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Review

Design and Development of a Conceptual Solar Energy Laboratory for District Heating Applications

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Abstract: The decarbonization of the district heating (DH) sector is receiving attention worldwide. Solar energy and heat pump technologies are widely considered in existing and new DH networks. There is a need to understand the influence of solar energy on district heating experimentally. However, only a few university laboratories are focused on district heating aspects. Further, the concept of such laboratories is not adequately disseminated in the scientific literature. The main objective of this paper is to develop a conceptual design of a solar energy laboratory with a focus on district heating systems. The proposed concept forms part of the preliminary study carried out by a research group at the Tallinn University of Technology. First, a brief literature review on solar energy laboratory development is provided. Then, the conceptual design of such a laboratory is presented, along with a case study. Regardless of project size, the main components of a district heating-based solar energy laboratory are solar collectors, thermal energy storage (TES) tanks, and a control system. The proposed laboratory is expected to serve multiple roles, such as a practical laboratory to provide interdisciplinary courses for students, a research and experimental platform for researchers, and a cradle to achieve the campus green initiative. It is roughly estimated that the thermal energy output from the proposed laboratory would meet around 25% of the heat demand of the institutional building during the summer season (May, June, July, and August). It is expected that the present study will be a reference material for the development of innovative energy laboratories in educational institutions.

Keywords: district heating; solar energy; energy laboratory; green campus; solar heat; PV

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1. Introduction

The decarbonization of district heating (DH) networks is getting attention worldwide. Over the years, the share of renewable energy for heating and cooling has been increasing gradually [1]. This is powered by heat technologies such as modern bioenergy, renewable heat pumps, solar thermal, and geothermal. In the European context, the highest share of renewable sources for heating and cooling is reported in Sweden (68.6%), Estonia (61.3%), Latvia (57.4%), and Finland (52.6%). This scenario was heavily dependent on biomass energy [2]. With the widespread adoption of low-temperature DH networks, the utilization of nonfuel heat sources such as solar energy becomes attractive. Moreover, solar photovoltaic (PV)-based heat pump technologies are widely considered by innovative DH utilities. Further, an increase in the deployment of solar energy systems is happening in the European regions.

A drastic transformation is happening in the energy sector (from a production profile to a consumption pattern). In the contemporary world, laboratories and experimental facilities focused on energy topics have become highly relevant. Engineering laboratories for new and emerging topics are important in terms of providing effective learning and training for university graduates. This supports forms of effective knowledge transfer and is an important part of any learning paradigm. Laboratory facilities provide a platform for experiments in real conditions, especially in the fields of engineering technology and applied sciences. It is worth noting that industrial visits cannot provide hands-on experience and an experimental platform for students.

The research focused on energy laboratories and their development/structure/capabilities are reported in the scientific literature. For example, Guo et al. [3] designed and developed a web-based laboratory for understanding the concepts of microgrids. It was observed that this virtual laboratory increased the knowledge level and learning involvement of students. Davidsson et al. [4] showed that a small-scale solar laboratory can be successfully developed and implemented in a developing country with the support of researchers from reputed universities abroad. Pantchenko et al. [5] reported effective student learning after providing a miniature central power concentrator system for understanding concepts about concentrating solar energy. Kallert et al. [4] described the development of an innovative lab for DH systems by Fraunhofer IEE in Kassel, Germany. This district LAB is equipped with a lab-scale flexible heating network, decentralized heat pumps, and a pipe test bench based on a digital control and automation concept.

It was observed that most of the solar energy laboratories are aimed at photovoltaic technology. Moreover, some labs are focused on solar thermal applications such as water heating, electric power, desalination, drying, etc. There are only a few laboratories focused on district heating concepts. An exclusive lab encompassed in innovative solar district heating concepts is rarely seen in European universities, especially in the Nordic-Baltic area. To the best of our knowledge, there is only a handful of experimental facilities, such as the Energy Exchange Lab, Italy [6], and the Solar Energy Systems Laboratory, Latvia, for solar district heating concepts [7]. In these laboratories, there is a strong relationship between district heating concepts and solar technology (solar PV/solar thermal), as shown in Figure 1.

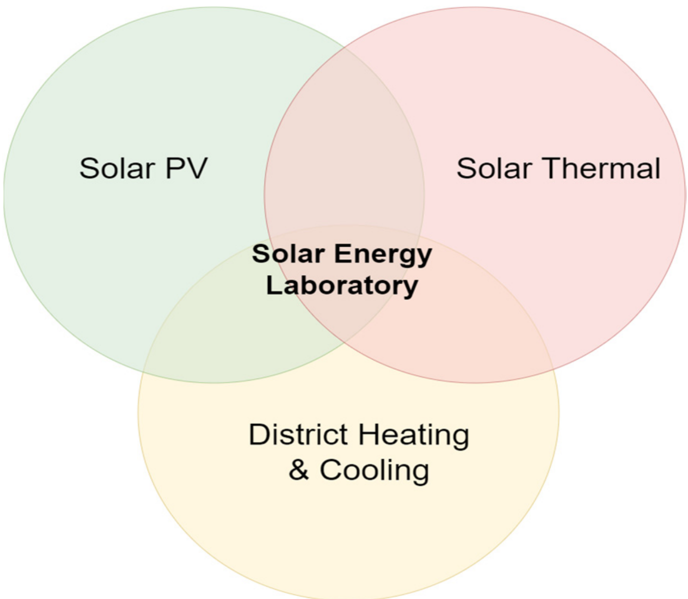

Figure 1. The concept of solar energy laboratories focused on district heating.

The aim of this study is to design and develop a conceptual district heating-based solar energy laboratory on a university campus. The proposed concept is a part of the preliminary study carried out by a research group at the Tallinn University of Technology. Once implemented, the proposed laboratory will become a state-of-the-art facility for solar district heating research in the Nordic-Baltic region and an effective platform to explore different operational & control strategies and digitalization aspects under a limited insolation climate. The paper is structured as follows. An overview of solar energy laboratory development in universities is presented in Section 2. The concept of a district heating-based solar energy laboratory is described in Section 3. The functionality of the proposed concept is discussed as a case study in Section 4. Conclusions are provided in Section 5.

