Annual Energy Performance of a Solar/Biomass HVAC System: Experimental Characterization through Concise Cycle Tests

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Abstract

This paper presents main results of Concise Cycle Tests (CCTs) carried out on the HVAC system developed under the Hybrid-BioVGE H2020 project. This system is driven by renewable energy sources (i.e., solar energy and biomass) and provides for space heating and cooling for small-scale residential and commercial buildings. The most innovative element of the HVAC system is a thermally-activated variable geometry elector (VGE) chiller, which provides for the building cooling load. Seasonal performance of the Hybrid-BioVGE system were assessed experimentally for both heating and cooling operating mode, according to the Whole System Testing (WST) methodology implemented by Institute SPF. Some components of the system were physically installed in the test bench, while other elements were simulated in TRNSYS and their performance was emulated and given to the test rig actuators according to the Hardware-in-the-Loop approach. Results point out that a significant part of the system energy demand can be satisfied by solar energy during the heating season: solar fraction is higher than 83% and, consequently, only 17% of the space heating energy need is provided by the back-up biomass boiler. On the contrary, the system energy performance for cooling operating mode is much lower than expected from numerical simulations. No sufficient cooling energy is supplied to the building due to the lack of cooling power from the VGE. Test results point out that a different control function to manage VGE operation must be defined necessarily.

Keywords: Whole system testing, Hardware-in-the-Loop, Variable-geometry ejector, Concise cycle test

1. Introduction

Nowadays, building sector is responsible for a large share of energy consumptions and greenhouse gas emissions, up to 40% worldwide (Alazazmeh and Asif, 2021). Furthermore, according to Braulio-Gonzalo et al. (2021), about 26% of final energy consumption in the European Union is associated to the use of energy in residential buildings (e.g., for space heating and cooling, domestic hot water production and appliances). Moreover, it is well known how the overall thermal energy demand of buildings depends on several drivers, such as climate, user behavior, envelope thermal properties and the availability of HVAC technologies. It is evident that, due to climate change, energy consumptions linked to space cooling are expected to grow significantly in the next future (Mutschler et al., 2021). In fact, a warmer climate results in a considerable increase of cooling energy demand in regions characterized by mild ambient temperatures during the hot season, thus resulting in a growing share of population installing an air conditioning device.

Currently, cooling energy need is mainly met by electric-driven vapor-compression units. Consequently, the forecasted growth of cooling demand will strongly impact power systems, for example affecting the electricity peak demand, especially during the hot season, and increasing the electricity off-take from the grid. Nowadays, decarbonization of energy systems is still ongoing and, for this reason, carbon emission factor for electricity from the distribution network maintains a high value (Ramsebner et al., 2021), since the highest share of electric energy is produced by fossil fuels in large and decentralized power plants.

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In this alarming framework, to limit the environmental impact and mitigate the climate change, a wider diffusion of sustainable HVAC systems, combined with on-site renewable energy systems, must be achieved in new and existing buildings. As pointed out by the open literature, solar-driven ejector cooling has high emission saving potential for space cooling applications. In fact, it is a simple, low-cost technology and an intrinsic correlation between solar irradiation and cooling demand can be found in common applications (Allouche et al., 2017).

Nevertheless, ejector-based cooling systems are typically characterized by low energy efficiency: the ejector Coefficient of Performance (*COP*) is lower than 0.3 in stationary operating mode and, furthermore, its performance is strongly influenced by current operating conditions (i.e., generator, condenser and evaporator temperature) and the adopted working fluid (Braimakis, 2021). Moreover, the best ejector energy performance can be achieved only for a narrow range of operating conditions. In fact, traditional fixed-geometry ejectors are sized for design working conditions and, under floating operating mode, the ejector fluid dynamics is strongly penalized, resulting in a significant reduction of *COP* (Varga et al., 2017). For above-mentioned reasons, the adoption of variable-geometry ejectors can improve sharply both the flexibility and the seasonal energy performance of this kind of systems (Van Nguyen et al., 2020).

Within this framework, the H2020 Hybrid–BioVGE project (Hybrid-BioVGE project, 2019) aims to design and demonstrate the energy saving potential of an innovative hybrid HVAC system, by means of which the energy needs for both space heating and cooling of residential and small-scale commercial buildings can be satisfied. The system developed along the project is driven by heat during the whole year, exploiting two renewable energy sources: solar energy and biomass. Its major components are solar thermal collectors, a biomass boiler, used as auxiliary heating device, two thermal energy storages and a thermally-driven variable geometry ejector (VGE) chiller, the most innovative element of the system.

Previous numerical works have pointed out the clear potential of the proposed VGE-based HVAC system in the current energy transition towards renewables. Dongellini et al. (2021) demonstrated that during the cooling season, almost 75% of the ejector's generator heat demand can be provided by solar energy, while about 90% of the system energy input is covered by renewable energy. Nonetheless, experimental tests are fundamental to assess the effective performance of Hybrid-BioVGE system and confirm its strong energy saving potential.

In this context, a reliable experimental evaluation of the Hybrid-BioVGE system performance is a difficult task, due to complexity of the system, dynamic operating conditions, interaction between components and master control logic. For this reason, Whole System Test (WST) approach is the only reliable test procedure to evaluate the effective performance of this system (Haller et al., 2013). In fact, when a complex HVAC system is used in a real building, transient phenomena which cannot be easily quantified by single component tests may arise, such as on-off cycling and stand-by losses. WST methods are based on the "Hardware-in-the-Loop" (HiL) concept and allow to test complete systems with realistic boundary conditions and for almost main operating modes, supporting the extrapolation of annual performance data of the tested system (Papillon et al., 2011). In recent years, dynamic WST methods have been developed and implemented in several European institutes to perform reliable tests on complex HVAC systems (Menegon et al., 2020).

