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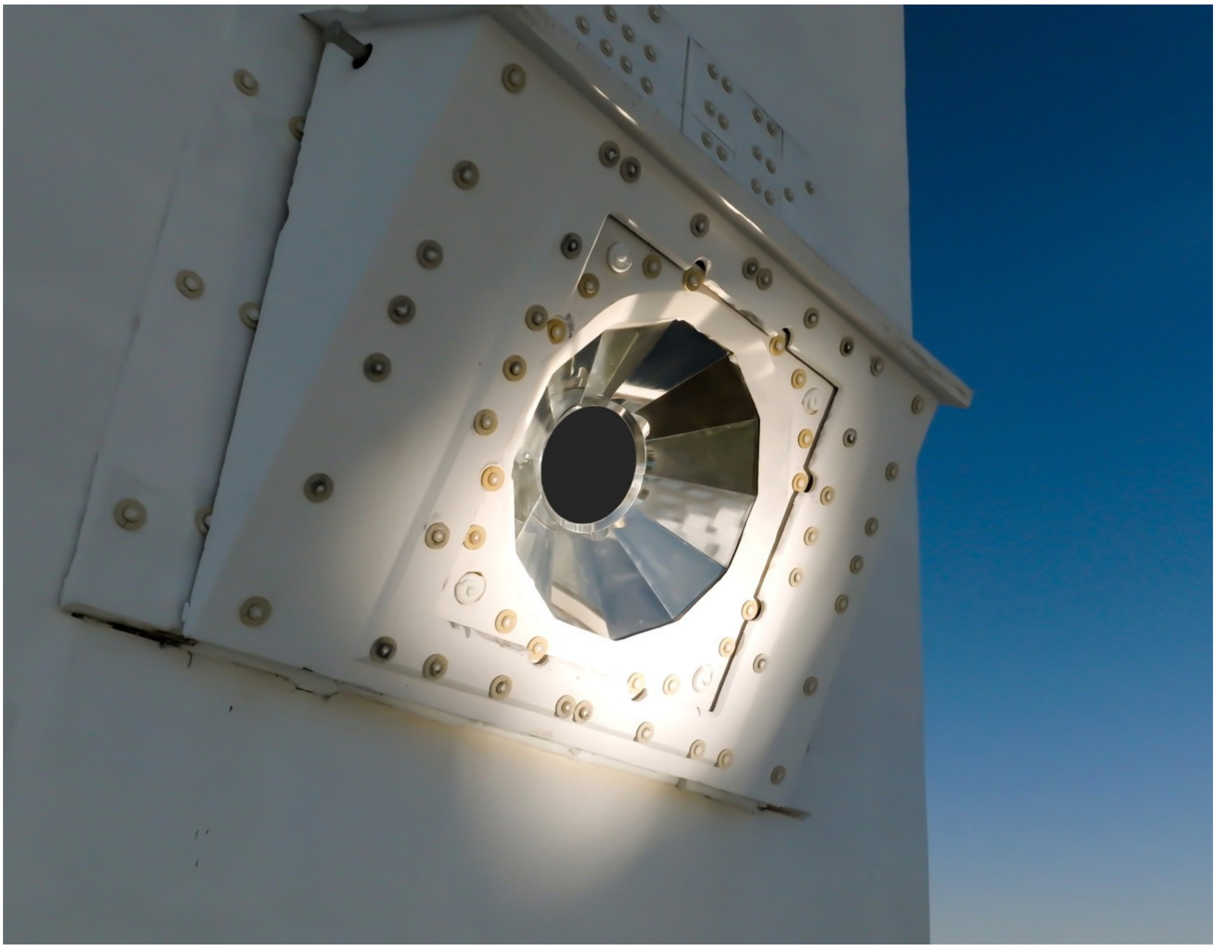
Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final report

FUELREC II

Solar Receiver for the production of solar fuels from H_2O, CO_2, and CH_4 – Part II



Source: © Synhelion SA

Date: 23 November 2023

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
Synhelion SA
Dufourstrasse 101, CH-8008 Zürich
synhelion.com

SUPSI – DTI – MEMTi
Via la Santa 1, Polo universitario Lugano - Campus Est, CH-6962 Lugano-Viganello
www.supsi.ch ; www.supsi.ch/memti

