Analysis of a heat pump-based energy system exploiting a low GWP refrigerant in different European climates

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Abstract. The objective of this research is to assess the operation of a heat pump (HP) under varying climatic conditions in Europe. To achieve this, a Dymola model is developed for a solar-assisted reversible water-to-water HP that utilizes a low global warming potential (GWP) refrigerant, R1234ze(E), and includes thermal and electrical energy storage systems. Experimental data is used to validate the primary components of the model. Simulations are conducted for both summer and winter seasons to determine the system's overall annual performance. The analysis covers energy exchange between the system and the grid and utilizes key performance indicators such as self-sufficiency and self-consumption index. Furthermore, a techno-economic analysis is conducted to determine the payback period of the heating and cooling energy system based on the components' capital expenditure and available incentives.

1 Introduction

The existing environmental crisis has prompted the development of low-carbon technologies and policies, leading to a rapid evolution in this area. Recent research has emphasized that the focus must shift to residential and commercial buildings to reduce the carbon footprint, which account for 40% of the European Union total primary energy consumption. One potential solution is to electrify the heating and cooling sector, where HP can play a crucial role. To further decrease carbon emissions, solar PV can be integrated with HP units, enabling the system to utilize locally produced renewable energy when it is available. This strategy also improves the self-sufficiency and self-consumption of the energy system, ultimately reducing its dependence on the main grid. This study also makes use of a novel refrigerant i.e., R1234ze (E) which has a GWP quite low (< 10) than other traditionally used refrigerants. Some previous studies have analysed this research topic such as Zanetti et al. [1] developed an optimal control strategy for a solar-assisted heating system and concluded that 20% higher energy savings were obtained. Beccali et al. [2] investigated suitable renewable methods to supply thermal comfort to a hotel in Lampedusa during the summer season. Calise et al. [3] proposed a system consisting of a solar-assisted water-to-water reversible HP and minimized the payback time of energy system through a set of control

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parameters. Roselli et al. [4] investigated the integration of PV and electrical storage with HP for an office in Southern Italy and reported higher energy savings.

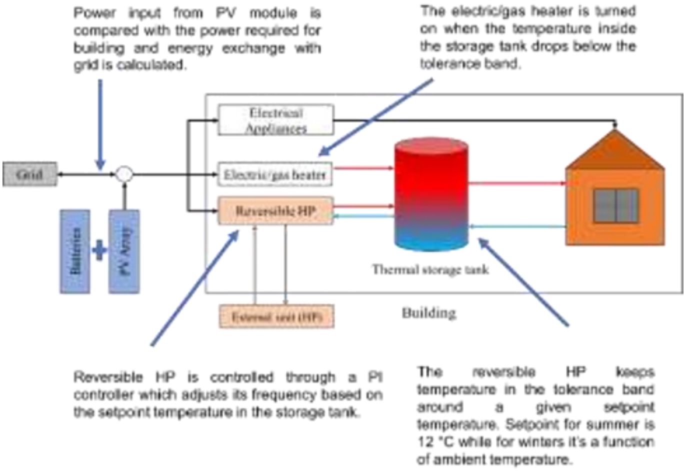
2 Modelling activity

The main components of HP model were validated with experimental data. Tests were performed for a HP on a testing rig available for thermal systems in CNR ITAE in Messina [5]. The system's cooling capacity and energy efficiency ratio (EER) were evaluated at different condenser inlet temperatures. Modelling activity was performed in Dymola (Modelica) [6] using TIL [7] and Photovoltaics [8] libraries.

The model mainly consists of a reversible 10 kW HP, thermal storage, photovoltaics (PV) panels and electrical storage. The simulations were made for Athens, Marseille and Stuttgart which represent Mediterranean, hot semi-arid and humid continental climates. The size of reversible HP selected for Athens and Marseille is 10 kW while size for Stuttgart is 15 kW. This selection was made to meet cooling load in Southern Europe while heating load in continental Europe. An electric heater was considered as a backup source for winters in Athens and Marseille while a gas heater was selected as backup source in Stuttgart. The building selected for simulations is class A+ and has surface area of 130 m^2.

A simple control strategy was considered for this model. Compressor and expansion valve were controlled by PI controller. For summer, the setpoint temperature of the tank was set at 12 °C with ±2 °C of tolerance. For winters, setpoint temperature of the tank depends on the ambient temperature. Lower ambient temperature results in a higher setpoint temperature for storage.

