Electric and Thermal Energy Networks

Replication Report

Responsible Partner

CISE – Electromechatronic Systems Research Centre

Authors

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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 1.3, in particular, seeks to foster the transfer of knowledge among the project partners with similar research interests, through the replication of demonstrators in the domain of renewable energies and energy system integration. Elective renewable energy technologies, namely photovoltaic energy conversion systems and thermal collectors, are hybridised to exploit their complementary benefits.

This report, related to Activity 1.3 of Project Tr@nsNet, describes the process of replication of electrical and thermal energy networks, aiming the creation of novel demonstrators devoted to energy technology. Particularly, the report describes the research capability integrated into the two demonstrators. Main challenges and conclusions complement a report describing the deployment of hybrid energy networks.

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.

The full exploitation of the hybrid energy networks' potential depends on developments regarding the coordinated control and operation of these complex structures, along with efficiency and reliability improvements on the energy system building blocks. In this context, prototyping and testing conducted on multidisciplinary demonstrators assumes pivotal relevance.

At the moment, there are a couple of demonstrators for hybrid energy networks entirely based on renewable energy sources which are already in place. Guarda International Research Station on Renewable Energies (CISE|GIRS-RES), one of the facilities of CISE - Electromechatronic Systems Research Centre, is one of those demonstrators, where technologies for the generation and utilisation of electrical and thermal energy are currently being studied.

Considering that knowledge transfer and open innovation are two of the pathways for successful and streamlined innovations, this activity seeks to foster knowledge transfer among project partners with similar research interests in the domain of renewable energies and energy system integration. Particularly, this activity aimed to replicate and study the complex interactions taking place in hybrid energy networks, where multiple forms of energy co-exist in a single energy system. A hybrid energy network involving electrical and thermal energy was implemented in UT3 according to the experience and knowledge of CISE on this subject. State-of-the-art renewable energy conversion technologies were considered for the implementation of the hybrid network.

3. Experience

As described in the Introduction section, Activity 1.3 involved the participation of the Electromechatronic Systems Research Centre (CISE) and Paul Sabatier University (UT3). Apart exchange of knowledge between partners, this activity also involved the study of renewable energy technologies deemed suitable for hybrid energy networks. Such technologies should enable the exploitation of renewable resources to obtain multiple energy vectors, as it is the case of electricity, thermal energy and hydrogen, in a sustainable manner.

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. Efforts were made in the sense of better understanding each energy source, individually. To do so, a comprehensive set of renewable energy technologies were instrumented and tested at CISE|GIRS-RES, to better understand and improve such technologies.

3.1.1. System implementation

Fig. 1 shows a representation of the demonstrator implemented at CISE|GIRS-RES. The demonstrator of the hybrid energy system, implemented both indoors and outdoors, comprises a broad set of technologies for the exploitation of the endogenous renewable energy sources.

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
	Hydrogen

The hybrid energy system operation is supported on three distinctive but interlinked energy networks. Each network carries one of the energy vectors (thermal energy, electricity or hydrogen). The electrical network comprises a common DC bus, considered the backbone of the DC microgrid.

On the energy generation side, the demonstrator integrates a vertical shaft wind turbine, thermal-photovoltaic panels (PVTs) and fuel cell. On the energy consumption side, the demonstrator includes an adsorption chiller and heat pump. Energy storage capability is ensured resorting to a pack of batteries and a bank of supercapacitors.

Further detail about each of the elements integrated in this demonstrator are provided in the upcoming sections.

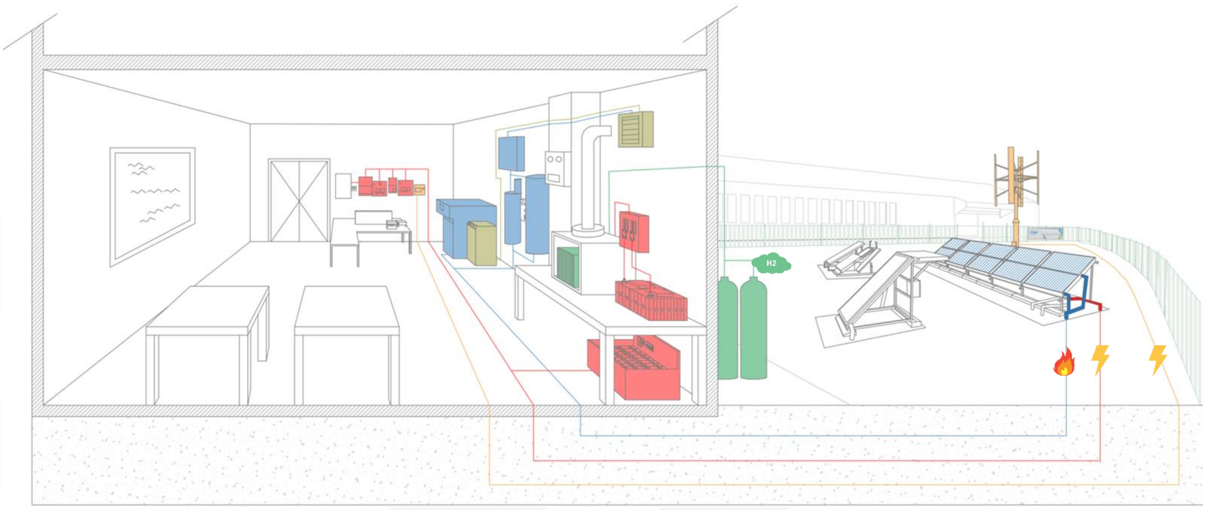

Fig. 1. Representation of the hybrid energy system implemented at CISE|GIRS-RES.