Authors:
Maurizio C., Barbato, SUPSI – DTI – MEMTi, maurizio.barbato@supsi.ch
Luca, Cornolti, SUPSI – DTI – MEMTi, luca.cornolti@supsi.ch
Giulio, Cottone-Palumbo, SUPSI – DTI – MEMTi, giulio.cottonepalumbo@supsi.ch
Marco, De Piaz, SUPSI – DTI – MEMTi, marco.depiaz@supsi.ch
Davide, Montorfano, SUPSI – DTI – MEMTi, davide.montorfano@supsi.ch
Riccardo, Puragliesi, SUPSI – DTI – MEMTi, riccardo.puragliesi@supsi.ch
Riccardo, Toffanin, SUPSI – DTI – MEMTi, riccardo.toffanin@supsi.ch
Simone A., Zavattoni, SUPSI – DTI – MEMTi, simone.zavattoni@supsi.ch
Gianluca, Ambrosetti, Synhelion SA, gianluca.ambrosetti@synhelion.com
Lukas, Geissbühler, Synhelion SA, lukas.geissbuehler@synhelion.com
Philipp, Good, Synhelion SA, philipp.good@synhelion.com
Matthias, Offergeld, Synhelion Germany GmbH, matthias.offergeld@synhelion.com
Vikas, Patil, Synhelion SA, vikas.patil@synhelion.com
David, Rutz, Synhelion SA, david.rutz@synhelion.com

SFOE project coordinator:
Stefan Oberholzer, stefan.oberholzer@bfe.admin.ch

SFOE contract number: SI/502256-01

Summary

The use of alternative fuels has been identified as a major lever for the reduction of the carbon footprint especially of aviation and maritime long-distance transport. One technological pathway for their production is via the conversion of biomass (i.e., agricultural residues, wastes, or manure). To this end, the biomass is fermented and the biogas is upgraded to synthesis gas by concentrated solar energy. To reach the required temperatures, sunlight is concentrated by a field of mirrors and focused on the top of a tower, where a receiver turns the radiation into high-temperature heat.

The development of efficient solar receivers is a cornerstone of the technology and has been progressed by a recent design of Synhelion, which makes use of the greenhouse effect to reach high temperatures at comparably low concentrations of solar radiation.

The FUELRECII project investigates the design and testing of two different solar receivers and thus helps to mature the technology and to prepare its implementation in a future plant design.

The FUELRECII project activities mainly focus two fronts:

- design and engineering of the first pre-commercial 0.6 MW (SM3) receiver;
- construction and on-sun testing of the 250 kW SM1D receiver prototype.

Concerning the former, the first pre-commercial 0.6 MW (SM3) receiver was designed and carefully analysed through a series of CFD simulations campaigns with the twofold aim of: (i) deeply understanding the physical phenomena taking place into the cavity, along with their mutual interaction, and (ii) optimizing its design in order to maximize the amount of solar energy collected by the heat transfer fluid. The receiver is currently in the final part of the engineering phase. The refractory lined cavity of SM3 was scaled by a factor two in diameter with respect to SM1D, which would allow for a factor four in power (1 MW) as originally targeted. However, due to the limited land size available for the industrial demo plant, the solar field size had to be reduced and the receiver's aperture area was designed for 0.6 m^2 or 600 kW concentrated solar input power. Nevertheless, a segmented window aperture, based on a sequence of quarter quartz tubes, was chosen for SM3, compared to the flat quartz window of SM1D. Even though the segmented window is not completely airtight anymore, specific CFD simulations allowed to observe the effective atmospheric sealing by the proposed solution. The manufacturability, and cutting, of the quarter quartz tubes were confirmed through specific tests conducted by the suppliers. Both concepts, the lightweight thermal insulation of the cavity based on fibre modules as well as the segmented window aperture are scalable to a commercial multi-megawatt scale. An innovative solution for insulating the receiver was also proposed and evaluated through a CFD-based approach. This active thermal insulation solution consists of a straight tubes bundle, parallel to the cavity axis, integrated into the conventional insulating material at few centimetres from the internal cavity walls. The heat transfer fluid is preheated by flowing through the tubes bundle from the rear part of the receiver to the front section where it is fed into the cavity. Despite the more complex mechanical design, the major foreseen advantages provided by this solution are: a reduction of the receiver thermal mass (useful to reduce the transients) and a slight reduction on the heat loss from the external surfaces. However, based upon the feedback from the insulation manufacturer underlying challenges in the installation of curved tubes through the insulation, it was decided to avoid the implementation of the active thermal insulation exploiting a conventional manifold to feed steam into the cavity. Furthermore, a preliminary design of the receiver aperture internal cooling, based on a series of radial jets parallel to the aperture, was also proposed and evaluated.

The 250 kW SM1D receiver prototype was constructed and then exploited to on-sun testing from July 2022 until October 2023. During the engineering and construction phase, special care was given to the design of a proper water-cooling system for the secondary concentrator which showed some malfunctioning during one of the experimental campaigns. In general, SM1D reliably delivered steam at temperatures above 1’000 °C and was successfully coupled to a gas-heated reformer for the production of solar syngas.

Zusammenfassung

Die Nutzung alternativer Kraftstoffe wurde als wichtiger Hebel zur Reduzierung des CO2-Fussabdrucks insbesondere im Luft- und Seefernverkehr identifiziert. Ein technologischer Weg zu ihrer Herstellung führt über die Umwandlung von Biomasse (d. h. landwirtschaftliche Rückstände, Abfälle oder Gülle). Zu diesem Zweck wird die Biomasse fermentiert und das Biogas durch konzentrierte Sonnenenergie zu Synthesegas veredelt. Um die erforderlichen Temperaturen zu erreichen, wird das Sonnenlicht durch ein Feld von Spiegeln gebündelt und auf die Spitze eines Turms fokussiert, wo ein Receiver die Strahlung in Hochtemperaturwärme umwandelt.