In this context, the aim of the present paper is to evaluate the effective energy performance of the Hybrid-BioVGE system according to the WST methodology. Main components of the developed system are installed in an indoor test rig located at the institute OST-SPF, in Switzerland. The test rig is composed by four hydronic loops, by means of which heating and cooling loads of a building, as well as solar collector field or boiler outputs can be emulated in real time and given as boundary conditions to tested components. Simulation models of emulated subsystems are implemented within the dynamic software TRNSYS 18.

In order to extrapolate directly the seasonal performance of the Hybrid-BioVGE system from WST results, two Concise Cycle Tests (CCTs) have been defined, one for the heating operating mode and one for the cooling operating mode. Each CCT involves a series of days, representative of the whole season. In detail, seven and six typical days have been selected from the Meteonorm (Meteonorm, 2022) weather database with 1 hour time resolution to define test sequences for heating and cooling seasons, respectively. Weather data from both test sequences are emulated in the test rig as well.

In this work, the results of CCTs carried out on the Hybrid-BioVGE system for both heating and cooling operating mode are reported. The energy performance of the system has been assessed experimentally, obtaining the seasonal solar fraction (i.e., the share of building energy demand covered by solar energy), the seasonal coefficient of performance of the VGE and the overall primary energy consumption of the system.

2. Methodology

CCTs performed at the institute OST-SPF aimed to evaluate the energy performance of the Hybrid-BioVGE system installed in one of the demonstrator of the project, located in Porto (Portugal).

2.1. Description of the Hybrid-BioVGE system

The HVAC system proposed by Hybrid-BioVGE consortium and studied in this work is coupled to a single-family detached home built during 2020 in Porto. The building presents an unheated basement, where the HVAC system technical room is present, and three heated floors (i.e. ground, first and second floor). The total net floor area of conditioned zones is equal to 186.3 m^2, while the heated volume of the building is 426.6 m^3. The building is characterized by a highly-performant envelope. For sake of brevity, thermal properties of envelope components can be found in Moser and Schranzhofer (2020).

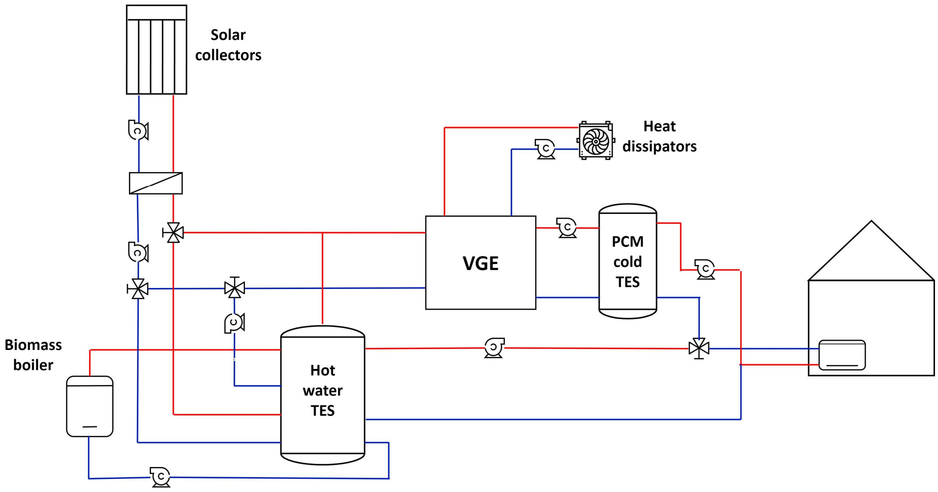


Fig. 1: Layout of the Hybrid-BioVGE HVAC system installed in the demonstrator in Porto

As pointed out in the previous section, the HVAC system developed by Hybrid-BioVGE consortium is composed by several components. In Figure 1, the simplified layout of the system is represented. Additional details on the complete design of the whole system are reported in Kalkgruber (2021).

Heat is mainly provided during both the seasons by nine flat plate collectors, installed on the building roof. Solar thermal collectors have a surface tilt (β) equal to 35°, while the azimuth (γ) is equal to 0° (i.e., collectors facing South). Optical efficiency η_0, 1st and 2nd order heat loss coefficients are equal to 0.706, 3.503 W/m^{2}K and 0.011 W/m^{2}K^2, respectively. These data, provided by the manufacturer, are related to the gross area of each collector, equal to 2.78 m^2. As pointed out in Figure 1, a plate heat exchanger decouples the solar collector field from the remaining part of the system.

During the heating season, solar collectors charge a 1000 liters hot water Thermal Energy Storage (TES). Heat is stored in the hot TES and then is provided to the building by means of radiant floor surfaces. A biomass boiler, fueled by pellet chips and characterized by a nominal heating capacity of 12 kW, is used as back-up heat generator during cloudy days with low values of solar irradiation.

The VGE chiller is most innovative element of the Hybrid-BioVGE project and is connected to several components of the HVAC system. The cooling device operates with R152a as refrigerant fluid and has been designed for a nominal cooling capacity of about 5 kW. As pointed out before, the ejector has the capability to adjust its geometry to maximize both the secondary mass flow rate (i.e., to obtain the highest cooling power) and the *COP*, depending on current operating conditions. In particular, the device has two degrees of freedom: i. the nozzle throat area can be varied by means of a movable spindle; ii. the relative position of the primary nozzle exit section with respect to the entrance section of the ejector throat can be adjusted by changing the nozzle position. Two linear stepper motors are coupled to the ejector to vary its geometry. In Figure 2, a picture of the whole VGE cooling device is reported.