3.1.1.1. Energy sources

The excellent wind conditions available at the city of Guarda make the adoption of wind turbine systems an excellent option for the demonstrator. Fig. 2 shows the wind turbine system, which is highlighted in orange colour. For its integration into the electrical component of the hybrid energy system, the 3 kW vertical shaft wind turbine, which is installed outdoors, is connected to a power converter installed indoors. This AC-DC converter is responsible for establishing the interface between the wind turbine and the DC bus and, at the same time, for maximizing the power extracted from the wind turbine.

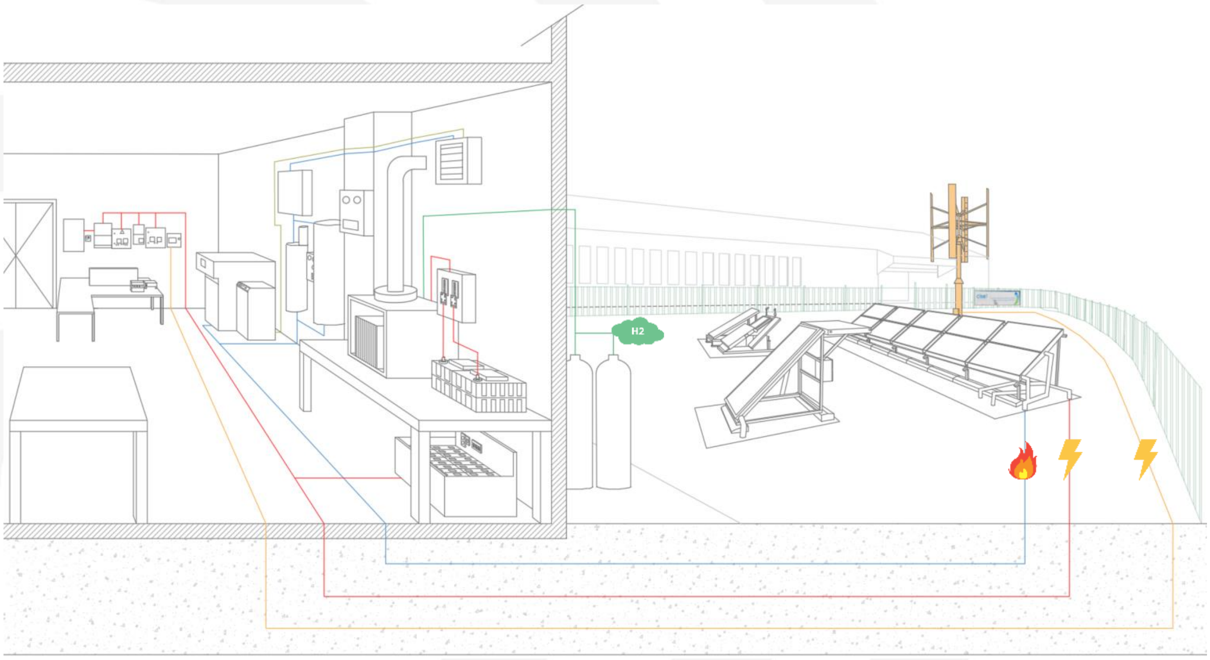

Fig. 2. Vertical shaft wind turbine.

Exploitation of the solar resources represents an important share of the overall renewable energies market. Solar energy technology is evolving, aiming more efficiency and sustainability. Among other prominent technologies, thermal-photovoltaic (PVT) systems stand out in recent years. PVTs combine the technologies of thermal collectors and photovoltaic panels in a single device. Thanks to such combination, a single device produces both thermal energy and electricity, while leveraging the efficiency of both technologies. Concurrently, it is possible to minimize land use for the implementation of solar technology devices.

Fig. 3 depicts the PVT array in use at the demonstrator, which is highlighted in blue colour. The PVT array integrates 10 PVT modules installed outdoors. The electrical connection of the PVT modules is reconfigurable, allowing the connection of groups of modules in series and/or in parallel. The electrical output of the PVT modules, rated at 2 kW, is interfaced with the main electrical grid through a power converter which delivers DC power to the energy system. The operation of the converter aims two objectives: inject the produced electricity into the grid and maximize the electrical power extracted from the PVTs. In turn, the thermal circuit of the PVT operates in a closed loop. Thermal fluid flows through the 10 modules to extract thermal energy available at the photovoltaic cells, lowering their temperature. Circulation of fluid is ensured by a small pumping system.