2. Energy Laboratory Development in Universities

The development of energy laboratories is reported in the literature. Zinsmeister et al. [8] demonstrated a case study of prosumer integration into a flexible district heating network. This experimental system consists of five thermal and electric prosumer units (houses) connected to a thermal and electric grid. It was understood that both the temperature and pressure constraints should be considered when designing model predictive control (MPC) for the control methodology.

Gentile et al. [9] showcased the development of an inexpensive solar laboratory in Mozambique, Africa, and reported that capital cost can be drastically reduced with a slight reduction in measurement accuracy. With a 9% measurement inaccuracy, a 90% reduction in equipment investment cost was achieved. Coleman et al. [10] discussed the hardware development of a solar laboratory environment that consists of photovoltaic arrays, battery storage, and different converters. This lab is designed to serve students and researchers with experimental learning on solar microgrids. István et al. [11] developed a solar simulator for a university laboratory and experimentally demonstrated that the fabricated system is on par with a commercial one, with a satisfactory measurement error (±0.022%).

Mansur et al. [12] studied the development of a halogen-based solar simulator to test the electrical characteristics and performance of PV modules. A prototype PV with 40 cells was tested under different irradiance conditions, showing a measurement error of ±0.022%. Restrepo et al. [13] compared two different energy management systems (EMSs) at an existing microgrid testing laboratory and showed that an optimization-based EMS could provide better overall performance than a rule-based EMS. Dafalla et al. [14] developed an educational-purpose solar simulator using off-the-shelf Xenon, Halogen, and LED lamps, which could be used by students to analyze PV panel parameters. Roberts et al. [15] demonstrated a dual-purpose solar simulator that could be used indoors and outdoors in a renewable energy laboratory.

Guo et al. [16] developed a living laboratory to assess the suitability of large-scale borehole thermal energy storage (TES) in a district heating network. It was reported that the average soil temperature increased by 25.6 °C with only a 2 °C increase 5 m outside of the storage boundary. In a lab-scale solar thermal system developed by Drozek et al. [17], the students had flexibility in terms of studying the effect of operating parameters on system performance. Jiao et al. [18] reported the design and development of a solar PV system for a mobile laboratory that is equipped with 3D printers, computers, and soldering stations. Coleman et al. [19] presented the development of a solar microgrid laboratory with a hardware setup. The major steps were the characterization of source outputs and system loss and voltage drop tests. It is concluded that the addition of a software simulation platform can effectively supplement traditional education in power systems. Kosonen et al. [20] described the possible development of a test setup for hydrogen production in a Finnish University. By using MATLAB software, it was found that a 20 kW solar PV system is good enough for the continuous operation of a 5 kW water electrolyzer. Jiang et al. [21] provided the details of a laboratory test bench for solar PV experiments based on a real-time digital simulator. It was revealed that this approach can narrow the gap between computer-based simulations and hardware experiments. Al-Arefi et al. [22] reported a case study on software-based laboratory learning using Bloom's taxonomy and concluded that it could enhance students' autonomous learning as well as their blended learning ability. Although the study was performed during the COVID-19 lockdown period, it can potentially be applied to many teaching sectors in the future.

Moreover, virtual and remote laboratories have become popular over the last decade. The development of remote laboratories in the area of energy technology is reported in the literature. Shankar et al. [23] presented a framework that was adopted for a remotely controlled solar thermal energy lab that was equipped with a parabolic trough collector (PTC). By using a web-based interface, the students could assess the heating capacity of the PTC by controlling parameters such as flow rates, angle of incidence, etc. Al-Aubidy et al. [24] also described the development of a remote laboratory consisting of a physical setup, a data control unit, and an IoT environment (with local and web servers). Martin et al. [25] presented the concept of a renewable energy laboratory consisting of three different renewable sources: solar, wind, and biodiesel. The hybrid power system was designed and simulated, and then a physical and virtual environment with the e-learning concept was introduced. Moreover, the importance of the charging controller and the energy storage system to govern the nonlinear system and to increase overall efficiency was reported. Kyomugisha et al. [26] developed a solar PV remote lab in which basic experiments were carried out by adjusting a solar simulator and the PV parameters. Pipattanasomporn et al. [27] presented the lab-scale implementation of the P2P energy trading applications of solar electricity based on an open-source blockchain technology called Hyperledger. Rus-Casas et al. [28] developed a MATLAB-based application to calculate solar radiation on a nonhorizontal surface in a virtual lab environment. The remote or virtual laboratory allows students and engineers to perform laboratory tasks more conveniently in a safe environment, which was not possible in the conventional laboratory setup.

The information about existing laboratories was not fully available in the scientific articles. Hence, an exhaustive list of solar energy laboratories in European universities is shown in Table 1. Since all laboratories have different research fields with heterogeneous facilities and equipment, it was hard to obtain common technical metrics for an intuitive comparison. Information on location, area of focus, and facilities is provided in tabular form.

Table 1. The exhaustive list of solar energy laboratories in Europe.

No.	Laboratory Name	Location	Focus Area	Facilities
1	Archimedes Solar Energy Laboratory (ASEL) [29]	Cyprus Technical University, Cyprus	Computational and experimental studies of various solar energy systems, testing of phase-changing materials (PCM) for energy storage.	PV modules, different solar collectors, solar simulators, solar absorption chillers, thermal energy storage, Flir Thermo camera.
2	Sustainable Thermal Energy Technologies Laboratory [30]	University of Warwick, United Kingdom	Testing of PV cell and small thermal collector, performance assessment of solar thermal and PV systems.	Solar simulators, spectrometer and pyranometer, weather station, and radiation monitoring.
3	Fraunhofer Institute for Solar Energy Systems (ISE) [31]	Fraunhofer ISE, Germany	Research and development on high-efficiency solar cells, electrical energy storage, emerging PV technologies, etc.	Clean-room lab. (740 m^2), Instrumentation for materials and components characterization, battery cells processing chain, battery testing equipment.
4	Energy Exchange Lab [6]	EURAC Research, Italy	Testing of grid-connected combined cooling, heat power plant (CCHP), examination of the interaction between system components.	Solar thermal installation, gas boiler, organic Rankine cycle unit, absorption chiller, electric heat pumps.
5	Solar Energy Systems Laboratory [7]	Riga Technical University, Latvia	Simulation and experimental study of solar heating systems, energy storage using phase change materials, control principles in TES tanks.	Outdoor PV, PVT, TES, electric heater, heat pumps, weather station, control and monitoring systems.