Fig. 2: Variable geometry ejector cooling system

The VGE cooling system presents three plate heat exchangers to exchange heat between refrigerant and water. The generator of the ejector-based unit is mainly driven by solar energy. As pointed out by the hydraulic scheme shown in Figure 1, the VGE chiller is directly fed by solar collectors when high levels of solar irradiation are present. On the contrary, generator receives heat from the hot TES during days characterized by low irradiation (e.g., cloudy or rainy days). In this way, thermal energy collected by the solar field in previous days with better climatic conditions can be exploited, increasing the overall solar fraction of the system. Finally, the biomass boiler is operated as back-up system when no solar irradiation is present and, simultaneously, the hot TES is discharged. VGE evaporator is coupled to the HVAC system distribution network by means of a 500 liters sensible-latent thermal storage, which stores refrigerated water and encapsulated PCM modules. About 30% of the cold TES volume is occupied by disk-shaped modules, filled with ATS15, a salt-hydrate PCM having a melting temperature of 15°C (Axiotherm, 2022). In this way, the storage capacity of the system can be improved at the same volume, allowing a better operation of the VGE, since the TES temperature remains higher after the phase change, during the charging process. Finally, heat from the condenser is rejected to the ambient air by means of two commercial dissipator units, connected in parallel and installed on the building roof, having a rated heating capacity of 25 kW.

Control logic of the VGE and master control strategy of the whole system have been defined by the consortium. The complete description of control rules adopted for the Hybrid-BioVGE system supervision (i.e., list of variables, possible operating modes, setting of parameters) can be found in Morini et al. (2021).

2.2. Description of the experimental test rig for Concise Cycle Tests

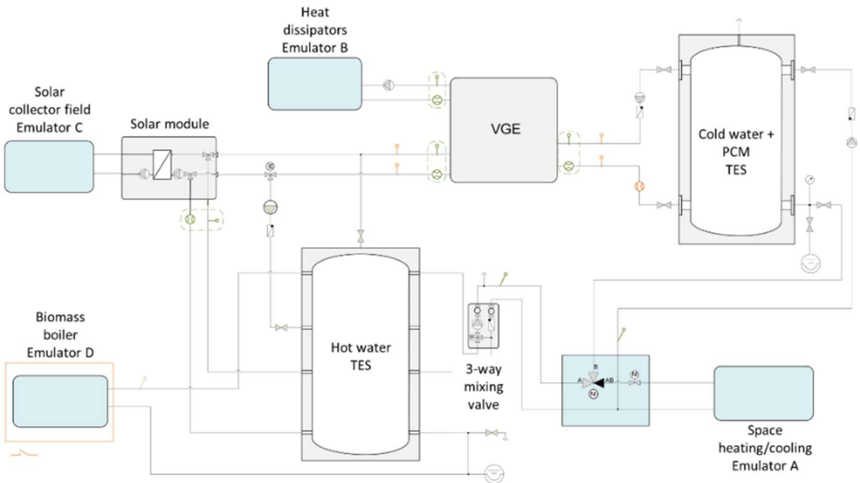
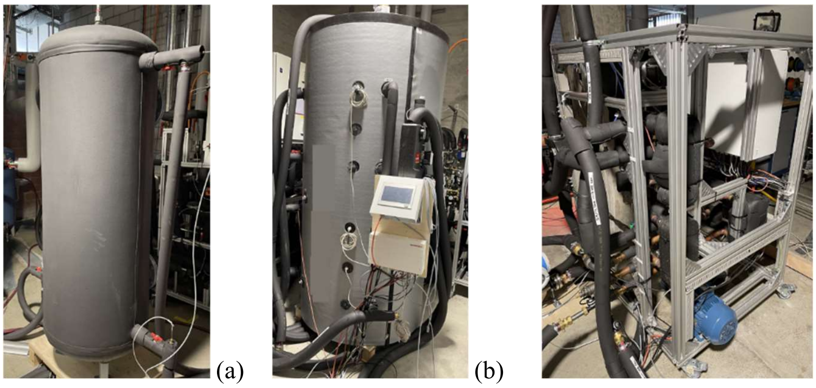


Fig. 3: Simplified hydraulic scheme of the experimental test rig installed at OST-SPF, with emulated and real installed components of the Hybrid-BioVGE system

The experimental test rig used to carry out CCTs on the Hybrid-BioVGE system is made of several components. Some of them are elements of the real HVAC system, others emulate pieces of equipment not installed within the test rig or the building thermal load. The overall layout of the experimental setup is reported in Figure 3.

As pointed out by that figure, both the hot water TES and the cold latent-sensible TES are installed at OST-SPF institute. They are hydraulically connected to the VGE cooling systems with pipes. Other elements of the real HVAC system, such as the solar module and the 3-way mixing valve module, are connected to the experimental test rig. In Figure 4, pictures of the main elements of the Hybrid.BioVGE system installed in the laboratory are reported.

On the other hand, the performance of solar collectors, biomass boiler and heat dissipator units is reproduced by emulators B, C and D, respectively, since these elements are not physically installed within the test rig. The building thermal load for space heating/cooling, evaluated by dynamic simulations, is emulated as well by means of emulator A. Additional data needed to run a CCT, such as weather data (i.e., ambient temperature, solar irradiation incident on solar collectors) and room temperatures, are reproduced by electronic devices and given to emulators and installed devices as inputs.



