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In-situ Monitoring of two Air-to-Water Hybrid Heat Pumps for Residential Buildings

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Abstract

This work describes the methodology used to realize a performance analysis of two hybrid heat pumps (HHP) designed for space heating (SH) and domestic hot water (DHW) production for residential applications. The systems are installed in the same climatical region in the northern part of Belgium. The household composition of both facilities and heat requirements are different between them. Both installations count with sensors that allow to register the appliances gas consumption, electrical consumption, water flows and temperatures. Settings data are known but not monitored. The data collected is daily sent to the Cloud and is used to compute performance indicators. Two years of data are analyzed per site, allowing to quantify the effect of different variables over the system performance. The differences found are described and discussed.

Keywords: Hybrid heat pump, Gas driven systems, Monitoring.

Introduction/Background

In the decarbonization pathway, heat pumps technology can play a main role. Studies point out that heat pumps are a good alternative to reduce the CO_2 emissions and the energy consumption, of which a significant part is destinated to buildings in Europe to meet the DHW and SH demands [1,2]. However, an abrupt transition is not possible due to restrictions such as housing requirements, available energy sources, technology cost, etc. That is why when complemented with hybrid solutions, the decarbonization and transition becomes more flexible, cheaper and easier [3]. This, however, could have associated problems. As several studies show, a proper control, correct system integration and monitoring are crucial to properly evaluate the potential and the impact of these technologies under an energetic and economic point of view without diminishing their performance [4-8].

The objective of this work is to compute performance indicators of two appliances under field conditions. The systems are installed in two residential houses in the northern part of Belgium, corresponding to the same climatical region. These locations have sensors that provide information that allows to analyze inputs and outputs to the appliances, enabling to compute performance indicators; sensors to measure indoor and outdoor ambient conditions are also placed. Heat meters are installed to measure the heating energy delivered by the appliances to each circuit that requires it (DHW and SH). Both sites count with photovoltaic panels and the household compositions differ between them, affecting the consumptions.

Both systems have been exhaustively monitored during 2021 and 2022. It is thanks to the monitoring that problems related to both installations were identified and corrected, allowing to quantify the penalization to the performances due to a faulty installation or misunderstanding of parameters. Besides this, changes are applied according to the needs of the users, achieving a better understanding of the system on their part and adjusting it to their needs.

Description of the systems

The schemes of the monitored appliances are shown in Figure 1 and Figure 2. These hybrid systems are a coupling of an internal module that includes a boiler, and an outdoor module composed by a heat pump. This assembly allows to cover the heat demands of a residential facility with only one module (only boiler, only heat pump) or both (hybrid mode), depending on the thermal demand circuit (DHW or SH) and the delivery water temperature required. The first location in Leest has a heat pump with nominal heating capacity of 7.9 kW under +7°C outdoor air temperature and outlet water temperature of +35°C, with an associated coefficient of performance of 4.34 according to the EN 14511-2. The system provides SH through radiant floor as well as radiators, and counts with a buffer tank of 177 liters in the internal module. Its technical features are shown in Table 1 and Table 2, for the heat pump and the boiler respectively. For Table 2, the values are given for rich gas (H) and lean gas (L).

Table 1. Heating mode: Water outlet temperature +35°C. Performances according to EN 14511-2 (Leest)

	Type of measurement	Unit	AWHP 8 MR-2 model
Outdoor air temperature +7°C	Heating capacity	kW	7.9
	Coefficient of performance (COP)		4.34
	Electrical power absorbed	kWe	1.82
	Rated water flow (ΔT = 5K)	m^3/hour	1.36
Outdoor air temperature +2°C	Heating capacity	kW	6.8
	Coefficient of performance (COP)		3.3
	Electrical power absorbed	kWe	2.06

Table 2. Internal module – Boiler characteristics (Leest)

			Gas H G20	Gas L G25
Rated heating capacity Heating mode (80°C/60°C)	Min-max	kW	3.0-14.9	2.5-12.1
Rated heating capacity Heating mode (50°C/30°C)	Min-max	kW	3.4-15.8	2.8-13.2
Rated heating capacity DHW mode G20 (HHV)	Min-max	kW	3.4-16.7	2.8-13.9
Space heating efficiency at full load (HHV) (80/60°C)		%	86.9	86.9
Space heating efficiency at full load (HHV) (50/30°C)		%	94.8	94.8
Gas consumption G20 (gas H)	Min-max	m^3/h	0.33-1.59	0.32-1.53
Electrical power absorbed – great speed	Max	W	101	101

