by discharging the battery. The night load is then covered entirely with the storage unit, no imports from the grid are necessary to support the load.

For the first five days of the week the load, PV production, battery charging and discharging follow similar patterns. For the last two days there can be observed a change in the demand, as the project is realized for an office building, which is not inhabited during the weekends, so only a constant load is present. For the used data it can be noticed that during the weekend the electricity generation from PV panels also drops, probably because of the weather change. This results in an insufficient storage charge, which is unable to cover the whole demand, even though the demand is lower than during the working days, and requires support from the electrical grid. The grid is also used to slightly charge the battery, so as not to exceed the lower state of charge constraint. There is also a single spike in charging battery from the grid around 154 hour. There is no apparent reason for this behavior, probably in prediction of reaching some constraint the battery is charged to a higher level, e.g. the battery may not be charged fast enough. The close-up of the last day showing in more detail the state of the system is presented in Figure 11, and the respective state of charge of the storage is in Figure 12. Following, the PV production provides electricity to cover the load and again charge the storage, but it can be assumed, based on the state of charge of the storage at the end of the week, that the generation is too low to cover the demand for the following day, and so imports from the grid would be necessary to cover this load. This is mainly caused by a period of bad weather, limiting the production.

The intermittency of the renewable resources poses a challenge when selecting the power of the production units and the capacity of the storage units. In order to obtain even more accurate sizing of the system, a longer period of time should be studied, requiring more resources. For the purposes of this work, for the selected time period, a well-balanced system based mainly on self-production was obtained.

Figure 11 Close-up of the power flow for the units connected to the electrical node for day 7 for case 1 concerning electrical storage.

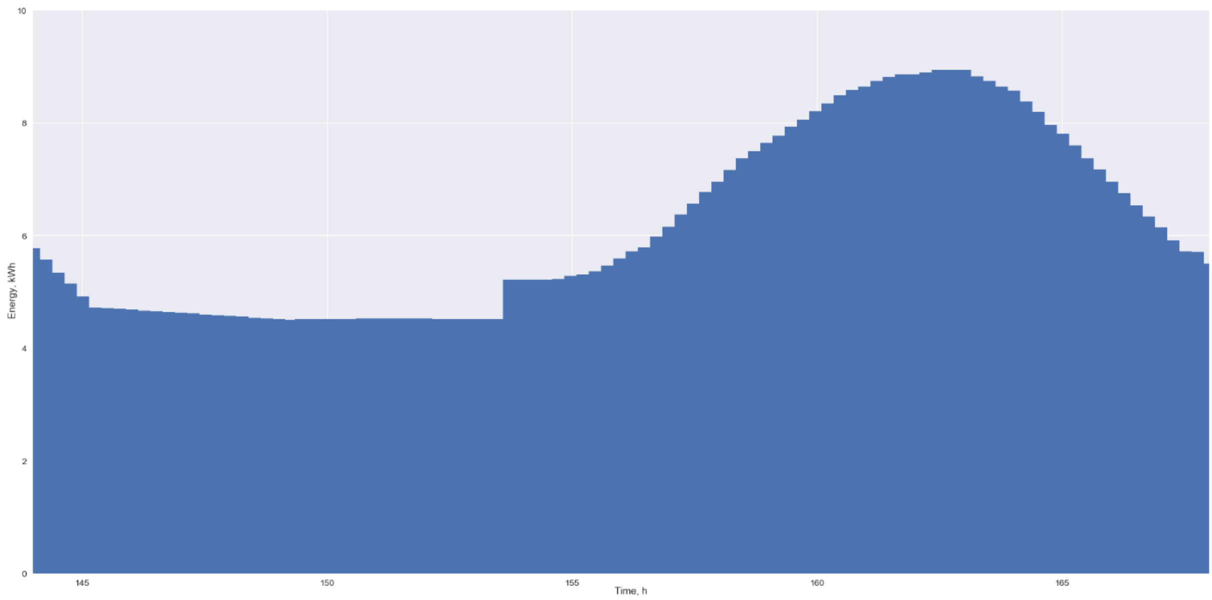

Figure 12 Close-up of the state of charge of the battery for day 7 for case 1 concerning electrical storage.

4.2 Case 2: thermal storage

Second case is similar to the previous one, but it concerns thermal part of the system. Demand for heat is covered by ST panels generation, supported by energy storage in a water tank and by imports from the heating network in case the production is insufficient. For this case, as only thermal part of the system is concerned, heat pump is not considered, and only possibility of covering the load from self-production together with storage is checked.

The data used is ST production profile with heat load profile. The data collected is for one week period in February in one hour time steps, different than for previous case where data with 15 minute time step was available. The storage unit has got maximal charging and discharging powers, equal to 10 kW for both values, losses connected to self-discharging, equal to 1% per hour, and is constrained by minimal and maximal state of charge of the storage, equal to 20% and 90%, respectively. The initial state of the storage unit is set to be empty, so it reaches the minimal state of charge constraint at the starting period.

The objective of this case is to minimize the imports from the heating network in order to maximize self-consumption and find an optimal storage capacity.

The graphical representation of the system is generated using OMEGAlpes web interface (Figure 13). The heating network is represented by a Variable Production Unit, as its production profile is unknown, the ST panels generation and heat consumption are represented using Fixed Units, as both profiles are known.

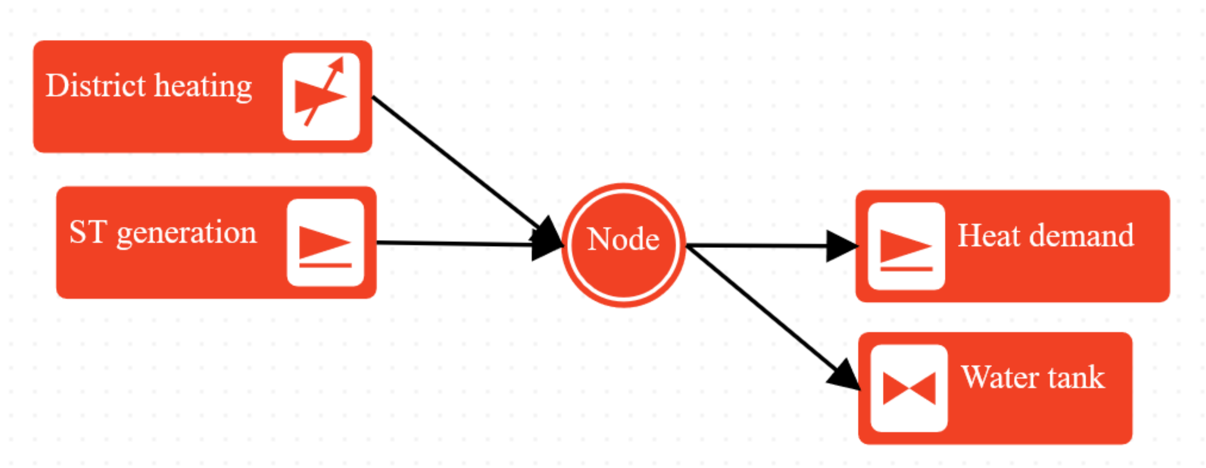

Figure 13 OMEGAlpes graphical representation of the basic thermal system with energy storage.

