Final report

1. Project details

Project title	EUDP 2020-II IEA SHC Opgave 64 Solar procesvarme
File no.	64020-2124
Name of the funding scheme	EUDP
Project managing company / institution	DTU Construct
CVR number (central business register)	30 06 09 46
Project partners	Heliac ApS, Aalborg CSP A/S
Submission date	18 April 2024

2. Summary

English:

The project focused on developing, validating, and optimizing solar heating systems with large-scale concentrating solar collectors, heat storage, and smart controls for integration into industrial processes, emphasizing standardization.

We applied and validated a generic model for various solar collector fields and developed and validated a theoretical and numerical model for Phase Change Material (PCM) water heat storages.

A reference Solar Heat for Industrial Processes (SHIP) system in Denmark was chosen for detailed study. We thoroughly investigated and analyzed the yearly performance of this system. To facilitate deeper analysis, we developed a simulation tool, enhancing our understanding of the system's dynamics.

Our research also involved identifying relevant standards and certifications for concentrating solar collector fields, along with an analysis of potential alignments and discrepancies between our developed methods and existing standards.

The project's outcomes include the publication of four SCI papers and the development of an online calculation tool for estimating the thermal performance of different solar collector fields. Additionally, we created a system-level simulation tool.

The mathematical models for solar collector fields and PCM water heat storages are valuable for scientific research. They provide robust frameworks for exploring and understanding the dynamics of these systems. The study of the reference system in Denmark serves as a source of inspiration and a benchmark for future

projects in this domain. Moreover, the simulation tools we developed are not only instrumental in scientific research but also hold potential for application in commercial projects. Their versatility and accuracy make them valuable tools for both theoretical exploration and practical application in the field of solar energy.

Danish:

Projektet fokuserede på udvikling, validering og optimering af solvarmeanlæg med store koncentrerende solindsamlere, varmelagring og smart styring til integration i industrielle processer, med vægt på standardisering.

Vi anvendte og validerede en generisk model for forskellige solfangerfelter og udviklede og validerede en teoretisk og numerisk model for faseændringsmateriale (PCM)/vandvarmelagre.

Et reference Solar Heat for Industrial Processes (SHIP) system i Danmark blev valgt til detaljeret undersøgelse. Vi undersøgte og analyserede grundigt systemets årlige ydelse. For at lette analysen udviklede vi et simuleringsværktøj, som forbedrede vores forståelse af systemets dynamik.

Vores forskning omfattede også identifikation af relevante standarder og certificeringer for koncentrerende solfangerfelter, sammen med en analyse af potentielle overensstemmelser og afvigelser mellem vores udviklede metoder og eksisterende standarder.

Projektets resultater inkluderer offentliggørelsen af fire SCI-artikler og udviklingen af et online beregningsværktøj til estimering af termisk ydelse af forskellige solfangerfelter.

De matematiske modeller for solfangerfelter og PCM/vandvarmelagre er værdifulde for videnskabelig forskning. De tilbyder robuste rammer for at udforske og forstå dynamikken i disse systemer. Studiet af reference systemet i Danmark tjener som en kilde til inspiration og et benchmark for fremtidige projekter inden for området. Desuden er de simuleringsværktøjer, vi har udviklet, ikke kun brugbare i videnskabelig forskning, men kan også anvendes i kommercielle projekter. Deres alsidighed og nøjagtighed gør dem til værdifulde værktøjer for både teoretisk forskning og praktisk anvendelse inden for solenergiområdet.

3. Project objectives

The objectives of the project are:

•To model and validate large-scale concentrating solar collector fields, heat storages and smart controls

•To model and validate feasible solar heating systems with large-scale concentrating solar collector fields and intelligently integrate the produced heat into industrial processes.