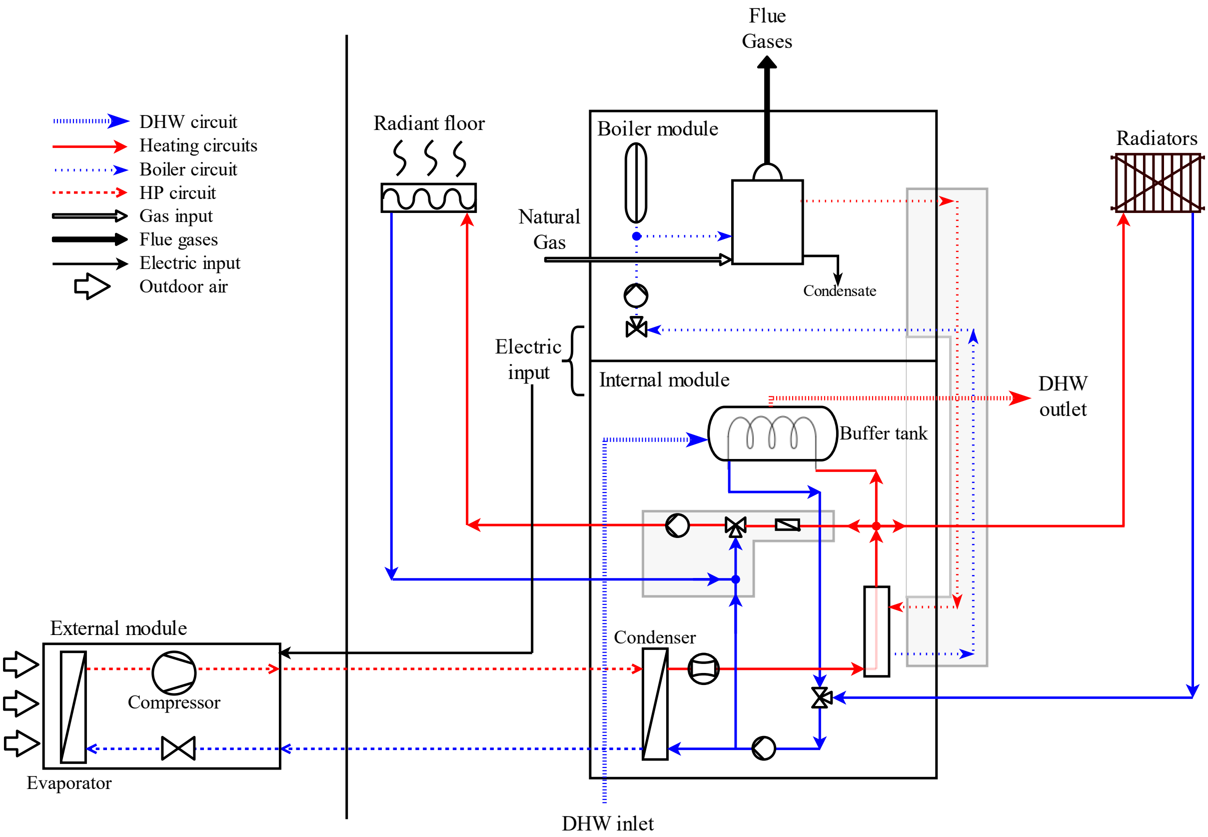


Figure 1. Monitored hybrid heat pump schematic, Leest

For Ruiselede, the SH circuit is based on low temperature radiators and there is no buffer tank embedded or installed in the hydraulic circuit. The technical features are shown in Table 3; for the gas consumption, values are shown for rich gas (G20) and lean gas (G25).

Table 3. Ruiselede monitored hybrid system technical features

External unit: Heat pump				
Rated heating capacity		kW		4.40 / 4.03
Rated power absorbed (heating)		kW		0.87 / 1.13
COP (heating)				5.04 / 3.58
Domestic hot water heating efficiency		%		96
Seasonal efficiency for ambient heating (water temp. outlet 55°C)		%		128
Internal unit: Boiler				
Gas consumption (G20)		Min-max	m^3/h	0.78 - 3.39
Gas consumption (G25)		Min-max	m^3/h	0.90 - 3.93
Space heating	Heat input (LHV)	Min-max	kW	7.6 - 27
	Output at 80/60°C	Min-Nom.	kW	8.2 - 26.6
	Efficiency	Net calorific value	%	98 / 107
Domestic hot water	Thermal load (LHV)	Min-Nom.	kW	7.6 - 32.7
	Efficiency	Net calorific value	%	105
Power consumption		Stand by / Max	W	2 / 55

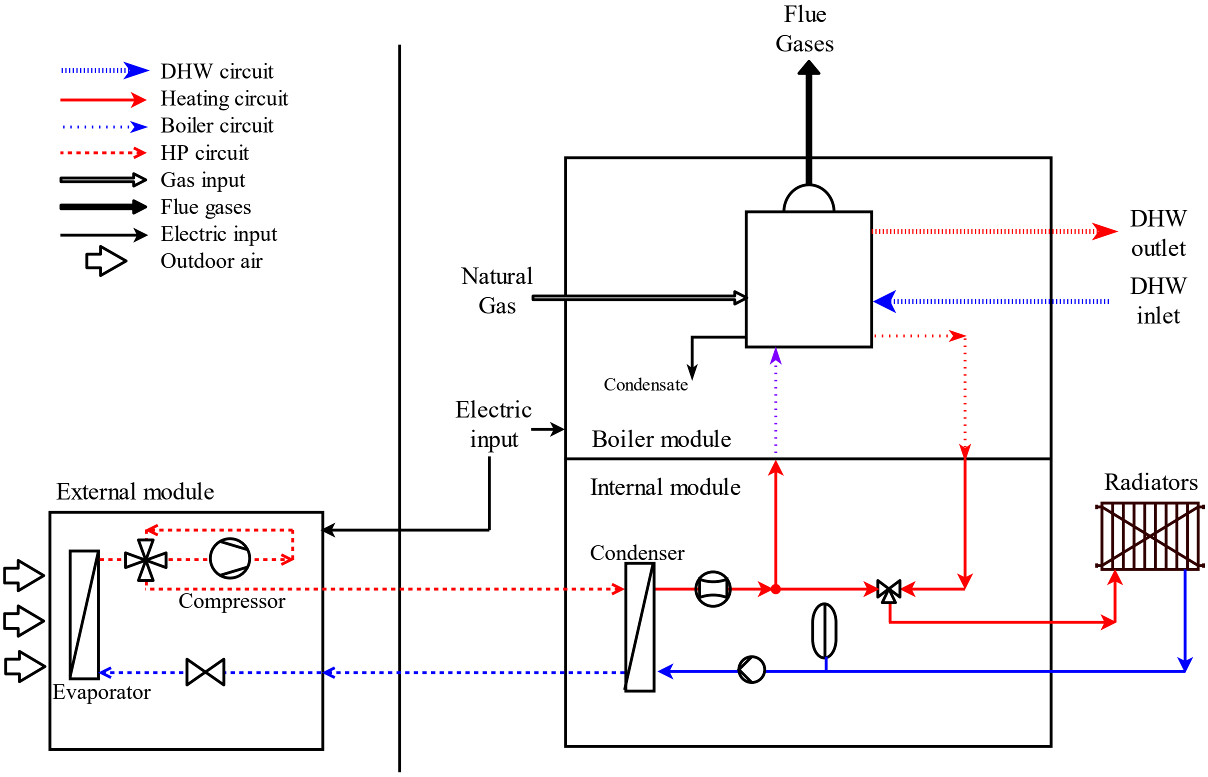


Figure 2. Monitored hybrid heat pump schematic, Ruiselede

Description of the monitored buildings

The monitored hybrid systems are installed in two residential buildings in the northern part of Belgium at Leest and Ruiselede, considered to be in the same climatic region. These locations are equipped with sensors whose collected data is daily sent to the Cloud; their technical features are shown in

Table **4**, and their position can be seen in the installation schemes shown in Figure 3 and Figure 4. Indoor and outdoor ambient conditions are measured, as well as gas and electric consumptions of the system; a heat meter is installed between the inlet and outlet pipes of the machine to measure the heating energy delivered by the appliance to each circuit (DHW or SH) based on the measurement of the water flow rate and its respective inlet and outlet temperatures, allowing to compute performance indicators of both systems.

Some control and internal parameters of the systems such as power modulation or temperature setpoint are not remotely controlled or monitored. This means that changes or modifications made by the user or installer could not be communicated, being difficult or impossible to identify only with the data analysis.

None of the monitored houses counts with a buffer tank for heat storage (besides the one embedded at Leest as shown in Figure 1).; additionally, both sites count with photovoltaic panels. In terms of users, the household composition in Leest correspond to a family (2 adults, 2 kids) while at Ruiselede the household is composed by only one person.