Table 1. *Cont.*

No.	Laboratory Name	Location	Focus Area	Facilities
6	Process, Material, and Solar Energy Laboratory [32]	University of Perpignan, France	Development of research related to concentrating solar systems at all levels.	Different types of solar furnaces and solar receivers, solar heating systems with stratified storage tanks, solar cooling, including PCM heat/cold storage.
7	SolarTechLAB [33]	Polytechnic University of Milan, Italy	Investigation of solar energy-based electrical and thermal power generation systems, development of forecasting models and storage systems.	PV, PVT, concentration systems, solar-assisted HP.
8	Solar Heating [34]	Denmark Technical University, Denmark	Theoretical and experimental activities, such as the investigation of solar collectors and components, numerical modeling, flow visualization.	Weather station, outdoor solar collector test setup, heat storage tanks, particle image velocimetry equipment.
9	Sustainable Thermal Energy Technologies [35]	University of Padova, Italy	Experimental study of heat pumps and refrigeration systems, performance characterization of solar energy collectors and nanofluid-based volumetric receivers.	Solar collectors (flat plate, evacuated tubes, parabolic trough), pyranometer and pyrheliometer, TES test rig for PCM.
10	Laboratory for Photo Electrochemistry and Solar Energy Conversion [36]	University of Warsaw, Poland	Investigation of photo-electrochemical properties of materials for solar energy conversion.	Solar simulators, potentiostats, electrochemical workstations, spectrophotometer.
11	Laboratory for Renewable Energies/Solar Energy Technology [37]	Technical University Ingolstadt of Applied Sciences, Germany	Testing and application possibilities of solar energy systems, development of new materials for solar collectors, simulation exercise for wind power.	Solar simulator, outdoor solar thermosiphon system, off-grid PV system, meteorological station, solar tracker, spectroscopy.
12	Solar Platform of Almería (PSA) [38]	Center for Energy, Environmental and Technological Research, Spain	Analysis of solar radiation and its spectrum, simulation and experimental study of different concentrating solar technologies, characterization and development of associated materials, evaluation of solar desalination and photochemical process.	Meteorological station, different capacity parabolic trough collectors, solar furnaces and central tower systems, molten salt TES facility, test bench facilities, pilot plants for solar-based water treatment.
13	Institute for Solar Energy Research in Hamelin (ISFH) [30]	Hamelin, Germany	Development and analysis of innovative photovoltaic components, materials, and solar-generated energy integration with HP and geothermal applications.	Industrial solar cell processing equipment, screen printer, firing furnace, clean room lab, laser lab, climate chamber, solar simulators, test roofs (400 m^2), various test facilities.
14	Institute for Building Energetics, Thermotechnology, and Energy Storage [39]	University of Stuttgart, Germany	Research and development on solar thermal systems and components, test methods, systems analysis, production, and inspections.	PVT collectors and systems, testing equipment for solar thermal and heat pumps.

Table 1. *Cont.*

No.	Laboratory Name	Location	Focus Area	Facilities
15	Laboratory for Combined Energy Systems (CoSES) [40]	Technical University of Munich, Germany	Investigation of integrated energy systems (electricity and heat), design and sizing of coupling components such as heat pumps, CHPs, and EVs.	Flexible electric grid, distributed generation, battery energy storages, EV charging stations, fully controllable domestic electric consumption/production, district heating/cooling grid.

It can be summarized that the theme of each energy laboratory is aligned with the specific research area of the working group. Hence, the concept of the existing laboratories cannot be directly adopted when developing a new laboratory. However, some experimental facilities and procedures in existing laboratories can be a reference for the design and development of the proposed laboratory by our research group.

3. Concept of Solar Energy Laboratory for District Heating

Solarization is seen as one of the pathways to decarbonize district heating systems. Solar district heating systems generally consist of solar collector fields, TES tanks, and distribution pipelines. Innovative DH companies have taken steps to improve the solar energy fraction in their plants. It is reported that the solar energy fraction in the Salaspils DH plant reached 46–49% of the total heat generation during the summer seasons [41]. Further, an increase in interest in solar energy utilization is anticipated in the coming years. In this context, the development of a solar energy laboratory is planned at the Tallinn University of Technology (Estonia) [42].

3.1. Overview

The conceptual laboratory is based on developing a facility for experimental research in solar district heating systems. Different solar energy technologies, as well as heat emulation stations, form an important part of the proposed concept. The conceptual solar laboratory can be divided into three parts. Firstly, the thermal systems consist of solar thermal collectors, TES tanks, heat emulators, heat exchangers, distribution pipes, and other hydraulic components. Secondly, the electric system comprises PV panels, PVT-electric, heat pumps, batteries, inverters, and other support units. Thirdly, it has digitalization and control-related components. Heat emulation units are considered to resemble the building's heat demands. Carbon reduction and the possibility of parallel consumption are considered. Heat consumers in the DH system usually have different energy consumption profiles, technical solutions, and energy performance indicators. The flexibility of the DH system enable heat consumers to use the heat produced by other energy sources. Nevertheless, one must encounter trade-off relationships between different energy sources, prices, and efficiencies. Therefore, the laboratory can provide an expansion in terms of research on finding the optimal parallel consumption scenarios and algorithms within the given DH system [43].

The main objective of this laboratory is to improve the student's knowledge of solar energy utilization in district heating networks. Each student will be given a pre-laboratory assignment to obtain results theoretically. In the laboratory, experimental results are obtained. There will be a post-laboratory assignment in which the lab results are compared with the simulated ones. Another highlight of the conceptual laboratory is the ability to carry out simulative methods as well as experimental tests. It allows for a comparison between simulated and experimental results.

The conceptual diagram focuses on the major components of the solar energy laboratory. The balance of system components (circulation pumps, control valves, etc.) can be considered for real implementation. A generalized diagram of the solar energy laboratory is depicted in Figure 2.

