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Evaluation of the potential of heat pumps in the reduction of energy consumption in energy communities: a case study in a Mediterranean district.

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Abstract

Energy communities play a key role to move towards a low-carbon and decentralized energy system with higher penetration of renewable energies, offering new opportunities for citizens to actively participate in the energy transition. However, the term energy community is widely addressed in literature as photovoltaic systems shared by several users to cover their electricity needs. The present work describes the georeferenced modelling and assessment of potential domestic hot water energy communities based on heat pumps thermal energy communities in 150 residential buildings in a representative Mediterranean city. With the objective of contributing to the development of this concept in the literature and provide insights on the potential at a district level for its energy transition. The aggregated economic and emission savings of domestic hot water in the district can reach up to 85% and 73% respectively for heat pumps. The analysis shows that the implementation of domestic hot water energy communities could represent a significant reduction in the CO2 emissions of the residential sector using the air as a heat source with a reduced cost compared with individual air source heat pump systems.

Keywords: Energy communities; energy transition; domestic hot water; positive energy districts; heat pumps

1. Introduction

Tackling climate change is one of the biggest challenges of the humanity. Nowadays, cities are one of the biggest problems, being responsible for 72 % of Global Warming Emissions (GWE) despite occupying only 3 % of the land [1]. Still, cities are the solution at the point where they face a huge transition towards energy efficiency and renewable energy inclusion. European Union (EU) settles the objective of decarbonizing the economy for 2050, with a reduction of 90 % GWE regarding residential sector among others [2].

Residential sector in Europe is responsible for 40 % of total energy consumption and 36 % of GWE. The majority of its energy use is due to HVAC purposes, with a 65 %, followed by 13.9 % due to Domestic Hot Water (DHW) [3]. The HVAC consumption will require energy efficiency actions directed to reduce the energy demand of buildings mainly through energy refurbishment. However, DHW demand cannot be reduced without affecting comfort. Considering that it represents on average 18.9% of the final energy consumption in the residential sector [10], energy efficiency measures will be necessary to reduce the energy consumption of the equipment to satisfy this demand.

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Many possibilities exist for improving the energy efficiency of current DHW production systems. Not only do there exist different technologies (solar thermal, biomass or heat pump (HP)), but also different options regarding the system production level (individual, building or full district). In the decision-making process on the energy planning of future cities, these decisions could change cities as we know them, as well as citizens and how they relate to the energy topic.

Among these alternatives, HP appears as a very promising solution for urban environments where a high population density living in multifamily houses are quite common. This kind of dwellings have the characteristics of limited amount of space and limited amount of solar surface irradiated, which postulates the HPs as one very reliable alternative overall if the climate conditions are soft like in the Mediterranean European area.

Energy Communities (ECs) are an initiative recently emerged that seeks the active participation of citizens in the energy transition. According to EU, this initiative definition corresponds with collective actions participated by citizens, public and private entities around a renewable energy project [4]. Energy Communities constitute a radical change towards distributed energy systems, promoting people empowerment and contributing to the formation of awareness among citizens regards a sustainable energy use.

In this way, this research work aims to give some hints on the best decision for this transformation and determine up to which level the HP could place an important role in that transformation. The paper focuses on DHW production, analyzing one full-district current state and different alternatives regarding system production level considering only the HP technology. The technologies studied and compared are gas boiler, immersion electric heater, individual Air Source Heat Pump (ASHP) and collective operated ASHP. The paper studies a representative Mediterranean city of the Europe warmer climate.

2. Method

For the study, the city of València with its neighborhood of *Illa Perduda* has been selected to perform the analysis. València city can be a city representative of Warmer EU climate and the conclusions here exposed can be of applicability to other Mediterranean cities. The district consists of an area with 164 total number of buildings, of which 150 are residential ones, mainly built during 60s-70s. The average building contains 17 dwellings, with a maximum of 210 dwellings in one building and a minimum of 6.

Figure 1. Analysis area selected for the study. District of Illa Perduda in València, Spain.

Concerning that the study considers different system level production, the DHW demand has been obtained for an individual dwelling and at a building level, considering each residential building of the district. Figure

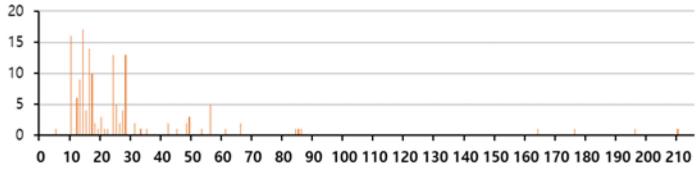

Figure 2. Histogram of the number of dwellings per building of the district.