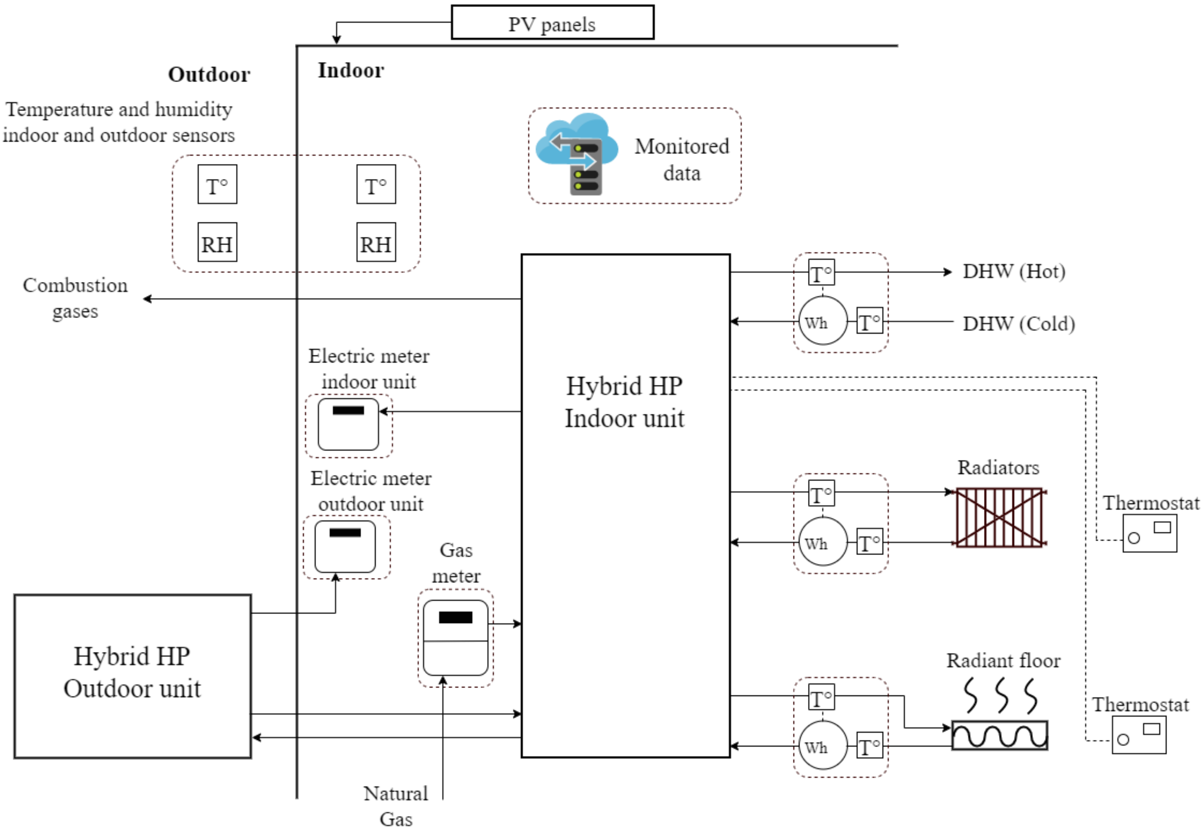


Figure 3. Installation scheme of Leest monitoring site

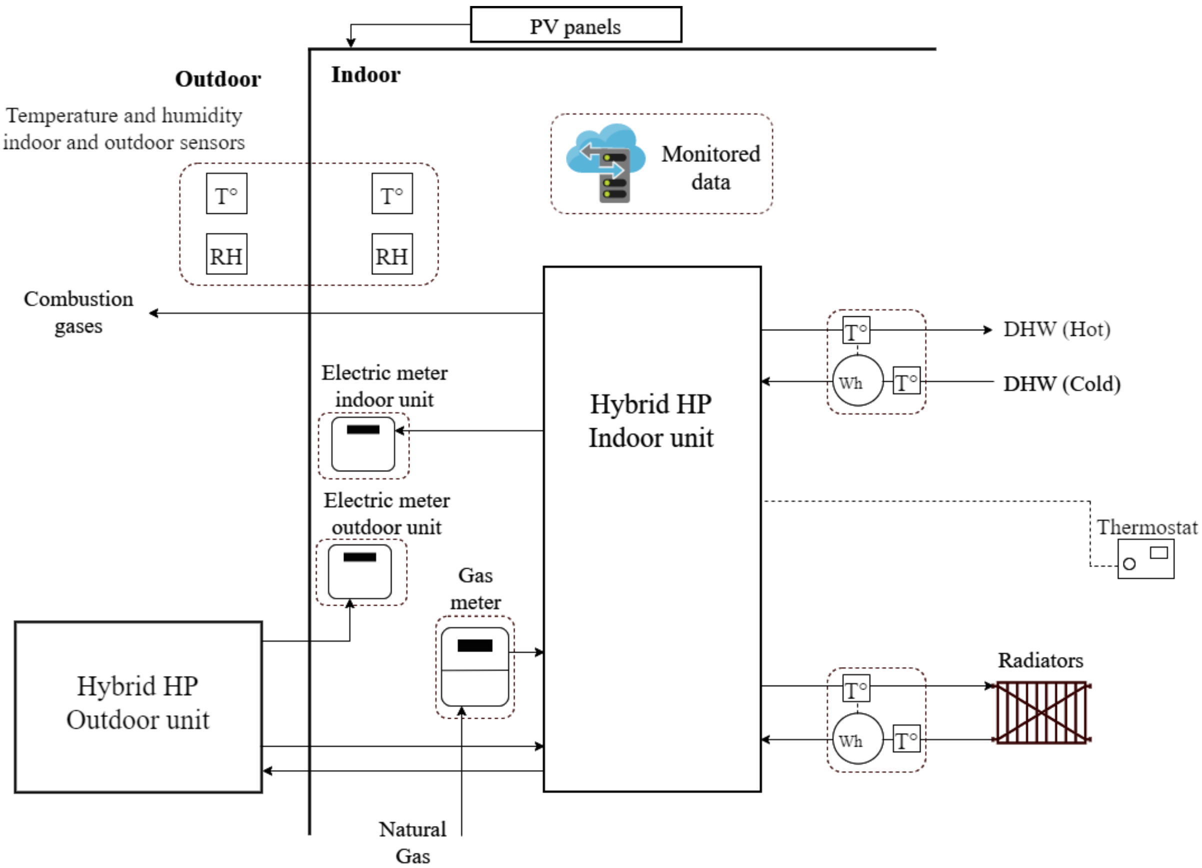


Figure 4. Installation scheme of Ruiselede monitoring site

Table 4. Reference of the monitoring sensors

Sensors	Reference	Resolution	Accuracy
Ext./Int. temp. ; humidity	Weptech Munia	0,1 K; 0,1%	± 0,3 K; ± 2%
Heat counter	Qalcosonic E1 Qn2,5 qi=0.025m³/h; L=130mm	1 kWh; 1 l; 0,1 K	Accuracy Class 2
Machine 1-way electrical energy counter	Iskraemeco ME162-D1A42-V12G22-M3K0	10 Wh	Accuracy Class 1
Gas volume counter	BK-G4T DN25 Qmax 6 m³/h	10 l	<0.5%
Data logger (cloud connection)	Viltrus MX-9	-	-