(a) (b) (c)

Fig. 4: Components of the Hybrid-BioVGE system installed in the test rig: cold sensible-latent TES (a), hot TES (b) and VGE chiller (c)

Simulation models of emulated components are implemented in the dynamic software TRNSYS 18 (Klein et al., 2017). Building heating and cooling loads are evaluated by means of Type 56 (Multi-zone building model). Solar collector model is “Flat plate collector with capacitance – Type 539”. Biomass boiler model is “Simple boiler with efficiency from data file – Type 751”, coupled to a series of equations needed to model the boiler control strategy (e.g., deashing procedure, hot and cold start-up). Both Type 539 and Type 751 can be found within TESS libraries. Heat dissipator units coupled to the VGE are modelled through the “Multi-dimensional data interpolation – Type 751” model, by means of which performance data of dissipators (i.e., thermal power and fan power input), given by the manufacturer, are interpolated as functions of fan speed, ambient air temperature and inlet water temperature.

2.3. Selection of heating and cooling test sequences

The heating and cooling demand of the building, as well as the yield of solar collector field, is of course dependent on the selected weather data. Therefore, two different test cycles were extracted from the annual weather data set for the Porto site, which was used for previous simulations. The first test sequence has been defined for the heating operating mode and the second test cycle has been designed for the cooling period. The reason for splitting into two sequences is the large inertia of the thermal masses involved in the system (i.e., building, hot and cold TES).

The test sequence from the heating period is composed by 7 days and consists of the week ranging from January 22nd to January 28th. On the other hand, the sequence from the cooling period consists of six selected days between May 28th and September 2nd. The selected days during the year can be seen in Figure 5, while the 7-day heating cycle and the 6-day cooling cycle are reported in Figure 6 and Figure 7, respectively. It is evident from these figures that selected sequences represents different climatic conditions occurring in Porto during the whole season. For example, the 6-day cooling cycle includes days with high values of both ambient temperature and solar irradiation (e.g., Day 1 and 3), as well as periods characterized by low solar irradiation and low or high ambient temperatures (e.g., Day 2 and Day 5, respectively).

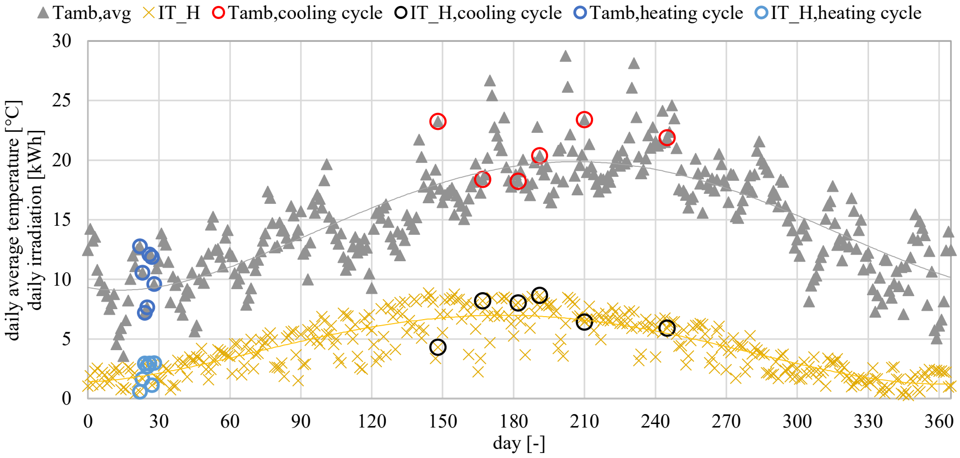


Fig. 5: Annual weather data with markings of the days selected for heating and cooling test cycles ($T_{amb,avg}$ = daily average ambient temperature, IT_H = daily global horizontal irradiation)