2 illustrates the number of dwellings per building for the full district. An average value of 2.3 inhabitants per dwelling has been assumed, matching EU average [5].

To model the energy demand, DHWcalc software has been used [6]. DHW 1-minute draw-off profiles have been obtained, including cleaning, shower, bath and cooking consumptions based on published indications in [7]. As an example, Figure 3 includes 2 draw-off profiles for a random day, for 1 dwelling and 20 dwellings.

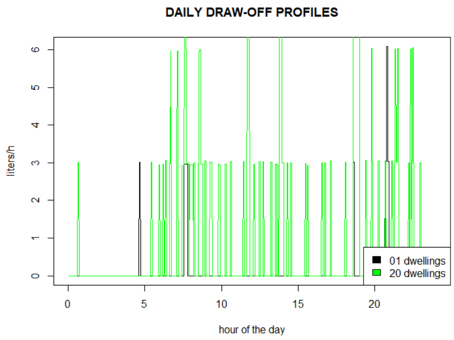

Figure 1. Exemplification of 2 random profiles for a random day of the year.

Concerning the dynamic energy simulations, TRNSYS software has been used [8]. The 4 different DHW production technologies studied and compared have been modelled and simulated in TRNSYS. All the models have been created and validated against commercially available systems. The net water temperature of València has been used, considering an average value for each month. The user demand has been considered at 45 ºC, whereas the set-point temperature for collective cases has been set at 60 ºC considering legionella normative. The models that include storage tank, consider a 0.8 $W/m^2 K$ value for the heat losses.

- **Immersion Electric Heater (IEH)**: it consists of an 80 L storage tank with an aspect ratio of 2 and a nominal capacity of 1.5 kW. The temperature sensor has been placed in the 1st node. 55 ºC set-point temperature has been considered to minimize energy consumption but also guaranteeing user comfort, matching energy-label of the commercial product.
- **Gas Boiler (GB)**: it consists of an instant-heating system of 28 kW and 92 % efficiency. As an instantaneous system, the annual energy consumption is not affected by the set-point temperature considering a fixed demand.
- **Individual ASHP**: an individual ASHP commercially available has been modelled at HP unit level using IMSTart software. A HP performance map has been created and included in a new TRNSYS type. The map was crated varying the external conditions for the operation of the HP, concerning more than 3,500 operating conditions.

  The HP works with propane as natural refrigerant and has 1 kW heating capacity and 180 l storage capacity. It consists of a plate heat exchanger condenser, a finned tube evaporator, an expansion valve, and a scroll compressor. The condenser is directly connected to the DHW stratified-storage tank, and it operates with a variable water inlet temperature (Tci) and a water outlet temperature (Tco) fixed at 64ºC. The HP is designed to heat up water from 10 to 64ºC. The HP unit as been optimized, according to its operation on the system, by the subcooling. In such a way that the high temperature lift on the water side match in an optimum way with the temperature profile in the heat pump.
- **Collective ASHP**: the individual HP unit of the ASHP model has been optimized using IMSTart to work under collective conditions, specifically adjusting the subcooling of the model. The HP unit model developed has been included in a new TRNSYS type. This type is connected to a stratified storage tank. In order to take into account the re-circulation losses, a 10 % annual energy consumption reduction has been considered. The HP size and tank volume have been properly analyzed for each building in the district through a parametric study varying the range of each of them and following comfort criteria explained in the following. For each of the buildings of the district, a performance map of the full system was created concerning different HP and tank sizes and taking into account the comfort restrictions of each simulation. Based on this map, the optimal sizing of HP and tank has been found for the minimum consumption point of the map. Thus. the

proper sized cases have been selected among those that comply with the comfort restrictions and achieve the minimum annual energy consumption.

Constraints settled have to do with comfort restrictions and HP starts. To guarantee user comfort, two restrictions have been defined: (i) the annual percentage of discomfort has to be lower than 0.5 % ; (ii) the maximum available time out of comfort for each hour of the day has been settled to 5 seconds. To guarantee system reliability, a maximum number of starts of 9 per hour has been set. In the collective installation case, the simulations that do not comply with the restrictions would not be considered. Whereas, in the individual DHW production level these restrictions will be considered as outputs, since the sizing is defined by the manufacturer.

In order to analyze each case and compare them, the following system performance indicators have been used:

- SPFuser: as the quotient between the useful heat received by the user and the total system energy consumption (including compressor, fan, and circulation pumps).
- COP: as the quotient between HP heat delivered and energy used by the compressor.
- Annual energy consumption: considering the consumption of the system, including compressor, fan, and circulation pumps.
- Annual emissions: considering an emission factor of 0.201 tCO_2/MWh for gas [9] and 0.112 tCO_2/MWh (ref) for electricity.
- Annual energy cost: considering an energy price of 0.067 €/kWh for gas and 0.2 €/kWh for electricity.