•To simulate and optimize the developed solar heating systems for industrial process

•To optimize and promote the developed methods, results, and guideline towards standardization

The technology area in focus for this project was solar heating systems, specifically concentrating on the development, validation, and optimization of large-scale solar collector field, heat storage, and smart control systems. The project aimed to integrate these technologies into industrial processes, with an emphasis on standardization. This involved creating both theoretical and numerical modelling of components and system level simulation tool. The study and analysis of the reference Solar Heat for Industrial Processes (SHIP) system in Denmark underpinned this project, reflecting a clear dedication to enhancing the efficiency and applicability of solar heating technologies in industrial settings.

4. Project implementation

The project progressed largely as anticipated, despite the unforeseen challenges posed by the pandemic at its onset. This necessitated a shift to online for expert and project meetings during the initial two-thirds of the project duration. However, we successfully transitioned to in-person participation in expert meetings during the final year and notably organized a successful expert meeting in Copenhagen.

Overall, the project unfolded as envisioned, successfully reaching all planned milestones and fulfilling its objectives.

5. Project results

The original objective of the project was obtained.

The obtained technological results are shortly summarised by deliverables.

Deliverable 1.1

In this deliverable a generic mathematical model for modeling solar thermal collectors and fields is introduced. The method is applied to three different solar collector fields in Denmark, namely, a flat plate, a parabolic trough, and a Fresnel lens solar thermal collector field. For each collector type, the performance coefficients are derived and discussed. Overall, the applied method was shown to have sufficient accuracy for modeling all the investigated types of solar collectors and is recommended to be used for future investigations and optimization of solar thermal systems.

An example of Fresnel concentrating solar collector field in Lendemarke, Denmark was illustrated in Fig.1 and the comparison of the simulated and measured heat production was shown in Fig.2.

Fig.1 Photo of the Fresnel lens solar collector field, Lendemarke, Denmark.

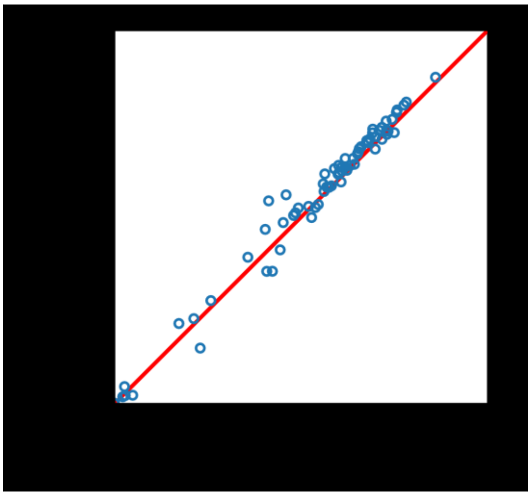

Fig.2 Comparison of simulated and measured heat production from the Lendemark solar collector field

Deliverable 1.2

In this deliverable a generic numerical model of PCM water heat storage is developed and validated by experiments. The numerical model consists of a water region and a PCM region. Models of the two regions are derived by the energy differential equations and solved by the implicit method. The solid-liquid PCM behavior is modelled based on its enthalpy-temperature relation, in which the melting/solidification phase is linearized. Special treatment is developed for the time steps with a phase change, which significantly improves the prediction accuracies of PCM temperatures and the melting fractions. An iteration method is applied to the two regions until converged results are obtained. The energy balance of the model is examined in each time step. Extended functionalities of the numerical model are further developed, including separate heat loss coefficients, auxiliary heaters, flexible inlet and outlet layout, the mixing effect in the water tank, and three PCM supercooling-activation modes. The experimental verification for a PCM water heat storage was carried out at Technical University of Denmark. The PCM and water layer temperatures are calculated. The simulated and measured outlet temperatures and heat content are compared. The results show that the simulated outlet temperatures are maximum of 4.6 K deviation from the measured. The relative error of the heat content is within 1%, and the energy balance errors are within 5%. The extended application and limitation of the numerical model are discussed, and the possible error sources are analyzed.