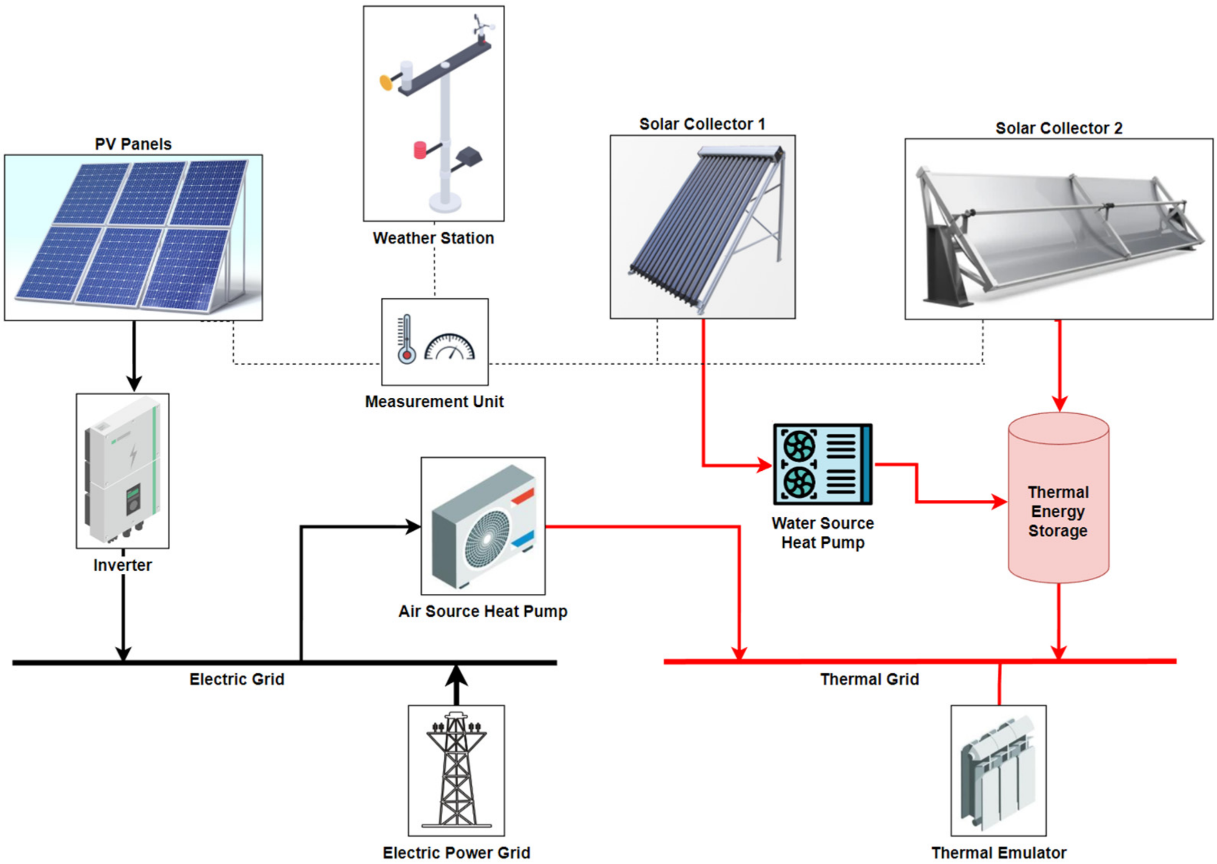

Figure 2. Generalized diagram for the proposed solar energy laboratory.

3.2. Major Components

A description of the major components and their functionalities in the conceptual solar heat laboratory is provided. Since the proposed laboratory is focused on district heating, most of the hardware system is related to solar thermal components.

Meteorological station: An exclusive weather station could provide accurate data for experiments and research. The first mission is to install the meteorological station to obtain accurate weather information, such as solar irradiance, ambient temperature, wind speed and direction, precipitation/snow, humidity, etc., which can be stored in a data logger. A typical weather station can be powered by a solar-powered combined rechargeable battery. The meteo data from the station is stored in a database that can be accessed onsite through a computer/remotely. As compared to historical weather data, these inputs are useful for accurately studying the influence of weather on solar energy systems and their thermal output. By using the data from a meteorological station on the university campus, Yadzhieva et al. [44] carried out a basic statistical and harmonic analysis of solar insolation in Ruse, Bulgaria. It was reported that solar radiation can be modeled with reasonable accuracy by considering only the constant term and the first component of the weather parameter.

Solar collectors: The selection of different solar collectors as heat generators is beneficial in terms of studying the performance of different technologies. For the proposed laboratory, solar thermal collectors, PVs, and PVT panels were considered to research the integration of different panels in a DH network and to supply the electric power necessary for heat pumps and system devices. The majority of the existing solar district heating plants in the EU are based on flat plate collectors (FPCs). The remaining SDH plants used parabolic trough collectors (PTCs) and evacuated tube collectors (ETCs). In 2020, the share of solar thermal collectors was reported to be evacuated tube collectors at 28% and flat plate collectors at 72% in Europe, whereas ETCs occupy 60% worldwide [45]. As a backup, electric heaters are suggested for the smooth operation of experiments irrespective of climate conditions. In colder regions, a brine solution is normally used in solar thermal collectors to avoid freezing. So, a heat exchanger is used for integration with the thermal grid. In a study by Tomson et al., it is reported that the energy output of ETCs is more than FPCs in the context of Tallinn when using simulation methods [46]. According to a heat transfer model presented and studied by Han et al. [47], PVs and PVTs for solar thermal behave differently under different ambient temperatures, inlet water temperatures, and solar irradiance. Both the electric and thermal efficiency of PV are higher than those of a PVT solar thermal system when the ambient temperature and solar radiation are low. However, this is the opposite when in higher ambient temperatures and stronger radiation conditions (PVT higher and PV lower).

Heat pump: This is one of the most promising power-to-heat (P2H) technologies for the decarbonization of DH networks [48]. There are two possible ways of using heat pumps in the context of the proposed laboratory. The electric output from PV or PVT panels can be used to power the heat pumps. The thermal output of ST collectors can be the input for the water-to-water heat pump.

Heat exchanger: This facilitates the use of different working fluids in the solar thermal systems and enables the connection to the remaining system. The thermal properties of the fluid, flow rate, surface area, and inlet and outlet temperature are the parameters to consider when choosing the type of heat exchanger. A heat transfer fluid that prevents freezing while having high thermal capacity is suggested for liquid-to-liquid heat exchangers in colder regions. According to a study carried out by Vaivudh et al. [49], a helical coil heat exchanger performs better than a vertical pipe in both the charging and the discharging process.