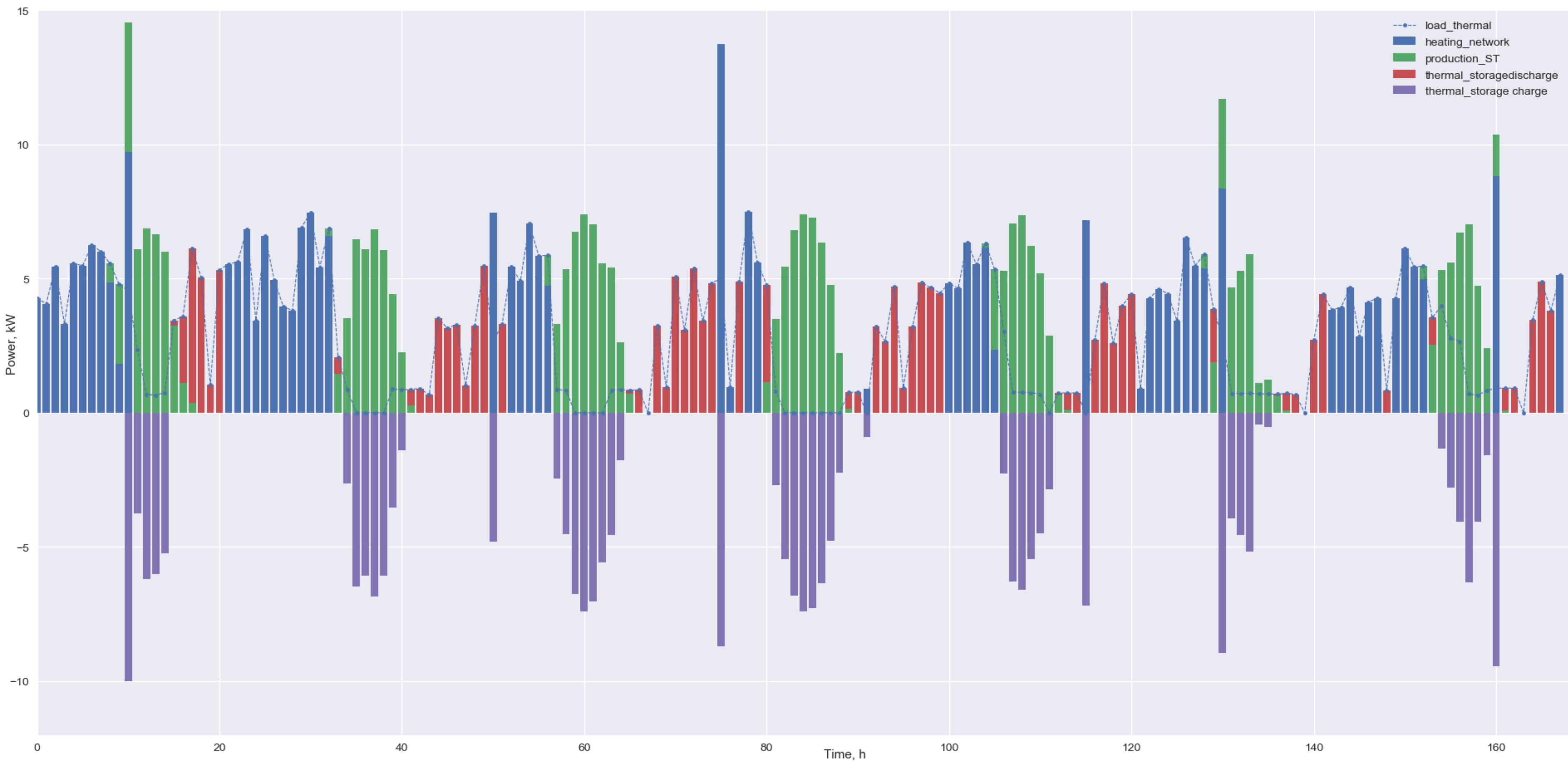

Figure 14 Power flow for the units connected to the thermal node over 1 week period for case 2 concerning thermal storage.

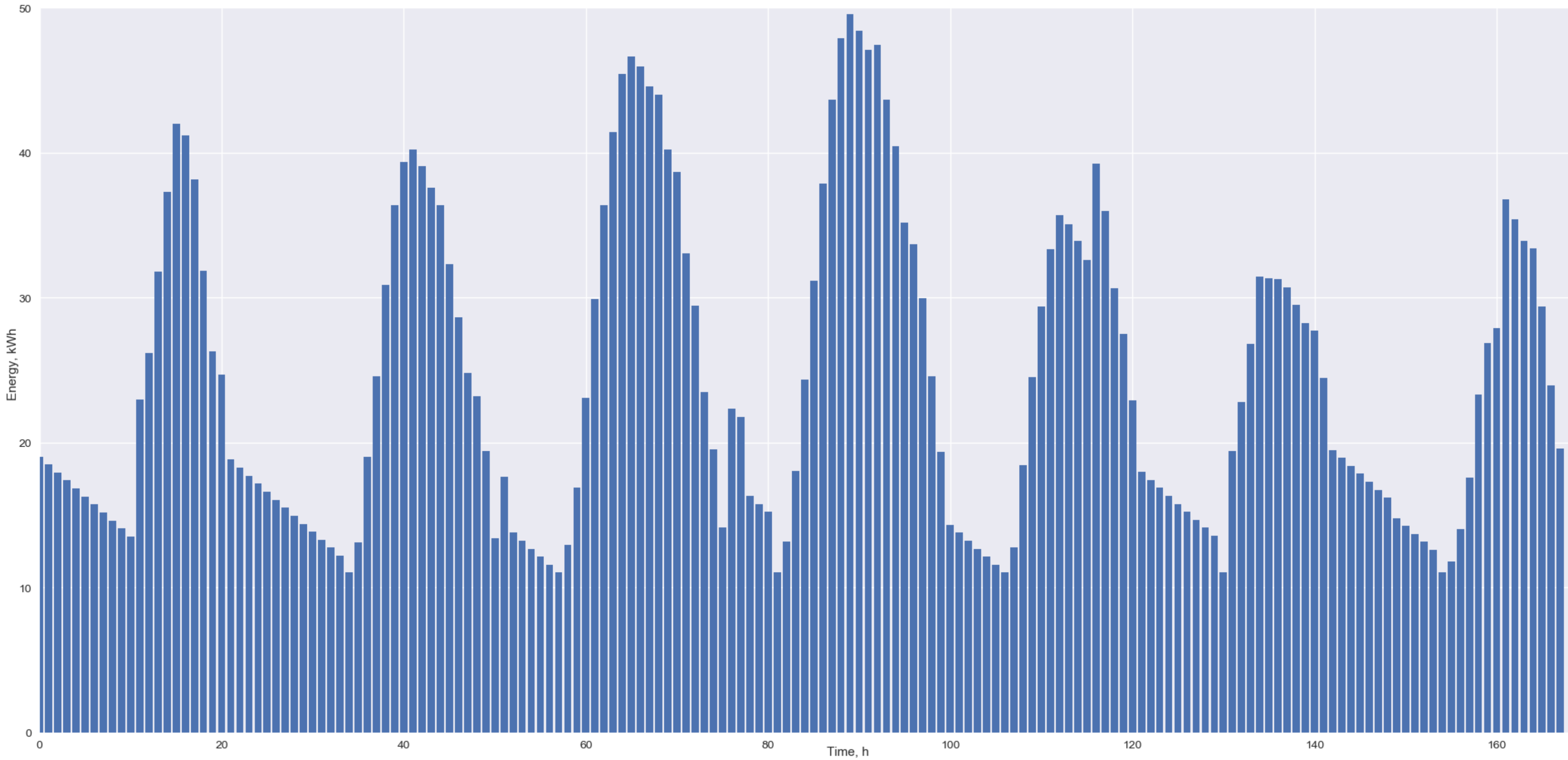

Figure 15 State of charge of the water tank over 1 week period for case 2 concerning thermal storage.

Table 3 Results of the simulation for case 2 concerning thermal storage.

Heat imports from the network	327 kW
Heat production from ST panels	266 kW
Heat consumption	500 kW
Optimal thermal storage capacity	**525 l**

From the graphical representation in figure 14 it can be clearly noticed that there are large fluctuations of the load throughout the day. It is connected with large daily temperature variations at this time, which is typical for Lisbon, Portugal during the winter-spring transition. The temperature distribution for the examined week is presented in figure 16. It can be observed that the difference in temperature between day and night usually reaches around 10 degrees. For the considered period, the lowest temperature reached equals 9.7˚C, and the highest 20.9˚C. That is why during the day the load is the lowest, as the outside temperatures reach around the level of thermal comfort and additional heating is mostly not necessary. However, in order to maintain similar temperatures during the cold nights and avoid intensive heating in the morning, there is higher nightly load, even though the offices are not used then.