A schematic diagram of the model is presented in **Fig. *1***.



Power input from PV module is compared with the power required for building and energy exchange with grid is calculated.

The electric/gas heater is turned on when the temperature inside the storage tank drops below the tolerance band.

Reversible HP is controlled through a PI controller which adjusts its frequency based on the setpoint temperature in the storage tank.

The reversible HP keeps temperature in the tolerance band around a given setpoint temperature. Setpoint for summer is 12 °C while for winters it's a function of ambient temperature.

Fig. 1 Schematic diagram of simulated system [9]

Three different PV sizes of 3, 4.5 and 6 kW were included in simulation along with three battery storage sizes of 5, 10 and 15 kWh. The size of thermal storage tank of size 700 litres was considered for Athens and Marseille while tank of 900 litres was considered for Stuttgart.

Simulations are performed for whole year and analysis is carried out on the basis of self-sufficiency index (SSI) and self-consumption (SC). Moreover, a cost-analysis is also carried out to find a discounted payback time period for HP energy system. The simulation model also took in to account the energy exchange with the grid and thus economic incentives, based on net-metering policies, were also considered. **Fig. *2*** shows the control strategy for simulated system which includes battery storage and PV system. The data for PV system is taken for PV panel model LG300N1C-G4. The experimental data for the lithium titanate oxide cells was taken from a dedicated testing activity at CNR ITAE. The data was later used for modelling the battery[10].

The control strategy compares the power being produced by solar PV and required power and then checks the state of charge (SoC) of batteries. Battery with SoC of 0.8 is taken as fully charged while value of 0.2 means that battery is empty. If batteries are charged, energy is withdrawn from them otherwise energy is taken from grid. Similarly, energy is sent to grid if batteries are charged, and energy produced is more than required.

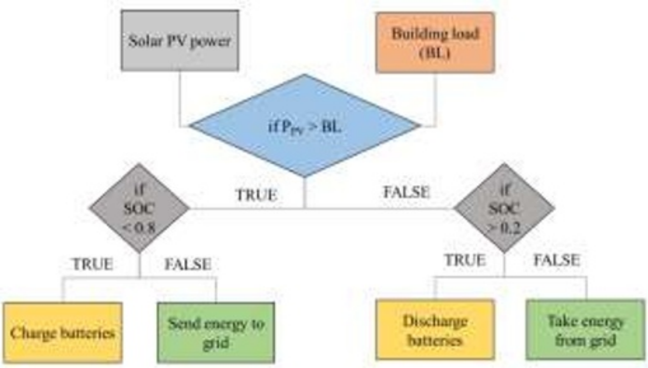


Fig. 2 Control strategy for simulated system (SoC- State of charge) [9]

The electricity profile of building was obtained from an integrated domestic electricity demand model developed by Centre for Renewable Energy Systems Technology at Loughborough University [11]. The thermal loads of building were taken from a TRNSYS simulation of an existing class-A building that has been used for analysis of solar cooling systems [12].

3 Results

Energy and economic analysis have been carried out to assess the performance of energy system under observation. Results presented below are for 6 kWp solar PV and 5 kWh battery size. Fig. 3 displays an annual overview for all the cities under consideration. It shows the energy produced by PV, building load, energy from HP and energy from backup source. Due to the high solar irradiation in Athens and Marseille the energy values produced by solar PV (6 kW) are almost equal in these two cities. Energy consumption for Athens, Marseille, and Stuttgart in terms of building area is 60.4, 76.6 and 115 kWh/m^2 respectively. So, reversible HP was able to cover thermal load for Athens and Marseille while for Stuttgart, backup source was needed for longer duration in winter season due to the low ambient temperature encountered during the heating season.