TES tanks: These play an important role in improving solar energy utilization. Solar thermal collectors are connected to storage tanks of an appropriate size so that they can be used on cloudy days [8]. As a rule of thumb, 50–80 L of volume is required for each m^2 area of a solar thermal collector [50]. It is suggested to have multiple inlet and outlet ports at different heights. A few temperature sensors are fixed at each port for experimental analysis. This setup is required to measure the temperature and heat variation throughout the tank. If an electric heating rod is placed inside the tank, it can be used during cloudy days and winter seasons for conducting experiments.

Thermal load emulators: These systems are designed in such a way that they resemble the heat demand in a building. For example, cooling or heating the water in the pipe. Parameters such as heat loss and temperature variation can be mimicked by using these emulators. Based on experimental conditions, different thermal points can be kept. For the proper operation of the thermal system, components such as check valves, control valves, and pressure gauges are required.

Balance of systems: In addition to the major components, several accessories, such as circulation pumps, inverters, thermal pipes, and electrical cables, are needed. The proposed system is expected to consider all the international standards, such as EN 12975 (solar collectors), IEC 61215 (solar photovoltaic), and EN 14511 (heat pumps).

System monitoring and control: In order to understand heat transfer, it is suggested that the flow rate and temperature (inlet and outlet) of each solar thermal collector be monitored on an hourly basis. Temperature sensors and flowmeters are utilized for this purpose. The electric power output from PVs and PVTs is also monitored periodically. The energy consumption of heat pumps and hydraulic pumps is measured. The water consumption of the entire system is another factor. The control and monitoring of different components based on digital approaches is important. All important information is collected and stored at regular intervals. The proper selection of sensors plays an important role in accurate measurement, which, in turn, affects the performance calculations. According to Schmelzer et al. [51], the measurement uncertainties are smaller for even inexpensive sensors if the solar fraction is higher. In the proposed laboratory system, minimal systematic errors are expected due to the use of small-scale solar collectors and auxiliary equipment.

Large volumes of data generated from weather stations, sensors, and measurement units are valuable sources with which to implement research on AI-based data processing and digitalization. Expanding and integrating the solar energy system into a district heating system requires a sophisticated control strategy. Due to the stochastic nature of solar irradiance, solar energy systems can provide an ideal platform to implement research on dynamic systems that require intelligent control and optimization technology. For example, many advanced control strategies for solar PV energy systems are introduced and reviewed by Basit and Jung [52]. Control systems for load-side converters, energy storage, voltage, and current controls can be used in the proposed concept. The system optimization of TES in solar DH based on the rule-based control strategy was studied by Saloux et al. [53]; they reported energy savings of 13 to 30% depending on the choice of storage duration (short-term or seasonal). Velarde et al. [54] studied multiple scenarios based on MPC algorithms and parabolic trough solar collector plants to achieve an improved energy storage and scheduling methodology.

4. Case Study for a University Campus

In this section, the functionality of the proposed laboratory is described. The expected outcomes of the project are discussed as a case study. In addition, the thermal energy output is estimated theoretically.

4.1. Site Description and Suitability

The rooftop of a university building was chosen for the outdoor section of the laboratory. Its suitability can be two-fold. Firstly, the selected location provides a shade-free vacant area. Secondly, it is accessible to the students and researchers of the university. Moreover, the solar radiation available on the rooftop is observed to be suitable as per the data from the Global Solar Atlas [55]. The site details are shown in Table 2 [56]. These energy systems are exposed to Baltic weather conditions. Nesovic et al. [57] reported a study about a similar experimental facility that consisted of a fixed flat plate solar collector on the rooftop of the university building.

Table 2. Details of the chosen site for the solar energy laboratory.

Particular	Quantity
Name of location	U06 building, TalTech
Latitude and longitude	59.48° N and 24.65° E
Climate type	Marine conditions
Terrain elevation	10 m
Optimum tilt of solar collectors	41°/180°
Global horizontal irradiation (GHI)	998.1 kWh/m^2/annum
Direct normal irradiation (DNI)	1070.7 kWh/m^2/annum
Diffuse horizontal irradiation (DIF)	477.1 kWh/m^2/annum
Air temperature	6.5 °C

As shown in Figure 3, solar thermal collectors and PV panels form an important part of the proposed lab. Four mounting structures that are already present on the building rooftop were utilized for the proposed laboratory. Since each mounting structure has an area of 8 m^2, the energy output of solar energy technologies is limited.

As tabulated in Table 3, four different solar energy technologies were selected, namely, a flat plate collector [50], a parabolic dish collector [58], PVT [59], and a standard PV panel [60]. The components, such as solar collectors, PV panels, weather stations, and heat dissipation units, will be located on the rooftop. The remaining components, such as heat emulation units and heat exchangers, will be housed in a separate space inside the building. A digitalization module will be developed for control and management with the help of experts from the School of IT, TalTech. The PV electric output will be mainly utilized to run the heat pumps. Excess electricity, if any, can be fed to the electric grid. Excess heat from solar thermal collectors that exceeds the heat demand of building U06, for example, in the summer, can be either directed to a heat dissipation unit (water cooler with a fan) or the district heating network of the university campus.