Fig. 3 gives an example of the simulation and experimental verification of one PCM water heat storage. The left two charts show the simulated PCM and water layer temperatures of the heat storage and the right two charts show the comparison of simulated and experimental results for the outlet temperature of the heat storage.

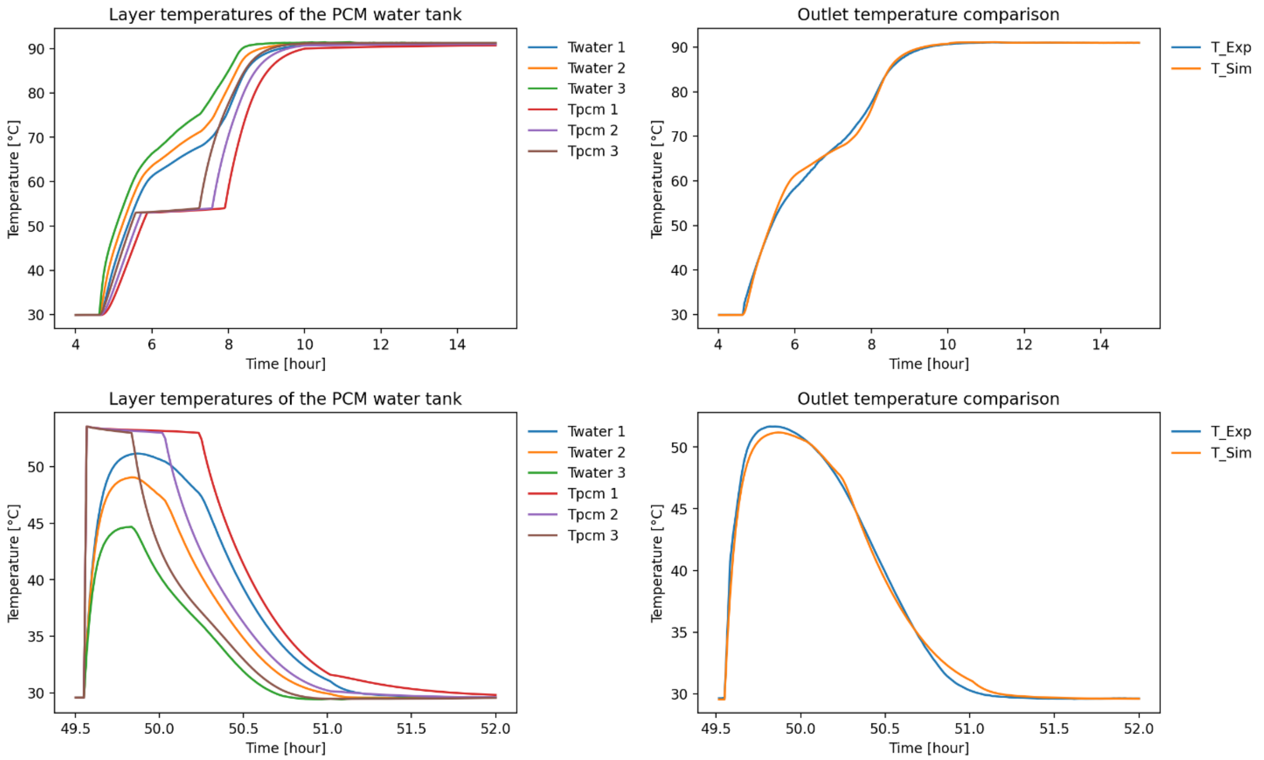

Fig.3 Simulated layer temperatures of PCM water heat storage (left) and experimental and simulated outlet temperature comparison (right) during charging and discharging period.

Deliverable 1.3

This deliverable is a literature study on the control techniques and control strategies for the Solar Heating for Industrial Process (SHIP) systems. It aims to provide the current technology overview and practical information on smart controls for the reference system in deliverable 3.2.

