Heat pumps associated with thermal energy storages to improve network utilization and flexibility: the case of Chrysa Xanthi, Greece

Matej Pečjak, Jernej Zupančič, Edin Lakić,
Assoc. Prof. Andrej F. Gubina, PhD
Laboratory of Energy Policy,
Faculty of Electrical Engineering,
University of Ljubljana, Slovenia
{Matej.Pecjak; Jernej.Zupancic; Edin.Lakic;
Andrej.Gubina}@fe.uni-lj.si

Estelle Mayer
Grenoble INP ENSE3
Engineering school
Auvergne- Rhône-Alpes, France
estellemayer@sfr.fr

Abstract— **Electric heating devices, in particular heat pumps, are a popular way of providing heat for space heating and domestic hot water. From the perspective of electricity network, heat pumps can be considered as a relatively large load, and the increasing number of heat pumps can put a strain on the existing infrastructure. However, heat pumps can also be considered as flexible loads that could improve the flexibility of the electricity network. Heat pumps alone can hardly provide any demand flexibility without affecting the comfort of occupants, but greater flexibility can be achieved by combining them with thermal energy storages (TES). In this paper, the flexibility potential provided by heat pumps has been assessed for the case of low voltage network of Chrysa Xanthi in Greece. Xanthi is one of the pilot sites in the Horizon 2020 project X-FLEX, aiming to maximize the integration of renewable energy sources (RES) and flexibility systems into the existing European network. For the purpose of this study, heat pumps together with photovoltaic (PV) generation were placed in a model of the existing network and cases where a large imbalance between generation and consumption occurs were studied. Additionally, TES was included in the heat pump demand model and the potential for increasing grid flexibility and improving the integration of RES was analysed.**

Index Terms--**Heat pumps, thermal energy storage, load flexibility, grid balance, renewable energy sources, power flow simulation**

I. INTRODUCTION

To achieve carbon-free generation goals a transition from the fossil fuel-based generation towards more renewable energy sources (RES) is needed [1]. In the electricity sector, the development and integration of RES, such as photovoltaic (PV) panels, wind turbines and controllable loads is crucial to achieve a net zero carbon energy system. However, these types of sources are intermittent and fluctuate according to weather conditions, which poses new challenges for the regulation and development of the electricity network due to the mismatch between generation and demand that can frequently occur [2]. On top of that, electricity demand is generally increasing, as well as power peak load [3]. Therefore, more flexibility is needed to maintain the balance of the network and to achieve a higher utilization of RES. According to EURELECTRIC, flexibility is a modification of generation and/or consumption patterns as response to external price or activation signal to provide a service within a system [4]. On the consumption side flexibility can be achieved through flexible loads whose consumption can be controlled according to the network conditions. These loads can annihilate the mismatch between power production and demand [5]. Flexible loads can also reduce power peaks, balance intermittent energy fluctuations and provide ancillary services to the network operator [6]. Among flexible loads also heat pumps can be considered.

Electrification of the heating sector with heat pumps has a great potential to achieve environmental targets, but only if the heat pumps are powered by RES [7]. According to the International Energy Agency (IEA), nearly 180 million heat pumps were used globally for heating in 2020. This number has increased by almost 10% per year over the last five years. Growth is evident across all primary heating markets: North America, North Asia and Europe. Despite their rapid growth, heat pumps still cover only a small share of residential heat demand (around 7% in 2020). In order to follow the Net-Zero Emissions by 2050 Scenario, the number of heat pumps must triple by 2030 [8]. A large number of heat pumps can present a burden for the electricity network, especially with the simultaneous large increase in electric vehicles, as this means an increase in peak power and also in the overlap factor. However, these effects can be at least partially mitigated by the flexibility potential of heat pumps. The flexibility of heat pumps is strongly dependent on the ambient temperature, the use of electric back-up heater [9] and the thermal capacity of the building. However, heat pumps are well suited for short-term flexibility, especially in combination with thermal energy storage (TES) [10]. To a certain extent, TES can provide an alternative to more expensive battery energy storage and allow flexibility in the power demand of heat pumps, that can be offered to other participants within the energy communities or in emerging local energy markets, bringing benefits for owners and grid operators.

