BUILDING A SUSTAINABLE ENERGY RESEARCH ENVIRONMENT

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ABSTRACT

The goal of the project has been to build a research and teaching environment that supports the sustainable energy transition. It is based on renewable energy sources and signifies the intelligent integration of different sectors and innovative technologies. The regional scale platform combining hydrogen, solar energy, and heat pump technologies has been integrated with electricity, water, and hydrogen storages systems housed in container units. This infrastructure enables cutting-edge research on energy systems, strengthening international collaboration and promoting the attractiveness of the region for green innovations. Given the complexity and interconnectivity of the systems involved, a risk assessment was also performed. The study includes the background of the equipment, its construction, and thoughts of its research and educational use.

1. INTRODUCTION AND MOTIVATION

Renewable energy (RE) is gaining wider use for power generation around the world nowadays, particularly due to societal concerns about environmental issues coming from the conventional method of electricity generation. The five major groups of renewable energy are solar energy, hydro energy, wind energy, bioenergy, and geothermal energy. They have their own operating conditions and energy conversion efficiency. Therefore, RE technologies will depend on the location and conditions [1].

For example, to replace energy peat, research into emission-free renewable energy, energy storage, and energy efficiency must be increased. These themes are key parts of a sustainable energy system of the future, the development of which is a prerequisite for the successful structural transformation of the green economy. Not only is a sustainable energy system based on renewable energy, but it also signifies the intelligent integration of different sectors and innovative solutions. The innovative solutions pertaining to clean energy production, storage, use, and sector integration developed in the project will create job and business opportunities for both the companies already located in the region and the companies considering new locations in the region. The investment project is expected to result in a unique research and piloting environment for a sustainable energy system, which will create a strong foundation for expanding and deepening the applied research, building international networks and obtaining competitive funding for the Kymenlaakso region, while also promoting the attractiveness of the region in the eyes of students, experts, and companies [2].

Changes in energy systems and progressive sector integration have been the focus of research in recent years. Especially battery power storage, solar and photovoltaic thermal (PVT), hydrogen, and thermal storage have been popular areas of research in scientific literature and patenting. Figure 1 shows the patenting activity since 2005 in Europe with a focus on renewable energy technologies, including solar power and PVT, thermal energy storage, battery electric storage, and hydrogen technologies. The data, sourced from [3], includes only active granted patents and patent applications within the European jurisdiction. Similar to the worldwide patenting trend, the European trend shows continuous increased activity and reflects an increased interest from the industry and research in developing new and improving current renewable energy and storage technologies in recent years.

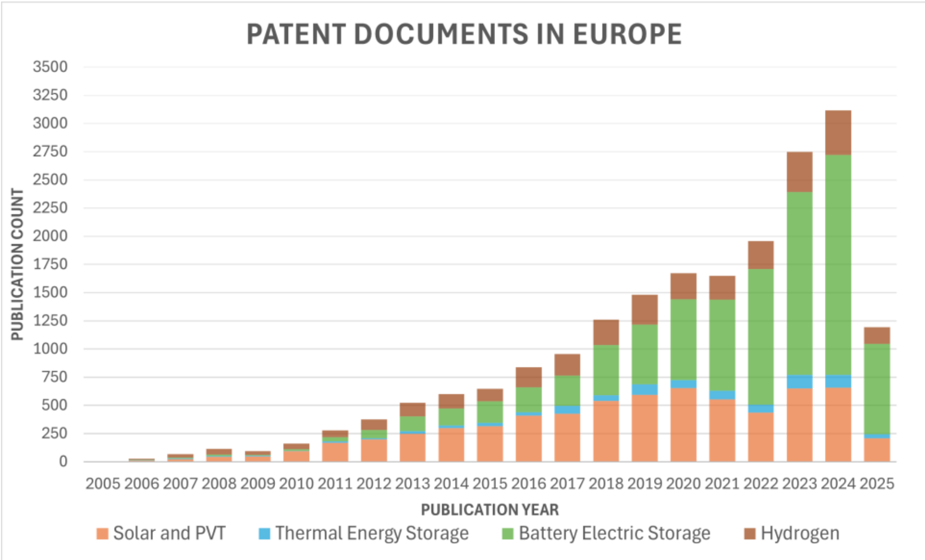

Figure 1: Renewable energy patents from 2005 to May 2025. Data sourced from and enabled by The Lens [3]

The provincial-level platform for sustainable energy research has been lacking until now. The designed research environment enables multiple purposes: It provides an infrastructure for innovative energy system research, enables the integration, testing, and simulation of various renewable energy applications, and functions as a teaching platform to address emerging skill requirements in the energy sector. The paper comprises sections related to its design, construction, safety issues, system operation, as well as its operation as an educational environment.