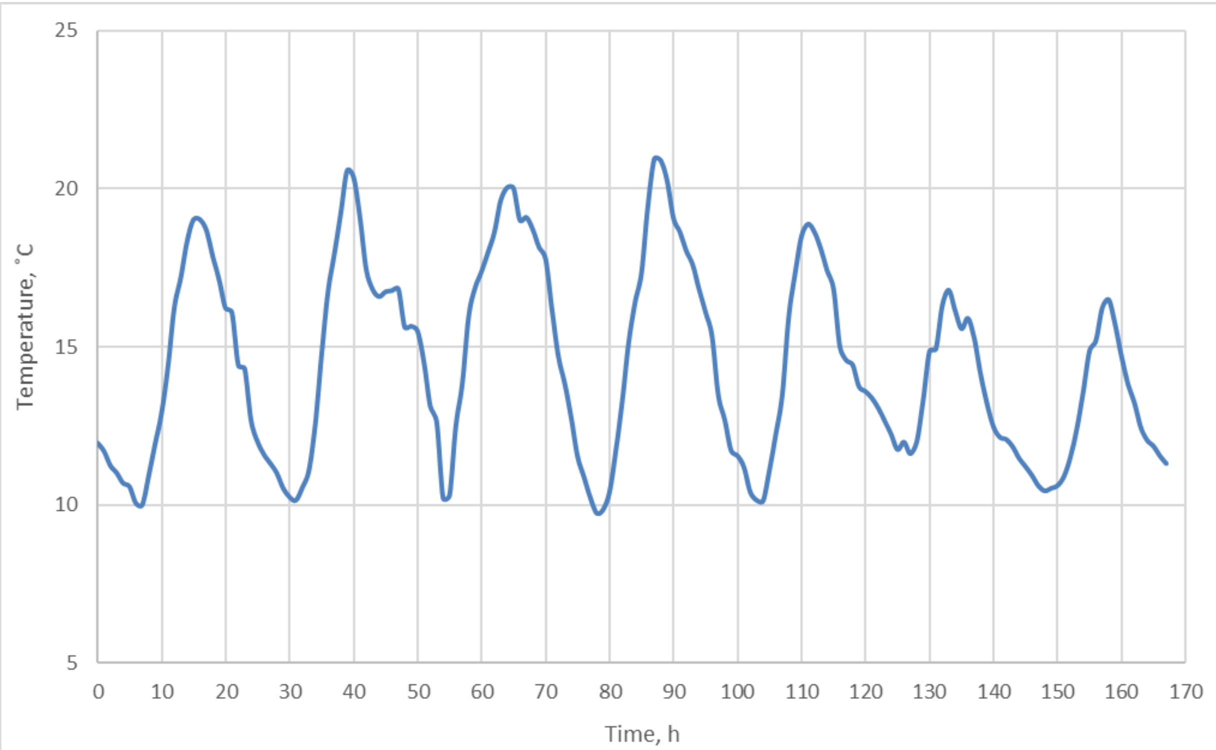

Figure 16 Temperature distribution for the considered week in February in Lisbon.

Similar as for the previous case, the energy storage unit starts with an empty state assumption, so the load for a first few hours is covered from the heating network. When the production from ST panels begins, the load is close to zero, and so the generated heat is mainly stored in the water tank. It can however be noticed that the self-production with storage is not sufficient to cover the higher night loads and support from the grid is necessary. There are also present spikes of imports from the network to charge the storage around hours 10, 50, 75, 115, 130. When correlated with the state of charge of the water tank (figure 15) it can be noticed that they result from approaching the lower limit of charge for the storage unit, and in prediction of soon reaching this limit before the storage could be charged from self-production, the network is used as a support.

As a result of the optimization in OMEGAlpes, the optimal storage capacity is calculated around 525 l (table 3). Sizing of a thermal system poses a greater challenge, as the heat load fluctuates significantly throughout the year, with high winter load and almost no load during summer. Another challenge is that the winter solar production is lower, due to shorter days and worse weather conditions, resulting in lower radiation, whereas the load is the highest. To obtain more accurate results a whole year load should be examined, in order not to oversize the production and storage systems by taking only high winter loads into account.

4.3 Case 3: electrical-thermal storage

The next considered case concerns a system composed of electrical and thermal microgrids with a heat pump. Part of the thermal load is covered by ST panels production and the rest is covered by a heat pump, that is using electricity generated by PV panels or from the grid in case the production is insufficient. Electrical and thermal storage units are used to support the intermittent renewable resources.

For this case, data for PV and ST production profiles, together with electrical and thermal loads, collected in May for time period of one week in 15-minute time steps is considered. The electrical storage is a battery with minimal and maximal state of charge equal 20% and 90%, respectively. Loses due to self-discharge amount 1% per hour. The maximal charging and discharging powers are both equal 5 kW. When it comes to the thermal storage in a water tank, the same parameters as for the battery are assumed. For both storage units the initial state of storage is assumed to be empty. The heat pump coefficient of performance is equal 3.

The objective for this case is to minimize imports from the heating network by maximizing self-consumption from ST panels, supported by a thermal storage and a heat pump that is using PV generation to help cover part of the thermal load. The optimal electrical and thermal storages' capacities are also found.

Figure 17 Power flow for the units connected to the electrical node over 1 week period for case 3 concerning electrical-thermal storage.

Figure 18 Power flow for the units connected to the thermal node over 1 week period for case 3 concerning electrical-thermal storage.

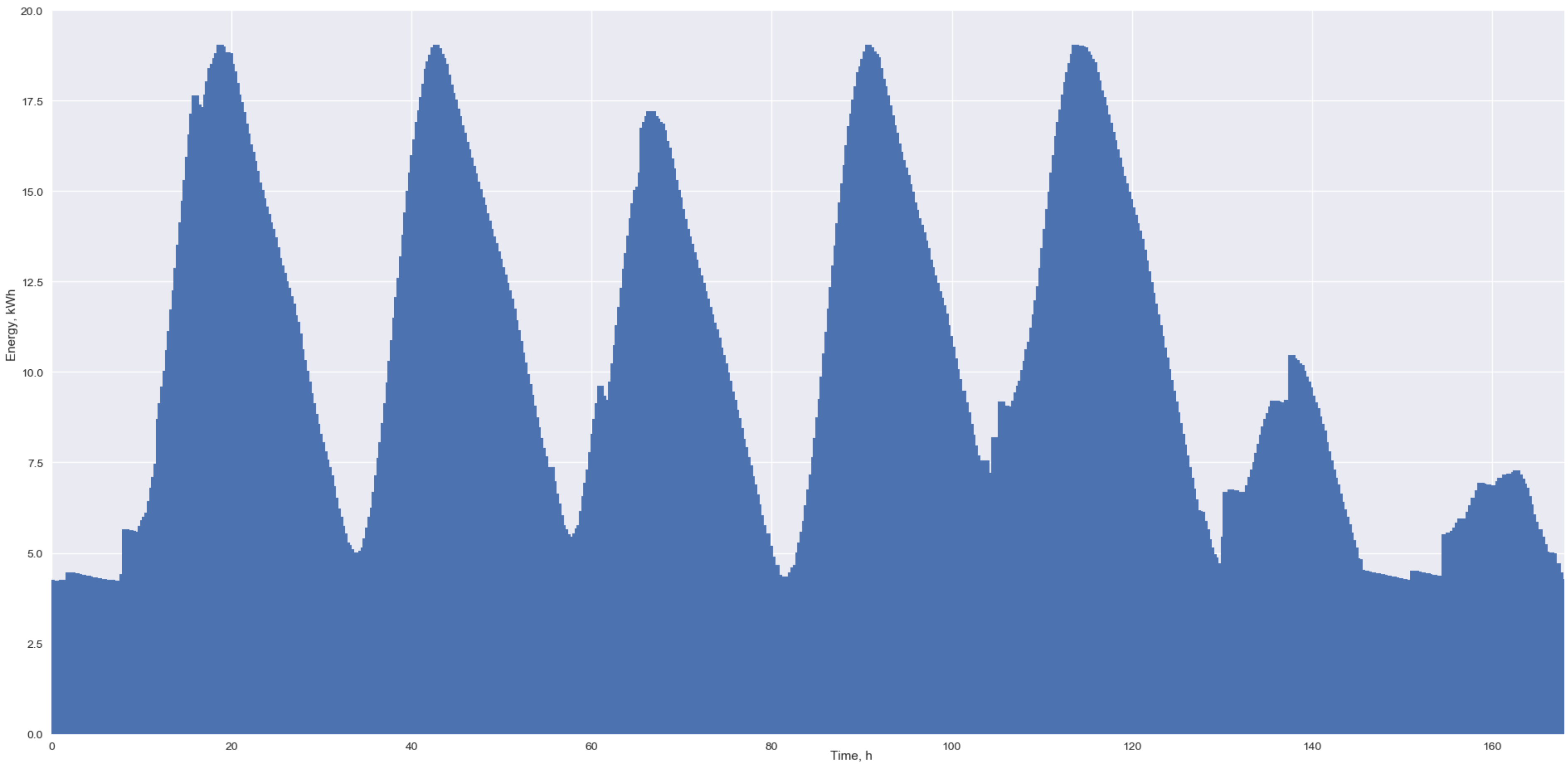

Figure 19 State of charge of the battery over 1 week period for case 3 concerning electrical-thermal storage.

