CLEAN ENERGY AND RESILIENCY CONCEPTS AND ITS APPLICATION IN WEDISTRICT PROJECT

CONCEPTE DE ENERGIE CURATĂ ȘI DE REZILIENȚĂ ȘI APLICAREA ACESTORA ÎN PROIECTUL WEDISTRICT

Mihai SANDULEAC[1], Constantin IONESCU [2], Ioan-Cătălin DAMIAN [3], Cristina EFREMOV[4], Teodor DIACONU [5]

Abstract: *The paper presents concepts for clean energy and resiliency applied for a combined heat and electrical energy community. By using renewable energy produced with local PV panels, the heat and cold obtained with a heat generation unit based on heat pumps can be shared to the community, while the thermal energy becomes clean on a year-based period, which is a win-win solution to contribute to future carbon-neutrality. The solution has the potential to build also a more resilient energy community, which is presented in the paper for three different energy community environments: district, suburban and rural communities. It is shown that there are common principles which are valid for all the three environments. Application of these principles is also presented in the concepts of the Romanian small-scale implementation demonstrator within the European WEDISTRICT project.*

Keywords: clean energy, resiliency, heat pumps, PV, storage

Rezumat: *Prezenta lucrare reflectă concepte legate de obținerea energiei curate și a rezilienței energetice aplicate pentru o comunitate care folosește în mod combinat pompe de căldură și producerea locală de energie curată. Prin utilizarea producției cu centrale electrice fotovoltaice se poate obține atât încălzirea, cât și răcirea produsă centralizat la nivelul comunității locale utilizând un sistem de pompe de căldură, prin folosirea de energie curată ce acoperă necesarul de energie electrică la nivel anual, fiind o soluție „win-win" ce contribuie la procesul de decarbonare, cu potențialul de a crește și reziliența comunității locale. Soluția este prezentată pentru trei situații: la nivel urban, la nivel suburban și rural. In articol se arata faptul ca exista principii comune care sunt valabile pentru toate cele trei situații analizate. Aplicarea acestor*

[1] Prof., PhD, Habil., Univ., University Politehnica of Bucharest, mihai.sanduleac@gmail.com
[2] Assoc. Prof., DSc., University Politehnica of Bucharest, ionescu.constantin@upb.ro
[3] Assoc. Prof., DSc., University Politehnica of Bucharest, ioan_catalin.damian@upb.ro
[4] DSc., Univ. lect., Technical University of Moldova, cristina.efremov@adm.utm.md, ceferemov84@gmail.com
[5] DSc., University Politehnica of Bucharest, diaconuteodor@gmail.com

principii este, de asemenea, prezentată în cadrul implementării demonstratorului românesc de mică dimensiune din cadrul proiectului WEDISTRICT.

Cuvinte cheie: energie curată, reziliență, pompe de căldură, PV, stocare

1. Introduction

Energy sector is facing multiple challenges, such as the need to produce green energy instead of carbon dioxide-based production, the need for higher efficiency and the need for having more resilient communities.

Smart cities are endorsing these values as well. To handle the complexity of such goals it is recommendable to make stepwise advancements. A hierarchical approach based on solutions on different levels, such as end-user, neighbourhood level and then city-based level, in a collaborative solution between levels has more chances to be developed in a healthy and sustainable manner.

There are several studies which are coupling the heat pumps (HPs) need of electricity with the production of electricity through renewables. In [1] it is presented a study regarding the optimisation of PV production in combination with heat pump water heater, which is considered to be a difficult task which ask for a multi-objective approach and possible trade-offs. The energy consumption of the ground-source heat pump coupled with the PV array in the micro-grid system has been calculated in [2] and the paper is assessing that economic benefit is improved in the micro-grid area.

In [3] it is presented a case study-based approach which allows an efficient evaluation of future PV systems with battery energy storage systems (BESSs) and HPs, the impact of such decentralized power-heat-storage systems on grid integration as well as proper incentive setting for sector coupling. It is also shown that such shifting technologies are required to avoid under sizing of PV systems.