In the initial phase of the project, visits were made to some national educational and research institutions. Their focus was on slightly different energy systems, but all parties were interested in the new systems of energy transition. For example, hybrid laboratories as an environment for the experimentation, learning, and development of energy communities were found. One of them had a long history with proton exchange membrane, solid oxide, and alkaline technologies. However, the system currently being designed is slightly different. National-level energy systems using renewable energy were now combined to work together (Figure 2).

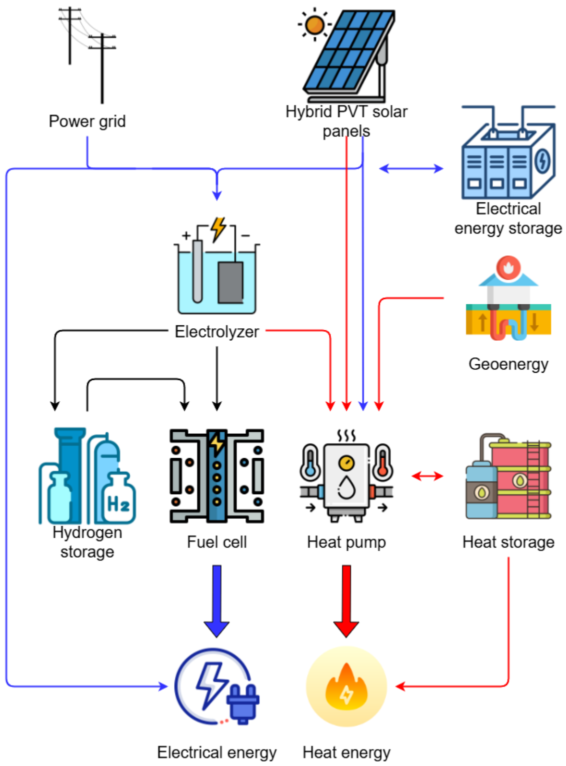

Figure 2: The principle of the renewable energy test facility

The original test facility consisted of the following parts: hybrid photovoltaic-thermal (PV/T) solar panels, electrical energy storage, power grid, proton exchange membrane (PEM) electrolyser, hydrogen storage, fuel cell, geoenergy well, heat pump (HP), and heat storage (Figure 2). The goal is to ensure that the system corresponds to the sustainable energy transition and use of renewable energy in future energy-smart cities. Sector integration aims to connect different energy sectors so that they can balance each other's consumption and production peaks and improve the cost-efficiency of the entire energy system [4].

An earlier study [5] investigated the utilization of waste heat generated during the process of water electrolysis. The project investigated the technical and economic aspects and potential of using waste heat from hydrogen production in South Karelia and Kymenlaakso regions in Finland. District heating networks were selected for further investigation due to their high heat demand and existing heat transfer infrastructure. The feasibility study showed that the recovery of waste heat from the electrolysis plant provides a significant revenue source for the electrolysis operator and reduces the production cost of hydrogen, although the analysis is sensitive to the parameters chosen for the calculation.

2. Construction of the Experimental Equipment

Several kinds of experimental environments have been developed to harvest renewable energy. For instance, Singh et al. [6] implemented a system using renewable energy consisting of a trigeneration plant with reversible solid oxide fuel cells (SOFC), hydrogen storage, Rankine cycle, and vapor absorption cycle. Al-Nimr et al. [7] investigated the behavior of a solar power generation system comprising a concentrated photovoltaic/thermal (CPV/T) system, which utilized an Organic Rankine Cycle (ORC) integrated with a geothermal condenser and an energy storage unit. Lastly, Atiz [8] proposed an integrated system for electricity production. The three different solar collectors were integrated with a geothermal source for electricity and hydrogen production which were compared. The principle in these systems was that each component should be selected carefully in a justified manner for the selected location.

