Hybrid Energy Systems

Implementation Report

Responsible Partner

CISE – Electromechatronic Systems Research Centre

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1. Introduction

The main objective of the project is to provide a model of LLs for the university and private organisations which specifies the process and the main steps needed to prepare the development of a LL. This model is based on experiences in innovative technologies, carried out in the framework of the project. Part of such experimentation derives from the replication of demonstrators from a university to another. As project Tr@nsNet aims at deploying multi-domain LL, focus is put into the main domains promoting the ecological transition, in line with Sudoe priorities: energy, mobility, water, biodiversity, citizens participation. Multi-disciplinarity is one of the conditions to tackle the challenges and opportunities presented by new technology emergence in the domains of environmental science, energy and mobility.

Activity 2.4, in particular, aimed to improve the capabilities of pre-established facilities and resources to enable the future implementation of Living Labs devoted to research and development activities on hybrid energy systems. The integration of renewable energy sources, currently operated in islanded mode, leads to the ultimate goal of establishing electrical and thermal networks, unified into a single hybrid energy system.

This report, related to Activity 2.4 of Project Tr@nsNet, details the process of implementation of each demonstrator, summarising the results of the activity.

2. Context

The adoption of unconventional innovation models, as it is the case of the Living Labs (LLs) approach, shows promising benefits for the development of breakthrough technologies, particularly in key domains like Energy.

The ongoing global energy crisis, along with the climate emergency, call for the development of initiatives suitable to ensure a more dependable and efficient use of energy, while promoting the adoption of renewable energy resources.

Despite the relentless efforts conducted to make renewable energy sources a widely accepted reality, their practical implementation still faces a multitude of challenges. The intermittency of generation, typical of renewable energy sources, makes the energy system heavily dependent on the availability of that energy resource, thus compromising its resilience against unexpected demand perturbances, or components faults. In this context, hybridisation of technologies provides key advantages. The adoption of complementary renewable energy resources like wind, solar, and hydrogen power leverages the self-sufficiency and dependability of energy systems supported by the exploitation of such energy resources, making them resilient against shortage of any of the energy resources. Particularly, the integration of multiple forms of energy (also termed as energy vectors) into a unified energy system is recognised as the key solution to resilient energy systems. Currently, energy networks based on the thermal energy and gas co-exist with conventional electric energy systems, operating in a decoupled fashion. Such lack of integration and coordination between energy networks jeopardises the potential complementary benefits linked to each energy vector, limiting the efficiency and sustainability of state-of-the-art energy systems. At the same time, the integrated exploitation of multiple energy vectors is regarded as a prominent mean for the enhanced exploitation of renewable energy resources, especially those classified as low-grade energy sources – waste heat, biomass, etc.

The establishment of fully integrated energy systems is envisioned as the framework that powers a climate-neutral economy. To that end, a diversified supply and a robust infrastructure is critical in ensuring security of energy supply and safety. In this activity, in particular, developments taken towards the promotion of ever-increasing integrated and digitalised energy systems profit from currently available facilities and resources to conduct research and development activities on the integration of distinctive forms of energy into unified, robust, and fully integrated hybrid energy systems. The activity involves the participation of the Electromechatronic Systems Research Centre (CISE) and the Research Centre for Smart Buildings and Energy Efficiency of the Polytechnic University of Madrid (CEDINT-UPM), partners with knowledge and resources suitable to study the integration of multiple forms of energy into a unified energy system. Renewable energy sources, currently operated in islanded mode, are integrated to establish electrical and thermal networks, and unified into a single hybrid energy system, featuring improved smartness. Instrumentation and remote metering capabilities are also embedded, aiming to support the optimal management and operation of each energy system.

It is worth noting that both demonstrators involved in the activity focus on hybrid energy networks, but are complimentary, in the sense that each one of them adopts a particular architecture, relying on distinctive state-of-the-art renewable energy, energy storage, and management technologies.

3. Experience

As described in the Introduction section, Activity 2.4 involved the participation of the CISE and CEDINT-UPM. This activity comprised the exploitation of currently available facilities and resources to combine distinctive forms of energy into unified, robust, and fully integrated hybrid energy systems.

Following sub-sections detail the experiences deployed at each demonstrator involved in the activity and the results attained from such experiences.

3.1. CISE

Much of the renewable energy technologies considered for the exploitation of unconventional energy vectors remain pretty much unknown to the research community. For that reason, CISE selected a broad set of meaningful renewable technologies for the exploitation of the endogenous renewable energy sources. Knowledge and results obtained in Activity 1.3, regarding the evaluation and understanding of individual renewable energy and energy storage technologies, were exploited to establish the proposed hybrid energy system.

Fig. 1 shows a representation of the demonstrator implemented at Guarda International Research Station on Renewable Energies (CISE|GIRS-RES). The demonstrator, implemented both indoors and outdoors, comprises a broad set of technologies for the exploitation of the endogenous renewable energy sources – particularly solar, wind and aerothermal. Note that the elements of CISE|GIRS-RES integrated in the hybrid energy system are coloured. Also note that the representation provides a simplification of the physical implementation, where only the key components are represented. Sensors, controllers or any other auxiliary elements are not included in it.

Three energy vectors are in use: electricity, thermal energy and hydrogen. To express the energy vector(s) provided by each energy source, the symbology shown in Table I has been considered.