The study in [4] presents results which show that increasing PV penetration increases the hours of critical states in the distribution grid, while air to water heat pumps reduce those effects slightly when they are added to the grid. It is also observed that an increasing penetration of heat pumps brings new problems, such as load peaks in the mornings and that integrating voltage dependent droop control into the heat pumps have the potential to reduce the negative effects on the distribution grid.

In [5] it is stated that geothermal heat pumps using ground as thermal source in summer and winter period, can reach high energy and economical advantages for heating and cooling of residential and commercial buildings compared with other systems and that even if it needs initial investment higher than other solutions, it has relevant energy saving in short term and economical reduction of management costs in long term period. The study made on a building block shows that the cost-effectiveness of this solution combined with PV production brings synergies. Moreover, in [6] it is also shown that combining heat pumps with PV production has the potential to reduce PV curtailment, thus better using its energy potential.

2. Concept of combined central heating with heat pumps using local and distributed electricity production

The recent interest in electrifying and decarbonating heating by using heat pumps for producing thermal energy for a final user and/or for a community is given by their efficiency in using electricity compared with classic resistor-based heating. Table 1 gives a comparison between the two heating technologies.

Table 1. **Comparison between the two heating technologies.**

No	Characteristic	Joule-based heat (classic)	Heat pumps
1	Primary used energy	Electrical energy E_{Elec}	Electrical energy E_{Elec}
2	Based on	Joule law $E_{Th} = I^2R * T$ (1a) $E_{Th} = \int_0^T i^2(t) * R * dt$ (1b)	Heat energy transfer by using electricity $E_{Th} = COP * E_{Elec}$ (2)
3	η (efficiency)	η = 1 (full transformation of electricity in heat)	It is instead used COP[1]
4	COP[1]	Not apply	Usually in range 2 .. 6
5	CAPEX[2]	low	High
6	OPEX[3]	$E_{Elec} = E_{Th}$ (3)	$E_{Elec} = E_{Th}/COP$ (4)
7	TCO[4] = CAPEX + OPEX (5)	High cost for high price of electricity	Medium cost for high price of electricity
8	To be used	In a classic approach	In renewables based / resilience approach
9	Distributed solutions	Yes	Yes, in various solutions, depending on technology
10	Environment dependency	No	Yes, especially for air-to-X HP technologies
11	Suitable for “green” label	Yes, if electricity is green as well	Yes, if electricity is green as well

Abbreviations: [1] Coefficient of Performance; [2] Capital Costs; [3] Operational Costs; [4] Total Cost of Ownership.

Heat energy E_{Th} can be split in energy used for the building where HPs are installed and $E_{Th_{Local}}$ and the energy sent to the neighbourhood participants:

$$E_{Th} = E_{Th_{Central}} + E_{Th_{Neighb}} \tag{5}$$

If we consider the energy received by the district / neighbourhood user, then:

$$E_{Th} = E_{Th_{Central}} + E_{Th_{Losses}} + \sum E_{Th_{User\_i}} \tag{6}$$

where

$$E_{Th} = E_{Th}{}_{T1}^{T2} = \int_{T1}^{T2} P_{Elec}(t) * COP(t) * dt \tag{7}$$

Equations (6) takes into account the transport losses of energy $E_{Th_{Central}}$ on the water pipes between central heating and local heat user of the neighbourhood, while equation (7) shows that E_{Th} is in fact an integral in the time interval $\Delta T = T2 - T1$ of the product between the momentary electrical power $P_{Elec}(t)$ and the momentary value $COP(t)$, as COP is also time dependent on external factors, such as outside temperature or temperature of soil or groundwater.

Central heating using heat pump technology at the level of neighbourhood or district is an efficient solution because of several factors:

– A heat pump unit of higher capacity has a lower specific price.
– For the heat pump associated pipes, acceptable surface which is accessible for works is easier to be found at community premises, as usually there are such local administration places which can be used for the community interest.
– The efficiency of a bigger unit is also higher than for several smaller units.
– Thermal storage at HP premises (e.g., heated water tanks) can be also economically implemented, while giving more flexibility related to the heat and cold consumption need in the district.