Die Entwicklung effizienter Solar-Receiver ist ein Eckpfeiler der Technologie und wurde durch ein aktuelles Design von Synhelion vorangetrieben, das den Treibhauseffekt nutzt, um hohe Temperaturen bei vergleichsweise geringen Konzentrationen der Sonnenstrahlung zu erreichen.

Das FUELRECII-Projekt untersucht die Konstruktion und Erprobung von zwei verschiedenen Solarreceivern und trägt so dazu bei, die Technologie zu verbessern und ihre Umsetzung in einem zukünftigen Anlagenentwurf vorzubereiten.

Die Aktivitäten des FUELRECII-Projekts konzentrieren sich hauptsächlich auf zwei Bereiche:

- Entwurf und Konstruktion des ersten vorkommerziellen 0,6-MW-Receivers (SM3)
- Bau und Erprobung des 250-kW-SM1D-Receiverprototyps auf der Sonne

Was den ersten Punkt betrifft, so wurde der erste vorkommerzielle 0,6-MW-Receiver (SM3) entworfen und durch eine Reihe von CFD-Simulationskampagnen sorgfältig analysiert, mit dem zweifachen Ziel: (i) ein tiefes Verständnis der physikalischen Phänomene, die im Hohlraum stattfinden, sowie ihrer gegenseitigen Wechselwirkung zu erlangen und (ii) sein Design zu optimieren, um die Menge der von der Wärmeträgerflüssigkeit gesammelten Sonnenenergie zu maximieren. Der Receiver befindet sich derzeit im letzten Teil der Konstruktionsphase. Der feuerfest ausgekleidete Hohlraum von SM3 wurde im Durchmesser im Vergleich zu SM1D um den Faktor zwei vergrössert, was eine Vervierfachung der Leistung (1 MW) ermöglichen würde, wie ursprünglich angestrebt. Aufgrund der begrenzten Landfläche, die für die industrielle Demonstrationsanlage zur Verfügung stand, musste die Grösse des Solarfelds jedoch reduziert werden, und die Aperturfläche des Receivers wurde für 0,6 m^2 oder 600 kW konzentrierte Solareingangsleistung ausgelegt. Dennoch wurde für SM3 eine segmentierte Fensteröffnung gewählt, die auf einer Abfolge von Viertelquarzröhren basiert, im Vergleich zum flachen Quarzfenster von SM1D. Obwohl das segmentierte Fenster nicht mehr vollständig luftdicht ist, konnte durch spezifische CFD-Simulationen die effektive atmosphärische Abdichtung durch die vorgeschlagene Lösung beobachtet werden. Die Herstellbarkeit und das Zuschneiden der Viertelquarzröhren wurden durch spezifische Tests bestätigt, die von den Lieferanten durchgeführt wurden. Beide Konzepte, die leichte Wärmedämmung des Hohlraums auf der Basis von Fasermodulen sowie die segmentierte Fensteröffnung, sind auf einen kommerziellen Multi-Megawatt-Massstab skalierbar. Eine innovative Lösung zur Isolierung des Receivers wurde ebenfalls vorgeschlagen und durch einen CFD-basierten Ansatz bewertet. Diese aktive Wärmedämmlösung besteht aus einem Bündel gerader Rohre, die parallel zur Hohlraumachse verlaufen und wenige Zentimeter von den inneren Hohlraumwänden entfernt in das herkömmliche Isoliermaterial integriert sind. Die Wärmeträgerflüssigkeit wird vorgewärmt, indem sie durch das Rohrbündel vom hinteren Teil des Receivers zum vorderen Abschnitt fliesst, wo sie in den Hohlraum geleitet wird. Trotz des komplexeren mechanischen Designs sind die wichtigsten Vorteile dieser Lösung: eine Reduzierung der thermischen Masse des Receivers (nützlich zur Reduzierung der Transienten) und eine leichte Reduzierung des Wärmeverlusts von den Aussenflächen. Aufgrund der Rückmeldungen des Dämmungsherstellers zu den Herausforderungen bei der Installation gebogener Rohre durch die Dämmung wurde jedoch beschlossen, die Umsetzung der aktiven Wärmedämmung zu vermeiden und stattdessen einen herkömmlichen Verteiler zur Dampfeinspeisung in den Hohlraum zu verwenden. Darüber hinaus wurde auch ein vorläufiger Entwurf der Innenkühlung der Receiveröffnung auf der Grundlage einer Reihe von parallel zur Öffnung verlaufenden Radialstrahlen vorgeschlagen und bewertet.