TABLE I CORRESPONDENCE BETWEEN SYMBOLOGY AND ENERGY VECTORS

Symbol	Energy vector
	Thermal energy
	Electricity
H2	Hydrogen

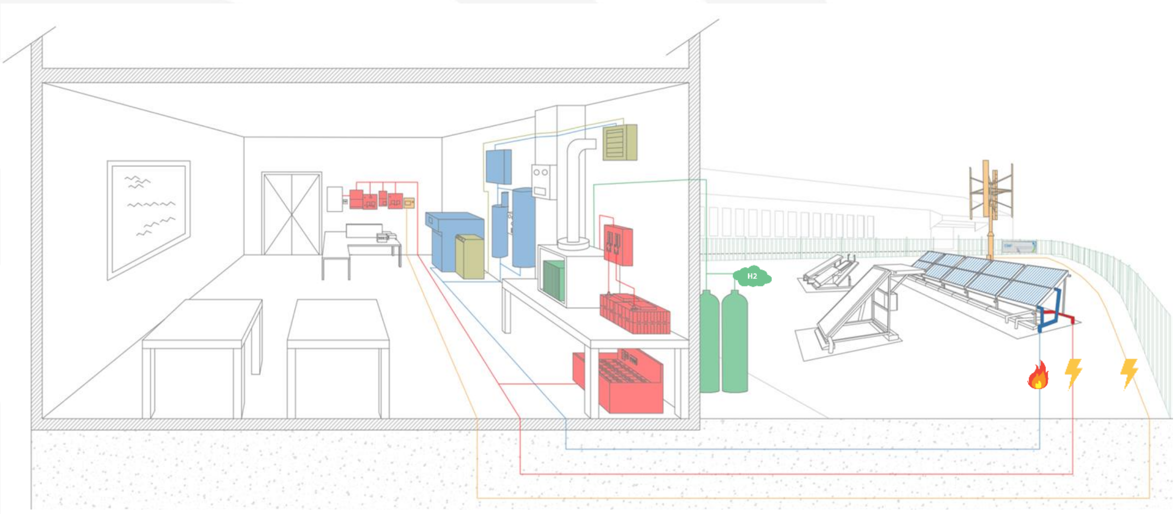

Fig. 1. Representation of the hybrid energy system implemented at CISE|GIRS-RES.

To fully exploit the three energy vectors in use, the technologies studied individually by CISE in Activity 1.3 have been combined to form four functional complex systems: trigeneration system, wind power generation system, hydrogen system, and heat pump. Following sub-sections describe with further detail each of these systems.

3.1.1. Trigeneration system

Fig. 2 shows the elements and interconnections between the building blocks of the trigeneration system. Elements integrated in the system appear coloured in Fig. 2 and comprise:

- Thermal-photovoltaic panels (PVTs);
- Adsorption chiller and its auxiliary elements - heat storage tanks, expansion valves, heat exchanger, among others;

- Li-ion battery pack;
- Power converters.

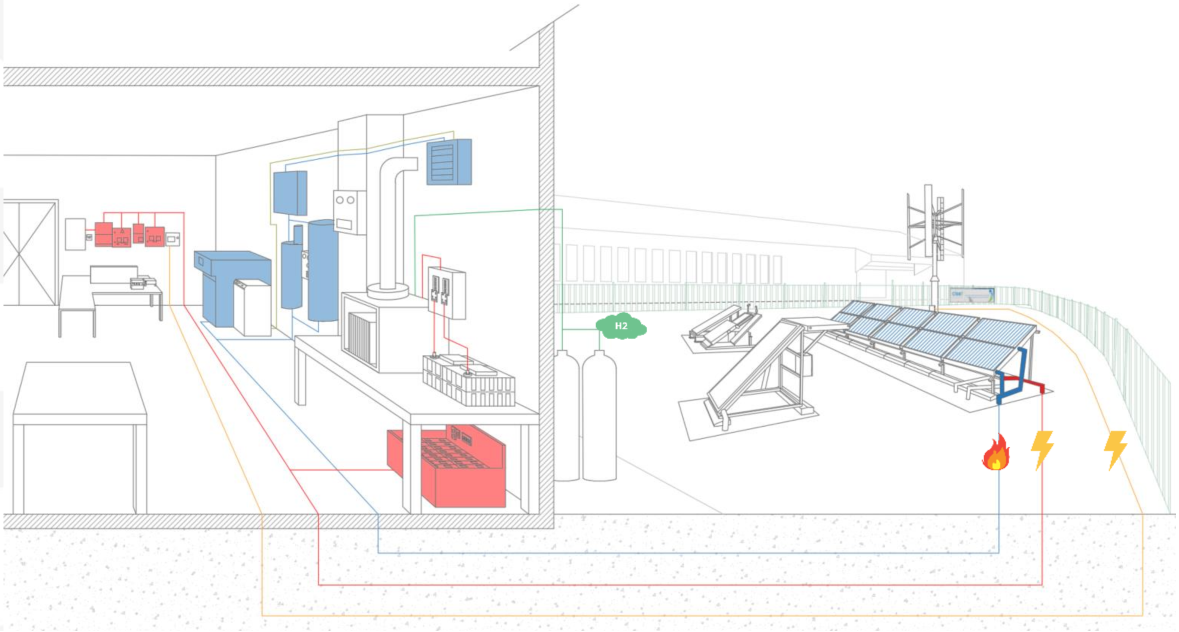

Fig. 2. Trigeneration system.

The concept of trigeneration is recent and attracts increasing interest because of its merits. With trigeneration systems, it is possible to cumulatively produce cooling, heating and electricity using a single energy source. In the particular case of the trigeneration system set up at CISE|GIRS-RES, such capability is attained through the articulated operation of PVTs and adsorption chiller. Besides, medium- to long-term energy storage capability is introduced thanks to the adoption of a Li-ion battery pack, which absorbs the surplus electricity produced by the PVTs.