The South-Eastern Finland University of Applied Sciences moved to new premises in the autumn of 2024. However, the newly planned research environment had to be located separately as a container solution. The geoenergy heating well was placed in the Sunila industrial area and the other equipment was installed in a hall next to the school. Due to the soil structure, the medium-deep thermal well was unsuitable in the vicinity of the educational institution. Thus, this paper discusses parts other than the geoenergy well.

The electrolysis of water is an electrochemical process in which the electrical energy is the driving force of chemical reactions. Water is decomposed to hydrogen and oxygen by passing a current through it. A fuel cell can convert the chemical energy in fuel to electricity and heat. Hydrogen can be used to power different types of renewable energy sources. Fuel cells have high efficiency compared to conventional techniques like power cycles [7].

Heat pumps are easy to use while utilizing the possibility of bringing low-temperature heat sources to a higher temperature. Thus, low grade renewable energy sources (such as air, water, ground, solar), as well as waste heat sources, can be used to reduce the demand for fossil fuels and greenhouse gas emissions. However, to fully exploit their potential, it is necessary to install thermal energy storage units into HPs to ensure that their operation is more continuous and economical [9]. Additionally, the influence of the water storage tank size and the air source heat pump size on the energy saving potential of the energy storage heating system has been investigated by Lyu et al. [10].

The operation of a solar cell is based on photoelectric phenomena. Solar radiation releases electrons from the surface of the cell. The photovoltaic-Thermal (PV/T) system is a combination system between photovoltaic and solar thermal components. Sunlight, as photon energy, is absorbed into the system. It generates electricity and some parts of it are converted to heat energy [11].

The experimental setup consists of PV and PV/T cells, inverter and electric storage, a heat pump and two water reservoirs, PEM electrolyser, hydrogen compressor, two hydrogen storage tanks, and a fuel cell. The main components of the research environment are specified in Table 1.

Table 1: Main components of the research environment

PV and PV/T cells (Dualsun Flash & Spring, 6x450 W_e & 6x450 W_e/~580 W_{th}/m^2), inverter (Growatt MOD 6000TL3-XH), electric storage (Growatt APX 20.0P, 20 kWh_e)
Heat pump (Gebwell Aries 6, 7.3 kW_{th}), water storage tanks (2x1000 l), energy meter (2x Kamstrup Multical 603), pumps, heat exchangers and fans
PEM electrolyser (Nel Hydrogen S40, 1.05 Nm^3/h, 13.8 barg), hydrogen compressor (H2 Planet HY-Comp XT HP, 12-210 bar), hydrogen tank (Mahytec 2x850 l, 60 bar)
PEM fuel cell (GreenHub2 PRO 3000, 48 VDC, 2.7 kW_e), inverter (Victron MultiPlus II 48V, 5000 VA, GX)

The studied research environment was placed in two separate containers. The first one primarily contains hydrogen-related components, including electrolyser, fuel cell and hydrogen compressor. The container is divided with a partition wall to separate the hydrogen compressor from the other equipment. The compartment with the hydrogen compressor is ATEX-classified. ATEX refers to systems and equipment intended for use in potentially explosive atmospheres and is specified in the European Directive 2014/34/EU [12]. The second container, larger in size, accommodates the rest of the infrastructure: a workstation, heat pump and thermal water storage tanks, and air conditioning unit. The larger container is situated inside a large hall owned by the city. The inverter and battery storage are placed inside the hall, close to the container. The photovoltaic and photovoltaic thermal panels are vertically mounted on the outside wall of the large hall, next to the hydrogen-related container located outside for safety reasons. In front of this container, the two hydrogen storage tanks are positioned. The layout and positioning of hydrogen-related components are detailed in Figure 3.