One traditional disadvantage is the reduction of the overall efficiency due to the heat and cold losses in the distribution network. However, this aspect can be also mitigated by building the HP unit at an acceptable low distance from the heat and cold users, in order to reduce heat losses in a smaller distribution network. This brings the solution of having HP units in the neighbourhood / district level, meaning at kilometres range rather than traditional central heating which can face tenths of km range between heat production and its customers.

The HP need for electricity can have also a local solution, with the following structure of energy production:

- Part of the energy can be obtained with a bulk PV plant on the HP premises or nearby it by using community administrated land; this brings also a lower specific price of the kW installed and of the produced energy, as expected for medium size units, e.g., of hundreds of kW up to MW range.
- Additional clean energy can be obtained from prosumers located in the neighbourhood / district area, mainly those which are also heat and cold consumers.
- Both bulk and distributed battery energy storage systems (BESS) can be implemented, meaning that at HP premises it can be implemented a higher capacity of BESS, with lower specific price of installed kWh, while the BESS capacities from neighbourhood prosumers can be also used to help using the PV production when the HP system needs it mostly.

An essential new characteristic of such solution is the potential of increasing resiliency.

The combined local heat production and local electricity production are establishing a real energy community. However, the whole functionality still relies on the existence of public electricity network, which allows electric energy supply to the HPs, from PV production, from BESS and of complementary energy (up to the total need in a certain moment), which all ask for a reliable electrical grid.

While power systems are designed with high reliability goals, several concerns exist:

- Interruption of energy supply at distribution level may exist, due to grid problems; these interruptions are usually from minutes to some hours long; small interruptions of some seconds may also occur, due to various faults which are cleared by protection relays.

– Blackouts scenarios are becoming serios threats due to different external causes; the possibility of such longer-term power outage (one to several days or even more than one week) is now a topic more seriously considered by policy deciders.
– Natural disasters due to heavy weather conditions are becoming also more likely to occur, bringing another threat to the power supply from public network.

These concerns are reasons for considering a certain level of resilience as an important added value to a local energy community such as the one presented above.

Three different types of energy communities with the HP and PV production spectrum are presented below, with clean energy and heating and cooling with resiliency features.

2.1. District microgrid

This is the basic of combined heat and electrical energy community and is presented in Figure 1.

Figure 1. District microgrid (urban area)

The above principles are implemented as follows:

- A district central HP facility is associated to an important building, such as the district administration building or other public important building. Based on the land nearby the building, the geothermal heat exchanger of the heat pumps system can be more easily implemented. Moreover, local PV and storage (both thermal and electrical) is implemented, supplying part of the electricity need for the HPs and ensuring a certain level of resiliency as well.
- Additional bulk PV production $E_{Elec_{Bulk\_PV}}$ and bulk storage can be deployed in other parts of the district, supplementing the electric energy supply for the district.
- Flexible and active actors acting as prosumers are also able to contribute to the HP electricity needs with a share of electrical energy in a deal to obtain heat and cold in community-level attractive conditions, by contributing to the total electricity consumed by HPs. Equation 8 presents the total contribution of electricity, by considering the bulk PV as well:

$$E_{Elec} = E_{Elec_{Central}} + E_{Elec_{Bulk\_PV}} + \sum E_{Elec_{User\_i}} \tag{8}$$

This solution can also bring an attractive business model where a community member delivers green electricity and receives green heat and cold, obtained with higher efficiency than traditional electrical heaters which are based on pure Joule effect.

- An electrical distribution grid allows the electric energy contribution, and a thermal distribution network allows heat and cold supply to the district customers. To be mentioned that if heat and cold do not need to be supplied at the same time, as central HPs are also working in one mode only at a time, there is also only one set of pipes to serve both heating during low outside temperature periods and cold during the summer period.

2.2. Suburban microgrid using the above district concepts

This is another solution of combined heat and electrical energy community and is presented in Figure 2.