In the following paragraphs, this paper focuses on the benefits for the operation of electricity network that heat pumps in combination with TES can be provide in different cases of imbalance, e.g. at power peak load or when there is a surplus of energy fed into the network. The study was carried out for the case of Chrysa, a western quarter of the town Xanthi, in northern Greece.

II. HEAT PUMPS AS FLEXIBLE LOAD

In general, heat pumps can be used for space heating and domestic hot water (DHW) or for DWH only. The main principle of operation of heat pumps is to transfer heat from a colder source to a warmer side using a refrigeration cycle [7], [11]. Heat pumps are characterized by a coefficient of performance (COP), which usually ranges from 2 to 4.5 for air source heat pump (ASHP) [7]. The ASHP is one of the three main types of heat pumps. The other two are water source heat pump and ground source heat pump. Heat pumps are one of the best and most cost-effective alternatives to conventional heating methods [7]. The reason for this lies in the COP, which defines the ratio of energy input to energy output. To improve the flexibility of heat pumps, without affecting the comfort of the users, TES can be added. The combination of heat pump and TES means that the heat pump has to operate at a higher power to meet the heat demand during operation and store the heat in the TES. Ultimately, this means a shorter operating times, which allows for a higher utilisation of RES. The most common type of TES is sensible heat storage, which is based on increasing the temperature of a solid or liquid material without a change of phase. The stored heat is then released by lowering the temperature of the material [7]. The heat stored can be calculated as follows:

$$Q = \rho \cdot V \cdot c_p \cdot \Delta T \qquad (1)$$

Where:

- Q is stored energy (heat) [J],
- ρ is density of the material [kg/m^3],
- V is volume of the material [m^3],
- c_p is specific heat capacity of the material [J/(kgK)],
- ΔT is the temperature difference between the initial and final state [K]

In (1), density and specific heat are constant and not the function of temperature [12]. Water is one of the most used materials for sensible heat storage due to its characteristics. It is abundant, inexpensive, easy to handle, non-toxic, easily stored in all types of containers and has a high specific heat capacity (4,283 J/(kgK) at 20°C, 1.01 bar). The optimal temperature range for the use of water in TES is about 25-90°C [13]. TES is also an alternative to battery storage, which is much more expensive. However, TES can only be used to increase the flexibility of heat pump, whereas battery storage can improve the flexibility of multiple loads.

III. CASE STUDY

The study was carried out for the case of Chrysa, an urban area of Xanthi in Greece. Xanthi is one of the four pilot sites (the others are also Luče (SI), Ravne na Koroškem (SI) and Albena (BG)) of the Horizon 2020 project X-FLEX. The X-FLEX project started in October 2019 and aims to design, develop and demonstrate a set of tools to facilitate the optimum combination and use of decentralised flexibility assets in the European network. X-FLEX is developing 4 main complementary products:

- GRIDFLEX tool: Advanced set of tools for automatic control and observability of the network
- SERVIFLEX tool: Integrated flexibility management tool
- MARKETFLEX tool: Market platform and new market mechanisms
- X-FLEX platform: Flexible and scalable integrated platform

The set of X-FLEX solutions is designed to offer services to all energy stakeholders from network operators (Distribution System operator (DSO), Transmission System operator (TSO)) to final consumers and prosumers, including intermediate parties as aggregators [14].

The considered electricity network of Chrysa consists of:

- One 100 kVA MV/LV substation,
- 4 feeders with 110 loads (33 three-phase and 77 single-phase loads),
- 3 PV power plants (two with an installed power of 10kWp and one with an installed power of 9.81kWp).

The topology of the Chrysa network is shown in Figure 1.