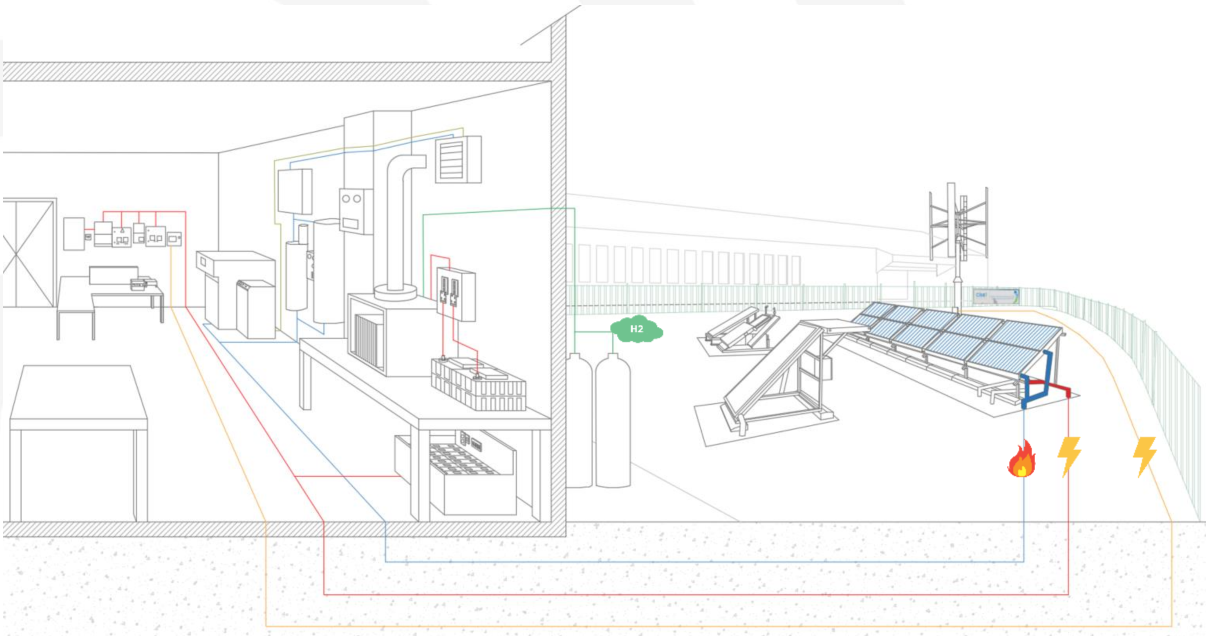

Fig. 3. Thermal-photovoltaic panels.

Interest on the adoption of hydrogen as a complementary energy source gains ever-increasing relevance in the future energy systems, thanks to the high density, dispatchability and sustainability of hydrogen. Fig. 4 shows the 3 kW proton exchange membrane (PEM) fuel cell and corresponding hydrogen supply, highlighted in solid green colour. Hydrogen supply to the system is ensured by a set of two hydrogen canisters installed outdoors.

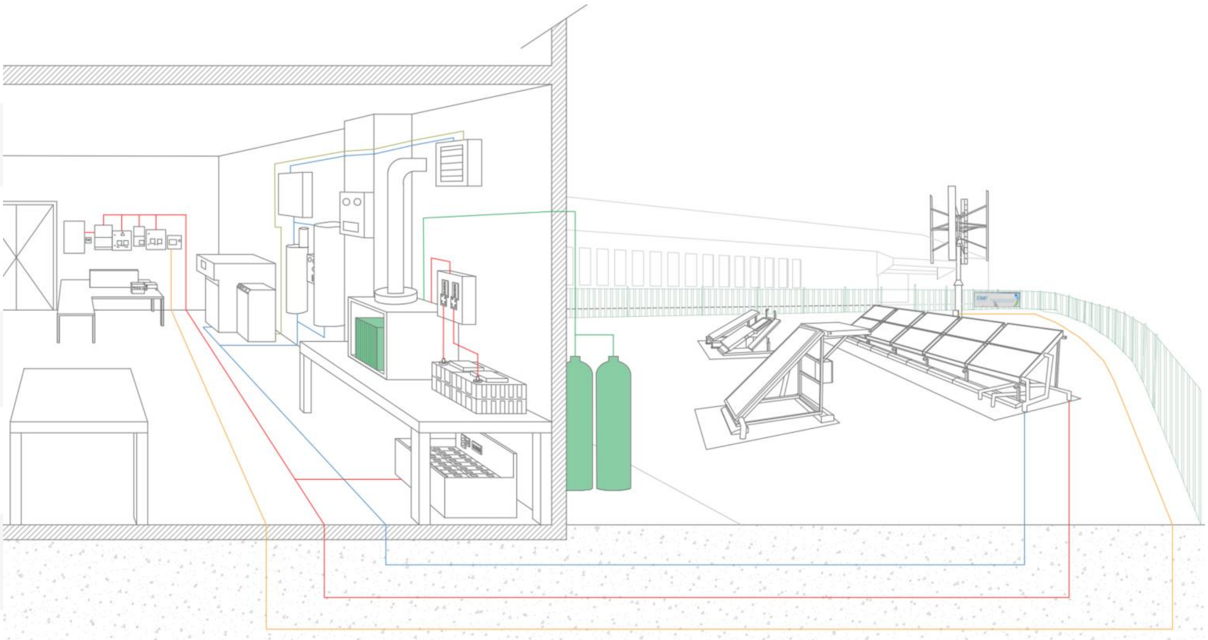

Fig. 4. Fuel cell and corresponding hydrogen supply system.