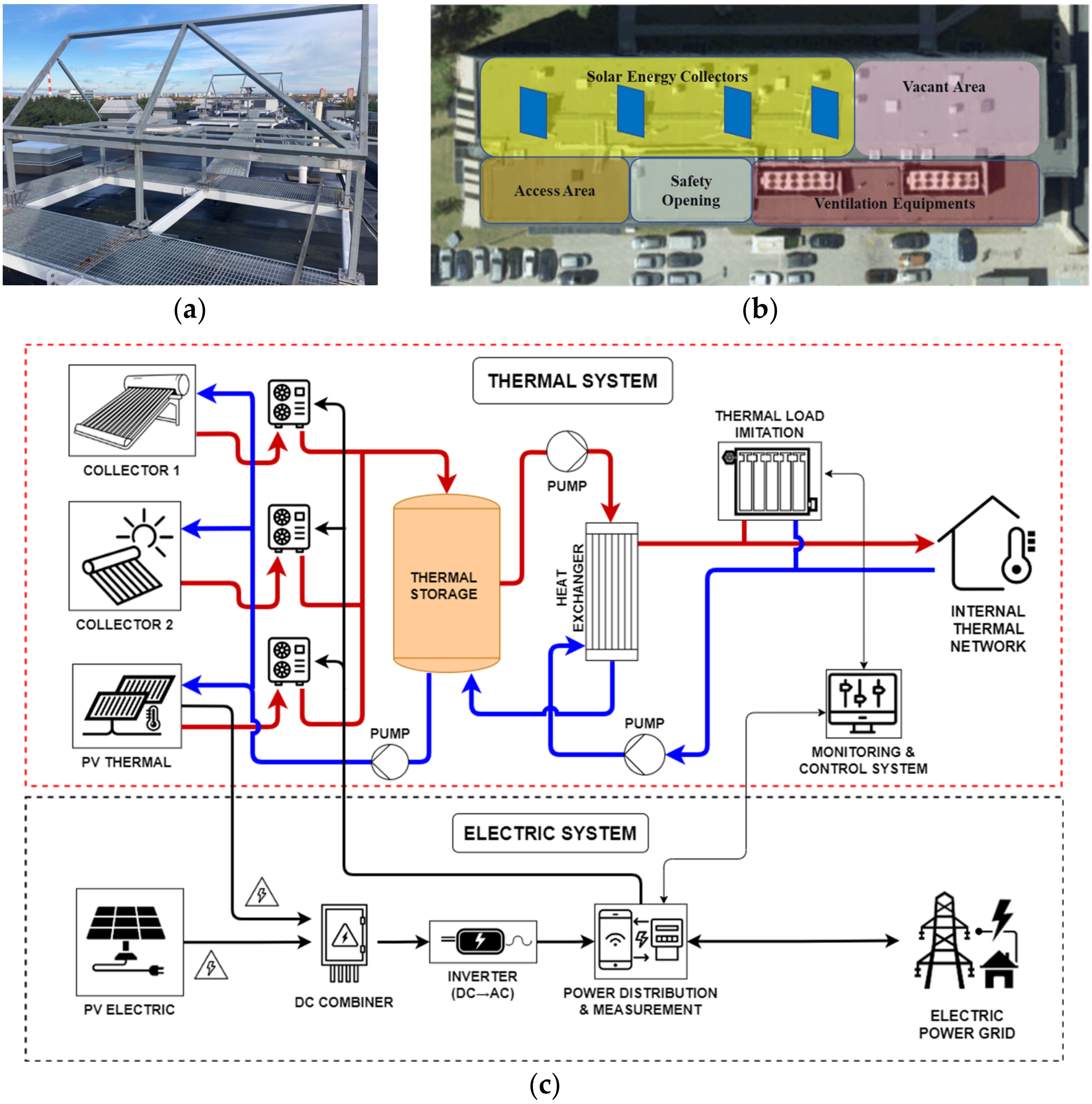

Figure 3. Rooftop view (**a**) and bird's eye view (**b**) of the outdoor installation site, and the proposed schematic for the solar energy laboratory (**c**).

Table 3. Information on the selected solar energy technologies.

Particulars	FPC	PTC	PV	PVT
Area (m^2)	2.86	3.36	2	2.08
Power (W_{ele})	NA	NA	400	425
Power (W_{th})	2091	1815	NA	1373
Electrical Efficiency (%)	NA	NA	20	20.4
Thermal Efficiency (%)	78.2	87	NA	62.1
Weight (kg)	46	97	22	35.6
Lifespan (years)	NA	>20	25	25

NA—not available.

4.2. Learning Possibilities

This will provide a platform for learning about solar energy utilization in district heating systems for both bachelor's and master's degree students. The learning possibilities include theory, computer simulations, laboratory experiments, and validation. The proposed laboratory aids research on solar energy applications in DH systems. Different experiments that are related to the smart district heating topic will be developed. With hands-on experience, the engineering students will have an opportunity to learn about the modern and innovative concepts of DH networks. Particularly, this educational lab provides insight into the working of solar thermal collectors, load balancing, parallel consumption, the integration of heat pumps, etc. This laboratory will be predominantly utilized in bachelor studies in Environmental, Energy, and Chemical Technology (EACB) and the master's course in the Energy Technology and Heat Power Engineering curriculum (MASM) [61]. The following are the planned theoretical and experimental topics that students can learn depending on the courses enrolled in.

- Understanding the theory and principles of solar energy technologies (FPC, PTC, PV, and PVT), heating networks, and the related components, such as TES tanks, heat exchangers, heat pumps, measuring equipment, and control systems;
- Interdisciplinary study combining thermal energy, heat transfer, thermodynamics, fluid mechanics, and machine learning-based intelligent control systems;
- Study and experiments on the thermal characteristics (flowrates, temperature, pressure, etc.) of the heating network when it is powered by fluctuating heat sources;
- The major input and output parameters of solar thermal systems—PV panel I–V characteristics, MPPT behavior, and the geometric and thermal parameters of solar collectors;
- Understanding different operation and control strategies (such as the control of heat pumps and flow values) with variations in solar output and heat demand;
- The evaluation of energy performance parameters for different solar technologies under different operating constraints;
- Study the influence of weather parameters (solar radiation, ambient temperature, wind speed and direction, and snowfall) on the overall system performance and resilience of a heating network;
- Simulation and validation exercises on the individual or the entire solar thermal system using software such as TRNSYS, EnergyPro, Polysun, MATLAB Simulink, etc;
- The modeling and simulation of various thermal components using ANSYS, COMSOL Multiphysics, Simflow, OpenFOAM, etc;
- Study the digitalization aspects of measurement and control systems with the associated big data analysis.

In addition to theoretical study and laboratory exercises, simulation software has a special place in renewable energy education. Over several years, TRNSYS has been a widely used energy simulation tool in academia. For example, Chargui and Sammouda [62] published an article in 2014 on the performance analysis of a dual source heat pump in a residential house using TRNSYS software and reported that this system could operate satisfactorily in the Mediterranean region with a coefficient of performance (COP) between 6 and 9. By using the simulation models that were built in TRNSYS, Pater [63] reported that the electric output from PVT modules can be increased by intensifying heat reception using a heat pump. Yu et al. [64] employed TRNSYS software to simulate the performance of different control strategies for a central air-conditioning system in a university classroom and observed lower energy consumption for the new scheme than that of the existing scheme.