Der 250-kW-SM1D-Receiverprototyp wurde gebaut und dann von Juli 2022 bis Oktober 2023 für Tests auf der Sonne genutzt. Während der Konstruktions- und Bauphase wurde besonderes Augenmerk auf die Entwicklung eines geeigneten Wasserkühlsystems für den Sekundärkonzentrator gelegt, der während einer der experimentellen Kampagnen einige Fehlfunktionen aufwies. Im Allgemeinen lieferte SM1D zuverlässig Dampf mit Temperaturen von über 1000 °C und wurde erfolgreich mit einem gasbeheizten Reformer zur Erzeugung von solarem Synthesegas gekoppelt.

Résumé

L'utilisation de carburants alternatifs a été identifiée comme un levier majeur pour la réduction de l'empreinte carbone, en particulier pour l'aviation et le transport maritime à longue distance. L'une des voies technologiques pour leur production est la conversion de la biomasse (c'est-à-dire des résidus agricoles, des déchets ou du fumier). À cette fin, la biomasse est fermentée et le biogaz est transformé en gaz de synthèse grâce à l'énergie solaire concentrée. Pour atteindre les températures requises, la lumière du soleil est concentrée par un champ de miroirs et dirigée vers le sommet d'une tour, où un récepteur transforme le rayonnement en chaleur à haute température.

Le développement de récepteurs solaires efficaces est la pierre angulaire de la technologie et a progressé grâce à la conception récente de Synhelion, qui utilise l'effet de serre pour atteindre des températures élevées avec des concentrations de rayonnement solaire comparativement faibles.

Le projet FUELRECII étudie la conception et les essais de deux récepteurs solaires différents et contribue ainsi à la maturation de la technologie et à la préparation de sa mise en œuvre dans une future centrale.

Les activités du projet FUELRECII se concentrent principalement sur deux fronts :

- la conception et l'ingénierie du premier récepteur pré-commercial de 0,6 MW (SM3) ;
- la construction et les essais au soleil du prototype de récepteur SM1D de 250 kW.

En ce qui concerne le premier, le premier récepteur précommercial de 0,6 MW (SM3) a été conçu et soigneusement analysé à travers une série de campagnes de simulations CFD dans le double but de : (i) comprendre en profondeur les phénomènes physiques qui se déroulent dans la cavité, ainsi que leur interaction mutuelle, et (ii) optimiser sa conception afin de maximiser la quantité d'énergie solaire collectée par le fluide caloporteur. Le récepteur se trouve actuellement dans la dernière partie de la phase d'ingénierie. La cavité à revêtement réfractaire de SM3 a été agrandie d'un facteur deux en diamètre par rapport à SM1D, ce qui permettrait d'augmenter la puissance d'un facteur quatre (1 MW) comme prévu à l'origine. Cependant, en raison de la taille limitée du terrain disponible pour l'installation de démonstration industrielle, la taille du champ solaire a dû être réduite et l'ouverture du récepteur a été conçue pour 0,6m2 ou 600 kW de puissance d'entrée solaire concentrée. Néanmoins, une fenêtre segmentée, basée sur une séquence de quarts de tubes de quartz, a été choisie pour SM3, par rapport à la fenêtre de quartz plate de SM1D. Même si la fenêtre segmentée n'est plus complètement étanche à l'air, des simulations CFD spécifiques ont permis d'observer l'efficacité de l'étanchéité atmosphérique de la solution proposée. La fabricabilité et la découpe des quarts de tubes de quartz ont été confirmées par des essais spécifiques réalisés par les fournisseurs. Les deux concepts, l'isolation thermique légère de la cavité basée sur des modules de fibres et l'ouverture segmentée de la fenêtre, sont extensibles à une échelle commerciale de plusieurs mégawatts. Une solution innovante pour l'isolation du récepteur

a également été proposée et évaluée par une approche basée sur la CFD. Cette solution d'isolation thermique active consiste en un faisceau de tubes droits, parallèles à l'axe de la cavité, intégrés dans le matériau isolant conventionnel à quelques centimètres des parois internes de la cavité. Le fluide caloporteur est préchauffé en circulant dans le faisceau de tubes depuis la partie arrière du récepteur jusqu'à la partie avant où il est introduit dans la cavité. Malgré une conception mécanique plus complexe, les principaux avantages prévus de cette solution sont : une réduction de la masse thermique du récepteur (utile pour réduire les transitoires) et une légère réduction de la perte de chaleur par les surfaces externes. Toutefois, sur la base des informations fournies par le fabricant de l'isolant, qui soulignent les difficultés liées à l'installation de tubes courbes à travers l'isolant, il a été décidé d'éviter la mise en œuvre de l'isolation thermique active en utilisant un collecteur conventionnel pour introduire la vapeur dans la cavité. En outre, une conception préliminaire du refroidissement interne de l'ouverture du récepteur, basée sur une série de jets radiaux parallèles à l'ouverture, a également été proposée et évaluée.