Fig. 5 shows the heat pump in use at the demonstrator, highlighted in faded green colour. It consists of an air-to-water system which exploits heat from the outside air, transferring it to water, which then warms the indoor environment. Based on its features, this system operates as a thermal energy source. The heat pump is connected to a fan coil unit, responsible for transferring the heat from the heat pump thermal circuit to the room air.

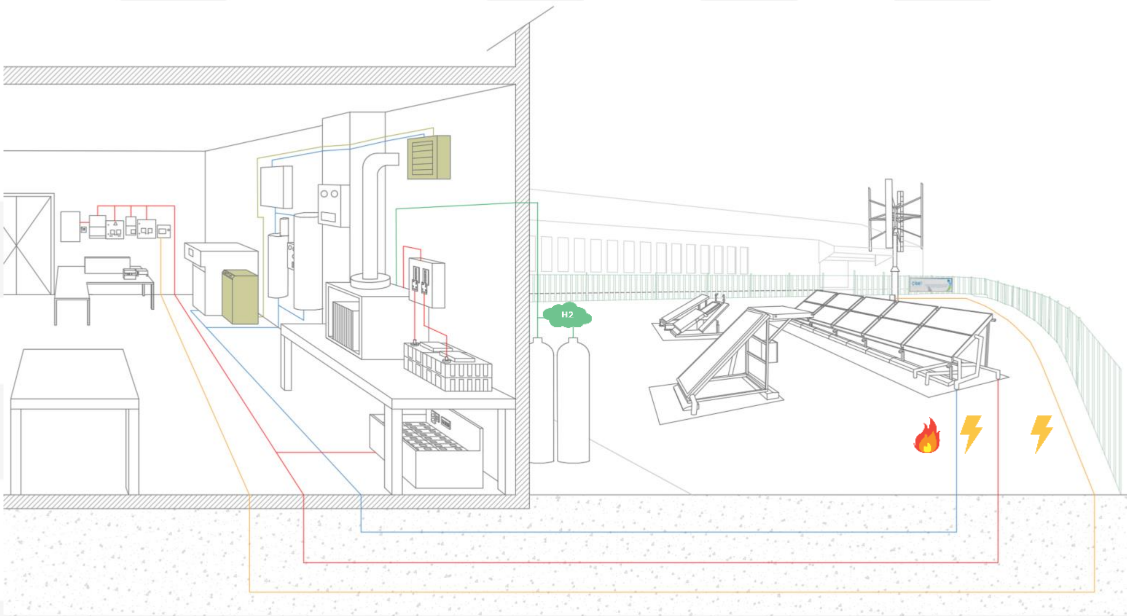

Fig. 5. Heat pump.

3.1.1.2. Energy storage

Energy storage capability is integrated at CISE|GIRS-RES resorting to two of the most recurring and mature technologies: batteries and supercapacitors.

Fig. 6 shows the battery pack, highlighted in red colour, integrated in the demonstrator. These 48 V DC battery pack, composed of 20 Li-ion batteries, receives electrical energy produced by the PVTs, wind turbine and, when applicable, by the fuel cell, storing it for later use. The in-built battery management system (BMS) assures proper management of the charging/discharging procedures of each battery and interfaces the battery pack with the remaining electrical grid, through a dedicated power converter. Li-ion batteries have high energy capacity and extended lifetime, making them suitable for storing energy during medium- to long-term periods.

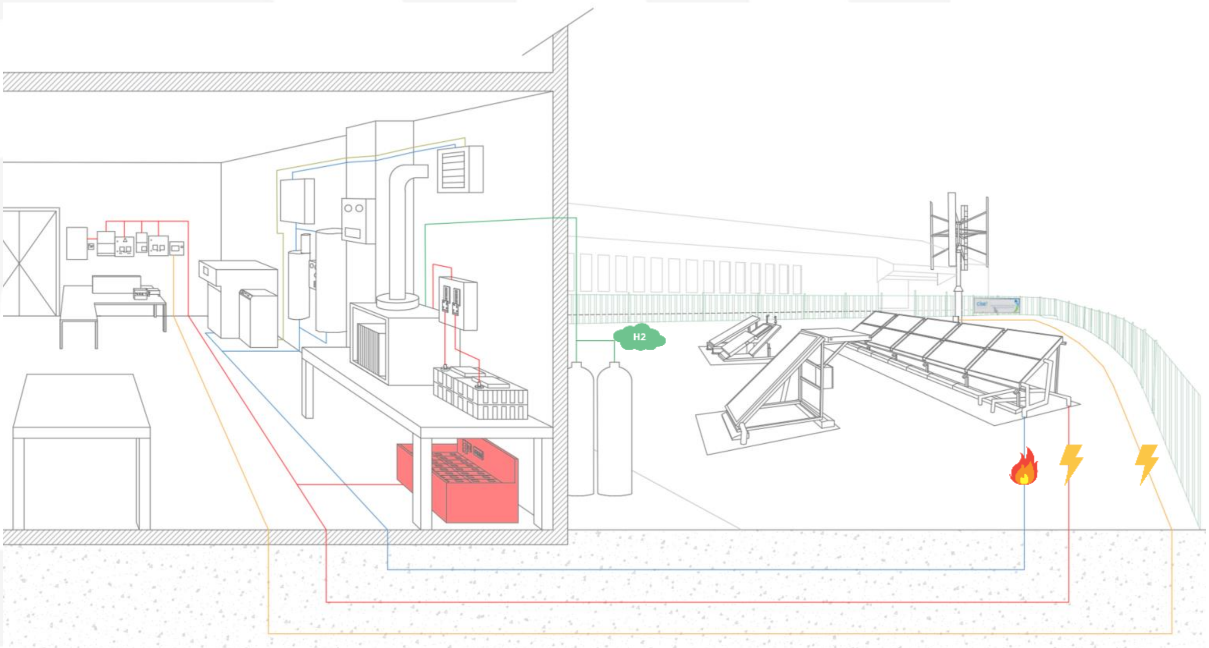

Fig. 6. Battery pack.