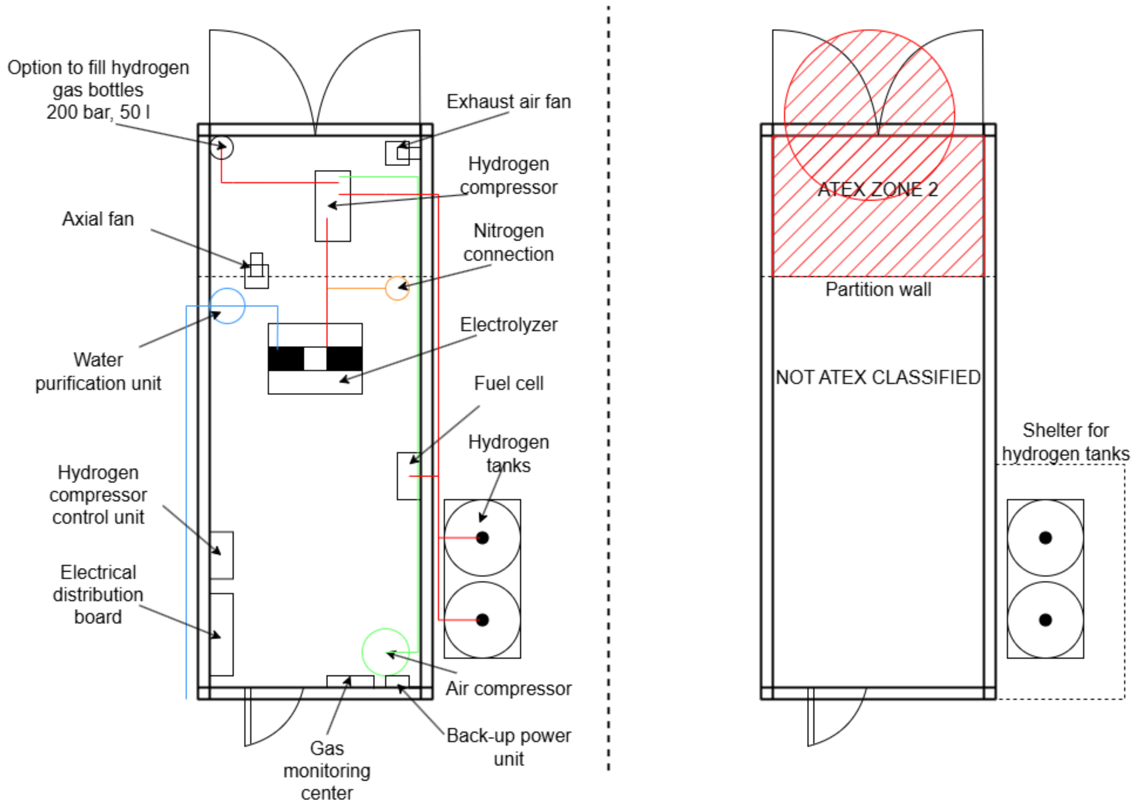

Figure 3: Layout and positioning of hydrogen-related components in the container

The heat pump system encompasses the following circuits: heat collection, evaporator circuit, charging, heating, heat recovery circuits, and condensation and space heating (Figure 4). The heat pump collects heat from the PVT hybrid collector and PEM electrolyzer. The system stores captured thermal energy in the warm water tank. Electrical energy can be stored in batteries, or after being converted into hydrogen, it can be stored in hydrogen tanks. The heating circuit supplies heat to the interior of the second container, while the remaining heat is condensed into the environment (corresponds to other consumers).