3.1.2. Wind power generation system

Given the typical complementary availability of solar and wind resources, wind power generation is also integrated in the hybrid energy system. Fig. 3 depicts the wind power generation system, its elements and interconnections between the building blocks. Elements integrated in the system appear coloured in Fig. 3 and comprise:

- Vertical shaft wind turbine;
- AC-DC power converter.

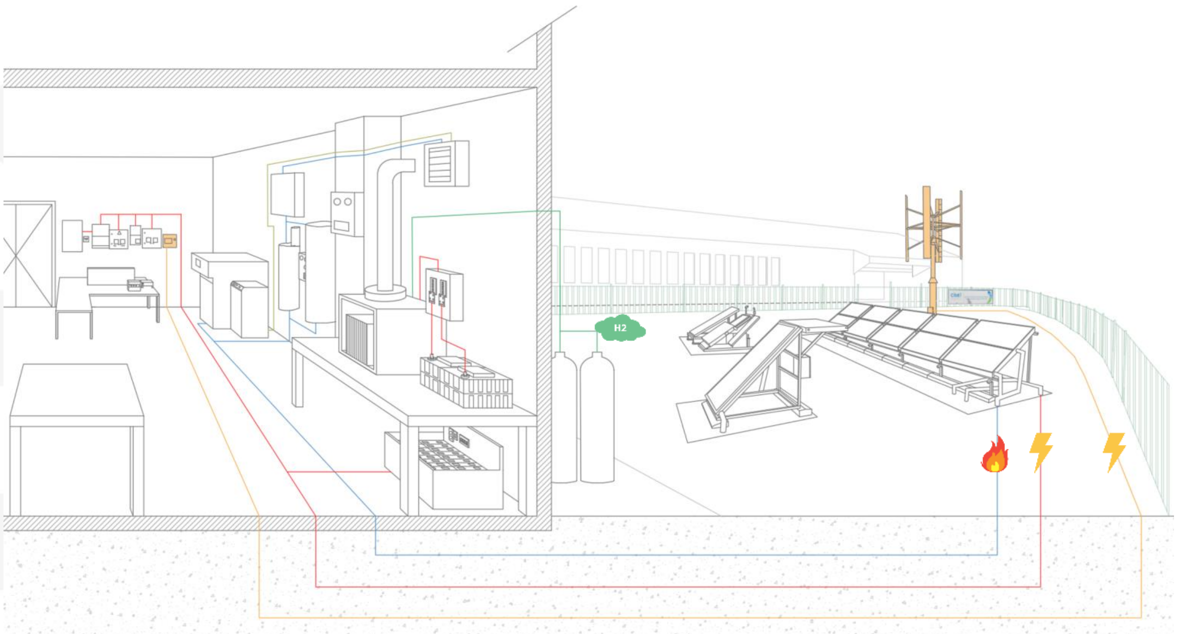

Fig. 3. Wind power generation system.

The electricity produced by the wind power generation system available at CISE|GIRS-RES aims general purposes and is directly injected in the main grid.

3.1.3. Hydrogen system

Even though solar and wind resources play an important role in renewables-based energy systems, their intermittency is a major drawback typical of such energy sources. Green hydrogen introduces a dispatchable energy resource in the energy system, assigning enhanced robustness to the energy system.

Fig. *4* shows the hydrogen system, its elements and interconnections between the building blocks. Elements integrated in the system appear coloured in

Fig. *4* and comprise:

- Hydrogen canisters;
- Fuel cell;
- Supercapacitors;
- DC-DC power converter.

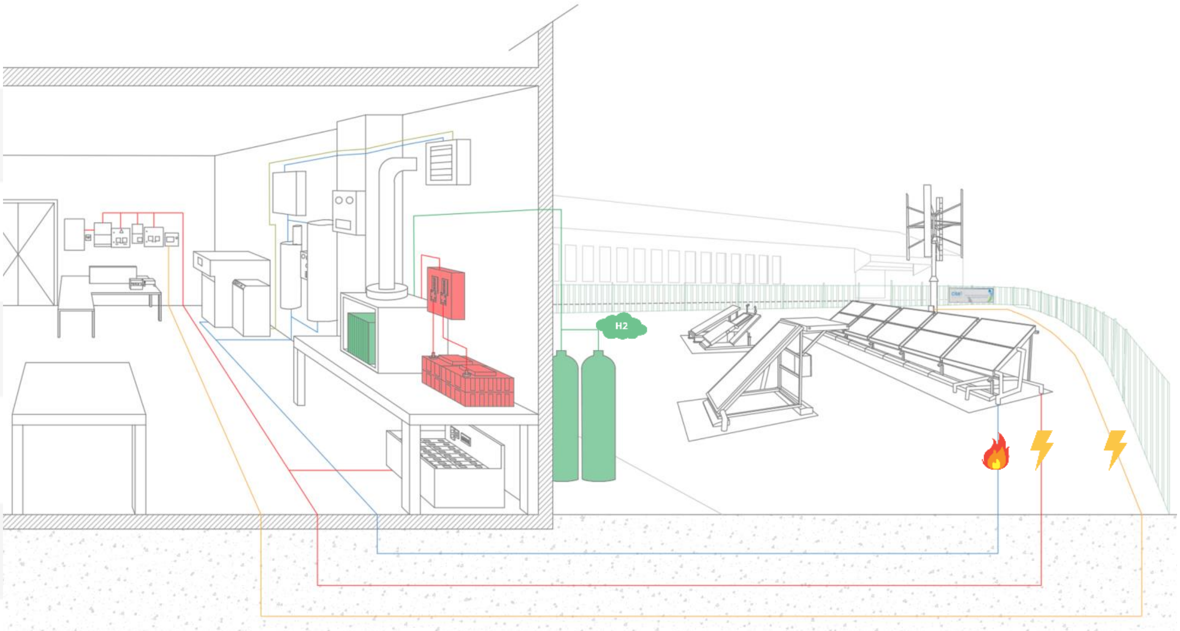

Fig. 4. Hydrogen system.