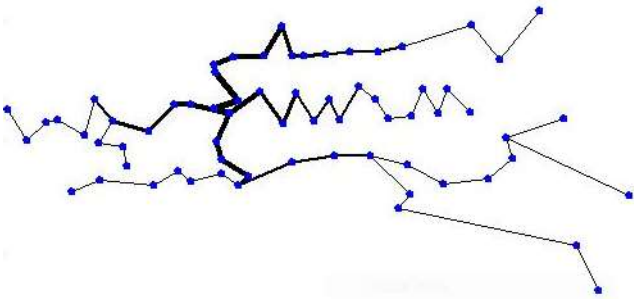

Figure 1: The topology of Chrysa network (black: power lines, blue: loads)

The simulation platform consisted of a detailed network model created in OpenDSS, an open-source power distribution system simulator [15] and the Python programming language used to define the power profiles, run power flow simulations and analyse the results. The following data was used for the study:

- Measurements from the Chrysa substation,
- typical load profiles,
- PV generation profiles,
- network data (power lines, transformer)

A. Existing loads and conditions

At the time of the study, neither PV generation nor consumption data were available for Chrysa, as users in Xanthi are not yet equipped with smart meters (installation of smart meters is planned under the X-FLEX project). Only typical consumption data for single-phase and three-phase loads were available, provided by the DSO. Therefore, based on these profiles and the measurements from the transformer substation, typical user profiles were generated. The profiles for PV were generated based on data from Kranj, Slovenia, taking into account the difference in solar radiation between the two locations. The generation profiles for the existing PVs in the network were subtracted from the transformer profile to obtain the aggregated load consumption. The aggregated consumption profiles for each day of the typical winter week are shown in Figure 2.

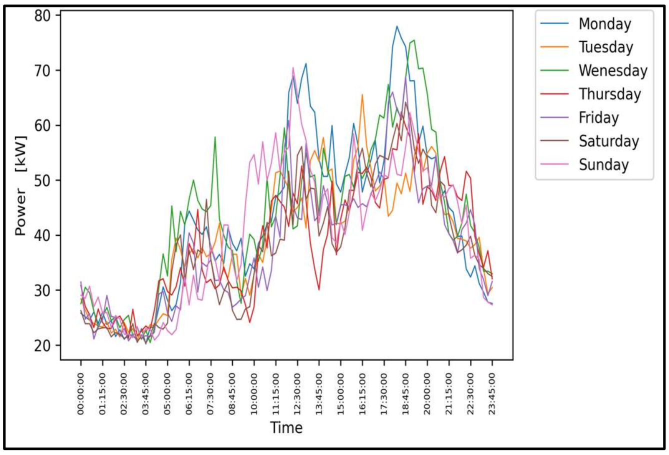

Figure 2: Aggregated consumption profiles.

The load profile of each user was modified with random noise (20% variation) so that the sum of the individual loads matched the aggregated profile. These profiles served as the basis for the power flow simulations.

B. Placing new heat pumps and PVs in the network

To assess the flexibility that the heat pumps could provide and the network conditions, new devices were placed in the network model. Information on heat pumps already installed in the network was not available. The heat pump consumption profile was determined based on data from the "When2Heat" dataset [16]. This dataset consists of synthetic national time series for 16 European countries, covering the time series of heat demand and COP of all three types of heat pump types and for each type two ways of heating (underfloor and radiator heating). Only ASHP with radiator heating were considered in this study. As Greece is not among the 16 countries included in this dataset, the average profile for Bulgaria (neighbouring country) and Croatia was used. The process of generating a typical heat pump consumption profile was divided into the following steps:

Step 1 – Generating a typical weekly winter heat pump profile for Bulgaria. The hourly heat demand in Bulgaria for space heating in single family houses (SFHs) in winter 2013 was used (2013 was the last year with available data in this category). The heat demand profile was divided by the hourly COP time series for the same period to obtain the heat pump power profile. As the data was aggregated for all SFHs in the country, it was divided by the number of residential dwellings for single families in Bulgaria in 2013, found in the EU Building database [17], to obtain the profile for a single heat pump.

Step 2 – Generation of a typical weekly winter heat pump profile for Croatia, same as for Bulgaria.