Le prototype de récepteur SM1D de 250 kW a été construit puis exploité pour des essais sur le soleil de juillet 2022 à octobre 2023. Au cours de la phase d'ingénierie et de construction, une attention particulière a été accordée à la conception d'un système de refroidissement par eau approprié pour le concentrateur secondaire, qui a présenté quelques dysfonctionnements au cours de l'une des campagnes expérimentales. En général, SM1D a fourni de la vapeur à des températures supérieures à 1000 °C et a été couplé avec succès à un reformeur chauffé au gaz pour la production de gaz de synthèse solaire.

Abbreviations

ATI	Active thermal insulation
CFD	Computational fluid dynamics
GHR	Gas heated reformer
HTC	Heat transfer coefficient
HTF	Heat transfer fluid

Contents

1 Introduction

1.1 Background information and current situation

The substitution of fossil fuels is one of the most pressing challenges that modern society is facing at the global level. Especially, liquid hydrocarbon fuels offer exceptionally high energy densities and are most convenient for the transportation sectors without changes in the current global infrastructure. However, their production from H_2O and CO_2 using solar energy has remained a grand challenge [1].

Synhelion is currently developing the technology for the production of solar fuels suitable for commercial scale operations. The key innovations introduced are related to: (i) an innovative solar receiver concept capable of operating at temperature levels beyond 1'500 °C; (ii) the thermochemical reactor wherein redox reactions for syngas production take place and (iii) a thermal energy storage system enabling continuous (24/7) operations.

The present project focuses on the development of the innovative high temperature solar receiver depicted in figure 1. This receiver exploits the ability of water vapor or carbon dioxide to absorb a significant fraction of longer wavelength thermal radiation while being mostly transparent to terrestrial solar radiation. The receiver operation principle is similar to the "greenhouse effect": it relies on a flowing gas volume between an aperture and the black internal surfaces of the cavity, heated by solar radiation, to absorb the thermal re-radiation of these surfaces and to shield the aperture from it. At the same time, the gas is heated by such absorption and acts as heat transfer fluid (HTF). In principle, the receiver works with thermal radiation only as heat transfer mechanism and does not require, *a priori*, any convective contribution.

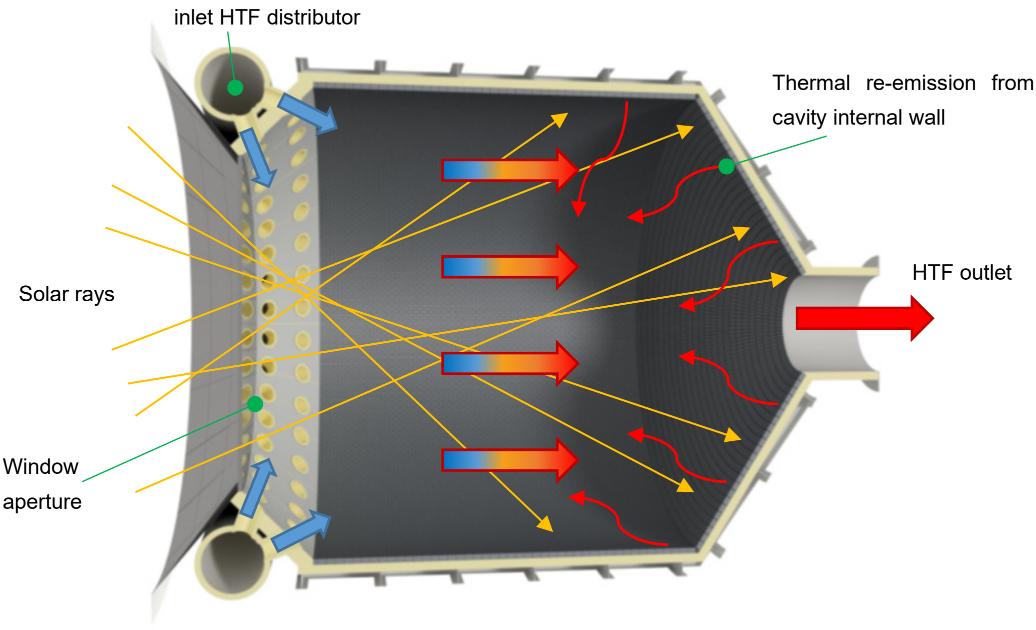


Figure 1: Schematic illustration of the cavity-type absorbing gas receiver concept.

1.2 Work performed in previous projects

Two projects form the basis for the work performed in this project: the ReceiverSIM project (10.2017 – 07.2018) and the FUELREC project (09.2018 – 12.2020).

ReceiverSIM project (SI-501618-01) - In the framework of the BFE funded ReceiverSIM project, a CFD-based approach has been developed on-purpose with the aim of accurately replicating the behaviour of this innovative absorbing gas receiver concept. However, to ensure a good compromise between accuracy and computing time, radiative heat transfer in participating media was modelled exploiting the discrete ordinates (DO) method with spectral variation of the participating medium radiation properties approximated through the weighted-sum-of-gray-gases (WSGG) model. Extensive CFD modelling of the receiver, including fluid flow and heat transfer, confirmed the results of the MC-LBL simulations and provided important information about the effects of parameters, such as heat transfer fluid mass flow rate, heat transfer fluid entrance angle, gravity, operating pressure, and concentrated solar flux distribution on the receiver performance (details about the study are available in [2]).