Short- to medium-term energy storage capability is introduced in the hydrogen system by the supercapacitors. These energy storage elements are controlled, by the DC-DC converter, in such a way to absorb short-term energy production peaks.

3.1.4. Heat pump

Fig. 5 shows the aerothermal heat pump system in use at the demonstrator. It consists of an air-to-water system which exploits heat from the outside air, transferring it to water, which then heats the indoor environment. Based on its features, this system operates as a thermal energy source. Elements integrated in the system appear coloured in Fig. 5 and comprise:

- Heat pump;
- Outdoor unit;
- Indoor unit.

It is worth noting that the heat pump system shows potential for integration with the trigeneration system. In the present state, the aerothermal heat pump is operating in a decoupled fashion.

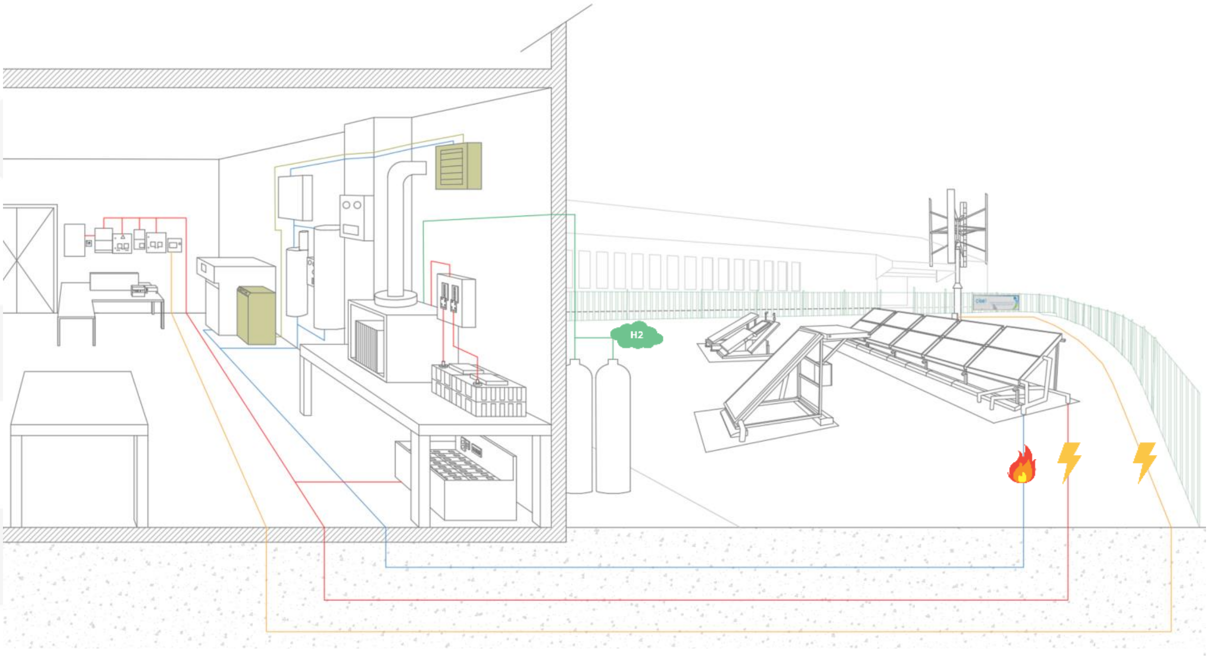

Fig. 5. Heat pump.

3.1.5. Experimental results

To evaluate the performance of the trigeneration system, this system has been operated for 80 minutes. Key parameters have been monitored in both PVTs and adsorption chiller.

On the PVT side, the following parameters have been monitored: solar radiation (*Ga*), electrical power (*Pelectrical*), thermal power (*Pthermal*), and output fluid temperature (*Tpv_out*). Fig. 6 shows the evolution of the solar radiation along the test.

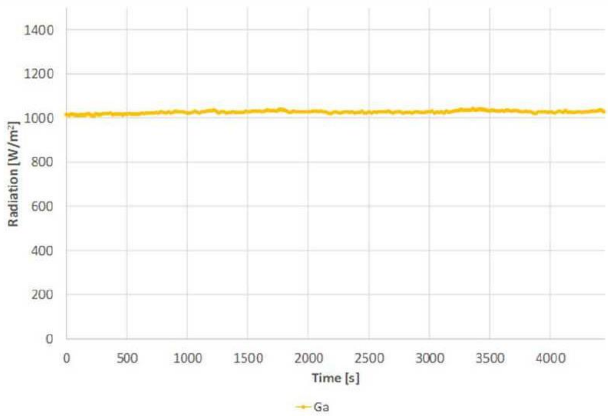

Fig. 6. Solar radiation.

Under such solar radiation conditions, the array of PVTs produce the electrical and thermal power shown in Fig. 7 and Fig. 8, respectively.