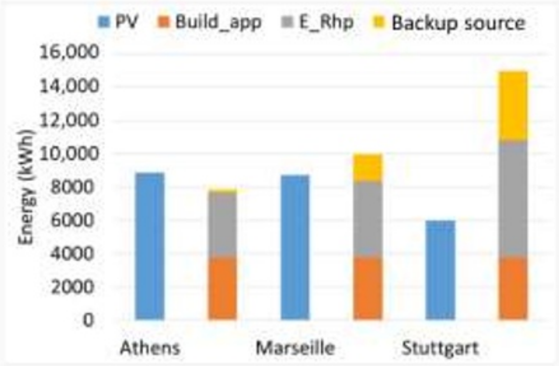


Fig. 3 Yearly summary for energy consumption in Athens, Marseille and Stuttgart [9]

Self-sufficiency index (SSI) and self-consumption (SC) are the indicators often used for techno-economic assessment. SSI is ratio of locally produced energy to total energy consumption. SC is the ratio of locally produced and consumed energy to total local generation. SSI is calculated as given in Eq. (1) while SC is calculated in Eq. (2).

$$SSI = \frac{E_{PV} - E_{to\ grid}}{E_{HP} + E_{Building\_appliances} + E_{Heater}} \tag{1}$$

$$SC = \frac{E_{PV} - E_{to\ grid}}{E_{PV}} \tag{2}$$

Fig. 4 shows the monthly SSI values for Athens, Marseille and Stuttgart for 6 kW solar PV and 5 kWh battery storage size. Athens reported highest SSI values among all cities since Mediterranean regions have high solar irradiation. The values obtained were in the range of 0.6 to 0.9 and only 30% of the required energy needs to be provided by electricity grid. Marseille reported high SSI values in summer and low in winter. Results indicate that a major portion of energy can be supplied through renewable generation. In the case of Stuttgart, less availability of solar irradiation and high heating load requirement resulted in lower SSI values.

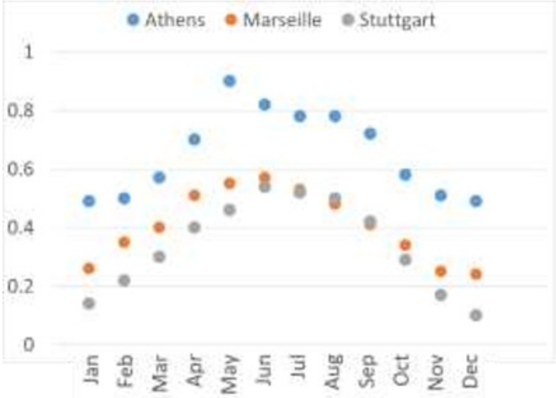


Fig. 4 Monthly SSI values for Athens, Marseille and Stuttgart [9]

Fig. 5 shows the average values of SSI vs SC for all three cities for different PV sizes. It can be seen that SC values are higher for 3 kW PV sizes since major portion of energy produced is used locally. SSI value increase with increasing PV size since amount of produced energy is directly linked with size of solar PV. Highest SC value is reported by Stuttgart followed by Athens and Marseille respectively while highest SSI value is reported by Marseille followed by Athens and Stuttgart.

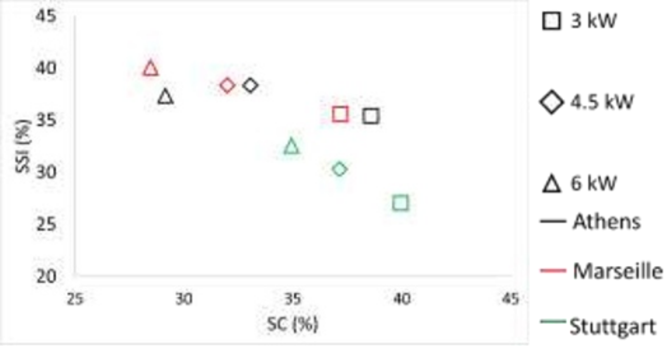


Fig. 5 Average values for SC (%) vs SSI(%) for three cities[9]

Table 1 reports the details for energy produced by PV and energy exchange with grid. It can be seen that increasing PV size results in selling more energy to grid. Stuttgart has the lowest share of selling energy to grid since a major portion of energy is consumed on-site. For 6 kW PV in Athens, energy sold to grid is higher than purchased from grid which helped in achieving payback time earlier.