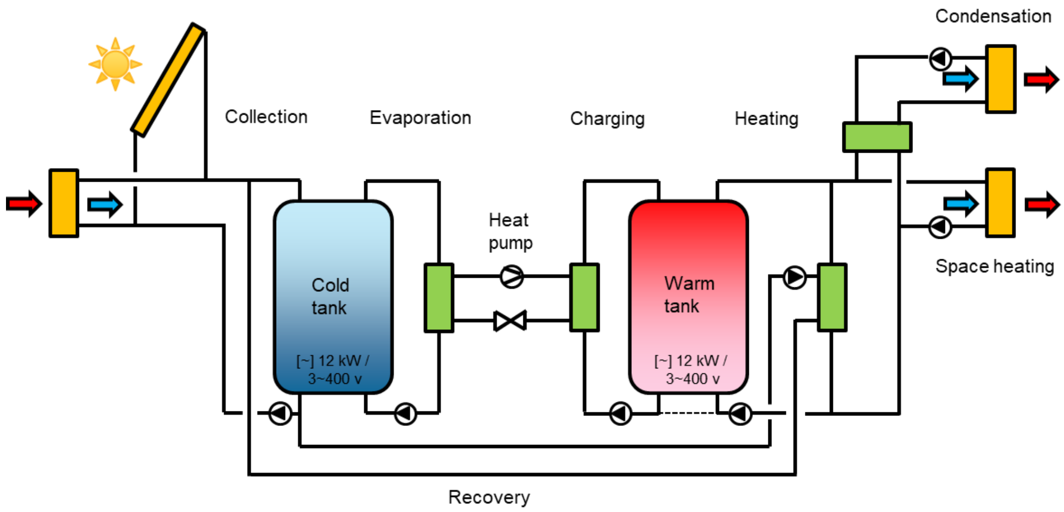

Figure 4: Simplified heat pump process diagram

The facility should be able to respond to changes in renewable energy capacity. For example, the selected PEM electrolysis reaches its operating state faster than alkaline electrolysis. The time it takes for alkaline electrolysis to reach a continuous state may pose a problem when production is intermittent. The temperatures of the water reservoirs should also be able to be raised to the desired simulation levels before starting measurements. Thus, auxiliary heating (two electric heating elements of 12 kW, Figure 4), and sufficient cooling loads can be inserted for the cold- and hot-water tanks to enable the simulation of the desired operating conditions without undue delays. Rehman et al. [13] explored how heat pumps and thermal energy storage (TES) serve as key technologies for integrating different energy systems, or "sector coupling," to increase resilience and reduce emissions.

To prevent unauthorized access or damage to the systems, concrete blocks and a fence have been installed around the hydrogen-related container. A camera surveillance system monitors the surroundings of both containers. The complexity and integration of numerous systems in the research environment inherently introduces potential risks. The implementation and research of hydrogen systems in particular are new to the authors. Therefore, a risk assessment was conducted to identify and mitigate potential risks before the operation. Several potential risks have been identified, with explosions caused by a hydrogen or oxygen leak from the hydrogen system; thermal runaway, overheating and ignition, or explosion of the battery system as the most significant ones. To mitigate these risks, the following actions have been taken:

- Fire response measures (fire blanket, fire alarms, fire extinguishers according to the corresponding fire class)
- Good ventilation in all spaces
- Monitoring and control of indicators through sensors and systems
- Automated shutdown of systems in emergency and automated emergency response messages
- Battery management system
- ATEX-classified container space

Additional risks identified during the assessment were considered low or medium in both severity and likelihood. Therefore, they are available only in the complete risk assessment report. Continued reassessments and reevaluations will be conducted regularly to ensure proper response and risk mitigation. Since the area with the hydrogen compressor is ATEX-classified, an explosion protection document for the small container is required. The document covers all possible risks previously mentioned and is approved by Finnish Safety and Chemicals Agency (Tukes).

Hydrogen, thermal, electrical, and automation design and construction, i.e., components, piping and electrical wiring of the system, were completed by professionals in co-operation with each other and Xamk. All pipelines containing hydrogen were installed by a gas industry specialist. The automation system (Simatic ET 200SP CPU) is central to the system, and its required installations were completed by Xamk's automation designer. The user interface of the control system is designed to be easy to understand since the environment will be used for educational purposes.

3. RESEARCH AND EDUCATIONAL USE OF THE EQUIPMENT

The heat pump and hydrogen systems were designed for research and teaching use. After commissioning, for example, the purpose is to enable an examination of the heat pump operation and efficiency calculation at different collector and heating circuit temperatures. In addition, the system can be used to study the yield of different heat recovery systems. Two different functionalities have been programmed into the automation system: the heat pump efficiency test and the heat collector yield test. A dynamic graphic has been created, which shows the pipe connections schematically, the operating status of pumps, fans, and other controlled devices, as well as the adjustment position of adjustable devices. All measurements and their set values are shown graphically.

The heat pump was designed to simulate various heating and cooling systems; for example, a heat pump as part of a data center or swimming pool air conditioning unit. The system follows the temperature setpoints given to the HP for cold or hot storage temperatures. As a part of the performance study, COP values can be presented graphically by students as a function of different temperatures of the cold and hot water tanks. It is broadening to explore the heat pump with thermal energy storage to fully exploit its potential, allowing for a more continuous and economical operation.

Hydrogen plant testing may include its performance, i.e., the efficiency of hydrogen production in the electrolyzer and efficiency of electricity production in the fuel cell, and a combination of these two. The produced hydrogen is stored in two tanks. Determining heat recovery from an electrolyzer is an interesting process. The electricity generated by solar cells is stored in batteries from which the testing equipment can be electrified. The power generated by fuel cells is also used directly in the test facility or fed into the power grid. The total energy production of the plant can also be examined by storing energy (electric, thermal, and hydrogen) when the price of electricity is low.