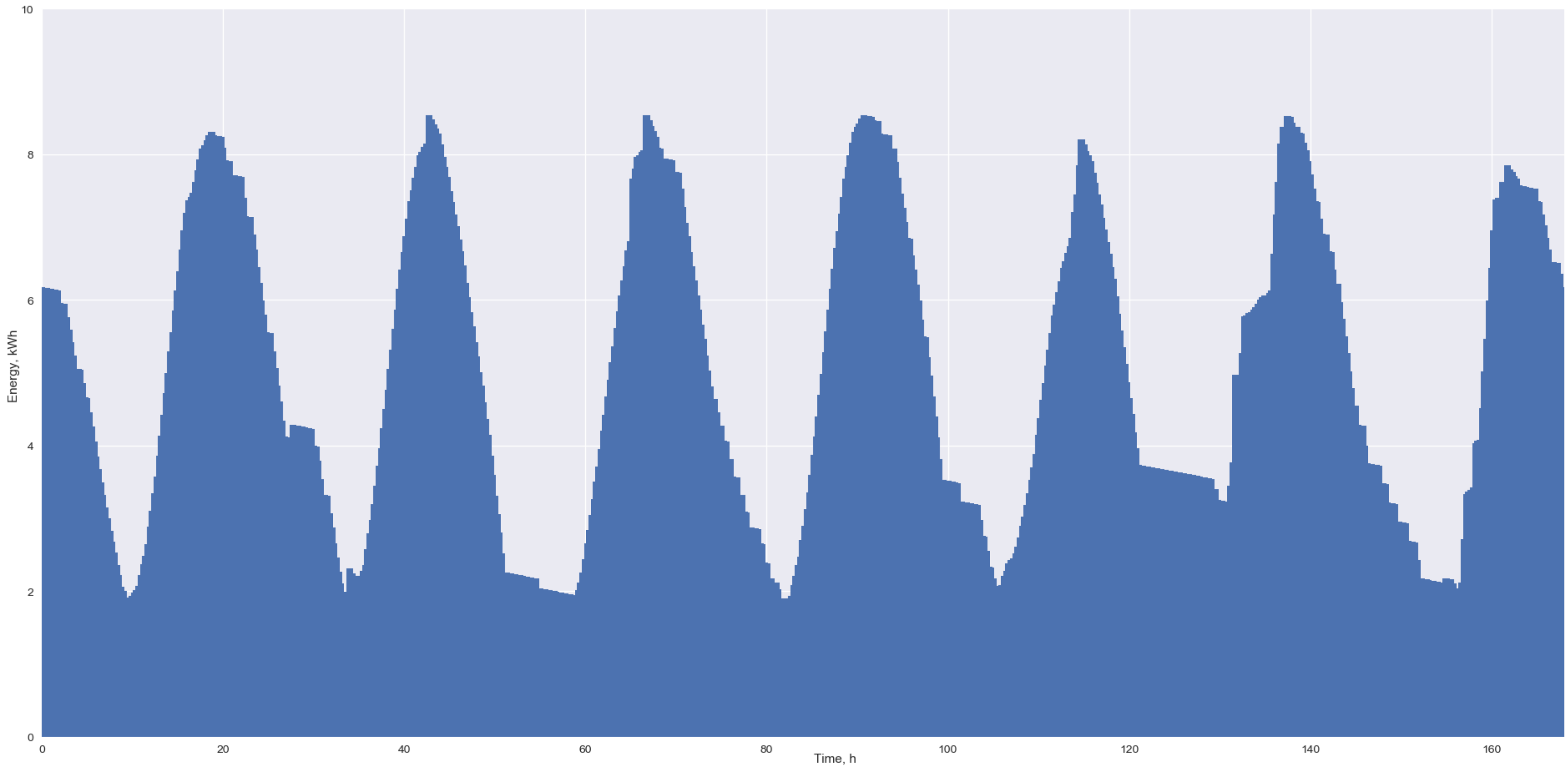

Figure 20 State of charge of the water tank over 1 week period for case 3 concerning electrical-thermal storage.

Table 4 Results of the simulation for case 3 concerning electrical-thermal storage.

Electricity imports from the grid	34 kW
Electricity production from PV panels	153 kW
Electricity consumption	158 kW
Optimal electrical storage capacity	**21 kWh**
Heat imports from the network	0 kW
Heat production from ST panels	78 kW
Heat consumption	130 kW
Optimal thermal storage capacity	**90 l**
Heat pump electricity consumption	19 kW
Heat pump heat production	56 kW

As a result of the optimization process the optimal electrical storage capacity is found to be around 21 kWh, and the thermal storage capacity around 90 l. Thermal load is entirely covered from self-production together with water tank and a heat pump. No additional heat imports from the network are necessary. Electricity to run the heat pump is either taken from PV panels production, battery discharge, or from the electrical grid.

The results are presented in Table 4. For the examined period, PV panels produced around 153 kW. The electricity consumption amounts 158 kW. Additionally, for its operation, heat pump consumed 19 kW of electric energy to produce 56 kW of thermal energy. This shows that the self-production of electricity covers about 86.5% of the demand. With the production from ST panels equal 78 kW and heat demand equal 130 kW, self-production covers 60% of the thermal load, and the rest is supplied by the heat pump.

The behavior of the electrical and thermal systems over one week period is presented in figure 17 and figure 18, respectively. The state of charge of the electrical storage is depicted in figure 19 and the thermal storage – figure 20. It can be noticed in figure 17 that for electrical grid self-production together with storage battery is mostly sufficient to cover the demand, as well as drive the heat pump. Imports from the grid are necessary mainly at the beginning of the considered period, as the energy storage starts with low level of charge, and after day 6, as a result of lower generation from PV panels. The state of charge of the battery (figure 19) follows quite repetitive and similar pattern for each day, with the exception of the last two days, when the charge level is much lower, due to lower self-production. The imports from the grid are also necessary when the state of charge of the storage unit approaches minimal constraint.

As already mentioned, the thermal system, depicted in figure 18, does not require the support of the district heating network. Part of the load is covered from ST panels, and the rest from the heat pump. The peaks in the heat demand are shifted in comparison to the electricity demand. The highest electricity loads are observed in the middle of the day, during working hours in the office building. When it comes to the heat load, it is highest during nights, when temperature is the lowest. Because of this, generation from ST panels during the day is mainly directed to charging the water tank storage, and discharging takes place during the night (figure 20). This causes the necessity of choosing larger storage capacity, able to store most of the heat generated throughout the day. However, heat pump operates mainly during the nights, which helps to balance the electrical load.

4.4 Case 4: electrical grid operating costs

The main case considered in this work is developed for the exact system and data presented and described in the case above (point 4.3). The objective is to minimize the operating costs of the electrical grid. The hourly costs distribution throughout the day is presented in figure 21. The code for the model developed using OMEGAlpes library is attached in appendix B.