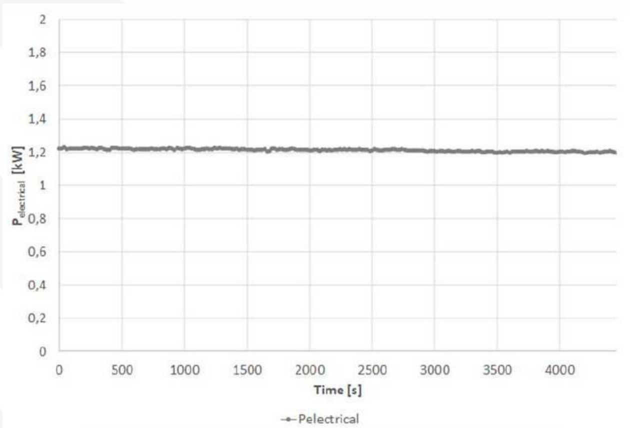

Fig. 7. Electrical power at the output of the PVT array.

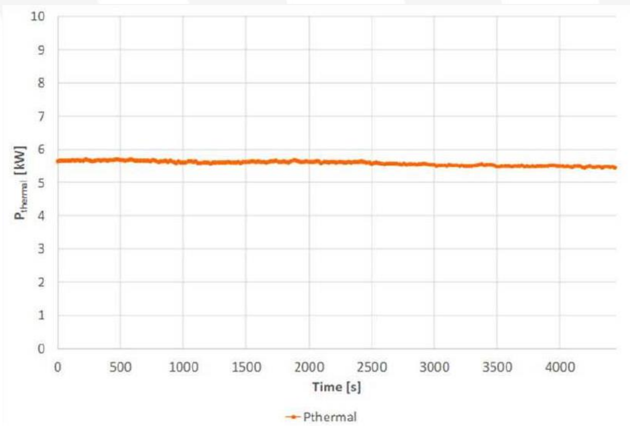

Fig. 8. Thermal power at the output of the PVT array.

The electrical and thermal power yields of the PVT array is noteworthy, particularly for a solar exploitation facility of such area. The electrical performance of PVTs is slightly increased with respect to PV devices, thanks to the lower cell temperatures. In turn, the thermal power is lower than that produced by a thermal collector with the same area.

The temperature of the fluid at the PVTs outlet is shown in Fig. 9.

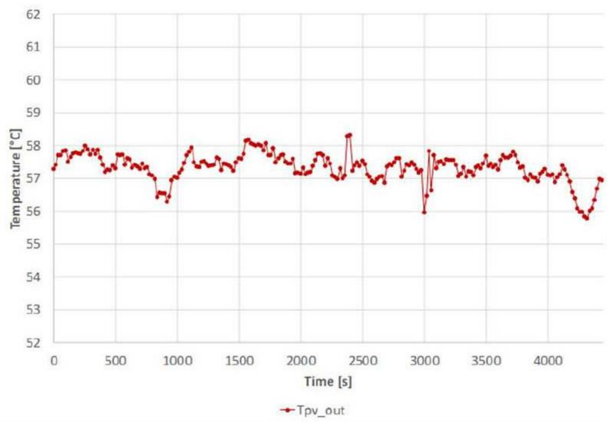

Fig. 9. *Fluid outlet temperature.*

The thermal power obtained using PVTs (more than 5.5 kW, according to the results of Fig. 8) is used as thermal energy source for supplying the adsorption machine. Fig. 10 shows the re-cooling and cooling temperatures measured in the adsorption machine.

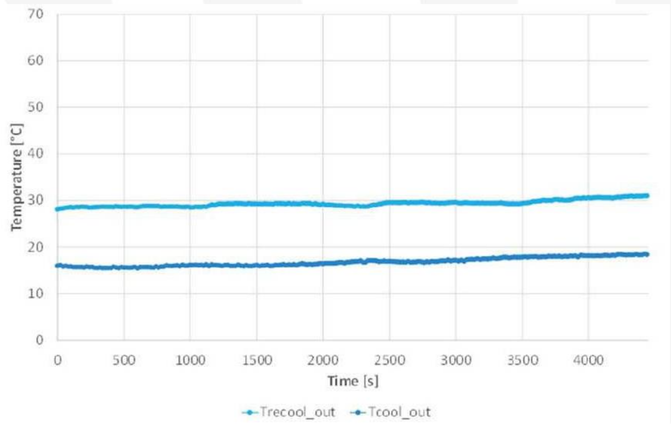

Fig. 10. *Fluid temperatures measured at the adsorption machine external circuits: re-cooling (cyan) and cooling (blue).*

This result proves the unique characteristics of the adsorption machine, demonstrating an interesting cooling effect, even with low input temperature at the generator (lower than 60 °C). Indeed, the coefficient of performance (COP) of adsorption machines is comparable with that of larger-size and/or higher-driving temperature machines.

3.2. CEDINT-UPM

The main goal of this activity is the integration of different renewable energy sources to implement a hybrid energy system, connecting electrical and thermal networks. Considering the existing energy related systems at the facilities of CEDINT-UPM and the latest research lines, we proposed three different approaches to implement the integration of electrical and thermal systems. Each approach is described in detail in the following subsections.

3.2.1. Approach 1

This proposal is based on the integration of renewable energy systems that were already available at CEDINT-UPM.