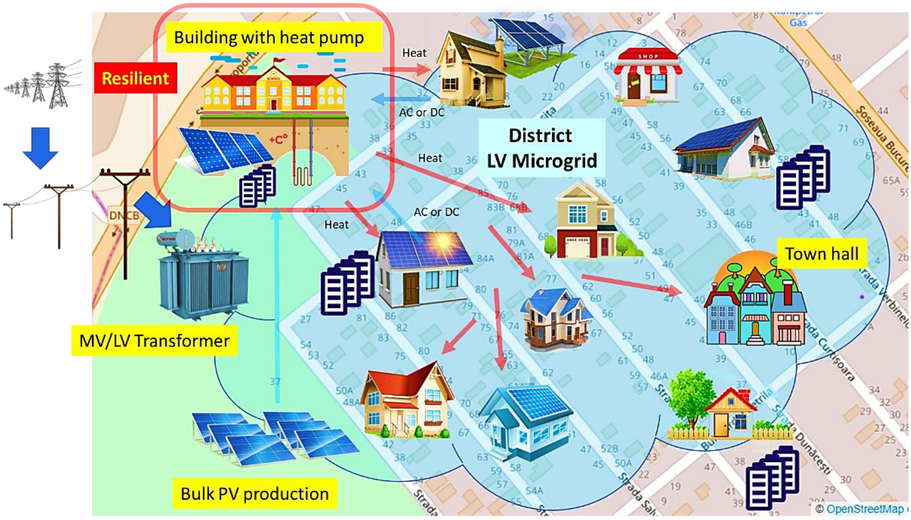

Figure 2. District microgrid in a sub-urban area

The above principles are similar with the basic situation:

– A suburban central HP facility is associated to an important building, such as the local administration building or a school, using land nearby the building to install the ground heat exchanger of the HP system, with local PV and storage to ensure at least a short-time resiliency. The HP-associated building can benefit as well from the central HP, which can deliver the $E_{Th_{Central}}$ component of its total E_{Th} which is produced at this level.

– Additional bulk PV production and bulk storage can also supplement the electric energy supply for the district.

– Prosumers from the neighbourhood can also contribute with electrical energy and can obtain heat and cold with preferential conditions.

– The local electrical distribution grid and a local thermal distribution network allows exchange of electricity respectively heat and cold supply inside the neighbourhood energy community.

2.3. Countryside microgrid

This is a combined heat and electrical energy community adapted for countryside where houses are still enough dense to allow economical distribution of heat and is presented in Figure 3.

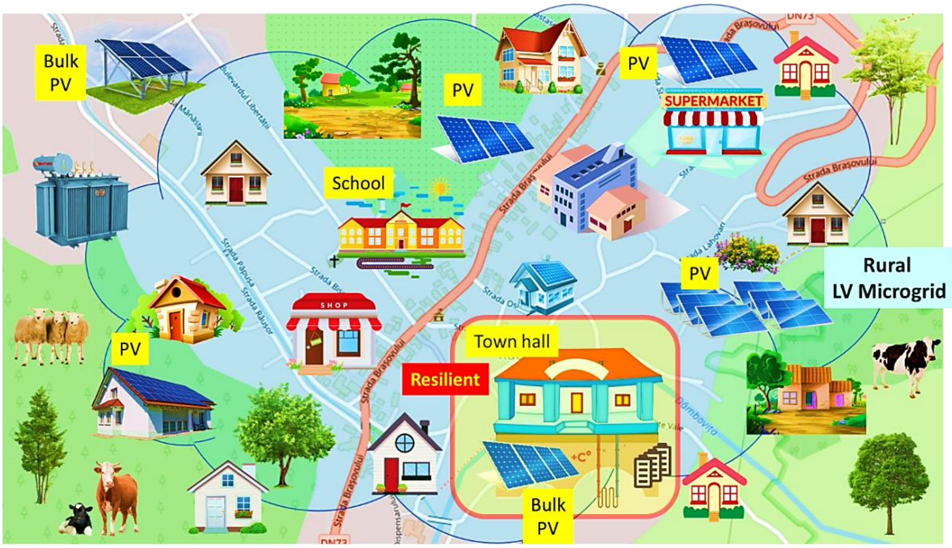

Figure 3. District microgrid in a sub-urban area

The presented principles can be adapted as well for constructing rural clean energy communities with resilience:

- A central HP facility associated to an important rural bulling, such as the local administration building or a school, with associated HP, local PV and storage to allow short-term resiliency.
- Additional bulk PV production and bulk storage can supply the HP.