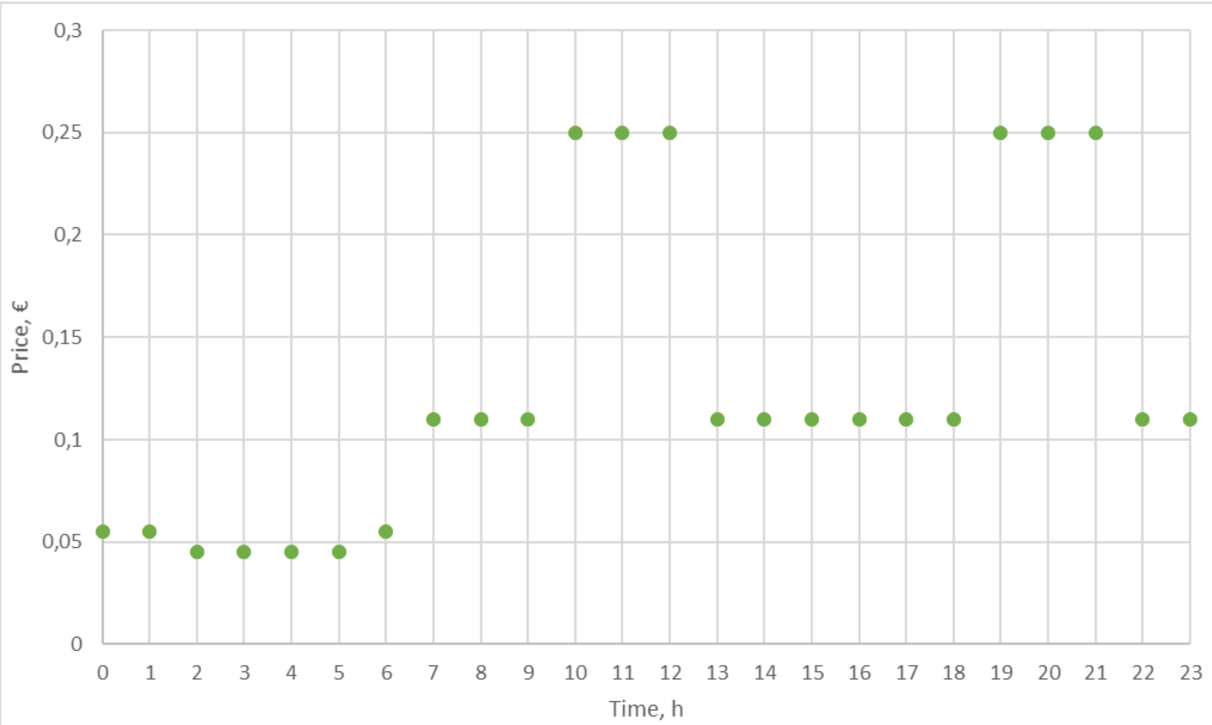

Figure 21 Electricity operating costs distribution.

Figure 22 Power flow for the units connected to the electrical node over 1 week period for case 4 concerning electrical grid operating costs.

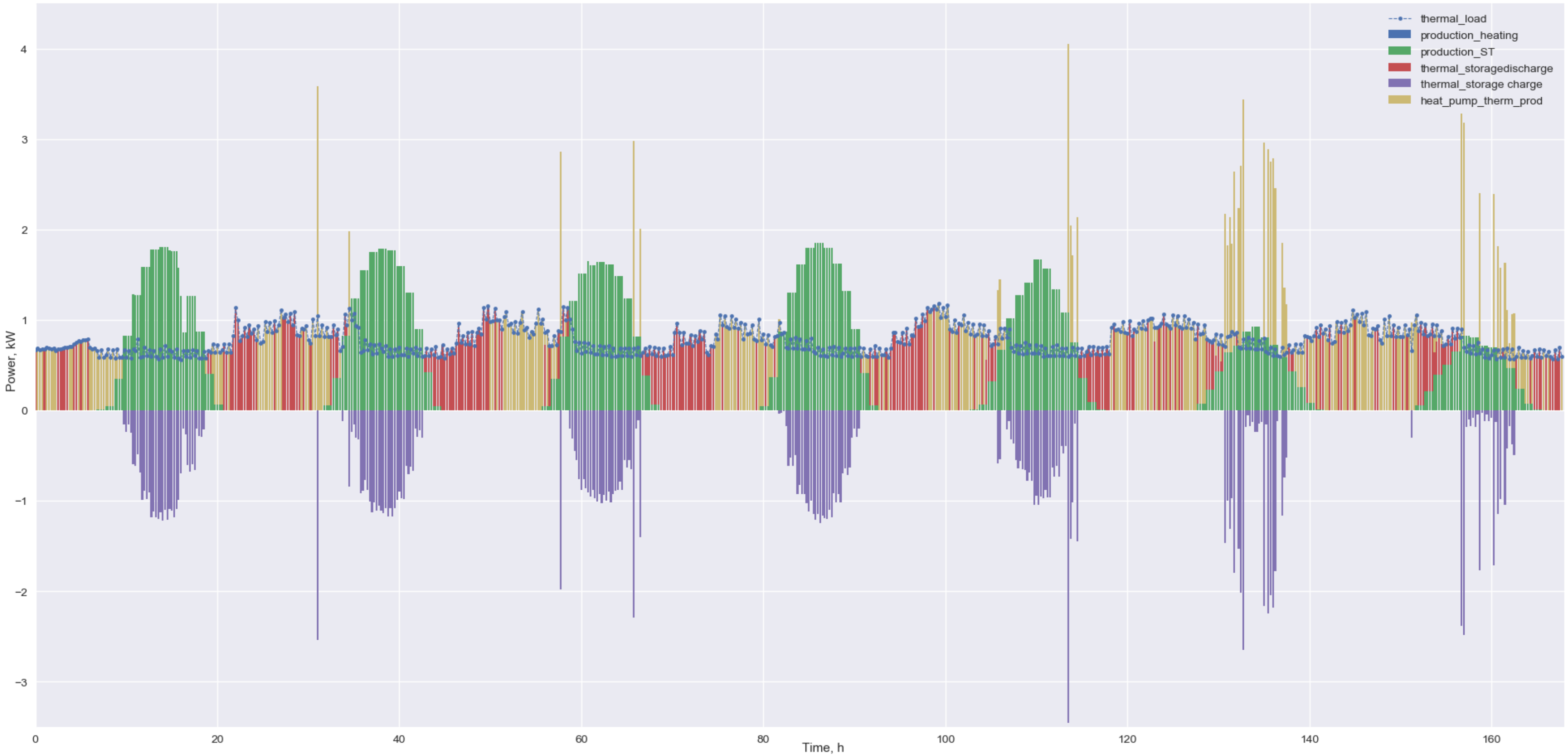

Figure 23 Power flow for the units connected to the thermal node over 1 week period for case 4 concerning electrical grid operating costs.