FUELREC project (SI/501796-01) - A relevant step forward in the development of the absorbing gas receiver technology was achieved through the consecutive BFE funded project FUELREC. In this project, besides allowing to deeply understand the physical mechanisms governing fluid flow and heat transfer into the receiver, along with their mutual interactions, the validated CFD model was also extensively exploited to assist the design phase of the first 200 kW prototype [3]. The latter, was experimentally tested at the world's largest solar simulator facility (DLR-Synlight) between summer 2019 and spring 2020 [4]. Several experimental campaigns were successfully carried out which led to the achievement of an HTF outflow temperature of up to 1'550 °C, and allowed also to demonstrate not only the feasibility of this receiver technology but also its reliability and, especially, its remarkable efficiency.

1.3 Tasks of this project

A major challenge for the commercial implementation of the receiver technology is its successful scale-up. Synhelion has devised a scale-up plan to arrive at MW-scale receivers that will allow to benefit from the more favorable surface-to-volume ratios at this scale. Heat losses can be significantly reduced both in the receiver and in the heat transfer to the reactor via the heat transfer fluid. However, a successful scale-up requires careful design of successively increasing receiver sizes to learn from earlier designs and to reduce the financial risk of a larger prototype. Therefore, this project aims at advancing the Synhelion technology through further development and engineering of the receiver to arrive at the design of a 0.6-1 MW pre-commercial scale prototype. The valuable knowledge acquired during previous experimental tests on a 200 kW prototype, performed in the framework of FLUELREC project (SI/501796-01), will be exploited, along with the support given by the CFD model previously developed, as relevant starting points for elaborating engineering solutions to overcome the major limitations observed.

Major challenges are mostly related to the thermal management of the quartz window located on the receiver aperture. For this reason, a window internal cooling system will be designed to achieve a proper thermal management of this delicate receiver component. Therefore, the design and realization of two new receiver prototypes is foreseen (SM1D – 250 kW with window internal cooling and SM3 – 0.6-1 MW pre-commercial scale) which will then be tested on sun not only to assess their performance but also to evaluate if additional engineering work is required prior the technology scale-up at commercial level.

Furthermore, some efforts will also be devoted to assess the feasibility of further advancing the receiver technology through the development of a "windowless" receiver wherein the quartz window will be substituted with, for instance, an aerodynamic sealing solution. This is a development that is required for the scale-up of receiver apertures beyond about 1 m of diameter. Windows this large would have to become very thick, which would attenuate the radiation and become very heavy and costly to manufacture. To this end, simulations can help to limit the cost of receiver development as the technology can be developed virtually and some preliminary testing and optimization can occur on the computer. The resulting optimal configuration is then manufactured and tested on-sun. The work performed in this project is thus applicable to the technological development of the whole field of CSP cavity receivers.

1.4 Objectives

From the identification of the main limitations of the prototypes used so far, and the need for further scale-up, the following objectives are deduced for this project.

1) Experimental validation of the CFD modelling approach, developed in the framework of the previous ReceiverSIM and FUELREC projects, against some relevant experimental data gathered during the tests at Synlight.
2) Study and design of the internal cooling for the receiver window. This point is relevant for the thermal management of the window and fixtures and for controlling the window aging (critical aspects observed during the experimental campaigns of FUELREC project).
3) Design of a new 250 kW prototype, with window internal cooling system, to be tested on field at DLRs solar tower test facility in Jülich.
4) Study and design of a windowless receiver based on aerodynamic sealing solutions.
5) Design finalization of the 0.6 MW pre-commercial scale receiver (e.g., HTF inlet manifold, HTF outlet section and circuit, thermal insulation).

2 Procedures and methodology

All the planned executive activities for this project can be grouped into two categories: conception & realization and testing. Concerning the former, the methodology followed was based on the exploitation of a CFD-based approach to assist the design phase of the components under investigation; while, for testing, specific tests procedures and protocols were applied to ensure safety and the reliability of the measured data.