3. Results

In this section, the main results are presented and discussed. First of all, an analysis of the current situation regarding the DHW production of the neighborhood under study is performed. Secondly, the results of the different alternatives to the current DHW production systems are described in terms of performance, energy consumption, emissions and energy costs. Finally, the alternatives technologies are compared, and the outcomes discussed.

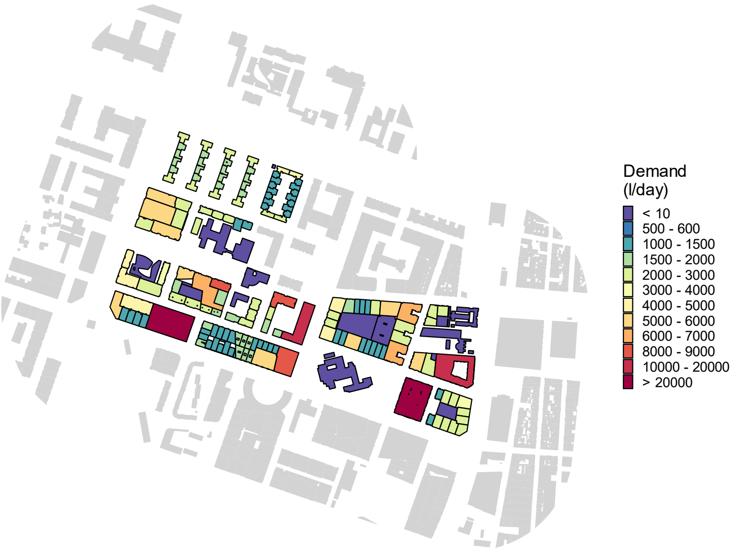

Figure 2. Demand, in l/day, for each building of the district.

Figure 4 depicts the DHW demand of each of the buildings of the neighborhood in liters per day. The demand is directly related with the number of dwellings in each building.

Current scenario

The current state in the neighborhood, regarding the production of DHW, is governed by low energy efficient and high polluting systems, considering the year of construction and the social vulnerability situation of it. According to recent literature, DHW is produced by 28.6 % of the dwellings using IEH, by 70.4 % using GBs [10].

Table 1 summarizes the current situation regarding the use of GB and IEH. The table shows the annual emissions and energy cost related to the DHW production in the district. On average, one dwelling is responsible for 532 kgCO2/y and has an energy cost of 464 €/y.

Table 1. Emission and energy cost of current DHW production situation

	Emissions ktCO2/y	**Energy cost M€/y**
Current situation	2.23	1.95

Individual ASHP renovation scenario

Concerning the results of individual ASHP, Table 2 includes the main results for 1 dwelling. In order to obtain global results, it was assumed that each dwelling in the district did the renovation. The results show an average COP of 4, with a reduced annual discomfort, with 200 hours per year year (2.3 % in front of the 0.5% of the collective scenario).. The total energy consumption accounted for 414 kWh/y, with an energy cost of 82.64 € and GWE of 46.28 kgCO2/y.

Table 2. Results from individual ASHP

	SPFuser	**COP**	**Annual discomfort**	**Working hours**	**Energy use**	**Emissions**	**Energy cost**
	-	**-**	**%**	**h/y**	**kWh/y**	**kgCO2/y**	**€/y**
Individual ASHP	3.27	4.05	2.28	1600.63	413.19	46.28	82.64

Collective ASHP renovation scenario

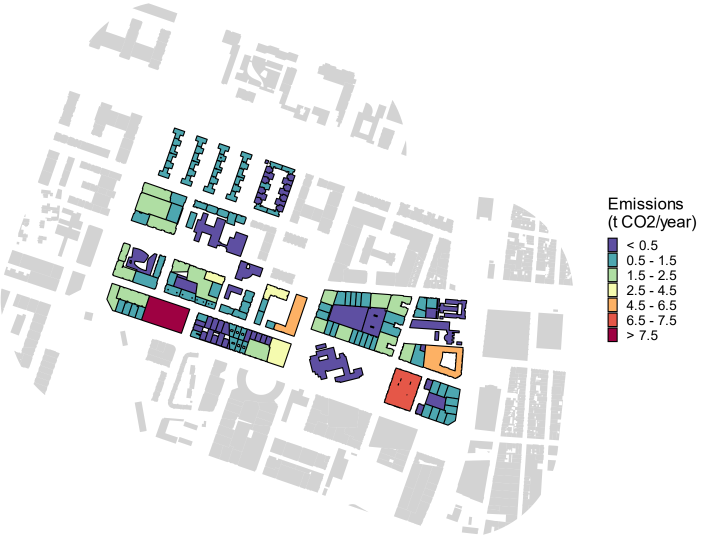

Figure 3. Annual emissions building to building.