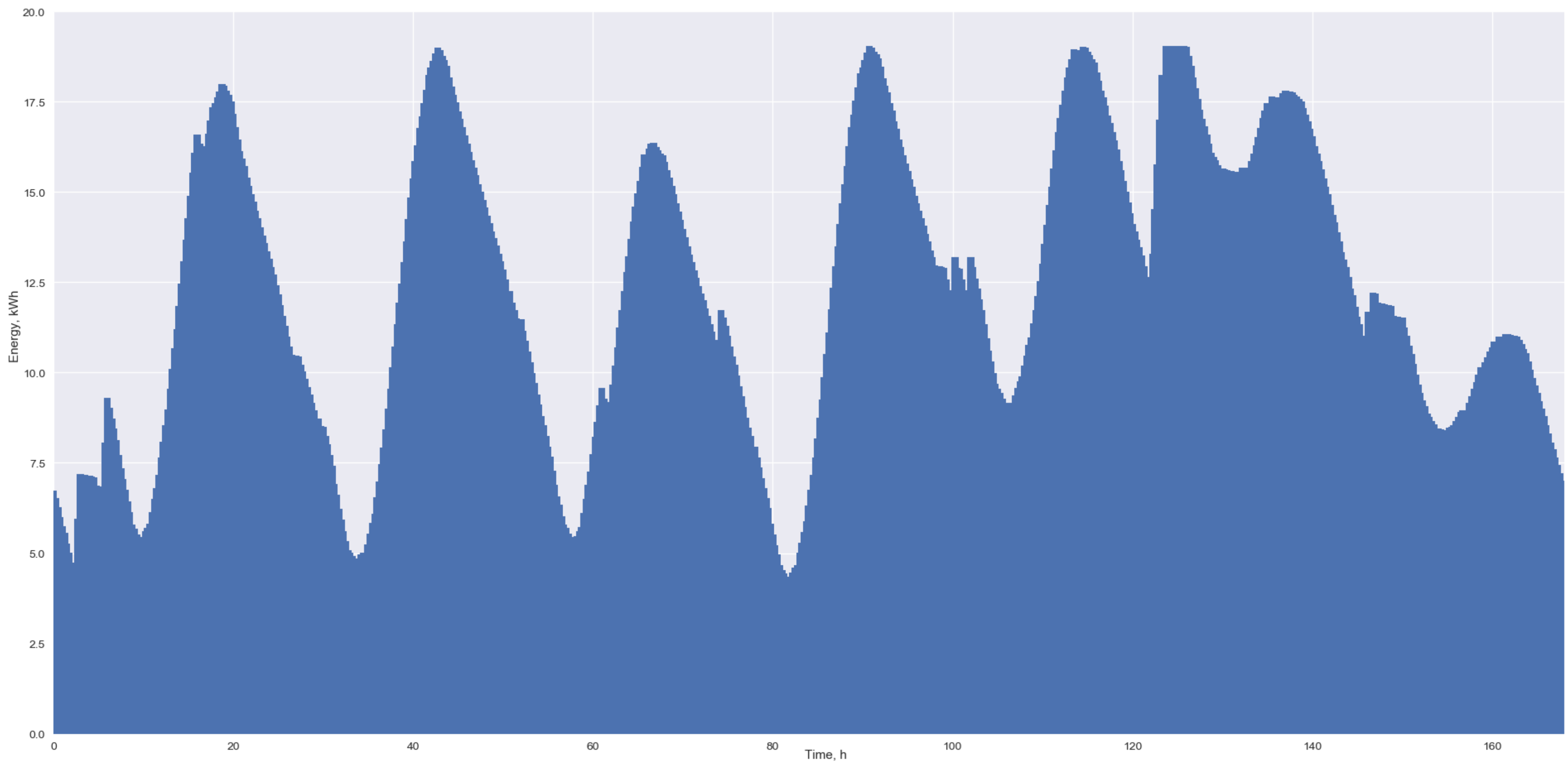

Figure 24 State of charge of the battery over 1 week period for case 4 concerning electrical grid operating costs.

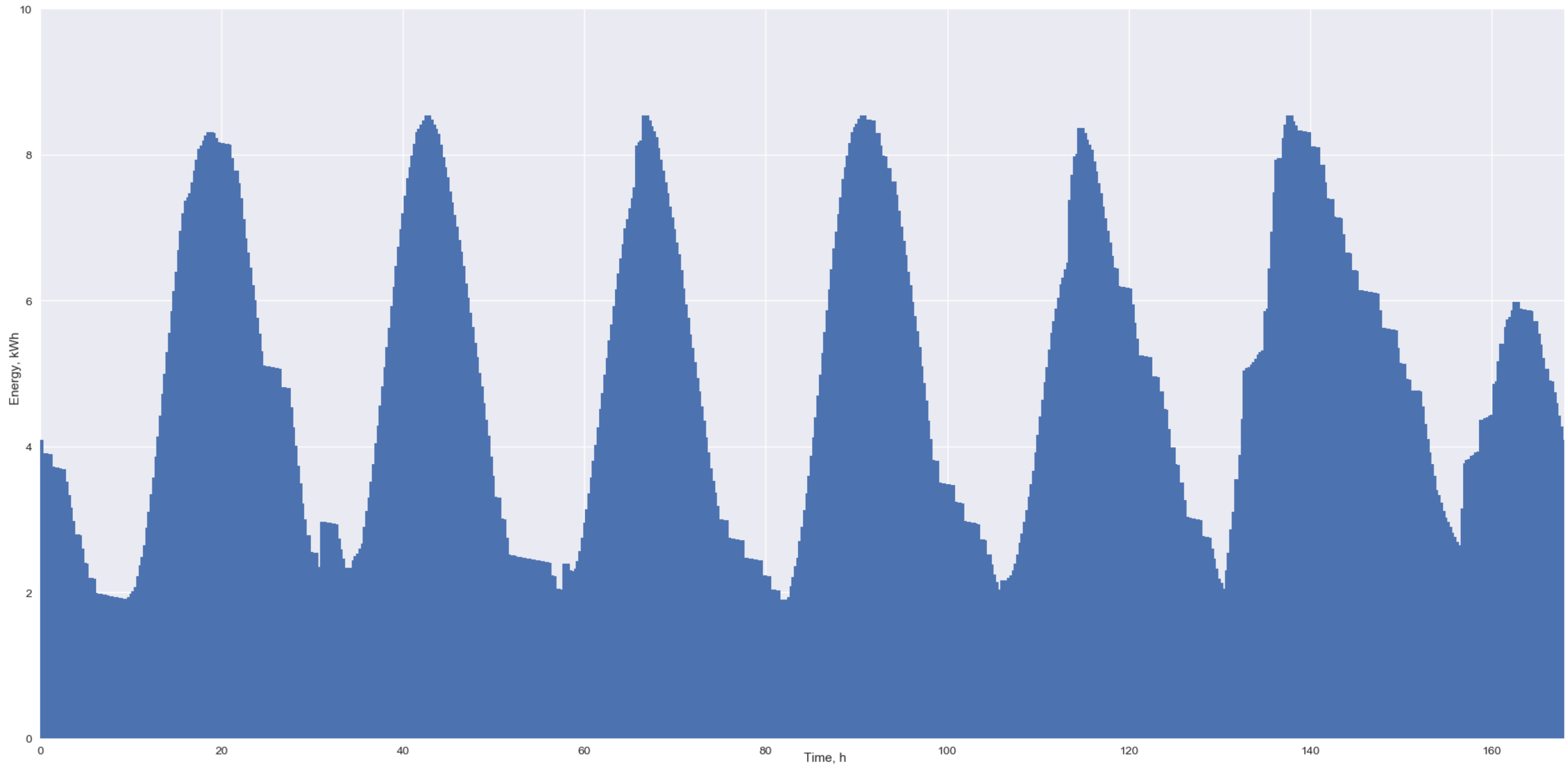

Figure 25 State of charge of the water tank over 1 week period for case 4 concerning electrical grid operating costs.

Table 5 Results of the simulation for case 4 concerning electrical grid operating costs.

Electricity imports from the grid	34 kW
Electricity production from PV panels	153 kW
Electricity consumption	158 kW
Optimal electrical storage capacity	**21 kWh**
Heat imports from the network	0 kW
Heat production from ST panels	78 kW
Heat consumption	130 kW
Optimal thermal storage capacity	**90 l**
Heat pump electricity consumption	19 kW
Heat pump heat production	56 kW

Analysis of the power flow for the electrical units (figure 22) shows that the electricity imports from the grid take place only during night hours for which the electricity price is the lowest. Charging of the battery storage (figure 24) from the grid is also conducted in the time range, when electricity is the cheapest. The close-up of the first day to better depicture the time when the grid is used is presented in figure 26. It can be noticed that electricity imports to cover the load, as well as to charge the storage, take place in the time range 2 AM - 5 AM, when price reaches the lowest point, equal 0.045 € for the energy unit (figure 21).

Figure 26 Close-up of the power flow for the units connected to the electrical node for day 1 for case 4 concerning electrical grid operating costs.

Comparing the electricity flow in the system before cost optimization (figure 17), and with operating cost minimization (figure 22) the change in behavior can be noticed. Electricity imports from the grid do not take place whenever the self-production or state of storage are too low to cover the loads, as it was observed for case 3, but the model predicts that in a near future the generation would not be sufficient or the storage would need charging not to reach the lower state of charge constraint, and in preparation to cover those loads uses electrical grid when the price is the lowest. It can be better observed in figures 27 and 28, where the distribution of imports from the grid over time for case 3 and 4, respectively, is presented. For case 4 it is clearly visible that the imports from electrical grid are taking place only for specific hours, which can be recognized as the hours with the lowest price when compared with price distribution in figure 21.