Another planning tool for solar thermal research is the Polysun software. According to Witzig and Kunath [65], this Switzerland-origin simulations software package is comparatively user-friendly, with a vast database of system components. Abdel-Aty et al. [66] investigated the usability and accuracy of Polysun and reported that it can be used as an effective tool in educational courses on solar thermal energy systems using diverse simulation scenarios and results visualization. Azhar-Kareem et al. [67] investigated the variation of tilt angle (0° to 90°) on the performance of a solar collector using Polysun and reported that the optimum value is around 40° for the selected location.

4.3. Research Potential

The proposed laboratory will facilitate multidimensional research in smart district heating, especially for master and doctoral researchers. The experimental data collection will be focused on solar heating, cascading, the parallel consumption effect, energy cascades, and digitalization. This facility can be a platform to validate new and innovative concepts without affecting the residents [8]. This laboratory could support theoretical study and experimental exercises parallelly, such as the validation of simulation models in lab equipment. Further, the laboratory facility will provide a collaborative environment with other scientific fields, such as data processing, control engineering, IT processes, and energy scheduling.

Another goal of the laboratory is to study the effect of parallel consumption on a main heat source, such as the heating unit of the district heating network and the gas boiler of the university campus. In this regard, the solar collectors can be connected to the heating network of building U06 through a plate heat exchanger in parallel with the existing heat sources. In essence, building U06 can receive heat from three heat sources that would be connected in parallel. Further, this lab facility can be a platform to create public awareness among school students and the public through visits.

Fundamental research on the main components of solar heating systems can be conducted. The areas of focus will be solar collectors, heat pumps, and TES. This laboratory can be developed as an experimental platform for research in sub-low temperature district heating networks [68]. This facility could play a major role because of the scarcity of suitable locations for practical studies [69]. The importance of phase change materials in TES tanks is widely accepted by the scientific community. It is one of the most promising substances for enhancing solar energy utilization in DH networks. Gupta et al. [70] analyzed the suitability of laboratory-grade Aluminum oxide (Al_2O_3) nanoparticles in an FP collector and reported a thermal efficiency of 9–40% higher than a normal scenario. Johansen et al. [71] tested sodium acetate trihydrate (SAT) as a phase change material for latent heat storage between different seasons. The SAT heat storage module heated up to 80 °C for 6 months using solar collectors and was able to discharge 11 kWh of stored heat for 39 days. Wheatley and Rubel [72] reported that blending different PCMs in optimum ratios can result in more than a 10% efficiency improvement for thermal water systems. Zhang et al. [73] assessed the effect of the inclination angle on a heat pipe-based PVT system and concluded that the optimal inclination angle is 40 degrees when using experimental and numerical approaches. Bott et al. [74] conducted an experiment on seasonal heat storage for local district heating, focusing on minimizing leakage and heat losses. Molten paraffin wax was proposed, as it increased the heat storage capacity up to over 40 MWh in a full-scale application case while minimizing wax leakage (between 1.5% and 17%).

4.4. Green Campus Initiative

Energy laboratories on university campuses not only aid education and research but also support their sustainable development goals. This becomes possible if the energy output from the proposed laboratory is used to meet the energy demand. Though the scale of the implementation is not large, the proposed laboratory can showcase the environmental stewardess of the university. Moreover, this project is in line with the strategic plan of any university that supports an environmentally friendly campus [75]. Similarly, a solar-powered water vapor/steam ejector chiller was developed by Kauffeld et al. [76] at Karlsruhe University of Applied Sciences. In addition to providing chilled water for a laboratory building, the developed system aided in improving the temperature of the local DH system in the winter seasons.

In the present case study, the area covered by the four mounting structures accounts for 32 m^2. The different parametric values of each solar energy technology were obtained from the respective datasheets. Then, sizing was carried out by considering the available area and component area. It was estimated to be 5.77 kW_{th} for a flat plate collector, 4.32 kW_{th} for a parabolic dish collector, 1.62 kW_{ele}/5.23 kW_{th} for PVT, and 1.6 kW_{ele} for standard PV panels. The monthly energy output from each solar technology is estimated using Equation (1).

$$E_{out} = G \times A \times \eta \quad (1)$$

In Equation (1), the historical solar irradiation is in kWh/m^2 (G), the available area is in m^2 (A), and the conversion efficiency is (η). Since the aim was to estimate the cumulative heat energy from the proposed laboratory, it was considered that the electric output from PVs and PVTs would run a heat pump with a capacity of 3.22 kW. It was assumed that the overall system loss and heat pump efficiency are 20% and 300%, respectively [77]. As per our rough estimation, about 27 MWh of thermal energy can be theoretically obtained from the proposed laboratory. It was observed that the energy output varied between 0.17 MWh (December) and 4.46 MWh (May). With a cumulative energy generation of 19.95 MWh, highly productive months can be anticipated from April to August.

Further, heat demand data for the same building were collected and compared with the theoretical energy generation, as shown in Figures 4 and 5. Around 25% of the heat demand in summer (May, June, July, and August) can be met. Hence, it is anticipated that the proposed laboratory could play an important role in supporting the green initiatives of the university. However, it is to be noted that the theoretical results cannot fully reveal the actual behavior of the real system. Therefore, the Department of Energy Technology, TalTech, plans to implement the physical version of the proposed solar energy laboratory.