Prosumers from the rural community can also contribute with electrical energy getting preferential heat and cold, while the local electrical distribution grid and a local thermal distribution network allows exchange of electricity, heat and cold supply inside the rural energy community.

3. WEDISTRICT pilot implementation

The European project H2020 WEDISTRICT [7] approached this hierarchy at district level, by studying different technological solutions to be applied in a district of a smart city. University POLITEHNICA of Bucharest (UPB), as part of the consortium, has developed a concept related to a district-level efficient heating system using heat pumps, which is supplied entirely by clean electricity on a year-based timeframe, which is produced locally, in a mix of bulk production at heat-pumps level with distributed prosumer's solution.

This concept is now studied in a project demonstrator developed in UPB, Faculty of Energy Engineering, by using the following smaller-sized components which can be used for the study of the concepts:

– A tandem master-slave heat pump is used to regulate the climate inside the ENc building of the faculty, by providing heat or cold during the whole year. Excess thermal energy (heat) is injected in the university heating network.
– A set of PV-based production entities, which cover on a year-based time interval the electrical energy needed by the heat pumps. The PV production intended to simulate a real environment in a district, with bulk production at heat-pump premises and with various PV plants owned by end-users, which can contribute to the centralized thermal production through a local distribution network.

Figure 4 presents the concept of WEDISTRICT project.

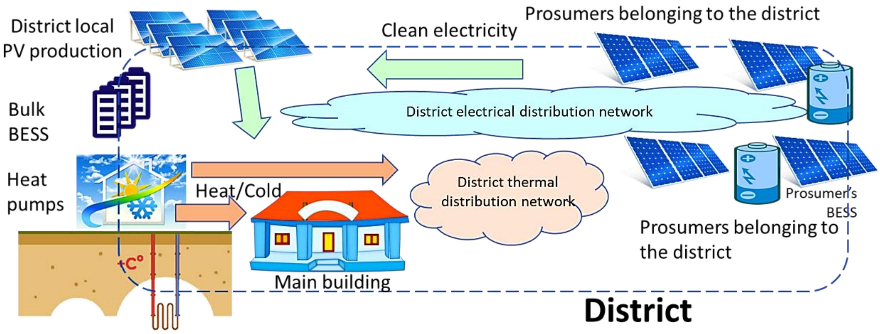

Figure 4. District microgrid in a sub-urban area

The following implementation is projecting the above concept:

– The main building is ENc building inside the Faculty of Energy Engineering.
– The two heat pumps and bulk BESS are also installed in the ENc building.
– The “District local PV production” is a roof-top PV installation on the ENc building. The total capacity of the PV system is 26 kW (peak power, also described by the notation kWp).
– Various prosumers in the district neighbourhood are implemented through 4 groups of PV panels installed on the roof of another building (EI building) belonging to the Faculty of Energy Engineering. The total capacity of the PV system placed on EI building roof is 40 kWp.

– The electrical grid is the faculty's low voltage grid, supplied from an MV network belonging to UPB. Two 630 kVA MV/LV transformers are used for supplying the LV network of the faculty.
– The thermal network of the "district" is the thermal network of UPB.

Moreover, at both buildings are placed BESS capacities (Lithium-based batteries using LiFePO4 chemistry) with internal electronics allowing digital communication and batteries equilibration), for adding resilience features to the different components of the system.

A general view of the microgrid developed in UPB is shown in Figure 5.