4. SUMMARY

A sustainable energy system, based on renewable energy, signifies the intelligent integration of different sectors and innovative solutions. Research has focused on changes in energy systems and progressive sector integration in recent years. The provincial-level platform for sustainable energy research has been lacking until now. The newly designed research environment provides an infrastructure for innovative energy system research, enables the integration, testing, and simulation of various renewable energy applications, and functions as a teaching platform to address emerging skill requirements in the energy sector.

The hardware comprises hybrid PVT solar panels, electrical energy storage, a power grid, a PEM electrolyser and fuel cell, hydrogen storage, heat pump, and two heat storages, all of which are placed in two separate containers. The first one primarily contains hydrogen-related components, including an electrolyser, a fuel cell, hydrogen storage, and a hydrogen compressor. The second container accommodates the rest of the infrastructure: a workstation, heat pump, thermal water storage tanks, inverter and battery system.

Since the complexity and integration of numerous systems in the research environment inherently introduces potential risks, a risk assessment was conducted. The research environment was completed by professionals in co-operation with Xamk. The user interface of the control system was designed to be easy to understand for educational purposes. It is expected that the building project will result in a unique research and piloting environment, creating a foundation for expanding and deepening the applied research and building international networks and promoting the attractiveness of the region.

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5. BIBLIOGRAPHY

[1] T.-Z. Ang, M. Salem, M. Kamarol, H. S. Das, M.A. Nazari, N. Prabaharan, A comprehensive study of renewable energy sources: Classifications, challenges and suggestions, Energy Strategy Reviews 43 (2022) 100939.

[2] Genesis application for funding, JTF: Sustainable energy system and new value chains of sector integration - GENESIS, development and investment, 2023.

[3] The Lens. Cambia. Available at: https://www.lens.org/

[4] M. Rämä, Heating, cooling and sector integration (in Finnish). Available at: https://www.vttresearch.com/fi/uutiset-ja-tarinat/lammitys-jaahdytys-ja-sektori-integraatio

[5] P. Kiviranta, J. Hyypiä, E. Inkeri, M. Keski-Luopa, S. Rahiala, T. Tynjälä, Hydrogen, power to the South-East – the potential for utilizing waste heat, South-Eastern Finland University of Applied Sciences (2023), 2489–4575 (in Finnish).

[6] U. R. Singh, A. S. Kaushik, S. S. Bhogilla, A novel renewable energy storage system based on reversible SOFC, hydrogen storage, Rankine cycle and absorption refrigeration system, Sustainable Energy Technologies and Assessments 51 (2022) 101978.

[7] M. A. Al-Nimr, M. Bukhari, M. Mansour, A combined CPV/T and ORC solar power generation system integrated with geothermal cooling and electrolyser/fuel cell storage unit, Energy 133 (2017) 513-524.

[8] A. Atiz, Comparison of three different solar collectors integrated with geothermal source for electricity and hydrogen production, International Journal of Hydrogen Energy 45 (2020) 31651-31666.

[9] E. Osterman & U. Stritih, Review on compression heat pump systems with thermal energy storage for heating and cooling of buildings, Journal of Energy Storage 39 (2021) 102569.

[10] W. Lyu, Z. Wang, G. Deng, Z. Xu, H. Li, Y. Yang, B. Zhan, M. Zhao, Influence of the water tank size and air source heat pump (ASHP) size on the energy saving potential of the energy storage heating system, Journal of Energy Storage 55 (2022) 105542.

[11] S. A. Hamid, M. Y. Othman, K. Sopian, S. H. Zaidi, An overview of photovoltaic thermal combination (PV/T) technology, Renewable and sustainable Energy Reviews 38 (2014) 212-222.

[12] European Commission. Equipment for potentially explosive atmospheres (ATEX). European Union. Available at: https://single-market-economy.ec.europa.eu/sectors/mechanical-engineering/equipment-potentially-explosive-atmospheres-atex_en

[13] O. A. Rehman, V. Palomba, A. Frazzica, L. F. Cabeza, Enabling technologies for sector coupling: a review on the role of heat pumps and thermal energy storage, Energies 2021, 14, 8195. https://doi.org/10.3390/en14248195