For case 4, the optimization process yielded decrease in the electricity costs of 58% in relation to the case 3 for the considered week.

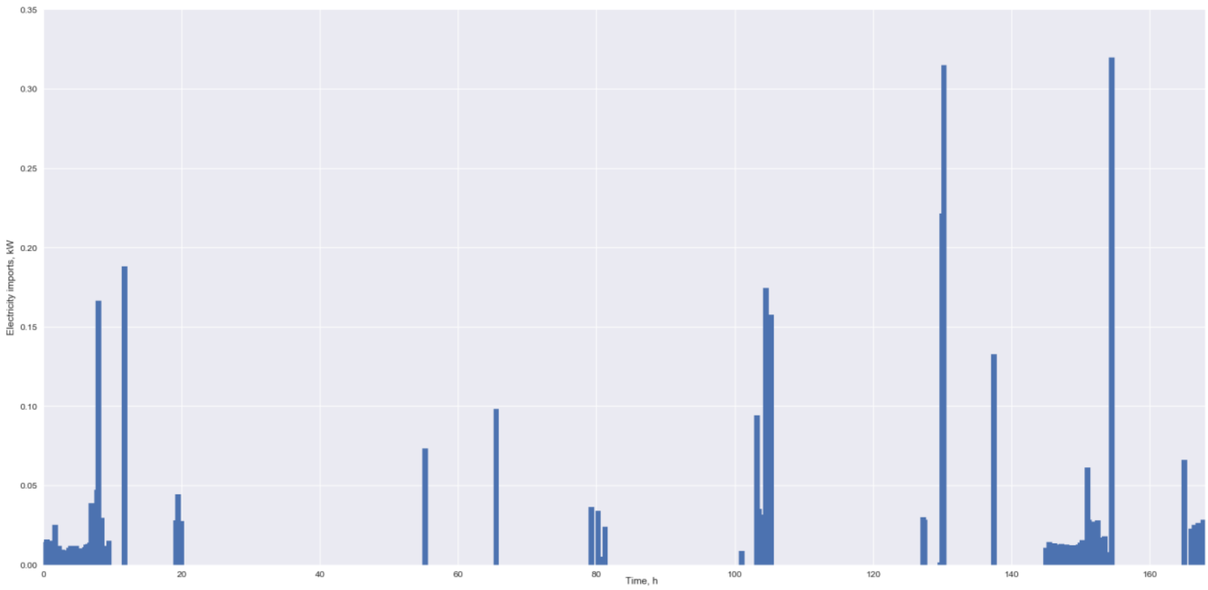

Figure 27 Distribution of the electricity imports from the grid over time for case 3.

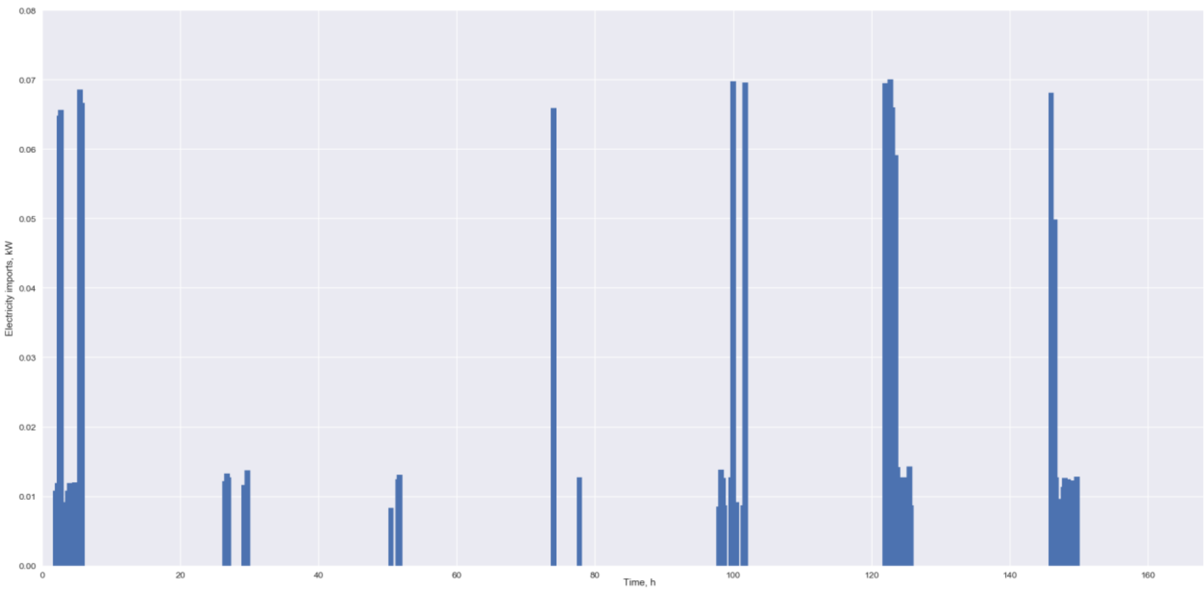

Figure 28 Distribution of the electricity imports from the grid over time for case 4.

5 CONCLUSIONS

This work focuses on a nZEB office building located in Portugal. The main model is developed using OMEGAlpes tool to optimize the work of the microgrid in a way that the costs of the electricity imports from the electrical grid are minimized. Additionally, the coverage of the thermal load from self-production from ST panels together with the heat pump driven by PV panels is maximized, so that the support of the heating network is not needed. Further the optimal electrical and thermal storages' capacities are found for the modelled system.

As a result of the optimization of the work of the system, 58% reduction in the electricity costs was achieved. The results also show that for the examined period of time the energy storage units are oversized. The currently installed battery for electricity storage has got a capacity of 31.68 kWh, when the conducted studies show the optimal battery size is 21 kWh. For the water tank for thermal energy storage, instead of 300 l capacity, the optimal size is found to be 90 l. As the storage units are already installed in the building, the best solution would be to increase the self-production, as there is still a potential to cover more of the load from on-site generation and in this way lower the imports from the electrical grid even more. In current state the building covers about 86.5% of the electricity demand and 60% of the heat demand from self-production from the renewable resources.

The building could be also further developed into a Positive Energy Building, if the self-production surpassed the loads throughout the whole operating period. Then the building would be considered as a kind of power unit, sharing its energy surplus with the infrastructure in the vicinity, like outdoor lighting. It could be a first step to going even further and developing the concept of a Positive Energy District, where the energy surplus would be used to balance other buildings' loads.

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APPENDICES

Appendix A

```
from omegalpes.energy.units.consumption_units import FixedConsumptionUnit
from omegalpes.energy.units.production_units import FixedProductionUnit,VariableProductionUnit
from omegalpes.energy.units.storage_units import StorageUnit
from omegalpes.energy.energy_nodes import EnergyNode
from omegalpes.general.time import TimeUnit
from omegalpes.general.optimisation.model import OptimisationModel
from omegalpes.general.utils.plots import plt,plot_quantity_bar,plot_node_energetic_flows
from pulp import LpStatus

state_of_charge_min=0.2
state_of_charge_max=0.9
self_discharging=0.0025 #1% an hour


def model(pv_generation,load_profile,charging_power_max,discharging_power_max):

    time=TimeUnit(periods=24*4*7,dt=1/4) #15 min time step for 1 week

    model=OptimisationModel(time=time,name="improvement")

#production units

    production_grid=VariableProductionUnit(time,'production_grid',energy_type='Electrical')

    production_PV=FixedProductionUnit(time,'production_PV',energy_type='Electrical',
                                      p=pv_generation)

#consumption unit

    load=FixedConsumptionUnit(time,'electrical_load',energy_type='Electrical',p=load_profile)

#electrical storage

    electrical_storage=StorageUnit(time,'electrical_storage',energy_type='Electrical',
                                   pc_max=charging_power_max,pd_max=discharging_power_max,
                                   soc_min=state_of_charge_min,soc_max=state_of_charge_max,
                                   self_disch=self_discharging,ef_is_e0=True)

#optimization objective
```

```
    production_grid.minimize_production()

#energy nodes

    electrical_node=EnergyNode(time,'electrical_node',energy_type='Electrical')

    electrical_node.connect_units(production_grid,production_PV,load,electrical_storage)

    model.add_nodes(electrical_node)


    model.solve_and_update()

    return model,time,production_grid,production_PV,load,electrical_storage,electrical_node
```