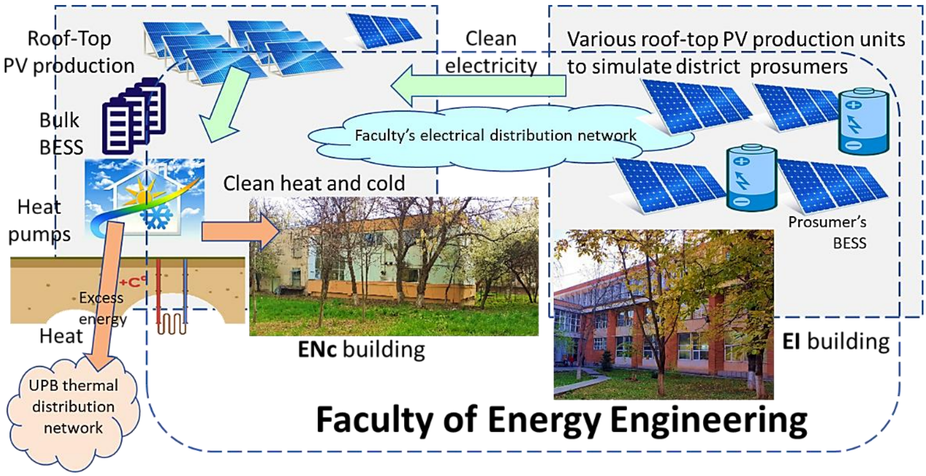

Figure 5. District microgrid in a sub-urban area

Some relevant recorded data from the SCADA system of the demonstrator are presented in the following Figures.

Figure 6 presents a summer day, when PV production is high and HP consumption is very low, due to the called "passive cooling". The Figure presents the energy generated and consumed in each hour of the day of 14.08.2022. The total PV production has been 158.8 kWh, while the consumption of the HP system has been 27.7 kWh, mainly due to circulation pumps and fan-based convectors. Figure 7 presents the PV production of the same day, using a time granularity of 1-minute.

Figure 8 presents a late autumn day (26.11.2022) on hourly basis, when the daily consumption is higher than the PV production (327.5 kWh versus 82.0 kWh).