At the beginning of the activity (December 2020), CEDINT-UPM was equipped with the following renewable energy technologies:

1. *A Photovoltaic Solar Plant located at the ceiling above the outdoor hall, as shown in Fig. 11.*

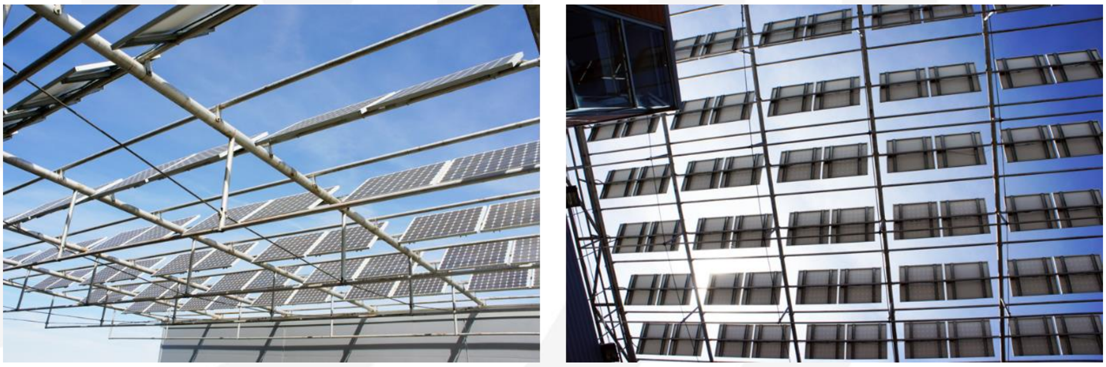

Fig. 11. PV panels installed above the outdoor hall of CEDINT-UPM building.

The installation consists of 70 PV covering a total area of 89 m^2, with nominal power of 11 kW. The electricity is injected in the main grid by means of 4 single-phase inverters (2.5 kW each). This PV is connected to the building main grid.

2. *An islanded Microgrid located at the rooftop of the building, as shown* in Fig. 12.

Fig. 12. Microgrid located at the rooftop of CEDINT-UPM: PV panels (left) and wind turbines (right).

The microgrid has a nominal power of 5 kW and is formed by 9 PV solar panels (300 W each) and 2 vertical axis wind turbines (1 kW each). It is not connected to the building main grid.

3. *A Heating, Ventilating and Air Conditioning (HVAC) system controller that enables remote access to HVAC units, as shown in Fig. 13.*

Fig. 13. HVAC control system that allows the communication with HVAC indoor units.

The integrated controlled provides seamless connection between VRV (Daikin) and BACnet BMS systems, allowing to start/stop and to regulate temperature/speed of several air conditioners from a central control unit.

To exploit the aforementioned resources and create a hybrid energy system, the proposal is to interconnect the PV solar plant, the Microgrid and the HVAC control system, reducing the building energy consumption. It is well known that the main contributors to energy consumption within buildings (more than 40 %), and R&D centres are not an exception, are HVAC systems. Being able to individually control the HVAC units, it is feasible to implement control strategies that depend on the energy production made by renewable sources, thus optimizing energy consumptions.

To evaluate the feasibility of the approach, the first step involved an evaluation to the status of the three systems and study how to integrate them.

- As for the PV solar plant above the outdoor hall, all the PV panels worked properly. Two inverters were damaged and needed to be repaired or replaced.
- Regarding the Microgrid, it was found that the wind turbines did not operate correctly. Reasonable energy generation is limited to extremely windy days. After performing a deep analysis, it was detected that the wind turbine start-up mechanism was wrongly sized. In the design phase, the study of the wind was

incorrect, resulting in an oversize of the starting speed (3 m/s), higher than the nominal speed. The only solution was the replacement of the turbines.

- When checking the functioning of the HVAC controller system, it was found out that the equipment had a breakdown. The technical service from Daikin inspection determined that the memory was corrupted. The only solution to recover its operation would be the replacement by a new one.

3.2.2. Approach 2

This proposal is based in the combination of low TRL technologies, such as radiative cooling or hydrogen electrolysis.

The Advanced Optical Engineering Group at CEDINT-UPM was working in a project focused on improving the performance of Radiative Cooling Systems by means of innovative optical designs. Radiative cooling refrigerates an object on the earth by emitting thermal infrared radiation to the cold universe through the atmospheric window (8–13 μm). This concept can be used to cool, among others, buildings, PV panes or HVAC systems. Besides, it can be utilized to extract potable water from dew, using the devices presented in Fig. 14.

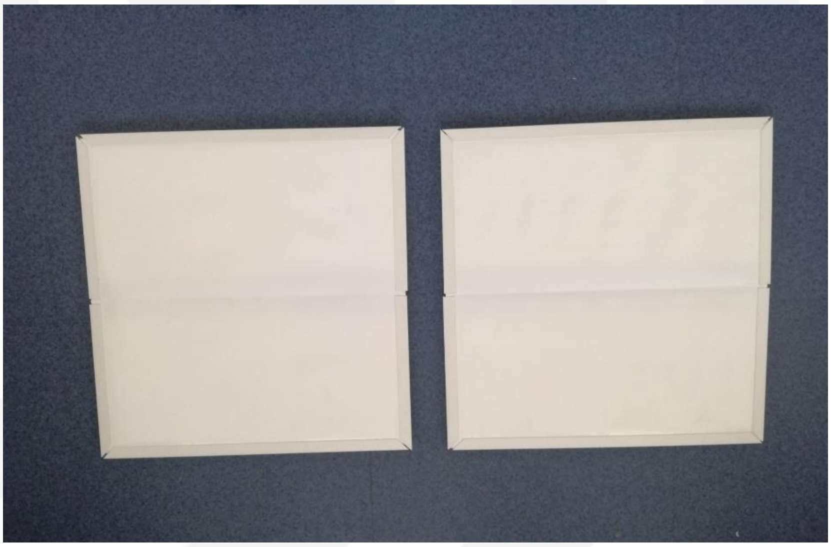

Fig. 14. Radiative Cooling panels for extracting potable water from dew.

With Radiative Cooling as flagship, we studied the combination of different technologies to create a hybrid energy laboratory, including:

- Energy sources based on the following technologies: photovoltaic (half cut and MBB), solar thermal (hot fluid) and radiative cooling (potable water).
- Energy and water use technologies: charging station (phone, tablet, scooter, car), hydrogen generation (electrolysis), and paper recycling.
- Use of optics design for efficiency improvement.