Fig. 7 shows the supercapacitor pack integrated in the demonstrator, highlighted in red colour. Since the supercapacitor pack does not have an in-built management unit, a custom solution has been devised, using the power modules acquired in the framework of this project. These elements perform the power conversion and energy flow management for the supercapacitors.

Unlike batteries, supercapacitors provide high power density and very long lifetime. These features strongly complement the advantages of batteries, making them suitable to provide high power for relatively short periods of time. Moreover, their construction is more sustainable thanks to the obviation of heavy metals or other polluting resources.

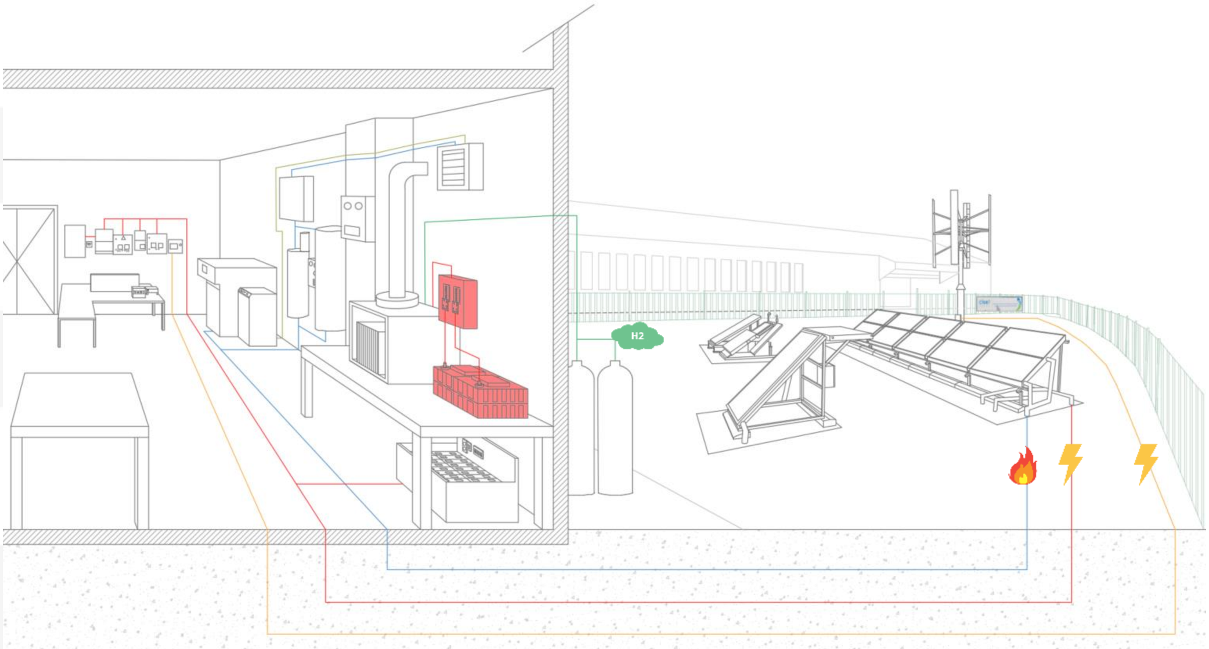

Fig. 7. Supercapacitors.

3.1.1.3. Loads

The electrical and thermal energy obtained in the demonstrator energy sources is used in thermally activated systems based on adsorption machine. This system is activated even with low temperatures (55-75°C), like those available from PVT panels, to obtain electricity and heat/cool at the same time. Such flexibility harnesses the interest in this technology.

Fig. 8 shows the adsorption chiller and auxiliary elements, highlighted in blue colour. These auxiliary elements include the heat storage tanks, expansion valves and heat exchanger.

In this particular demonstrator, the adsorption chiller is integrated with the PVTs, receiving thermal energy from them. Once activated, the adsorption chiller operates to regulate the indoor temperature.