The advantages of using control technologies in SHIP systems are introduced. Three typical levels of control strategies are identified and reviewed according to their degree of difficulty and formulation basis. Other advanced techniques that may increase the control intelligence are introduced including using all sky imager system and artificial intelligence algorithms for solar irradiation and solar power output prediction.

Deliverable 2

In this deliverable, the Ørum solar heating plant from Aalborg CSP was selected as the reference system, focusing on its integration of eco-friendly energy production methods. The plant initially consisted of a solar field and an accumulation tank, but to meet increasing winter demands, a heat pump was added to reduce reliance on gas-fired engines/boilers.

The system's energy production is based on natural gas supplemented with solar heat. By integrating the heat pump, the facility has reduced energy costs, lowered gas consumption, and enhanced flexibility in energy production. The plant can produce approximately 10,000 MWh of heat annually, covering about 93% of customers' heat demand.

The deliverable analyzed the impact of this integrated system on energy efficiency, showing significant improvements and optimization potential. The integrated system's operation is automated and can adjust based on the availability of solar radiation and the relative costs of electricity and gas, enhancing the plant's operational flexibility.

In the second part, Heliac present a detailed technical proposal for the integration of a solar thermal energy system at a brewery, emphasizing the potential for significant renewable energy use and discussing various technical and operational considerations to optimize the system's performance.

Deliverable 3.1

A web-based simulation tool has been developed specifically for large-scale solar collector field simulation, accessible at https://solperfield.streamlit.app/. Furthermore, a TRNSYS component, Type 7000, has been formulated for the simulation of PCM water heat storage, rendering it functional for TRNSYS system simulations. Fig.4 shows the homepage of the online calculation tool.

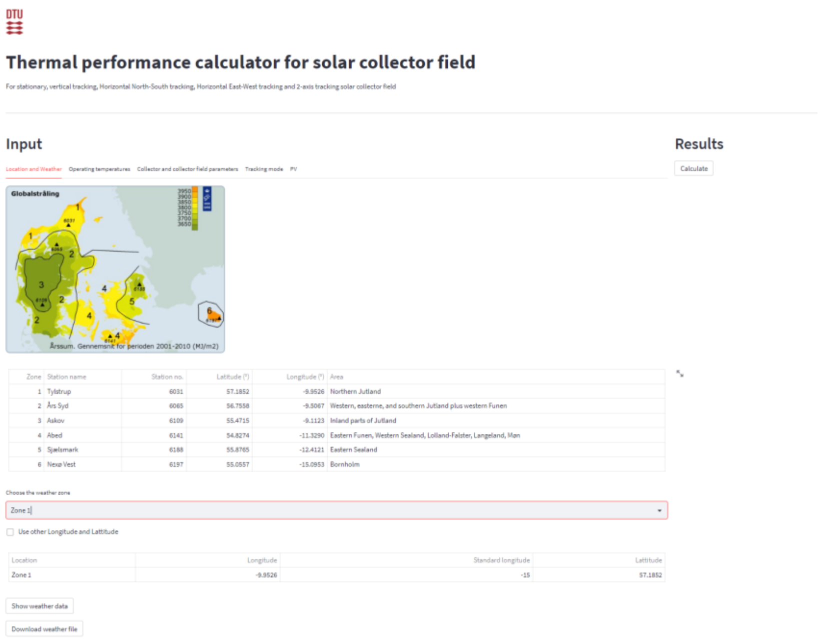

Fig. 4 Home page of the online calculation tool for solar collector field

Deliverable 3.2

This deliverable details the development, validation, and application of a Python-based simulation system for the Ørum solar heating plant. The system's design, featuring modular Python classes, allows for accurate and flexible simulations of solar heating components and their interactions. The validation process, conducted over a year, showed a high degree of accuracy with less than 3% error compared to actual plant performance, underscoring the simulation's reliability.

Further, the deliverable highlights the system's capability for optimization. Through parametric studies, it was found that increasing the tank volume and solar collector field area could significantly enhance the plant's efficiency. This insight is crucial for future improvements in design and operation.