From the beginning of the monitoring visits had been made to solve problems linked to the installation and settings at each site, whose consequences are reflected in the monitoring data. These problems and misunderstandings did not allow the appliance to work as a hybrid system before September 2021 at Ruiselede, and the same applies for Leest before December 2021. On the other hand, the electricity consumption of the heat pump was recorded in none of the two facilities before September 2021. Based on these two observations, it is possible to say that both systems worked based only on the boiler thermal production until these dates, and that the electrical measurements registered on each site correspond only to the boiler.

Discussion and Results

Both installations are supplied with natural gas. Along the study, Ruiselede always counted with rich gas (H), while at Leest a transition from lean gas (L) to rich gas was made in June 2022. The mean High Calorific Values (HCV) used for the further analysis, per site and per year, are shown in Table 5.

Table 5. Mean high calorific value used per site, per year

High calorific value [Wh/m3]		**Year**	
		2021	**2022**
Site	Leest	10.3570 (L)	Until May : 10.3361 (L) From June : 11.5699 (H)
	Ruiselede	11.5376 (H)	11.5612 (H)

From here under, the nomenclature used per graph is shown in Table 6.

Table 6. Nomenclature used in monitoring analysis graphs

L	Leest
R	Ruiselede
Global	Global
Th	Thermal
El	Electrical
DHW	Domestic hot water
SH	Space heating
int	Internal
ext	External
Gas	Gas

The COP_{global} is computed as the ratio of the thermal power output to heat and electric power inputs as defined in Equation (1). The COP_{Th} and COP_{El} are shown in Equation (2) and (3) and correspond to the same definition considering only the thermal or electrical input respectively; the thermal input is considering the high calorific value of the used gas. Similarly, the COP_{Th} and COP_{El} for DHW of SH are computed as shown in Equation (4) and Equation (5), taking into account only the DHW or SH production respectively.

$$COP_{global} = \frac{\dot{Q}_{DHW} + \dot{Q}_{SH}}{\dot{Q}_{gas} + \dot{W}_{El}} \quad (1)$$

$$COP_{Th} = \frac{\dot{Q}_{DHW} + \dot{Q}_{SH}}{\dot{Q}_{gas}} \quad (2)$$

$$COP_{El} = \frac{\dot{Q}_{DHW} + \dot{Q}_{SH}}{\dot{W}_{El}} \quad (3)$$

$$COP_{Th,DHW} = \frac{\dot{Q}_{DHW}}{\dot{Q}_{gas}} \; ; \; COP_{Th,SH} = \frac{\dot{Q}_{SH}}{\dot{Q}_{gas}} \quad (4)$$

$$COP_{El,DHW} = \frac{\dot{Q}_{DHW}}{\dot{W}_{El}} \; ; \; COP_{El,SH} = \frac{\dot{Q}_{SH}}{\dot{W}_{El}} \quad (5)$$

The available number of days to analyze during 2021 is 356 for both sites. For the analysis it must be taken into account that, as previously mentioned, the system worked during some months only based on the boiler thermal production. The most visible effects are due to:

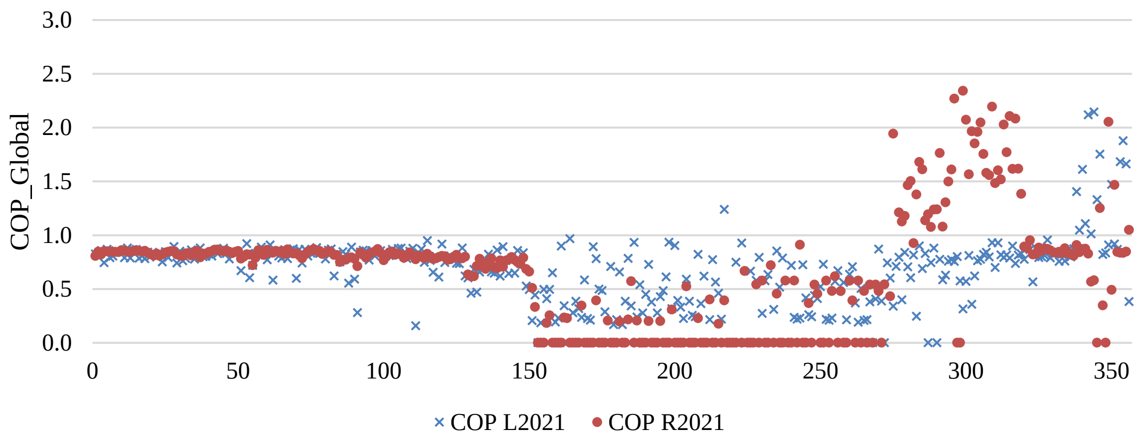
- An electrical meter installation in each facility to measure the heat pump electrical consumption (not registered until then) in early September (day ~250); is worth to mention that the electrical consumption of the boiler (indoor module) was measured all the time.
- Modification of the tariff settings at Leest in mid-December (day ~340), allowing the system to work as a hybrid appliance.
- Modifications in the energy tariffs at Ruiselede in early August (day ~220) and mid-November (day ~320), first to benefit from the PV production and afterwards, to promote the use of natural gas.

These changes are visible in Figure 5, where towards the end of the year the COP global of both facilities increases, as well as the effect in the thermal and electrical COP. These changes are more affected by the SH production during winter since the DHW production remains all over the year as pointed in Figure 7.

At Leest, the datasheets of the appliance do not give an efficiency value for the DHW production based only on the boiler operation as they do for the SH production (Table 2), so no conclusions can be concisely drawn. It can be seen though, that the efficiency for the SH production of the system operation based only on the boiler heat supply (before December 2021) is within the ranges announced by the manufacturer (86.9-94.8% based on HHV, it must be considered that at Leest the installation is powered with lean gas). The seasonal effect is clearly appreciated also in the SH production, while the DHW production remains relatively constant throughout the year. Only a few points above 1 can be seen for the COP global on the second half of December due to the change of tariffs that promotes the use of the heat pump and electricity over natural gas as shown in Figure 8, for an almost identical SH and DHW to that at the beginning of the year 2021. Even more, a switch in the electricity consumption can be identified (a reduction in the internal electricity consumption linked to the boiler for an increase in the external one liked to the heat pump) as well as a decrease of the natural gas consumed, revealing the change on the internal control of the appliance towards a hybrid mode due to the modifications performed. The effect can be seen also in the change during the start and the end of the year in the thermal and electric COP for DHW and SH production as shown in Figure 6, increasing the efficiency of the gas and diminish the electrical one.