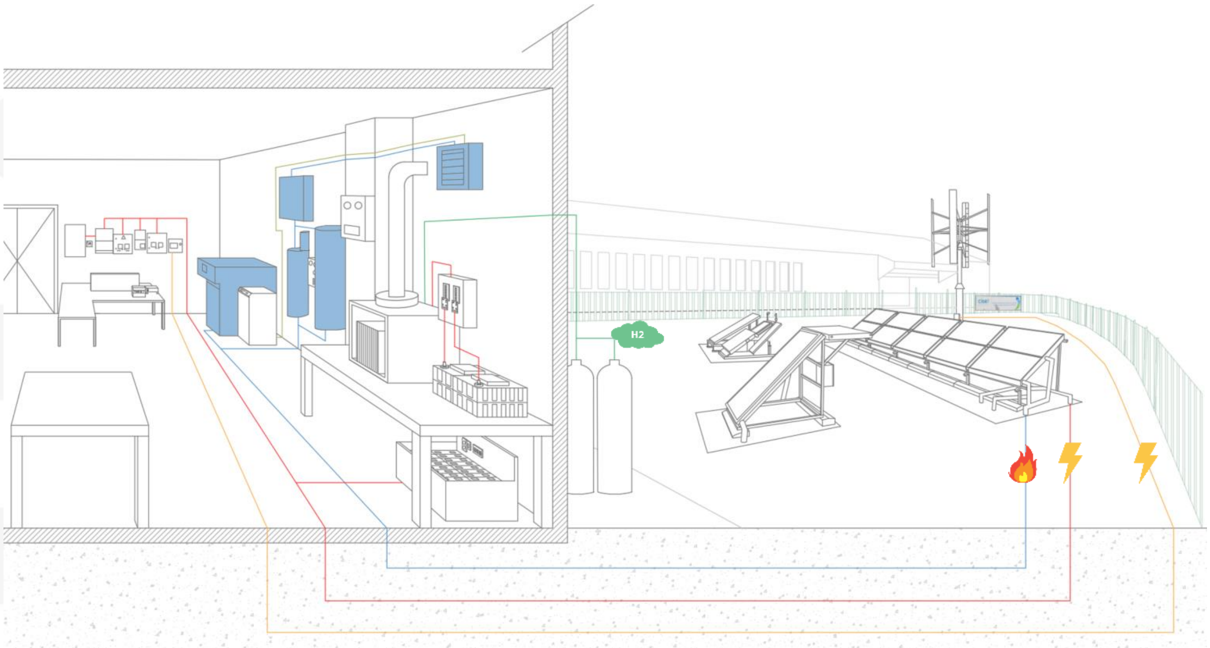

Fig. 8. *Adsorption chiller.*

3.1.2. Experimental results

The elements studied at CISE|GIRS-RES and described in the previous sections were tested to validate their effective operation. For the sake of fairness, the experimental results provided in this report focus on the evaluation of the hybrid energy system exploiting the PVT technology.

Fig. 9 depicts the daytime evolution of critical parameters defining the performance of the PVT system installed at CISE|GIRS-RES, assessed in a typical summertime day, with clear sky. Data related to irradiance (G), wind speed (v_{wind}), environment temperature (T_a), fluid inlet temperature (T_i), fluid outlet temperature (T_o), panel back temperature (T_{bck}), and front glass temperature (T_c) is provided in the graph. It is of particular interest to note the excellent conditions observed on the site, translated by the high peak irradiance observed at around 13h00m.

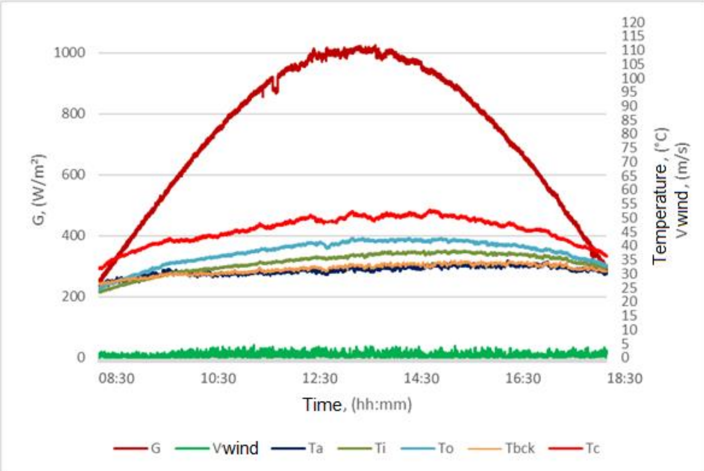

Fig. 9. PVT system temperature data and meteorological data.

Considering that the mass flow rate is an important parameter in the thermal and electrical performance of the PVT, it is relevant to establish the optimal value of mass flow rate leading to optimal PVT efficiency. In order to determine the desirable mass flow rate and understand how the fluid flow affects the system performance, this parameter should be related to the PVT efficiency. To do so, three efficiency metrics are established: η_e – electrical efficiency; η_t – thermal efficiency; η_{total} – total PVT efficiency. Fig. 10 presents the evolution of the electrical, thermal and total PVT efficiencies, calculated as a function of the mass flow rate. For a fair comparison, all efficiency values were acquired for a constant value of solar radiation of 1000 W/m² and constant fluid temperature at the PVT inlet, ranging between 36.5 °C and 37 °C.