The simulation's adaptability is also demonstrated in its application to high-temperature industrial processes. By integrating different types of solar collectors, the system successfully simulated conditions for industrial heat generation.

Deliverable 4

The deliverable reviews literature on thermal testing methods, including steady-state, quasi-dynamic, and dynamic, and their relevance to concentrating solar collectors. It outlines the challenges in thermal performance testing of solar collectors, especially large-scale concentrating types for solar heating in industrial processes. It addresses different solar thermal technologies and the necessity for manufacturers to accurately predict energy yields. The report identifies inconsistencies in testing methods, like irradiance measurement and power output modeling, which hinder direct comparisons between technologies. It calls for standardized procedures, noting that while flat plate and evacuated tubular collectors are covered by ISO 9806:2017, concentrating solar collectors lack such comprehensive standards, leading to a reliance on in-situ testing.

Target group:

- Energy and utility companies focusing on sustainable and renewable energy solutions.
- Government and regulatory bodies interested in promoting green energy initiatives.
- Environmental organizations and researchers studying the integration of renewable energy in process heat

Added Value for Stakeholders:

- Energy Companies: Gain insights into the integration of renewable energy sources with traditional heating systems, offering a model for future projects.
- Government and Regulatory Bodies: The project serves as an example of sustainable energy usage, aiding in policy formation and promotion of green initiatives.
- Environmental Organizations: Provides a case study for the effectiveness of integrated renewable energy systems in reducing carbon emissions and reliance on fossil fuels.

Published journal papers:

- Jensen, A. R., Sifnaios, I., Caringal, G. P., Furbo, S., & Dragsted, J. (2022). Thermal performance assessment of the world's first solar thermal Fresnel lens collector field. Solar Energy, 237, 447–455. https://doi.org/https://doi.org/10.1016/j.solener.2022.01.067
- Jensen, A.R.; Sifnaios, I. (2022). Modeling, Validation, and Analysis of a Concentrating Solar Collector Field Integrated with a District Heating Network. Solar, 2, 234-250. https://doi.org/10.3390/solar2020013
- Kong, W., Wang, G., Englmair, G., Nielsen, E. N. N., Dragsted, J., Furbo, S., & Fan, J. (2022). A simplified numerical model of PCM water energy storage. Journal of Energy Storage, 55, 105425. https://doi.org/https://doi.org/10.1016/j.est.2022.105425
- Pan, X., Xiang, Y., Gao, M., Fan, J., Furbo, S., Wang, D., & Xu, C. (2022). Long-term thermal performance analysis of a large-scale water pit thermal energy storage. Journal of Energy Storage, 52, 105001. https://doi.org/https://doi.org/10.1016/j.est.2022.105001

Presentations in conferences:

- Jakob Jensen. Model for subsidy-free solar thermal competitive to fossil fuels. IEA Task 64 5th Expert meeting. 2021
- Jakob Jensen. Large-Scale SHIP Installations Without Risks & Investments. UNIDO (webinar). 2021
- Jakob Jensen. Evaluation of high-temperature solar thermal opportunities in the Netherlands. TNO (advising the Dutch government on subsidy schemes needed to support solar thermal). 2021
- Weiqiang Kong. Numerical simulation of PCM heat storages. CEBE conference. 2021.
- Jakob Jensen. Market potential for industrial process heat <200C, Heliac solution, and competing solutions for this temperature range. Energistyrelsens fjernvarmegruppe under 'Center for Global Rådgivning. 2021.
- Jakob Jensen. Market potential for industrial process heat <200C, Heliac solution, and competing solutions for this temperature range. Dansk Industri (conference: "Sol Over Danmark"). 2021.