The integration of these technologies into a hybrid energy system leads to the architecture presented in Fig. 15.

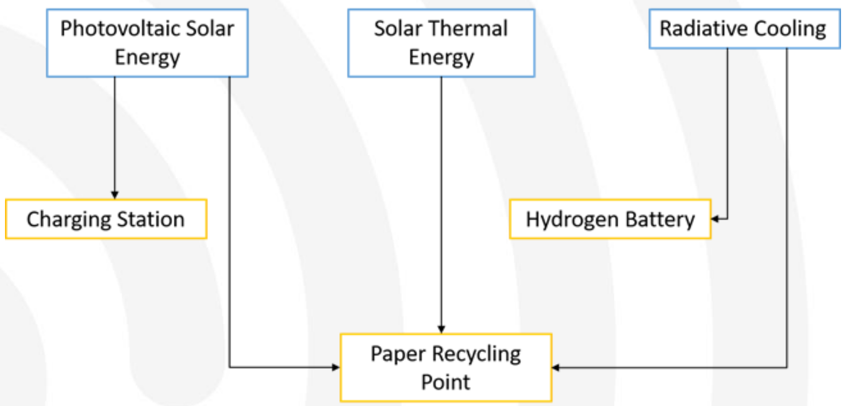

Fig. 15. Proposed architecture of the hybrid energy laboratory.

The integration of the aforementioned technologies, enabling the cumulative production of electrical and thermal energy, would lead to the following interactions:

- The radiative cooling system would refrigerate the hydrogen generation procedure and generate potable water for the paper recycling process.
- The PV panels would power the charging station and the paper recycling process.
- The solar thermal source would heat the water for the paper recycling process.

3.2.3. Approach 3

The goal of this proposal is to reduce the energy consumption of the building through the combination of existing and new components.

The Internet of Things Laboratory from CEDINT-UPM is a research and demonstration space with a heterogonous demand for HVAC conditions. Fig. 16 shows the indoor and outdoor facilities of the Internet of Things Laboratory from CEDINT-UPM.

Fig. 16. Indoor and outdoor views of CEDINT IoT Laboratory.

Located at the south side of the building, the IoT Laboratory is a 52 m^2 room surrounded by an office room (east), a corridor (north), entrance hall (west) and street (south). Such positioning of the IoT Laboratory, illustrated in Fig. 17, makes this space strongly affected by outdoor weather conditions.

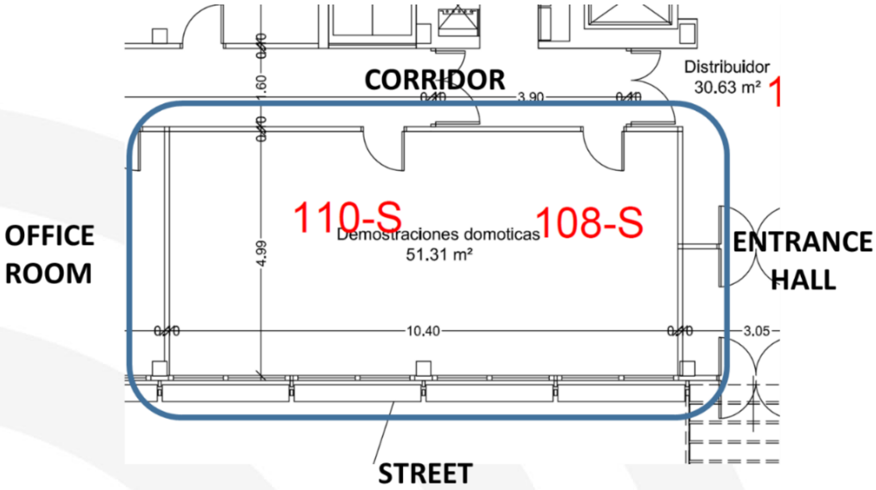

Fig. 17. Floorplan of the IoT laboratory.

Because of the demonstration use, the temperature comfort shall be kept constant, even in scenarios where the space remains unoccupied. As a result, the heating and cooling efficiency of this room is very poor.

In order to minimize the impact of this room in the sustainable behaviour of the building, we intend to improve the HVAC system resorting to a hybrid electrical-thermal solution. It is proposed to replace the existing HVAC system (two indoor split units and one outdoor unit) with an aerothermal heat pump system powered by PV panels. The result is a fully autonomous system, without any impact in the energy consumption of the building. Fig. 18 provides a schematic representation of the proposed hybrid energy system.