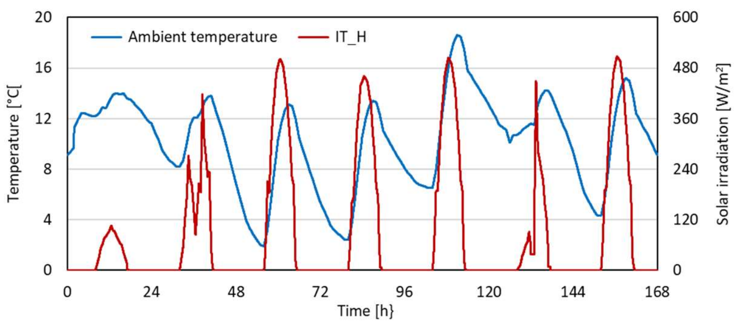


Fig. 6: Weather data of the 7-day heating cycle

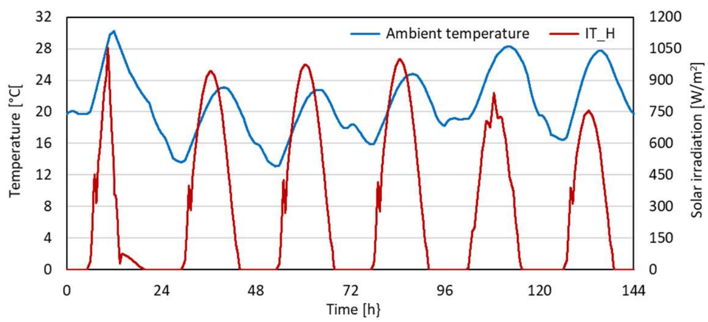


Fig. 7: Weather data of the 6-day cooling cycle

3. Results and discussion

3.1. Heating operation

Results of CCT carried out for heating operating mode are reported in Figure 8 and Table 1. As pointed out by outcomes of experimental tests, the Hybrid-BioVGE system is characterized by excellent energy performance. Globally, a total of 189.4 kWh of heat was supplied to the building for space heating. Solar collectors provided about 224.1 kWh, while the biomass boiler energy output was equal to 31.9 kWh. Consequently, the system solar fraction for heating mode (SF_h), defined as the share of building's thermal energy demand for heating provided by solar energy, is very high and equal to 1 for 6 days of the sequence (i.e., space heating energy need totally satisfied by solar collectors' yield and no energy supplied by the biomass boiler). The back-up boiler delivers heat to the hot TES and, consequently, provides for the space heating, only during the third day of the sequence, characterized by very low values of ambient temperature during the night (see Figure 6 and Table 1 for reference). The overall solar fraction of the Hybrid-BioVGE system throughout the heating cycle is 0.83. Therefore, test results perfectly agree with previous numerical simulations. Moreover, the electric energy demand of controllers and pumps was limited to 6.7 kWh, corresponding to about 3.5% of the building energy demand.

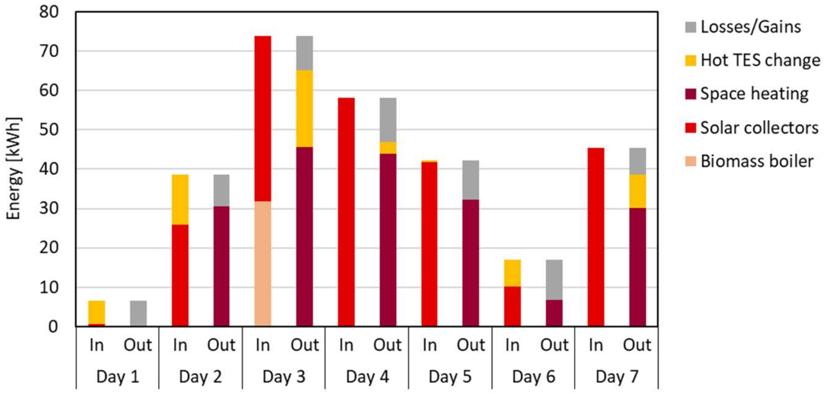


Fig. 8: Results of the 7-day heating cycle with inputs/outputs on a daily basis

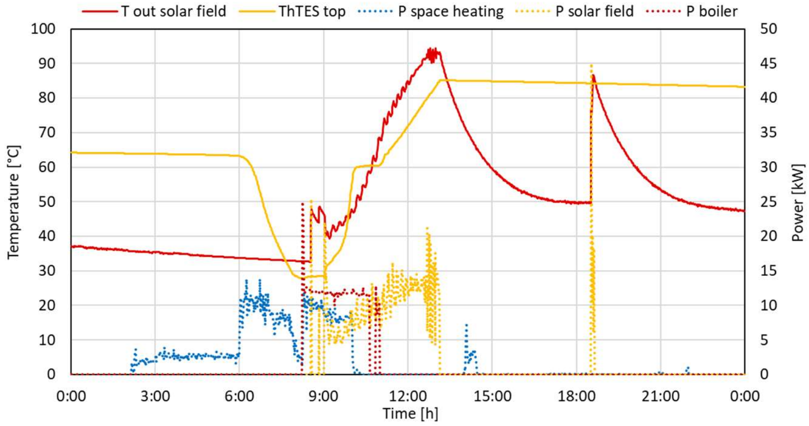
Tab. 1: Results of the 7-day heating cycle

Day	$T_{amb,avg}$ (°C)	$I_{tot,hor}$ (kWh/m^2)	Q_{sh} (kWh)	Q_{col} (kWh)	Q_{bmb} (kWh)	Q_{hTES} (kWh)	SF_h
1	12.5	0.574	-0.2	0.6	0.0	6.1	1.00
2	10.6	1.662	-30.5	25.8	0.0	12.8	1.00
3	7.2	2.950	-45.7	41.9	31.9	-19.5	0.30
4	7.7	2.699	-44.0	58.2	0.0	-2.8	1.00
5	12.1	2.945	-32.2	41.8	0.0	0.5	1.00
6	11.9	1.120	-6.7	10.3	0.0	6.7	1.00
7	9.6	2.979	-30.1	45.5	0.0	-8.4	1.00
Total	10.2	14.929	-189.4	224.1	31.9	-4.6	0.83

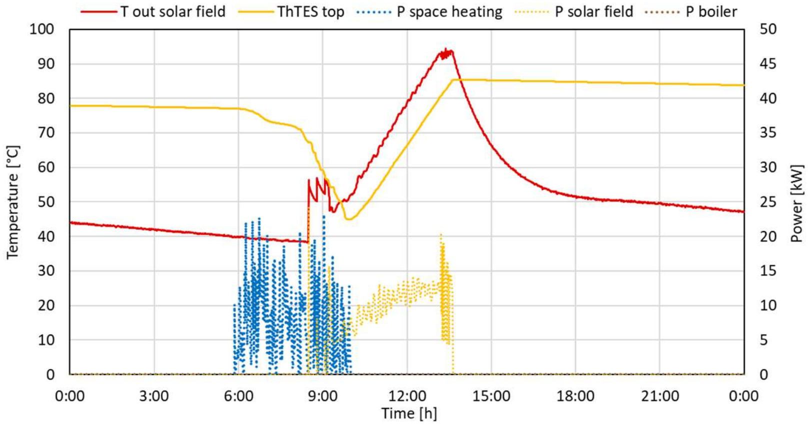
$I_{tot,hor}$ = total solar irradiation on horizontal; Q_{sh} = space heating energy; Q_{col} = collector field energy input; Q_{bmb} = energy supplied by biomass boiler; Q_{hTES} = change of hot TES stored energy (positive values: discharge of TES, negative values: charge of TES)