The receiver digital twin, for the conception & realization phase, was developed in the framework of the previous ReceiverSIM and FUELREC projects. It was developed exploiting the commercial code Fluent from ANSYS which relies on the finite volume method to numerically solve the fundamental transport equations (i.e., mass, momentum, energy, turbulent quantities, etc.) exploited to replicate the thermo-fluid dynamics behavior of the real (physical) system. As previously described (see paragraph 1.1), the receiver mimics terrestrial greenhouse effect exploiting the flow of a gaseous heat transfer fluids, with suitable optical properties, to volumetrically, and effectively, capture the incoming concentrated solar radiation in the form of thermal energy. Therefore, to ensure a good accuracy of the numerical model, radiative heat transfer in participating medium (i.e., a medium that absorbs, emits, or scatters the electromagnetic radiation travelling through it) was accounted for. In detail, the discrete ordinates (DO) method, coupled with the weighed-sum-of-gray-gasses model, were selected as suitable solution to solve the radiative transfer equation and to account for the spectral variation of the HTF optical properties respectively. Despite not being the most accurate numerical methods available to model radiative heat transfer in participating media, they were anyway selected as reliable options offering a good tradeoff between accuracy of the results and computational time (and resources) needed to complete the simulations. Here are some other numerical details related to the developed modeling strategy. The pressure correction equation was solved by coupling the pressure and velocity fields using the SIMPLE (i.e., semi-implicit method for pressure-linked equations) algorithm. The pressure values at the cell faces were interpolated through PRESTO! (PREssure STaggering Option) scheme and the spatial discretization of the transport equations were performed with a second order accurate upwind scheme [5]. Convergence was considered to have been achieved when the mass, momentum and turbulent quantities residuals were below 10-5, the DO and energy residuals were below 10-8 and 10-9 respectively.

After a first numerical validation, this receiver digital twin was extensively exploited not only to drive the receiver design and engineering phase nut also to predict the receiver performance (i.e., temperature distribution, flow field, pressure field, receiver efficiency, etc.) assuming it to operate under representative operating conditions.

3 Activities and results

3.1 Short summary of previously reported activities and results

The activities of the first six months of FUELRECII project, from June 2021 until December 2021, were mainly focused on two fronts:

- experimental validation of the CFD model, developed in the framework of former BFE-funded ReceiverSIM and FUELREC projects, aimed at replicating the thermo-fluid dynamics behaviour of the innovative absorbing gas receiver concept proposed by Synhelion;
- design, engineering and realization of the new SM1D receiver prototype with window internal cooling.

Concerning the CFD model experimental validation, two reference experimental campaigns, carried out in the framework of FUELREC project, were selected as reference to be numerically replicated. The major difference between these cases was the total heat transfer fluid (HTF) mass flow rate; in one case the nominal of 209 kg/h, leading to a measured HTF outflow temperature of 1’200 °C, was assumed; while, in the second case, the minimum HTF mass flow rate of 50.1 kg/h, which allowed to achieve the record-high measured HTF outflow temperature of 1’550 °C, was considered. According to the simulations results, a good accuracy was observed for the case of nominal HTF mass flow rate wherein the predicted HTF outflow temperature was lower by 0.6% only with respect to the measured one. The model accuracy decreases, in the case of minimum HTF mass flow rate, leading to an underestimation of 5% with respect to the measured HTF outflow temperature. Nevertheless, the model accuracy was considered to be satisfactory and hence, no additional improvements activities were executed.

The other relevant project activities were focused on the design, engineering and realization of the new 250 kW SM1D receiver prototype, including the window internal cooling system, which will be tested on-sun at the DLR’s solar tower facility in Jülich. The window thermal management solution under investigation was based on a series of radially-oriented gaseous jets located in the vicinity of the internal surface of the window. For the design of this window cooling solution, a CFD-based parametric analysis was conducted with the aim of evaluating the effect of relevant parameters, such as jets inlet velocity, jets number and inlet cross section, on the cooling effectiveness of the system. Various CFD simulations campaigns were conducted which allowed to determine the most suitable configuration of the parameters analyzed. In detail, among the proposed configurations, the 72 jets solution, with 4 mm inlet section diameter and 25 m/s as inlet velocity, allowed to achieve the highest cooling effectiveness evaluated in terms of window temperature distribution and resulting heat transfer coefficient. The effect of integrating a tangential component on the jets inlet velocity vector, up to 60°, was also investigated but without obtaining promising results.

Based on the simulations results, the SM1D receiver prototype with window internal cooling system was designed and its performance were preliminarily evaluated exploiting the validated CFD modelling approach. Two representative scenarios of receiver boundary and operating conditions were analysed and, for both of them, the efficiency resulted to be higher (up to 3% at most) with respect to the receiver operating without any window thermal management system. Given the promising foreseen results, once the engineering phase was completed, the SM1D receiver prototype was realized. In parallel, the preliminary design phase of the first 0.6-1 MW pre-commercial scale receiver was also started.

The activities of the second part FUELRECII project, from January 2022 until March 2023, were mainly focused on three fronts:

- numerical feasibility study of a windowless version of the Synhelion receiver;
- design and engineering of the first pre-commercial 0.6-1 MW (SM3) receiver;
- construction and on-sun testing of the 250 kW SM1D receiver prototype.