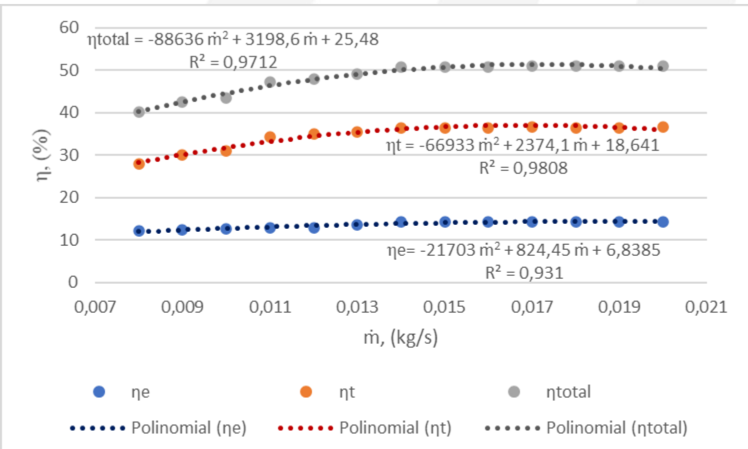

Fig. 10. PVT system efficiencies.

3.2. UT3

The installation of the thermal-electrical systems at the Paul Sabatier University (UT3) was delayed for more than 6 months due to logistical and technical delays (agreement of the University authorities; technical interventions made by plumber, electrician and verification and control office).

All the equipment is installed in a faculty facility dedicated to the study of electrical power systems (power converters, motorized systems, lighting systems, plasmas, etc.). Thermal-photovoltaic panels (PVTs) have been installed on the roof above this room. To connect the PVTs to the indoor facility, several walls had to be drilled to pass the electrical cables and the hydraulic cooling circuit of a panel. All the material acquired in the framework of the project has been received.

3.2.1. System implementation

Fig. 11 provides a schematic representation of the hybrid energy system implemented at UT3. The arrows represent the energy flows taking place between the different blocks of the system. For simplicity, the safety devices (fuse, isolating switch, etc.) and measurement devices are not shown in this figure.

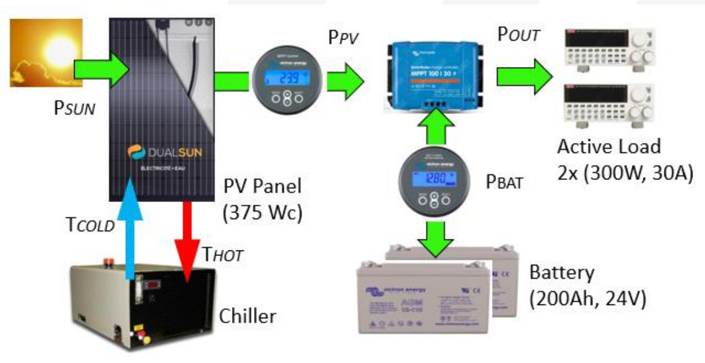

Fig. 11. Schematic representation of the hybrid energy system deployed at UT3.

The PVT panel installed at the pilot is a Dualsun, model Spring 375. TABLE II lists the panel specifications.

TABLE II PVT PANEL SPECIFICATIONS

Parameter	Value
Rated output power	375 W
Open-circuit voltage	50 V
Short-circuit current	10 A
Area	1.9 m^2
Mass	32 kg

Fig. 12 shows the location of the hybrid energy system within UT3 campus, while Fig. 13 shows the PVTs installed in the roof of the building.

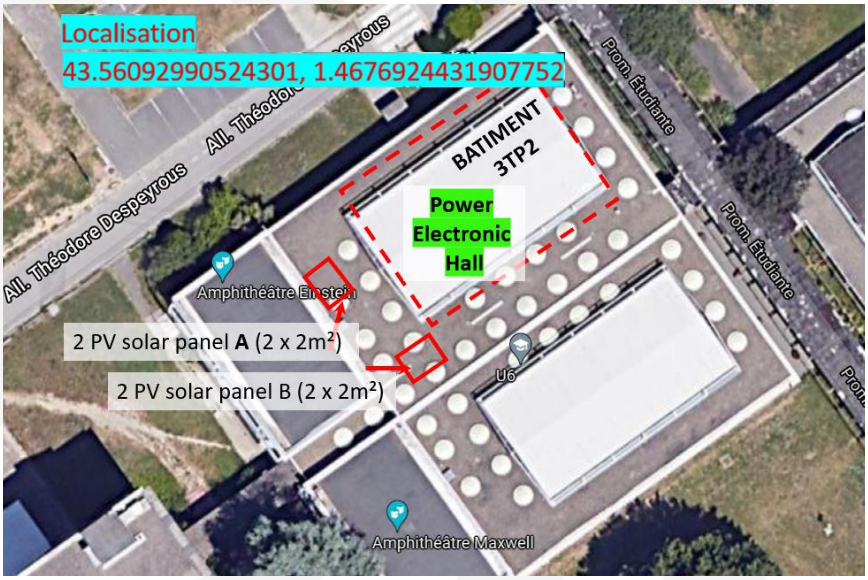

Fig. 12. Localisation of the hybrid energy system at UT3.

Fig. 13. Dualsun PVT panels.

The hydraulic part of the PVT is connected through pipes to the chiller and can be cooled during its operation. The chiller (model LABO 07) allows a flow rate between 1 l/min and 9 l/min with sufficient pressure for the cold water to rise to the PVT panel installed on the roof. The temperature can be programmed between 5 °C and 20 °C for an ambient temperature between 10 and 40 °C. A temperature setpoint between 15 °C and 20 °C should be sufficient to study the impact of cooling on the panel. To control flow rate, the chiller is fitted with a flow meter (SM6000). Temperature measurements upstream and downstream of the solar panel will provide a measurement of the thermal energy flow.