Appendix B

```
from omegalpes.energy.units.consumption_units import FixedConsumptionUnit
from omegalpes.energy.units.production_units import FixedProductionUnit,VariableProductionUnit
from omegalpes.energy.units.storage_units import StorageUnit
from omegalpes.energy.units.conversion_units import HeatPump
from omegalpes.energy.energy_nodes import EnergyNode
from omegalpes.general.time import TimeUnit
from omegalpes.general.optimisation.model import OptimisationModel
from omegalpes.general.utils.plots import plt,plot_quantity_bar,plot_node_energetic_flows
from pulp import LpStatus


el_state_of_charge_min=0.2
el_state_of_charge_max=0.9
el_self_discharging=0.0025 #1% per hour

th_state_of_charge_min=0.2
th_state_of_charge_max=0.9
th_self_discharging=0.0025 #1% per hour
```

```
def model(pv_generation,st_generation,el_load_profile,th_load_profile,el_charging_power_max,
el_discharging_power_max,th_charging_power_max,th_discharging_power_max,heat_pump_cop,
heat_pump_pmax,op_cost_grid):

    time=TimeUnit(periods=24*4*7,dt=1/4) #15 min time step for 1 week

    model=OptimisationModel(time=time,name="improvement")

#electricity production units

   production_grid=VariableProductionUnit(time,'production_grid',energy_type='Electrical',
                                                          operating_cost=op_cost_grid)

    production_PV=FixedProductionUnit(time,'production_PV',energy_type='Electrical',p=pv_generation)

#heat production units

    heating_company=VariableProductionUnit(time,'production_heating',energy_type='Thermal')

    production_ST=FixedProductionUnit(time,'production_ST',energy_type='Thermal',p=st_generation)

#electricity consumption unit

    electrical_load=FixedConsumptionUnit(time,'electrical_load',energy_type='Electrical',p=el_load_profile)

#heat consumption unit

    thermal_load=FixedConsumptionUnit(time,'thermal_load',energy_type='Thermal',p=th_load_profile)

#electrical storage

    electrical_storage=StorageUnit(time,'electrical_storage',energy_type='Electrical',
                                       pc_max=el_charging_power_max,pd_max=el_discharging_power_max,
                                       soc_min=el_state_of_charge_min,soc_max=el_state_of_charge_max,
                                       self_disch=el_self_discharging,ef_is_e0=True)
```

```
#thermal storage
    thermal_storage=StorageUnit(time,'thermal_storage',energy_type='Thermal',
                                pc_max=th_charging_power_max,pd_max=th_discharging_power_max,
                                soc_min=th_state_of_charge_min,soc_max=th_state_of_charge_max,
                                self_disch=th_self_discharging,ef_is_e0=True)

#heat pump
    heat_pump=HeatPump(time,'heat_pump',cop=heat_pump_cop,pmax_in_elec=heat_pump_pmax)

#objectives
    heating_company.minimize_production()
    production_grid.minimize_operating_cost()

#energy nodes
    electrical_node=EnergyNode(time,'electrical_node',energy_type='Electrical')
    electrical_node.connect_units(production_grid,production_PV,electrical_load,electrical_storage,
                                  heat_pump.elec_consumption_unit)

    thermal_node=EnergyNode(time,'thermal_node',energy_type='Thermal')
    thermal_node.connect_units(heating_company,production_ST,thermal_load,thermal_storage,
                               heat_pump.thermal_production_unit)

    model.add_nodes(electrical_node,thermal_node)
    model.solve_and_update()
    return
model,time,production_grid,production_PV,heating_company,production_ST,electrical_load,thermal_load,
heat_pump,electrical_storage,thermal_storage,electrical_node,thermal_node
```

```
def print_results(model,time,production_grid,production_PV,heating_company,production_ST,electrical_load,
thermal_load,heat_pump,electrical_storage,thermal_storage,electrical_node,thermal_node):

    if LpStatus[model.status] == 'Optimal':
        print("- - - - - OPTIMISATION RESULTS - - - - -")
        print("The optimal electrical storage capacity is {0} kWh".format(
            electrical_storage.capacity))
        print("The optimal thermal storage capacity is {0} kWh".format(
            thermal_storage.capacity))
        print('Electricity consumption = {0} kWh.'.format(
            electrical_load.e_tot))
        print('Heat consumption = {0} kWh.'.format(
            thermal_load.e_tot))
        print('Electricity imports from the grid = {0} kWh.'.format(
            production_grid.e_tot))
        print('Heating imports from the grid = {0} kWh.'.format(
            heating_company.e_tot))
        print('Electricity production from PV panels = {0} kWh.'.format(
            production_PV.e_tot))
        print('Heat production from ST panels = {0} kWh.'.format(
            production_ST.e_tot))
        print('Heat pump electricity consumption = {0} kWh.'.format(
            heat_pump.elec_consumption_unit.e_tot))
        print('Heat pump heat production = {0} kWh.'.format(
            heat_pump.thermal_production_unit.e_tot))
```

```
        print('Grid operating cost = {0} E.'.format(
            sum(production_grid.operating_cost.value.values())))

        plot_node_energetic_flows(electrical_node)
        plot_node_energetic_flows(thermal_node)

        plot_quantity_bar(time=time,quantity=electrical_storage.e,title='State of charge of the electrical storage (kWh)')
        plot_quantity_bar(time=time,quantity=thermal_storage.e,title='State of charge of the thermal storage (kWh)')
        plot_quantity_bar(time=time,quantity=production_grid.operating_cost,title='Grid operating cost')

        plt.show()

    elif LpStatus[model.status] == 'Infeasible':
        print("Sorry, the optimisation problem has no feasible solution.")
    elif LpStatus[model.status] == 'Unbounded':
        print("The function of the optimisation problem is unbounded.")
    elif LpStatus[model.status] == 'Undefined':
        print("Sorry, a feasible solution has not been found (but may exist).")
    else:
        print("Sorry, the optimisation problem has not been solved.")

if __name__ == '__main__':
    PV_GENERATION=[]
    EL_LOAD_PROFILE=[]
```

```
SOLAR_THERMAL_GENERATION=[]

TH_LOAD_PROFILE=[]

EL_P_CHARGING_MAX=5

EL_P_DISCHARGING_MAX=5

TH_P_CHARGING_MAX=5

TH_P_DISCHARGING_MAX=5

HP_COP=3

HP_P_MAX=1000

OPERATING_COST_GRID=[]


MODEL,TIME,PRODUCTION_GRID,PRODUCTION_PV,PRODUCTION_HEAT,PRODUCTION_ST,ELECTRICAL_LOAD,THERMAL_LOAD,HEAT_PUMP,ELECTRICAL_STORAGE,THERMAL_STORAGE,ELECTRICAL_NODE,THERMAL_NODE=model(pv_generation=PV_GENERATION,st_generation=SOLAR_THERMAL_GENERATION,el_load_profile=EL_LOAD_PROFILE,th_load_profile=TH_LOAD_PROFILE,el_charging_power_max=EL_P_CHARGING_MAX,el_discharging_power_max=EL_P_DISCHARGING_MAX,th_charging_power_max=TH_P_CHARGING_MAX,th_discharging_power_max=TH_P_DISCHARGING_MAX,heat_pump_cop=HP_COP,heat_pump_pmax=HP_P_MAX,op_cost_grid=OPERATING_COST_GRID)


print_results(MODEL,TIME,PRODUCTION_GRID,PRODUCTION_PV,PRODUCTION_HEAT,PRODUCTION_ST,ELECTRICAL_LOAD,THERMAL_LOAD,HEAT_PUMP,ELECTRICAL_STORAGE,THERMAL_STORAGE,ELECTRICAL_NODE,THERMAL_NODE)
```