At Ruiselede, the hydraulic system is simpler and direct. The household composition implies that there's almost no DHW production, therefore most of the results are associated to the SH production; however, these results are far from the ones announced in Table 3. It must be considered that they are based on a low calorific value (LHV) for the declared efficiencies, and that the results shown are based on the gas HHV available on site; thus, to be able to compare, it must be considered that the graphic results are ~11% lower in LHV terms.

The gas boiler at Ruiselede is sized for a space heating output range between 8.2 and 26.6 kW; as can be seen in Figure 7, the SH demand is rarely equal or higher than the minimum output of the gas boiler. Thus, it can be said that the gas boiler of the system is oversized for the SH requirements of the household, resulting in poor daily performance indicators before the modifications of August. The heat pump at Ruiselede has a smaller heating capacity that the gas boiler, so after the modifications (around day 220) and since the heat pump is allowed to work, improvements in the COP's are observed due to the fact that now the unit sizing is more suitable for the main demand (SH). Nonetheless, these values decrease drastically after the change of tariffs in mid-November (day 320). This can be observed also by correlating the results shown in Figure 8.



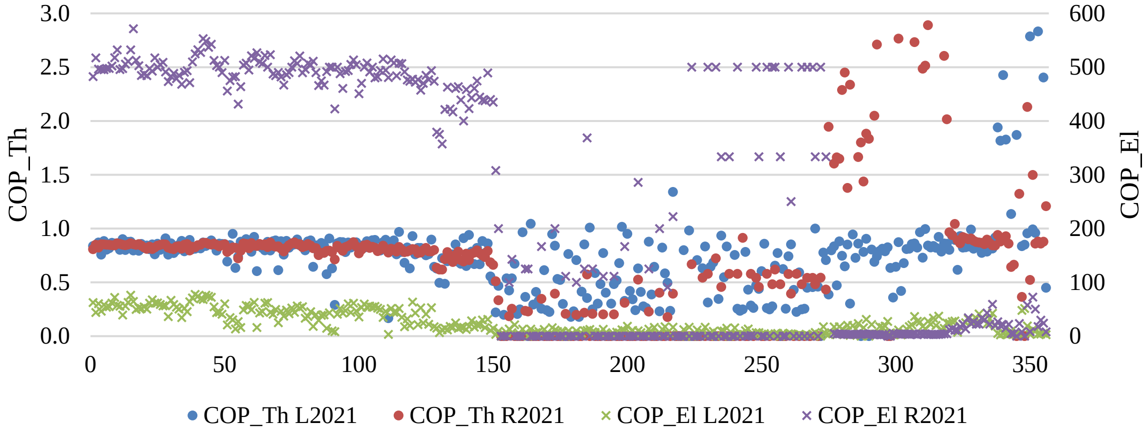


Figure 5. Daily global COP for both sites during year 2021 (top); Daily Th and El COP for both sites during year 2021 (bottom)

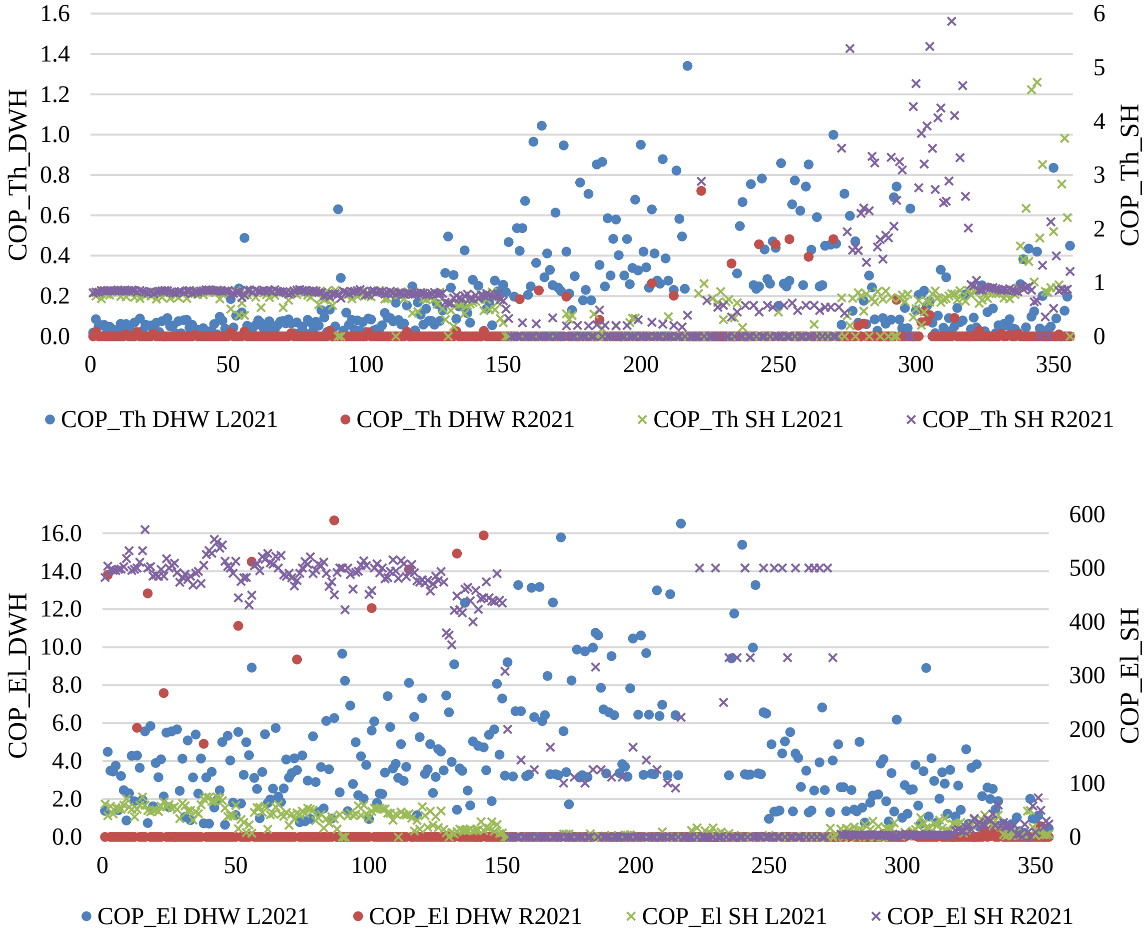


Figure 6. Daily COP Th for DHW and SH for both sites during year 2021 (top); Daily COP El for DHW and SH for both sites during year 2021 (bottom)