From the results it can be seen that a significant amount of heat is collected by the solar field during the heating cycle and, consequently, during the whole heating season. It is evident how the largest quantity of solar energy is collected during days 3, 4, 5 and 7, having high values of solar irradiation and a significant thermal load from the building. In these days, in fact, the energy demand for space heating is significant during night and early morning hours and, for this reason, the hot TES is discharged before daytime. Consequently, water temperature within the storage decreases and a huge amount of heat can be potentially collected by the solar field, charging the hot tank and avoiding stagnation phenomenon. In this way, thermal energy stored in the hot TES can be exploited during the following days, if needed. Results confirm that, typically, the energy content of the storage is sufficient until the time when solar energy is available. As an example, during the second day of the heating cycle, space heating energy is higher than solar energy collected by the solar field and hot TES is partially discharged to provide for building's thermal energy demand. On the contrary, a low amount of solar energy is collected during days characterized by higher values of ambient temperature and, consequently, lower heating load from the building. In this case, which is very frequent in locations as Porto characterized by a mild winter, the hot thermal storage is charged rapidly during the morning and stagnation of solar collectors cannot be prevented.

One of the most significant findings of CCT performed for heating operating mode of the Hybrid-BioVGE system is the significant influence of thermal losses on the system energy performance. As pointed out by Figure 8, daily average thermal losses are equal to 8.8 kWh, with a maximum value of 11.3 kWh obtained on the sixth day of the sequence. Along the overall heating cycle, almost 28% of heat collected by the solar field is dissipated from the hydraulic circuit. Since thermal losses from emulators and piping can be neglected, heat is mainly dissipated from the hot TES. In fact, experimental data point out that the temperature of water stored within this tank is very high. The average hot TES temperature throughout the heating cycle is equal to 70°C and rises to 74.8°C and 74.3°C during day 5 and day 6, respectively. It is worth to mention that for the sixth day of the sequence, thermal losses are almost equal to collector field energy input. This outcome is a strong indication that particular effort has to be paid to the minimization of heat losses from the storage system. For example, the hot TES should be located in environments having a warm temperature throughout the heating season, such as the building basement, and additional layers of thermal insulation should be included in the blanket.



(a)



(b)

Fig. 9: Excerpt from the heating cycle CCT, showing the effective behavior of the system: day 3 (most severe day) (a) and day 7 (typical winter day with high solar irradiation and low ambient temperature) (b)

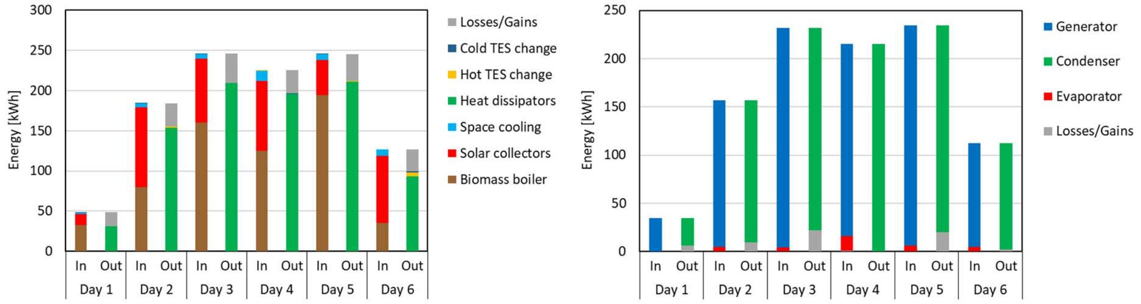
In order to highlight the potential of this kind of test, in Figure 9 an excerpt from heating cycle test data is shown. More in detail, test results from day 3 and day 7 of the heating cycle are reported in Figure 9a and 9b, respectively.

As pointed out by Figure 6, day 3 is the most severe day of the selected heating test sequence. Minimum and average ambient temperature are equal to 2°C and 7.2°C, respectively. During the night, the energy content of the hot TES is not particularly high, due to the low solar irradiation of the previous day, but the storage is able to provide for the building thermal load. Since the building space heating is linked to a time program, every morning at 6:00 rooms' internal set-point increases and required thermal power sharply rises to 10 kW. The thermal storage is discharged very fast and the biomass boiler is activated before solar energy is available. Then, as soon as solar irradiation increases and rooms are heated up, the boiler is switched off and solar collectors charge the storage until the maximum allowed temperature (85°C) is reached.

On the other hand, day 7 of the heating cycle represents a typical winter day for the Porto site. It is characterized by high solar irradiation and low ambient temperature ($I_{tot,hor}$ and $T_{amb,avg}$ equal to 2.979 kWh/m^2 and 9.6°C, respectively). Graph reported in Figure 9b shows that the storage tank has stored a significant amount of energy throughout the previous day, with a temperature in the upper part of the hot TES close to 80°C. Thereby, the building space heating energy is supplied with no activation of the biomass boiler and the tank is discharged. Then, solar collectors charge the thermal storage in about 3-4 hours and sufficient heat is stored for the next day.