- Jakob Jensen. Solar thermal technology: OPPORTUNITY –DEMAND –SUPPLY. EuroSun conference. 2022.
- Andreas Zourellis. Aalborg CSP's solar heating solutions. IEA Workshop at DTU. 2022.
- Weiqiang Kong. Solar process heat IEA Task 64. IEA Workshop at DTU. 2022.
- Weiqiang Kong. Numerical simulation of PCM heat storages Part 2. CEBE conference. 2023.

Dissemination:

To disseminate our findings, a workshop was hosted by the DTU on November 31, 2022. Additionally, the 11th expert meeting, organized by DTU, Aalborg CSP, and Heliac, took place in Copenhagen on May 31 and June 1, 2023, facilitating further project communication.

6. Utilisation of project results

The obtained technological results from the project showcase advancements in solar thermal technology and its integration with existing heating systems, offering insights for a range of stakeholders. In the future, these results will be utilized primarily by renewable energy companies, environmental engineers, and industrial entities seeking to implement eco-friendly energy solutions. The detailed models for solar thermal collectors and PCM water heat storage systems will aid in optimizing the design and efficiency of solar thermal installations. Control strategies and simulation tools developed for Solar Heating for Industrial Process (SHIP) systems will provide advanced methodologies for effectively managing solar energy production. Moreover, the insights into thermal testing methods and the need for standardized procedures will guide manufacturers and researchers in developing more efficient and reliable solar thermal technologies. Overall, these technological results will play a crucial role in advancing the application of renewable energy in industrial sectors, contributing to a more sustainable energy future.

The project results advance energy policy objectives by promoting the use of renewable energy, particularly through the development and optimization of solar thermal technologies and integrated heating systems. These advancements not only enhance energy efficiency and innovation in both residential and industrial sectors but also contribute to environmental sustainability by reducing reliance on fossil fuels and lowering greenhouse gas emissions. Furthermore, they support economic growth and job creation in the renewable energy sector, while also aiding in the establishment of standardized procedures and best practices, crucial for the consistent and reliable implementation of energy policies focused on sustainable development and energy security.

7. Project conclusion and perspective

The project concludes that the integration of advanced solar thermal technologies, including efficient large-scale solar collector fields and heat storage systems, enhances the efficiency and effectiveness of renewable energy applications in both residential heating and shows great potential in industrial processes. These studies and reference system demonstrate a viable pathway for reducing reliance on fossil fuels, thereby contributing to environmental sustainability. The project also highlights the importance of developing control strategies and simulation tools for optimizing solar energy production, and calls for standardized testing procedures to ensure reliability and comparability across different solar thermal technologies. Overall, the project showed the potential of these technologies in advancing global energy policy objectives, particularly in promoting renewable energy and improving energy efficiency.

Currently, energy companies face challenges in promoting Solar Heating for Industrial Process (SHIP) system projects, largely due to the necessity of demonstrating tangible benefits to potential customers. These benefits primarily revolve around the systems' cost-effectiveness and their ability to operate reliably over extended periods. To address these challenges, researchers should focus on developing innovative hybrid SHIP systems. These new concepts aim to enhance system robustness and reduce operational costs, making them more appealing to customers. Looking ahead, it's anticipated that future research in this domain will concentrate on novel approaches to integrating these systems, with a particular focus on advanced simulation tools. These tools are expected to offer more precise predictions and optimizations of SHIP system performance, catering to the specific needs of different industrial processes. This research direction not only promises to refine the technology but also supports the creation of more customized, efficient, and cost-effective SHIP solutions.

The future of solar thermal technology, as shaped by the project's findings, lies in expanding and optimizing these systems for broader commercial application, coupled with ongoing research for efficiency improvements and cost reductions. Emphasis will be placed on standardizing testing procedures, integrating with other renewable sources, and enhancing control strategies using advanced technologies. These developments are expected to be supported by targeted energy policies and industry-specific adaptations, driving increased market penetration and public awareness. Collectively, these efforts will solidify solar thermal technology's role in the transition to sustainable and renewable energy solutions globally.

8. Appendices