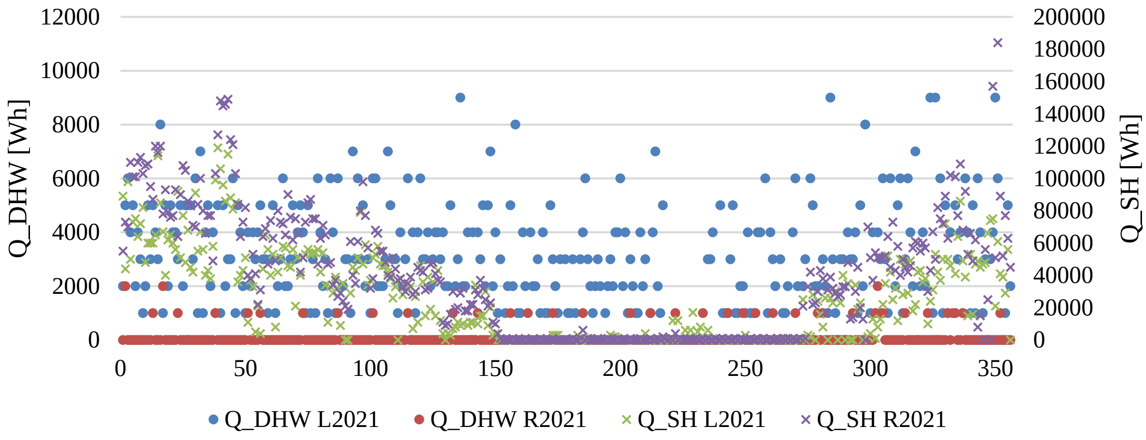
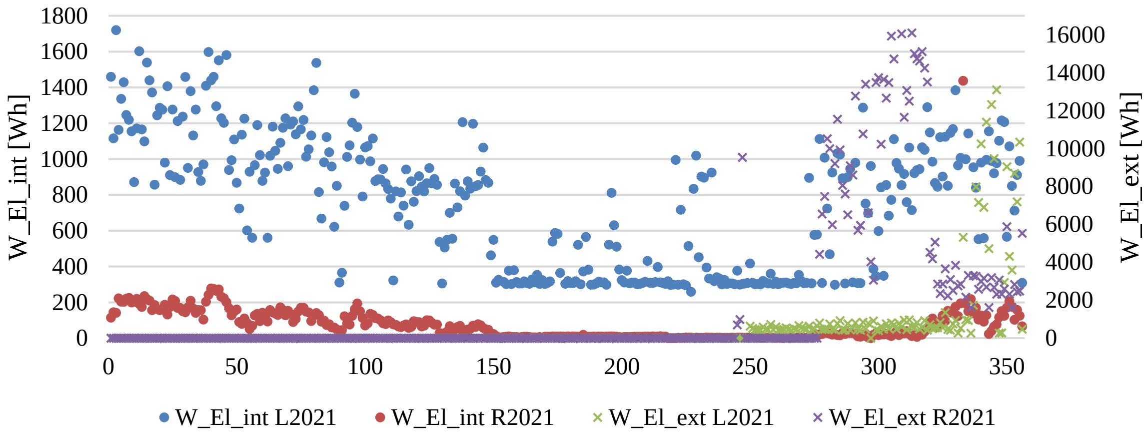


Figure 7. DHW and SH production for both sites during 2021



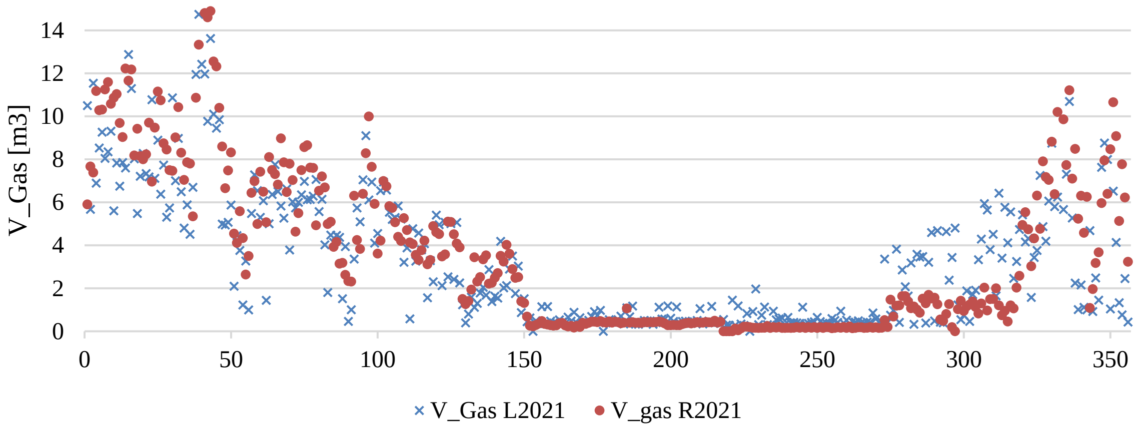
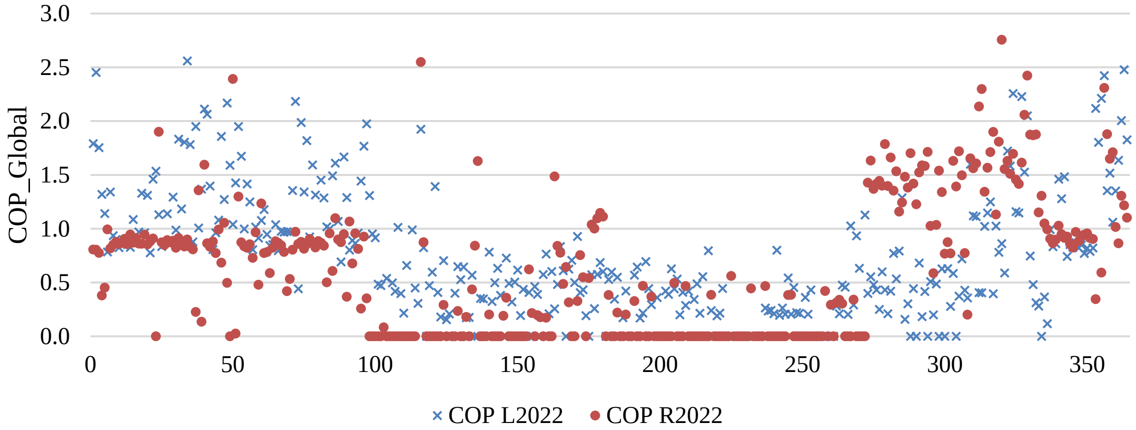


Figure 8. Internal and external electricity consumption for both sites during 2021 (top); gas consumption for both sites during year 2021 (bottom)

For year 2022, the available number of days to analyze is 364 days for both sites. Compared to year 2021, better daily results are observed in Figure 9 (top) for Leest through the first cold months, result of the last modifications performed in December 2021; these improvements, once again, are mostly related to the SH production as shown in Figure 11, where the DHW is a small part of the total. Figure 12 (bottom) shows that the gas consumption decreased compared to the previous year, effect that is inline with the increase of the external electrical consumption during 2022 compared to 2021 (Figure 12, top).