Table 1 Results for energy exchange with grid (*values in kWh) [9]

Cities	PV Power (kW)					
	3		4.5		6	
Athens	PV production (kWh)					
	4435		6653		8870	
	To grid *	From grid	To grid	From grid	To grid	From grid
	1532	4753	3379	4403	5408	4176
Marseille	PV production (kWh)					
	4352		6258		8704	
	To grid	From grid	To grid	From grid	To grid	From grid
	1751	6783	3587	6443	5549	6235
Stuttgart	PV production (kWh)					
	2996		4494		5992	
	To grid	From grid	To grid	From grid	To grid	From grid
	1251	9064	2362	8677	3577	8394

Table 2 shows the details related to costs, available subsidies and discounted payback time. The interest rate is taken as 2.5% for all calculations. A study was made in to the subsidies available in Greece, France and Germany. The payback time for all PV sizes for Athens is quite close to each other. The payback period for 6 kW PV size is 3.9 years which is close to other PV sizes. Results for Marseille indicate that payback time period for 3, 4.5 and 6 kW PV size can be achieved in 5.8, 6.1 and 6.6 years. Stuttgart reported the highest payback period of 8.1, 8.9 and 9.9 years for 3, 4.5 and 6 kW PV sizes. This analysis takes in to account the net-metering incentives, subsidies and savings made in comparison to a reference energy system which constituted of 24 kW gas boiler with 95% efficiency for winter season. The reference system consisted of split air conditioners with a capacity of 10 kW with a COP value of 2.5 for summer season.

Table 2 Results for costs, subsidies, and payback time (in years) [9]

Cities	**PV Power (kW)**			
		3	**4.5**	**6**
Athens	Capital expenditures (EUR)	21605	23079	24553
	Subsidy amount (EUR)	6112		
	Discounted payback period (y)	3.8	3.8	3.9
Marseille	Capital expenditures (EUR)	21608	23082	24556
	Subsidy amount (EUR)	4000		
	Discounted payback period (y)	5.8	6.1	6.6
Stuttgart	Capital expenditures (EUR)	24166	25640	27114
	Subsidy amount (EUR)	2800		
	Discounted payback period (y)	8.1	8.9	9.9

Fig. 6 shows the levelized costs of electricity (LCOE) for three cities for different PV sizes. LCOE is used to compare alternative production methods. Lifetime period of energy system is taken as 25 years. LCOE is calculated as given in Eq. (3).

$$LCOE = \frac{\sum_{n=0}^{N} \frac{CAPEX}{(1 + interest\ rate)^n} + \sum_{n=1}^{N} \frac{OPEX}{(1 + interest\ rate)^n}}{\sum_{n-1}^{N} \frac{Total\ energy\ demand}{(1 + interest\ rate)^n}} \quad (3)$$

It can be seen that with increasing PV size, LCOE value decreases. As the PV size increases, operating costs reduce and annual savings increase, because of which LCOE reduces. Athens has the lowest LCOE value for PV size of 6 kW i.e. EUR 0.18/kWh since energy sold to grid was higher for mentioned PV size. Stuttgart reported the maximum LCOE value for 3 kW PV size i.e. EUR 0.32/kWh.

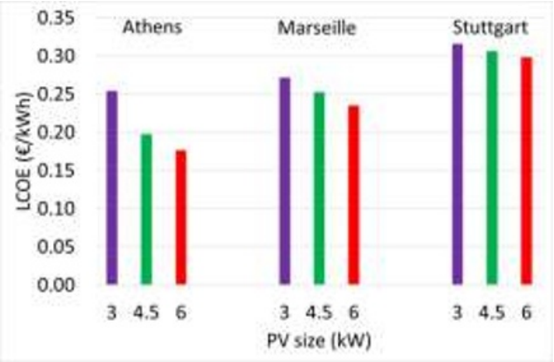


Fig. 6 LCOE with three PV sizes (3, 4.5 and 6 kW) and 5 kWh battery capacity

Conclusions

The study focused on an energy system with low GWP HP assisted by onsite installed renewables and further aided by thermal and electric storage. A novel refrigerant named

R1234ze (E) is employed in the HP. Dymola/Modelica was used to validate the model with the help of experimental data. Analysis for Athens, Marseille and Stuttgart was conducted to assess the HP performance in different European climates. It turned out that SSI is directly linked with PV size while there is no significant difference in SSI and SC with increasing battery storage size above 5 kWh. A 6 kW PV size can achieve significant high SSI values in Athens (0.9) while it is limited to 0.5 in Marseille and Stuttgart. The proposed system had a better performance than a reference energy system which consisted of gas boiler and split air conditioners. Results showed that payback periods can be achieved in 3.8 years in Athens while Stuttgart reported payback periods of more than 8 years. The LCOE is much lower for Athens i.e. (0.18 EUR/kWh) as compared to Stuttgart which has LCOE value of EUR 0.32/kWh. Future studies will focus on inclusion of demand-response strategies, defrost cycles and domestic hot water production.

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