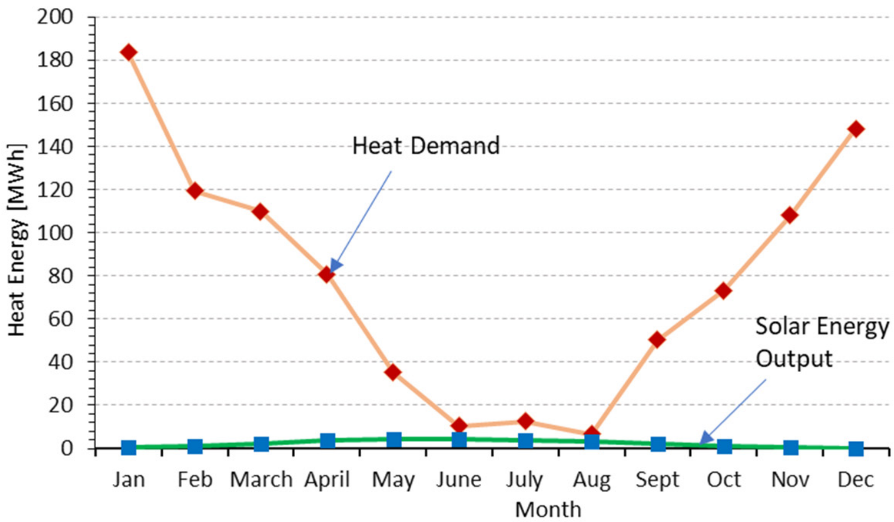

Figure 4. Monthly variation in heat demand and expected solar energy output.

The environmental benefits of clean energy technology on university campuses are reported in some pieces of literature. Hiltunen et al. [78] assessed the feasibility of a low-temperature energy cascade connection in the context of a university campus and reported that such initiatives could have significant environmental benefits by mitigating 955 tons of CO_2. Papanicolas et al. [79] presented a near-zero energy laboratory building using solar thermal and PV systems with advanced energy conservation measures and smart energy management, which resulted in reducing energy consumption by 27%. Zomer et al. [80] studied building-integrated PV (BIPV) systems from architectural perspectives (different technologies, tilt angles, and azimuthal deviations) and concluded that a higher performance ratio can be obtained from BIPV systems in comparison to ground-mounted PVs. Visa et al. [81] compared a novel trapeze solar thermal collector with a conventional flat plate version in the context of building facades. A higher efficiency steadiness was observed for the former technology under a long-term monitoring scenario. Khan et al. [82] proposed a rooftop solar PV system for a university campus for charging EV infrastructure and reported an energy generation of 1587 MWh, thereby mitigating 60,031 tons of CO_2.

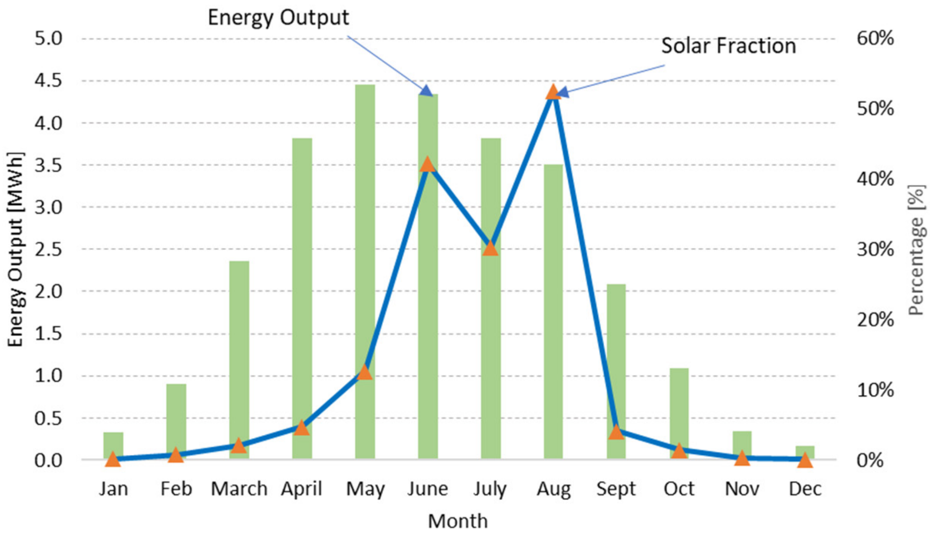

Figure 5. Monthly variation in solar energy output and solar fraction.

4.5. Discussions

The strengths and limitations of the proposed laboratory are discussed in this section. In general, laboratories provide a platform to facilitate experiments and research in a pseudo-realistic environment. It is worth noting that the direct implementation of innovative ideas in real-life situations involves socio-economic challenges. The interactions between system components can be studied effectively in lab setups. Dordelly et al. [83] conducted an experiment to investigate the impact of PCM on the ventilation performance of two different solar chimney prototypes under laboratory conditions. The proposed laboratory will act as a connecting link between simulation models and pilot projects for solar district heating systems [8]. Laboratory environments provide a suitable environment for assessing the realistic behavior of system components.

Since solar energy output depends on climatic conditions, the operation of the outdoor laboratory will be affected in the winter seasons. Moreover, the possible connection with the university's thermal grid may affect the flexibility of the experimental setup in the proposed laboratory. The energy output is roughly estimated in this study. The operational and performance aspects of the proposed laboratory will be assessed using software tools such as TRNSYS, MATLAB, etc. The concept, design, and scope of the proposed laboratory can be customized as per the learning curriculum.

The inclusion of solar cooling elements is expected to improve the scope of the proposed concept. This laboratory concept can be modified in such a way that it will operate smoothly, independent of the weather conditions. The use of laboratories remotely over the internet using computers could offer an educational service to students worldwide [24]. The development of a virtual platform could support this e-learning concept. Moreover, the proposed laboratory can be upgraded as a facility for testing solar collectors, heat pumps, distribution pipes, etc. For example, an industrial test bench for solar collectors forms a part of the Process, Material and Solar Energy (PROMES) laboratory in France [32]. Overall, the proposed system can be developed into a living laboratory for education, testing, and research on smart district heating systems.

5. Conclusions

In this paper, the design and development of a conceptual solar energy laboratory is attempted. The conceptual laboratory is based on developing a facility for experimental research in solar district heating systems. Different solar energy technologies, as well as heat emulation stations, form an important part of the proposed concept. A case study is carried out for an educational building at Tallinn University of Technology. Overall, it can be concluded that the outdoor solar energy experimental lab can support the learning, research, and green initiatives of an education campus. Due to small-scale implementation, the annual energy savings and environmental benefits from the proposed laboratory may not be significant. As per rough estimation, about 27 MWh of thermal energy can be theoretically obtained from the proposed laboratory. Around 25% of the heat demand of an educational building can be met in the summer season (May, June, July, and August). It can be concluded that the widespread adoption of solar thermal technology along with PV modules on the rooftops of the university will be a game-changer.

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