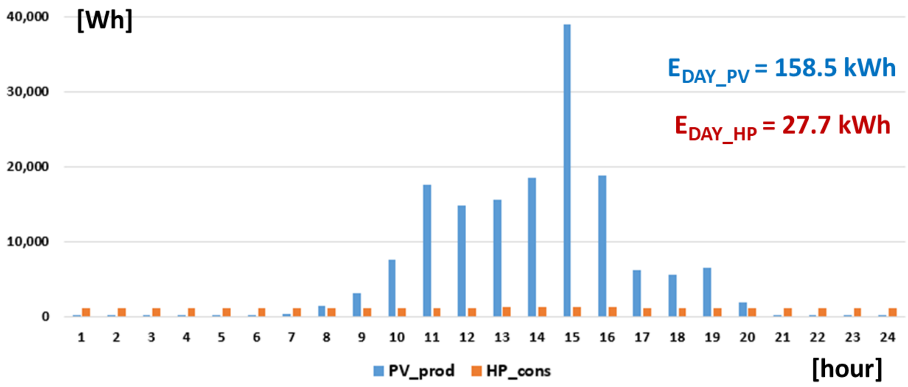

Figure 6. Hourly PV production and HP system consumption in 14.08.2022

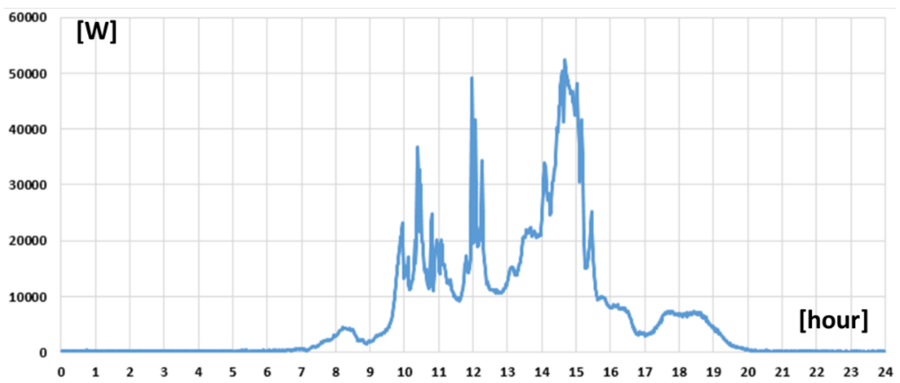

Figure 7. One-minute / detailed evolution of PV production in 14.08.2022

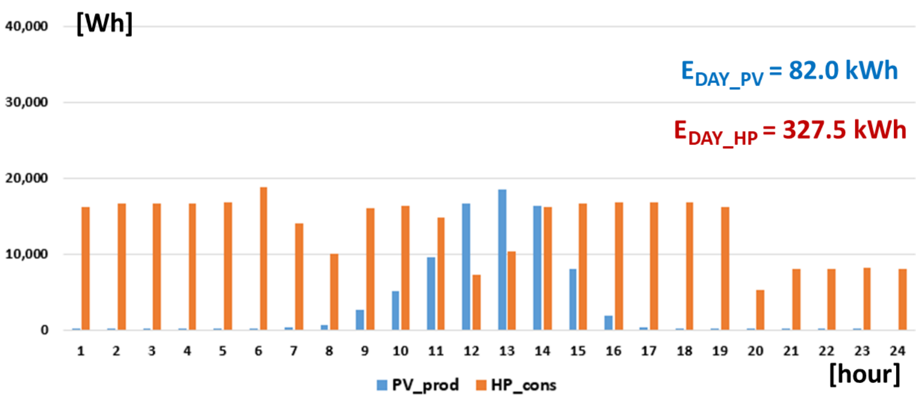

Figure 8. Hourly PV production and HP system consumption in 26.11.2022

4. Discussions and conclusions

The paper presents general concepts for a combined heat and electrical energy community based on clean energy and resilience. It is well known that in many European countries the yearly energy for heating houses is considerable high and overpasses the electrical energy used by these premises. In these conditions, the concept of heat and cold delivered by using clean electrical energy is a win-win solution for a more holistic approach for a carbon-neutral energy goal.

The concept of clean energy and resiliency is projected to three different environments: district, sub-urban and rural areas, showing that similar implementation can be applied in all these situations.

A final section presents an implementation of these concepts in the Romanian demonstrator of the WEDISTRICT project implemented at UPB, considering small scale implementation to be able to assess in a realistic way the principles presented in previous sections.

ACKNOWLEDGEMENT

This work has received funding from the European Union’s Horizon 2020 research and innovation program, under grant agreement No 857801. This text reflects only the author’s views and the Commission is not liable for any use that may be made of the information contained therein.

R E F E R E N C E S

[1] *Yusuke Yoshida; Yuzuru Ueda, Optimization of residential PV and water heating system's configuration and operation using Multi-Objective Particle Swarm Optimization*, 2016 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 6-9 Sept. 2016, Minneapolis, MN, USA.

[2] *Lili Song; Xu Yin; Linghai Meng; Feng Gao; Yinghui Han; Yunpeng Jiao; Hui Fan; Yunpeng Liu, Analysis of micro-grid integration with PV, energy storage and ground-source heat pump based on DeST simulation*, 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), 26-28 Nov. 2017, Beijing, China.

[3] *Jan von Appen; Martin Braun, Sizing and Improved Grid Integration of Residential PV Systems With Heat Pumps and Battery Storage Systems*, IEEE Transactions on Energy Conversion (Volume: 34, Issue: 1, March 2019).

[4] *Kilian Dallmer-Zerbe; David Fischer; Wolfgang Biener; Bernhard Wille-Haussmann; Christof Wittwer, Droop controlled operation of heat pumps on clustered distribution grids with high PV penetration*, 2016 IEEE International Energy Conference (ENERGYCON), 4-8 April 2016, Leuven, Belgium.

[5] *G. Manfroi; M. Maistrello; L. C. Tagliabue, Synergy of geothermal heat pumps and PV plant for buildings block*, 2011 International Conference on Clean Electrical Power (ICCEP), 14-16 June 2011, Ischia, Italy.

[6] *Marc Brunner; Krzysztof Rudion; Stefan Tenbohlen, PV curtailment reduction with smart homes and heat pumps*, 2016 IEEE International Energy Conference (ENERGYCON), 4-8 April 2016, Leuven, Belgium.

[7] WEDISTRICT project: https://www.wedistrict.eu/, accessed 2022.05.