Step 3 - As there were no significant differences between the profiles of the two countries, the average value of the two profiles was used. The maximum power of the heat pump profile was 2.4 kW, which corresponds to the typical maximum power of the heat pump for space heating without immersion heaters. In total, 10 new heat pumps have been placed in the existing network model; the locations are presented in Figure 3.

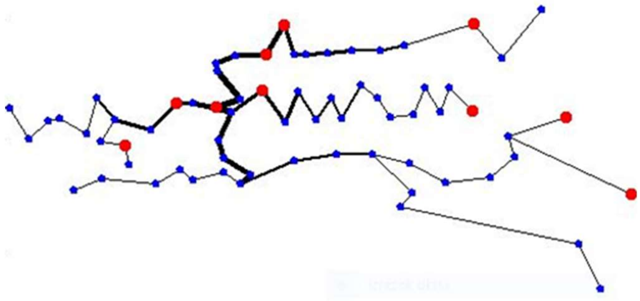

Figure 3: Chrysa network with locations of new heat pumps (red dots).

Based on the number of new heat pumps placed in the network, the required installed power of new PVs was calculated, taking into account the energy consumed by the heat pumps and the energy produced by the PVs. The results revealed that 160kWp of newly installed PV is needed to power 10 newly installed heat pumps. The purpose of this study was not to optimise the energy self-supply of an individual user, but to assess the flexibility potential at network level. Also, no information on available roof areas was available. Therefore, the required power of new PVs was not only distributed among the users with a newly installed heat pump, but among the different users, considering a maximum installed PV power of 10kWp (similar to those already installed in the network). The results of the simulation with the new heat pumps and PVs are presented in Figure 4.

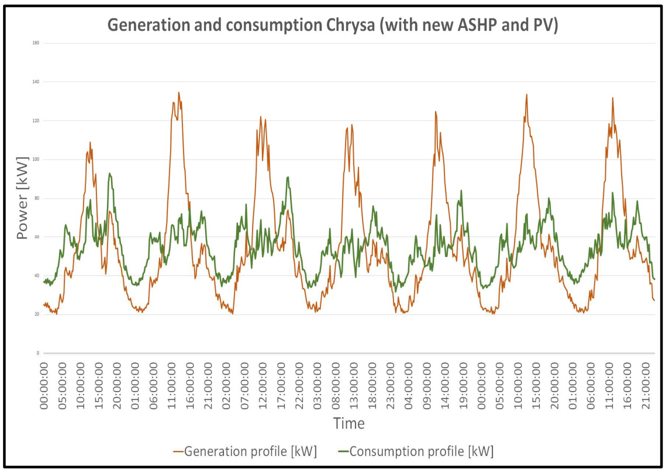

Figure 4 : Generation and consumption profile of the Chrysa network, a typical winter week with new PVs and heat pumps installed.

As can be seen from the figure, in this case there is a large mismatch between consumption and generation. To omit this mismatch battery storage or thermal energy storage systems should be added to the network.

C. *Placing Thermal energy storage*

To mitigate the mismatch between generation and consumption in the network, heat pumps were combined with TES. First, the total TES capacity needed for the whole network was calculated. A TES efficiency of 0.8 was considered, meaning that the TES can only return 80% of the stored heat. To compensate for these losses additional 30kWp of PV is needed. In the case analysed, a total thermal capacity of 1760 kWh is required to store the surplus energy produced by the PVs and not consumed by existing loads and newly installed heat pumps at the time of generation. The required TES volume was calculated using (1) and the following parameter values:

- ρ = 1000 kg/m^{3,}
- c_p = 4183 J/(kgK),
- ΔT = 50K

The required volume of one TES is 3m^3, which requires a lot of space. The required volume could be reduced by increasing the storage efficiency, while the temperature range considered was already quite high. The transformer profile for both case with newly installed PVs and heat pumps with and without TES is presented on Figure 5.