In conclusion, measurements show that, in case of the heating season, the capacity of the hot TES is sufficiently large to store energy throughout the day and provide for the space heating demand when it is needed in the next morning. In combination with the time program of the building emission sub-system, a very high solar fraction can be achieved. Nevertheless, the storage tank is charged to its maximum energy content on a significant part of the heating cycle (i.e., four out of seven days). Consequently, the solar field is in stagnation while the supply of energy to the building is inactive. To further decrease the biomass consumption, the building could be heated to higher temperatures and store thermal energy in the envelope.

3.2. Cooling operation



(a) (b)

Fig. 10: Results of the 6-day cooling cycle with inputs/outputs on a daily basis for Hybrid-BioVGE system (a) and VGE chiller (b)

Tab. 2: Results of the 6-day cooling cycle

Day	1	2	3	4	5	6	Total
$T_{amb,avg}$ **(°C)**	23.1	18.5	18.2	20.4	23.3	22.0	20.9
$I_{tot,hor}$ **(kWh/m²)**	4.311	8.204	8.559	8.675	6.420	5.904	42.072
Q_{sc} **(kWh)**	1.2	4.4	5.8	13.0	6.8	7.7	38.9
Q_{col} **(kWh)**	13.8	99.8	79.3	86.7	44.1	84.1	407.8
Q_{bmb} **(kWh)**	32.8	79.8	160.4	125.0	194.1	34.9	627.0
Q_{hTES} **(kWh)**	0.5	-1.7	0.0	0.4	-0.6	-4.1	-5.5
Q_{cTES} **(kWh)**	0.5	0.2	0.3	-0.7	0.5	-1.9	-1.1
Q_{gen} **(kWh)**	34.9	152.1	227.6	199.1	228.5	107.5	949.7
Q_{cond} **(kWh)**	-28.7	-147.3	-209.8	-215.2	-214.3	-110.7	-926
Q_{eva} **(kWh)**	0.0	4.5	4.4	15.0	6.1	5.1	35.1
Q_{dis} **(kWh)**	-31.5	-153.6	-209.4	-196.2	-211.3	-93.7	-895.7
SF_c	0.06	0.48	0.30	0.37	0.15	0.68	0.34

Q_{sc} = space cooling energy; Q_{cTES} = change of cold TES stored energy (positive values: discharge of TES, negative values: charge of TES); Q_{gen} = energy provided to VGE generator; Q_{cond} = energy rejected by VGE generator; Q_{eva} = energy absorbed by VGE evaporator; Q_{dis} = energy rejected by heat dissipators

Results from the cooling cycle CCT are reported in Figure 10, Figure 11 and Table 2. Along the cooling cycle, a total of 38.9 kWh of cooling energy is supplied to the building. Solar collectors' yield and biomass boiler energy output are equal to 407.8 kWh and 627 kWh, respectively. The room temperatures obtained from the virtual building highlight that there is no sufficient cooling energy supplied to the building thermal zones. In particular, rooms at the first floor reach a maximum temperature of 28.5°C, significantly far from the desired value (25°C). The main KPI of the system is the solar fraction for cooling mode (SF_c), defined as the share of thermal energy demand of the VGE generator provided by solar energy. SF_c ranges from 0.06 to 0.68 on a daily basis and its average value throughout the cooling cycle is equal to 0.34, almost the half of the expected value.

As will be pointed out later, the cooling system operates permanently and, for this reason, the electric energy demand for auxiliaries (e.g., controllers, pumps, actuators) is very high. The total electric energy consumption is 68.9 kWh, almost the double of supplied cooling energy, a significant part of which (33.7 kWh) is needed for the VGE chiller only. It is evident that the Hybrid-BioVGE system expected performance is not achieved and a dramatic difference between test results and numerical simulations is obtained.

Experimental results point out that during the first day of the cooling cycle, characterized by: low solar irradiation and very high ambient temperature, the VGE cannot operate due to excessively high condensing temperature. For this reason, the VGE operation should be shifted to periods with lower ambient temperatures to store cooling energy in the cold PCM thermal storage.

Furthermore, a critical behavior of the Hybrid-BioVGE system can be observed also for other days of the cycle. Due to safety limits, the hot TES can be heated up to 85°C by solar collectors and the biomass boiler (for scarce availability of solar energy) and the capability to store heat from the solar field is limited. Moreover, as soon as the VGE is activated and thermal power is required to drive the ejector, the water temperature within the tank drops fast to 75-80°C . Consequently, the temperature available for the generator is too low and no cooling power can be obtained, even for low condensing temperatures. In addition, test results reveal that even with an inlet temperature to the generator higher than 100°C, in correspondence of high solar irradiation and direct feeding of the VGE through solar collectors, only a small cooling effect can be realized at the evaporator. Therefore, the maximum cooling power achieved by the VGE is equal to 1 kW, which is not sufficient to charge completely the cold TES. In fact, the lowest tank temperature obtained during the cooling cycle is 13°C, above the supercooling temperature of PCM modules. Thus, the room temperature cannot be maintained within the desired range.