At Ruiselede and as shown in Figure 9, until the end of summer the results are in line with the change of tariff performed in November 2021, decreasing the COP's; however, this changes when the cold season starts in October (around day 270). There are no variations observed in the behavior of the demand of the household (Figure 11), yet the energy consumption changes with electricity having a main role and most of all, the heat pump (Figure 12, top); this also matches the gas consumption behavior shown in Figure 12 (bottom).

The changes on the external electrical consumption are difficult to explain for the last months of the year; the observed behavior is similar to what is expected from a change of tariff as it was observed in 2021 to promote the heat pump utilization, but there is no record about a change in this respect informed by the user.



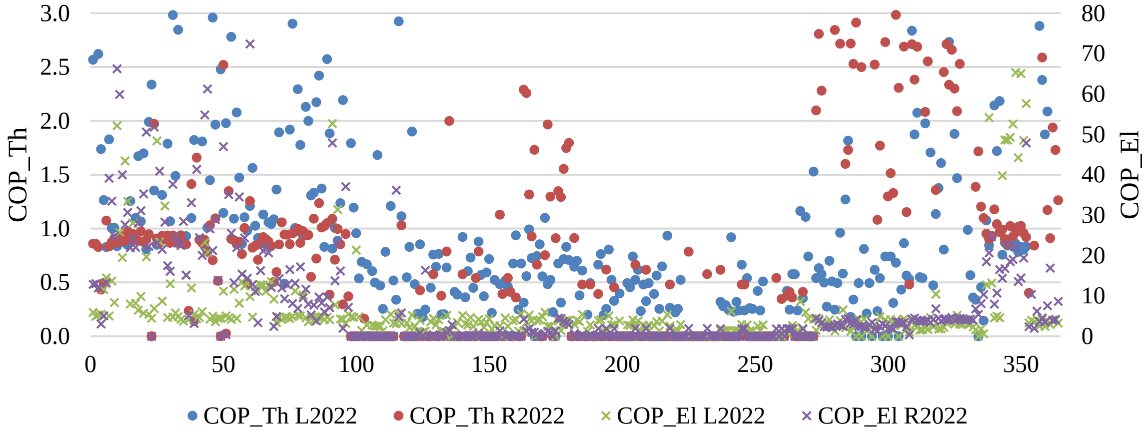


Figure 9. Daily global COP for both sites during year 2022 (top); Daily Th and El COP for both sites during year 2022 (bottom)

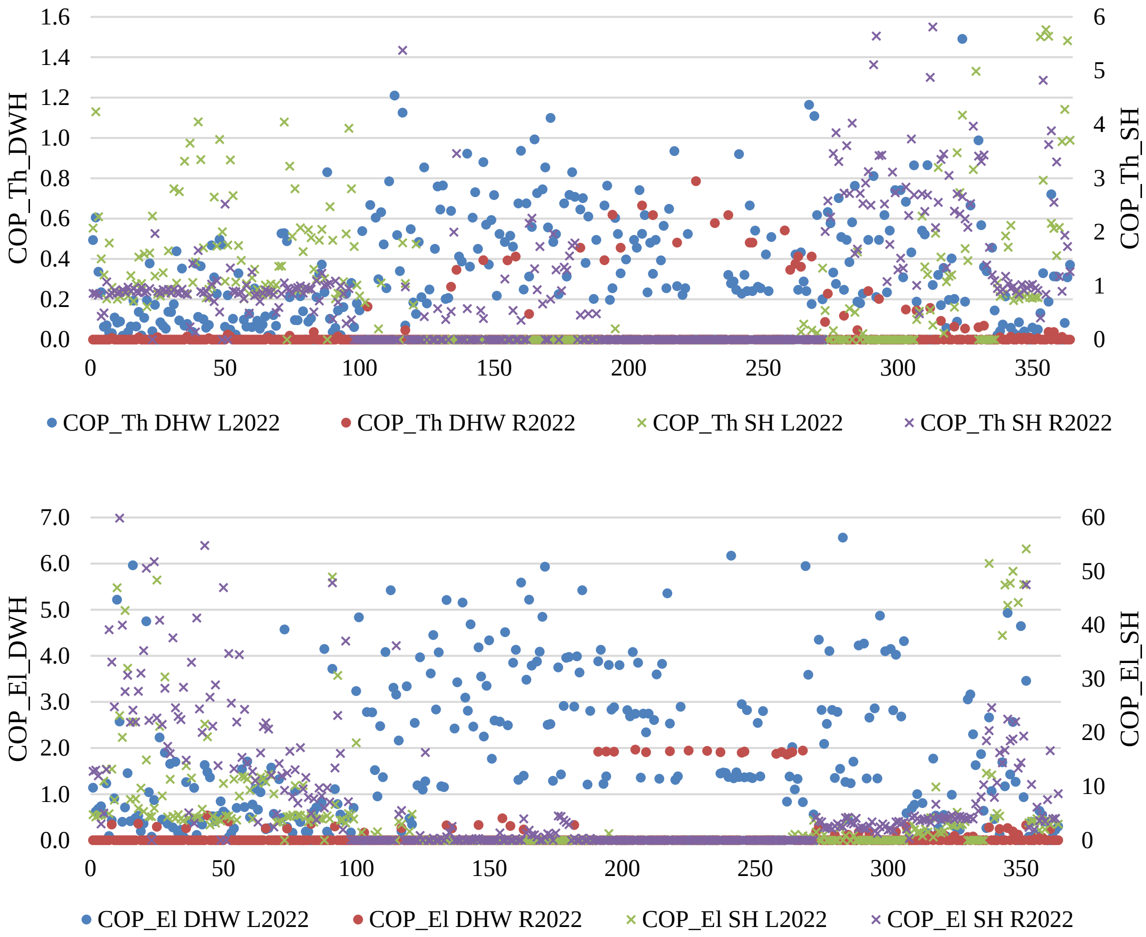


Figure 10. Daily COP Th for DHW and SH for both sites during year 2022 (top); Daily COP El for DHW and SH for both sites during year 2022 (bottom)