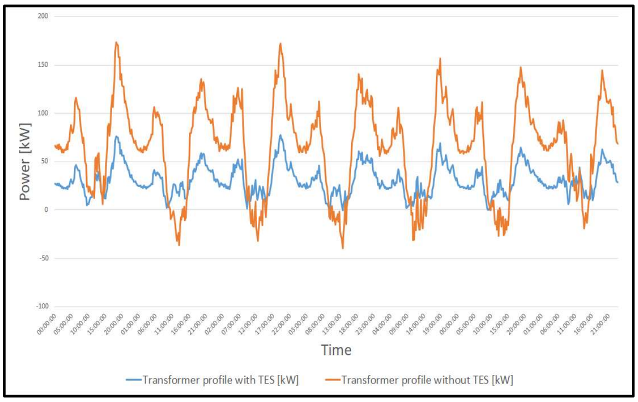

Figure 5: Transformer profile for Chrysa for the case with and without TES

As can be seen from the figure, if only new PVs and heat pumps without TES are added to the network, the transformer has to supply much high power, especially during peak load periods, and it can also be observed that the power curve is negative in some periods, as the energy generated by the PVs is not well used and is fed into the HV part of the network. On the other hand, in the case heat pumps are combined with TES, the transformer profile is much lower and the energy generated by the PVs much better utilised locally. Network and RES utilization is improved because the heat pumps absorb the excess energy generated by the PVs, store it as heat and deliver it when it is needed, (almost) without using the power from the network.

IV. DISCUSSION

The amount of upward flexibility that could be provided by heat pumps is equal to the maximum operating power of the heat pumps. However, the flexibility that heat pumps can provide is mainly available in winter and for a limited period during the day. The flexibility of heat pumps could be offered in the evolving local electricity markets, which is also the subject of the X-FLEX project. Local electricity markets, which also include local flexibility markets, are a relatively new concept and there are many barriers to their implementation and operation. Currently in Greece, Demand Response aggregators as well as final consumers and prosumers can participate in the new balancing market as (or trough) Balancing Service Providers, but the minimum bid to enter the capacity or energy market is set at 1MW [14]. There are also two interruptible demand-side programs that aim to extend the existing ancillary services markets by including flexibility. They are open to HV and MV consumers with at least 2MW of flexible load. Aggregation is not yet allowed, but developments are moving in this direction. In July 2020, Greece also adopted a Transitory Electricity Flexibility Remuneration Mechanism to remunerate the availability of flexible generation capacity. The purpose of this mechanism is to ensure the long-term availability of capacity and to set obligations for suppliers. However, all the mechanisms currently in place exclude small scale flexibility providers, including heat pumps. Greece also has no current plans to develop local flexibility markets [14]. In general, the barriers for the use of small-scale flexibility can be divided into two main parts. The first part covers operational barriers related to lack of equipment to control flexible devices (not all users are yet equipped with smart meters, which is an essential prerequisite for a smart grid solutions). The second part relates to regulatory barriers, as legislation in this area is not yet in place. Even if all the technical and regulatory conditions for using the flexibility provided by heat pumps were met, there is still the question of economic viability. The cost of one TES for a recommended size of 3m^3 is estimated at around €3,000 with installation. For comparison, replacing a 100kVA with 160kVA transformer is estimated at €3,250 [18]. In 2021, the average electricity price for households in Greece was around €0.187/kWh (including all components of the electricity bill) [19]. Investments in TES can be recovered through dynamic tariff and/or payments for ancillary services, which are difficult to assess for small-scale providers as they require the operation of several supporting services, such as the operation of the local market.

V. CONCLUSIONS

Within the study power flow simulations were performed to analyse the impact of newly installed heat pumps for the case of Chrysa, an urban area of the town Xanthi in Greece. The purpose of this study was to assess the flexibility potential that the heat pumps could provide and to analyse the relevant network conditions. In the presented study it is shown that the heat pumps in combination with thermal energy storage can improve the integration of renewable energy sources by increasing demand-side flexibility. In the future, this analysis can be extended to other seasons, in particular summer, to analyse the effect of heat pumps used for cooling.

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