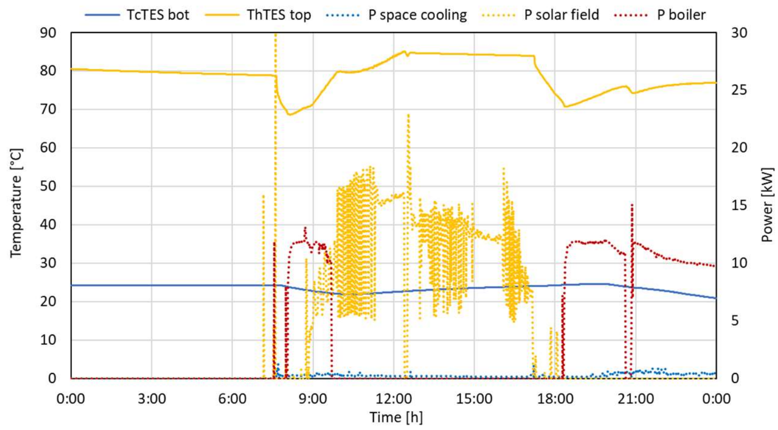
Moreover, it is important to highlight how the relevance of thermal losses strongly increases for cooling operating mode. Test results point out that heat losses from hot TES and piping range between 17.3 kWh and 36.4 kWh per day, having an average value along the cooling cycle of 28.6 kWh/day. Thereby, a significant share of the system thermal energy input (i.e., solar field yield and biomass boiler output) is dissipated with no useful effect.

In Figure 11 an excerpt from cooling cycle test data is shown. In this figure, measurements for Hybrid-BioVGE system and VGE chiller from day 4 of the cooling cycle are reported. (Figure 11a and Figure 11b, respectively).

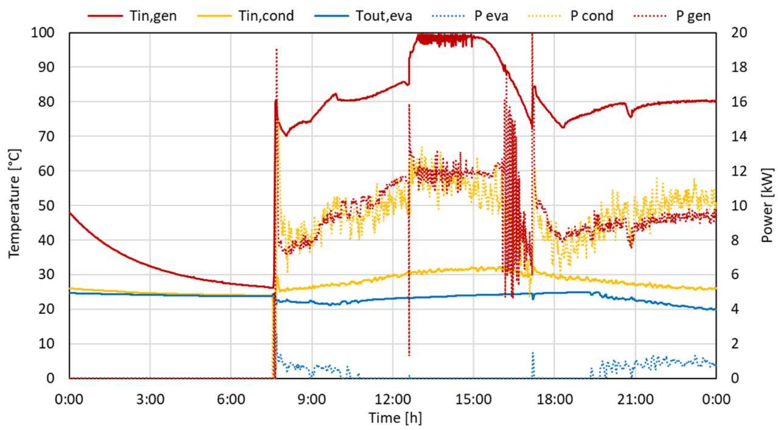
As mentioned before, an extremely high deviation between test results and numerical simulations of the VGE performance is achieved. A series of findings from experimental tests will be implemented in the next prototype, which will be installed in two demonstrators (the residential building in Porto and a small office building in Austria). For example, measurements not reported in this paper for sake of brevity point out that very large pressure drops, up to 6 bar, occur between internal pump outlet and generator inlet on the refrigerant side of the VGE. The cause of such dramatic pressure loss is a valve, installed between above-mentioned components, which will be eliminated in the next release of the VGE chiller since its presence is redundant.

As pointed out before, the building room temperature cannot be lowered due to the lack of significant cooling output of the VGE. Thereby, a permanent cooling demand on the system is present and the operating time of the VGE is correspondingly high, up to 24 hours per day. In order to prevent a not efficient operation of the VGE, an additional setting has been implemented in the system controller. The ejector-based chiller can be activated only when the difference between the temperature available to drive the generator and the ambient temperature is higher than 60°C.

Moreover, measurements in the cooling operating mode shows that the hot TES is discharged in less than 2 hours by the operation of the VGE chiller. It is evident from Figure 11 that when the VGE is operated, water temperature within the storage tank drops sharply and this leads to the activation of the biomass boiler to provide heat. Therefore, the capacity of the hot TES is not sufficient to extent the VGE operation with solar energy during periods characterized by colder climatic conditions and, consequently, better coefficient of performance.



(a)



(b)

Fig. 11: Excerpt from day 4 of the cooling cycle: effective behavior of the Hybrid-BioVGE system (a) and VGE chiller (b)

To conclude, test results point out that a strong improvement concerning both the piping and control strategy of the VGE has to be performed in the development of the next chiller prototype. In particular, measurements show that a different function, based on the actual generated cooling power is necessary to control the VGE operation.

4. Conclusions

In this paper, findings of experimental tests carried out on the HVAC system proposed by the Hybrid-BioVGE project, according to the Whole System Testing methodology, are reported. Some components of the system, such as variable-geometry ejector (VGE) chiller, hot and cold thermal storages, were physically installed in the test bench, while other elements, such as solar collectors, biomass boiler, heat dissipators, building load and climatic data are emulated. A seven-day and a six-day test sequence were defined to assess the effective performance of the system for heating and cooling operating mode, respectively.

Results point out that the Hybrid-BioVGE system has an excellent potential during the heating season. A very high share of the building space energy demand, up to 83%, can be provided by solar collectors and the biomass boiler consumption is limited. Moreover, arrangement and capacity of the hot thermal storage is coherent and the daily demand of heat can be satisfied even for severe climatic conditions by thermal energy stored from the previous day.

On the contrary, measurements show that the tested prototype of VGE cooling system cannot deliver the planned cooling capacity. Main reasons for this unexpected behavior are the presence of very high pressure drops on the refrigerant side of the VGE, caused by a valve placed among the internal pump and the generator, and a not optimal control strategy. Adjustments on the dimensioning of VGE piping and heat exchangers are necessarily for the development of further prototypes, as well as the implementation of a different control function, which has to include the actual generated cooling power in its algorithm.

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