Figure 5 and Figure 6 show the emissions and economic costs resulting from the use of the collective ASHP in each building of the district. Assuming every building in the district does the renovation, the total savings are shown in Table 3. The results show a total equivalent annual emissons of 150 tCO2 and 270 k€. The average dwelling was responsible for 36 kgCO2/y and had an energy cost of 65 €/y.

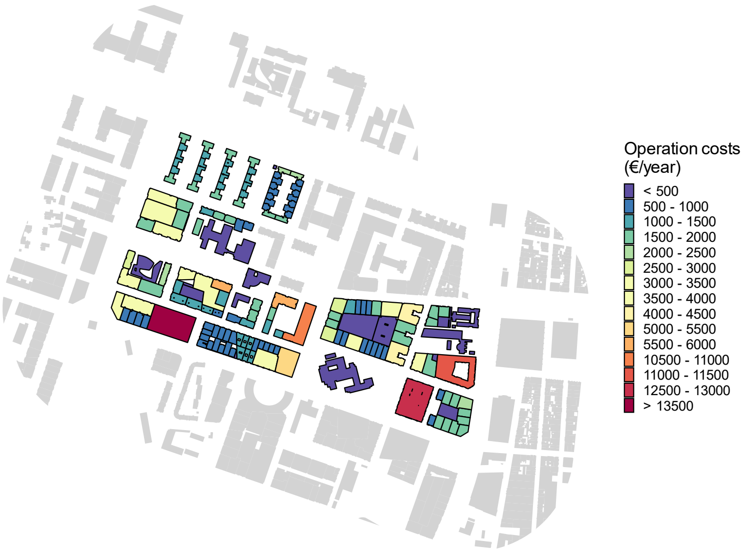

Figure 4. Annual energy cost building to building.

Comparison

Table 3 includes the results for the current scenario and each alternative regarding emissions and energy cost. The results show:

- Emission savings for both the alternatives over 90 % with respect to the current scenario, and energy costs savings above 80 %.
- Absolute annual savings over 2 ktCO2 and 1.6 M€ regarding the current scenario.
- The ASHP collective alternative shows 20 % higher savings than the individual ASHP. In details, the collective ASHP saves 42 tCO2 and 75 k€ more compared to the individual ASHP.
- The individual ASHP shows annual savings of 400 € per dwelling, whereas the collective one shows savings of 2310 € for the average building block.
- The installation of collective ASHPs in the district only requires 150 HP units and tanks, against the 4194 units needed with the installation of individual ASHPs.
- On average, the collective alternative needs 3 % less HP capacity and 85 % less storage volume than the individual one.
- Although this research works does not analyze in detail sustainability and investment efficiency matters, some opinions can be extracted:
  - Regarding sustainability matter, much less equipment is needed, and the HP size and tank volume are more reduced in the case of collective installations. This positions the collective alternative ahead of the individual.
  - Regarding investment efficiency matter, in 10 years the individual option achieves 4,000 € in savings whereas the collective reaches 23,100 € for the average building block. {Bibliography}Considering also that the collective installation needs of HP size and storage are more reduced, this option could be much more cost-effective than the individual installation case.

Table 3. Results comparison of each alternative, regarding GWE and energy cost.

	Emissions **ktCO2/y**	**Energy cost** **M€/y**
Current situation	2.23	1.95
ASHP individual	0.19	0.35
ASHP collective	0.15	0.27

4. Conclusions

This work has shown the high potential of ASHP to reduce the emissions associated to the DHW demand in buildings without the necessity of implementing complicated infrastructures like geothermal wells or having a centralized district heating network. It has been proved that for template climates like the one present in the Mediterranean coast a ASHP installed in each house without the necessity of neighborhood coordination could be the most easy solution to reach remarkable emission reduction objectives.

Nevertheless, the initial investment of this type of installation is far from being suitable and environmental responsibility of the users or some kind of public fundings must be promoted to install that kind of systems. On the other side, the collective installations and the development of thermal energy communities present the advantages of having a slightly higher potential of CO2 emissions reduction, having a significantly lower initial price of the HP components, and having a significantly less space requirements in the building which in some cases could be a critical argument for them. However, this kind of system requires the agreement between all the members of the community and some points regarding the legal implications of it are still under development.

Acknowledgements

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