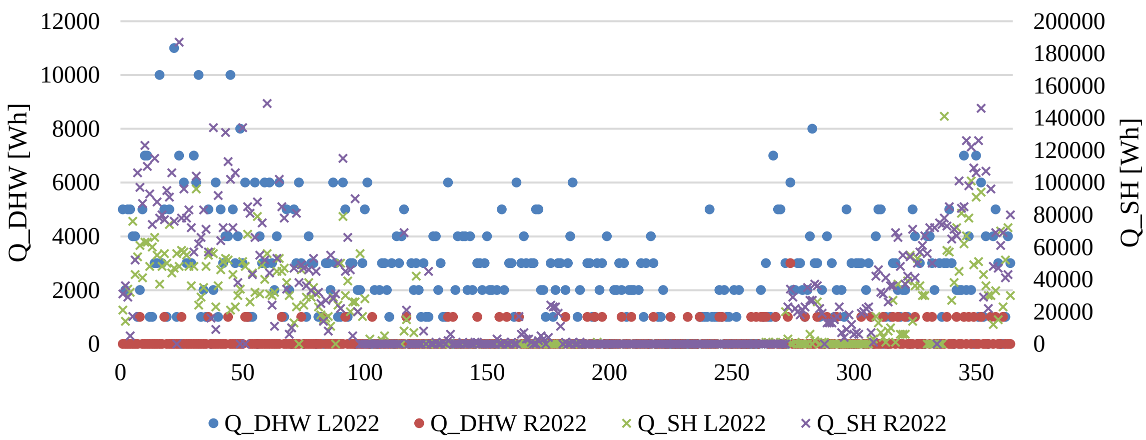


Figure 11. DHW and SH production for both sites during 2022

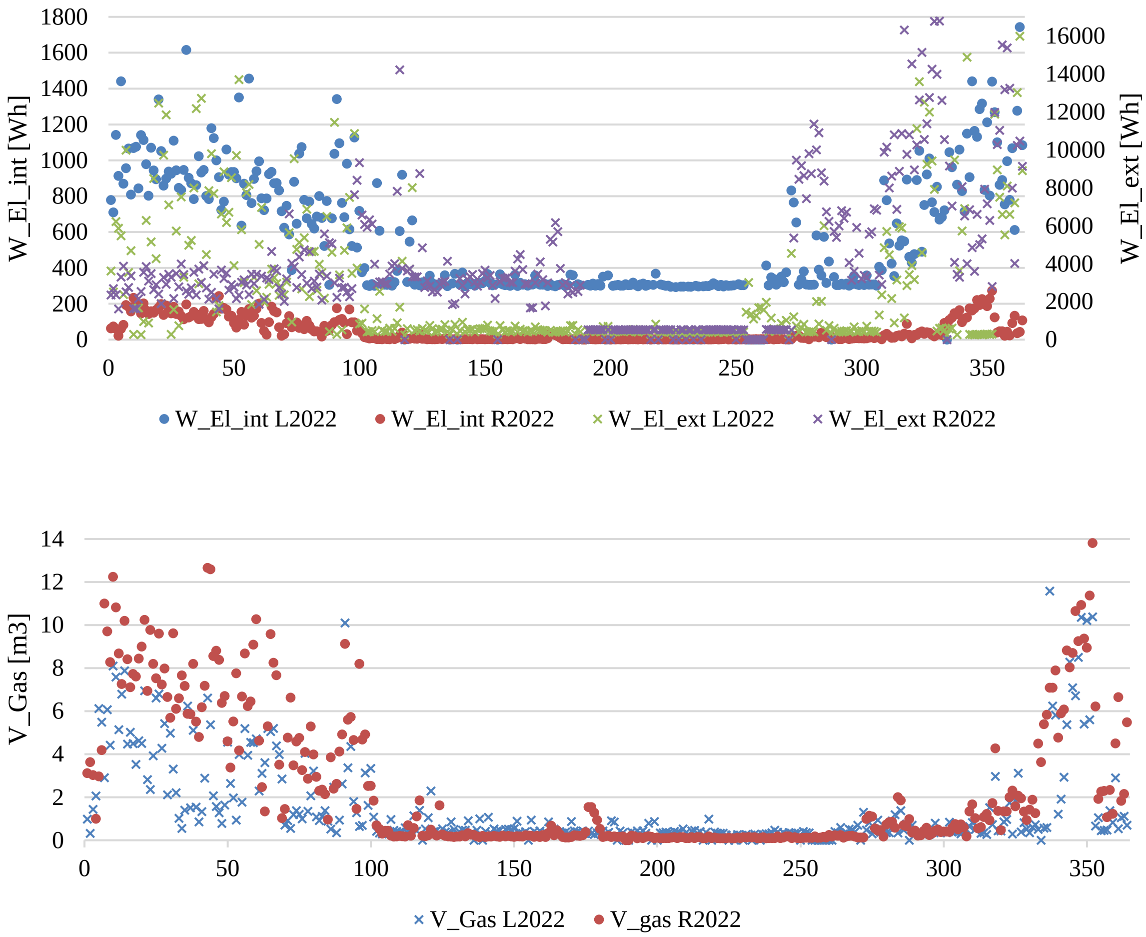


Figure 12. Internal and external electricity consumption for both sites during 2022 (top); gas consumption for both sites during year 2022 (bottom)

Conclusions

The results obtained from two years monitoring of two hybrid heat pumps have been presented and findings discussed.

The results shown along this work evidence that the appliances in the field are not exempt from presenting problems starting from the installation phase made by qualified technicians until the daily use phase made by the owners. These problems are hard to identify without a proper comprehension of the systems and communication with the final user, making the monitoring and follow up of the installations crucial to obtain, at least, acceptable performance results.

The correct parameter setting has a great impact on the system performance and mode of operation, especially when the control is based under energy prices. A misunderstanding or a bad setting can make the difference between a system that works under efficient conditions or not, affecting the performance results, pointing out the vulnerabilities of hybrid technologies and special attention to reach the maximum profit possible. Therefore, installation and parametrization must never be neglected; it can even be stated that monitoring the performance seems necessary until the technology (and the way it is installed and used) has statistically demonstrated its robustness in field-tested applications.

Finally, the results obtained along both years and the modifications that have been implemented point out the fact that the solutions must be adapted to the specific needs of each site, being possible to achieve benefit from the coupling with other systems such as PV panels.

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