In turn, the electrical part of the PVT is connected to a Victron Smart Solar charge controller integrating maximum power point tracking (MPPT) capability, model 100|20 (24 V, 20 A), and 2 Victron Energy 12 V 110 Ah Lead Gel batteries. Energy consumption is emulated resorting to 2 active loads (300W max each, 30A). These loads can be controlled manually or from a computer. They allow to simulate different use cases. Several displays allow direct visualisation of the main electrical parameters (voltage, current, power). Numerous sensors (pyranometer, thermometer, voltmeter, ammeter) make it possible to record relevant data. All the measurements collected are sent to acquisition cards and recorded on a computer. These measurements will later be made available on a university server. The software part is functional.

Fig. 14 shows the elements of the hybrid energy system installed indoors. Apart power converters, batteries and active loads, a PC is also integrated in the system, for monitoring purposes.

Fig. 14. Indoor apparatus of the hybrid energy system.

This system allows to:

- Analyse the sizing of the system (photovoltaic surface, battery capacity) with respect to the available solar resource and energy consumption profiles.
- Evaluate the quality of the predictions of a system simulation carried out with commercial software (PVSYST): recoverable energy, battery state of charge, etc.
- Create a database of parameters (meteorological, thermal and electrical parameters) that can be used by the academic community for future work with students.
- Constitute a showcase on photovoltaics visible to all students who pass through this practical work room dedicated to power electronics.
- Simulate a complete, autonomous photovoltaic installation on a small scale (thanks to the controllable active loads).
- Analyse the impact of the cooling of solar panels on their performance.

3.2.2. Experimental results

After installation of the PVT system, tests were undertaken to evaluate its performance. Particular attention is devoted to the electrical part of the system. Fig. 15 shows the evolution of voltages at the PVT output and battery pack, over a 7-day timeframe.

Fig. 15. 7-day evolution of the PVT output voltage.

Fig. 16 shows the evolution of the irradiance, over one day, at the PVT installation site.

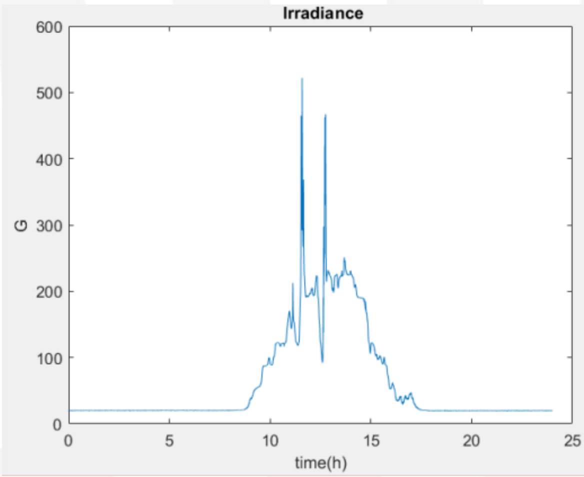

Fig. 16. Solar irradiance measured at the PVT installation site.

4. Concluding remarks

The hybrid energy systems set up at CISE and UT3 provide relevant data to the evaluation of this new, more efficient paradigm for energy production and distribution. Given the delays in the commissioning of technologies, the first measurements were obtained at the end of the project. Even though it was not possible for the partners to fully exploit the obtained results, some important outlines were taken. The profits and advantages of hybridisation reveal promising.

Despite the very encouraging benefits of the PVT technology with regards to efficiency, its integration with a chiller involves a case-by-case study. In this case study, the electrical consumption of the cooler will certainly remain higher than the gain in electricity production. Larger-scale thermal-electrical systems should allow to obtain more relevant gains and, consequently, increase the practical interest of this integrated solution composed of PVTs and chillers.

5. Future plans

5.1. CISE

Future actions in CISE|GIRS-RES aim at consolidating the features of some of the building parts of the hybrid energy system, namely the hydrogen system. To improve sustainability of the hydrogen system with regards to the hydrogen supply, future plans involve the replacement of the existing hydrogen supply solution by a fully sustainable system for the local production of green hydrogen through electrolysis. The electricity consumed for the electrolysis shall be obtained through the complementary renewable energy resources in operation at the demonstrator.

At the same time, planned actions aim to enhance the efficiency of the fuel cell. Even though the current system is solely used to transform hydrogen into electricity, there is potential to exploit the waste heat resulting from the reaction to obtain both electricity and thermal energy, thus improving the global efficiency of the conversion process. With such evolution, the hybrid energy system can be complemented with an additional thermal energy source.

5.2. UT3

In the very near future (6 months), the hybrid energy network demonstrator installed at UT3 will be used as a training platform for innovative photovoltaic energy technologies for isolated sites. Heating/cooling can be used in well-defined cases, such as heating water in a swimming pool. A careful study of heat exchange mechanisms taking place in the implemented system will make it possible to validate the concept of cooling the panels.

For the start of the 2024 academic year (September 2023), these systems will serve as an experimental base, during student projects, to develop and set up a wireless and energy-autonomous instrumentation system that would double the existing measurements and would make it possible to have a reflection on measurement rates, processing at the sensor level, etc.