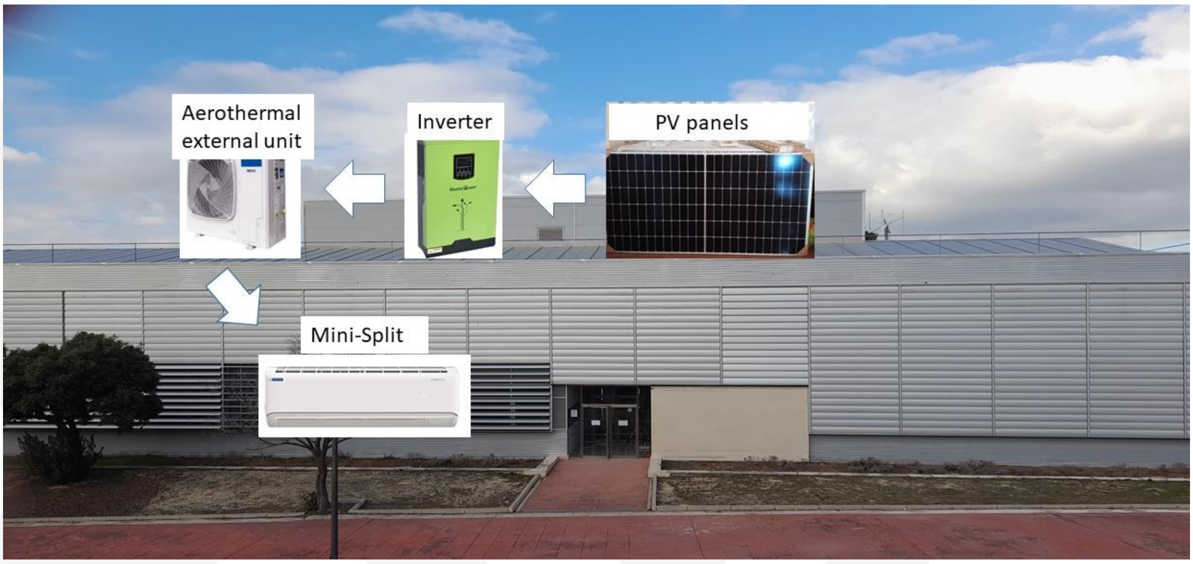

Fig. 18. Architecture of the PV-powered aerothermal source for HVAC of the IoT laboratory.

3.2.4. Implementation of a hybrid energy system

After carefully analysing the three approaches with regards to aspects like cost of implementation or expected gains, it has been decided to put into practice Approach 3.

Approach 1 is the most conservative option and provides excellent results. Nonetheless, the reparation and replacement costs (> 40.000 €) exceed the available budget for the activity. Besides, there are additional difficulties caused by lack of supply in some equipment.

In turn, approach 2 involved meaningful risks. When checking the availability of the equipment and the complexity of deployment within the building facilities (especially in terms of regulation with hydrogen), it was decided to find a more feasible system. Besides, the high risk caused by the low TRL of radiative cooling technologies resulted in the lack of commercial materials.

In order to put into place approach 3, the following equipment was acquired:

- 8x 550 Wp PV modules (RSM110-8-550M from RISEN) - Fig. 19;

Fig. 19. PV panels for electricity production.

- 1x 4 kW Inverter (SG4.0RS from SUNGROW): the function of this element, represented in Fig. 20, is to transform the DC current generated by the PV panels into AC current to power the aerothermal system;

Fig. 20. Inverter to transform the DC current generated by the PV panels into AC current to power the aerothermal system.

- 1 x Aerothermal heat pump outdoor unit (Platinum BC Plus Monobloc 2 from BAXI): this element, shown in Fig. 21, aims to exploit and collect the energy available in the outside air, sending it to the indoor space;

Fig. 21. Outdoor unit of the aerothermal heat pump.

- 1 x HVAC indoor unit (Enerfit ST 800 from ENERTRES): this component, shown in Fig. 22, sets up the desired temperature in the room.

Fig. 22. Indoor HVAC unit of the aerothermal heat pump.

The PV installation (PV panels, inverter and complementary electronics) has been designed to allow the connection of both the aerothermal heat pump equipment and the main AC grid. The resulting design is provided in Fig. 23.

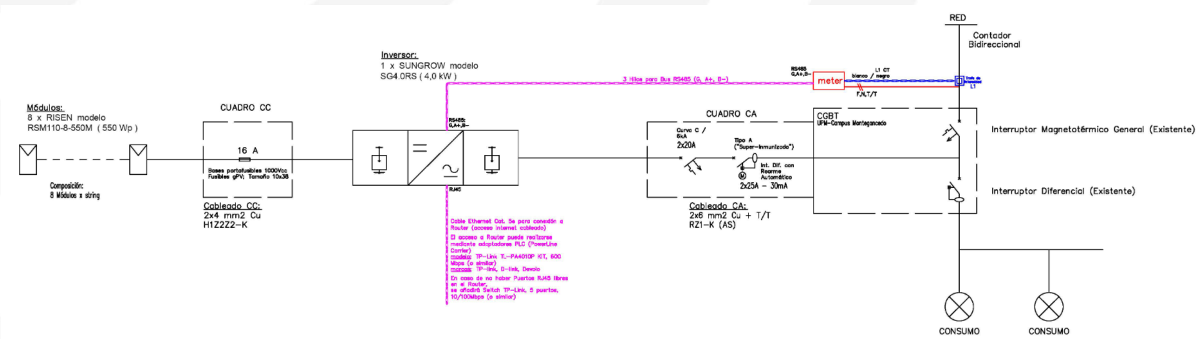

Fig. 23. Electrical connections of the hybrid energy system.

To introduce enhanced smartness on the energy system, remote metering capabilities have also been integrated. To monitor the amount of power generated by the PV panels and characterize the system operation, we have acquired and installed different IoT devices from the BATNET family: smart meters to monitor the energy production at the inverter (Fig. 24) and controllers to register the equipment status and possible failures (Fig. 25).

Fig. 24. BatMeter device.

Fig. 25. BatNet devices.

4. Concluding remarks

Hybrid energy systems open a plethora of possibilities for the enhanced exploitation of renewable energy sources. Even though the partners involved in this activity focused on a relatively short set of renewable energy sources, it was possible to identify the potential to obtain various distinctive combinations that can be exploited to enhance the robustness and efficiency of hybrid energy systems.

Although this activity enabled important advancements in the development of technologies for hybrid energy systems, further integration of technologies shall be promoted. Particularly, the integration of PVTs, adsorption chiller and heat pump in a single trigeneration system reveals potential advantages.