In the field of cavity-type solar receivers, quartz windows are commonly exploited to physically separate the cavity from the external environment. However, despite being the state-of-the art solution for cavity isolation, limitations like costs, thermo-mechanical stability under severe temperature gradients and surface dullness due to dust and debris deposition, make it a delicate component for an efficient receiver operation. For this reason, an in-depth feasibility study of a windowless version of the Synhelion receiver, based on aerodynamic sealing solutions, has been conducted with the aim of proposing a suitable cavity isolation alternative allowing to get rid of the conventional quartz window. Several configurations of aerodynamic sealing were proposed (e.g., single, double, quadruple, radial or vertical, and so on), and numerically tested through specific parametric analyses, with the aim of obtaining a design which ensures a suitable steam concentration (> 95%), on the cavity outlet section, for a proper operation of the plant. The major conclusion of this activity was that, despite all the variations tested, none of the proposed windowless receiver design solutions was capable of meeting the sealing requirements.

In parallel, the first pre-commercial 0.6-1 MW (SM3) receiver was preliminarily designed. Apart from the receiver capacity (4 times higher than the prototype), the major difference with respect to the previous receiver prototype lays in the implementation of a segmented window aperture, based on a sequence of quarter quartz tubes, instead of a flat quartz window. Despite this causes the aperture not to be airtight any more, specific CFD simulations allowed to observe the effectiveness of the proposed solution. The manufacturability, and cutting, of the quarter quartz tubes were confirmed through specific tests conducted by the supplier.

Furthermore, the 250 kW SM1D receiver prototype was constructed and then exploited to on-sun testing from August 2022 until November 2022. During the engineering and construction phase, special care was given to the design of a proper water-cooling system for the secondary concentrator which showed some malfunctioning during one of the experimental campaigns.

The following chapters document the activities carried out during the final part of FUELRECII project. These activities were mainly related to:

- updates on the advancement in the design and engineering of the SM3 receiver prototype (including the engineering of the external metallic shell, the thermal insulation, the CFD-assisted design of the active thermal insulation (ATI), the preliminary design of the internal aperture cooling system and some preliminary high-temperature tests of the proposed materials to sustain the quartz tubes constituting the receiver aperture);
- updates on the construction and on-sun testing of the 250 kW SM1D prototype.

3.2 Advancement in the design and engineering of the SM3 receiver prototype

3.2.1 SM3 receiver metallic shell – Detailed engineering

The design of the SM3 receiver metallic shell underwent a series of changes (see figure 2). The initial design was a massive, cylindrical vessel that was eventually deemed too heavy. Following discussions with the manufacturer, the design was changed to a lighter, sheet metal, 8-sided vessel for ease of manufacturing while still maintaining structural strength. The design was eventually revised through further discussions to a 16-sided vessel to approximate a cylindrical cavity as practically as possible, which would be advantageous for heat transfer and fluid flow. The receiver front section, that houses the window and aperture cooling, was also revised in parallel from a large, square box to a compact, 16-sided box for convenient connection with the main shell and for saving space in the solar tower.

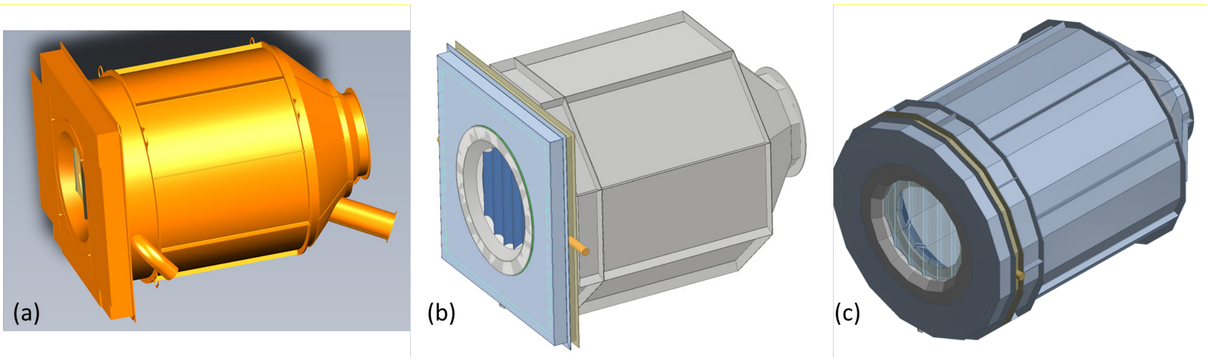


Figure 2: Evolution of the receiver metallic shell design: (a) initial, massive cylindrical vessel, (b) intermediate, lightweight sheet metal, 8-sided vessel, (c) final, lightweight sheet metal, 16-sided vessel.

Furthermore, key components of the shell were implemented in detail, including steam condensate traps at the bottom, thermocouple sleeves, cable ducts, lifting lugs, and consoles at the front and rear for fixing the receiver to the tower beam structure (see figure 3). The receiver will be suspended from the tower structure and tilted 25° from the horizontal using the consoles. The front console consists of an adjustable bolt screw connector. The back console consists of a shaft and bearing connection. Thermo-mechanical simulations were also performed to design the consoles for safely accommodating thermal stresses and strains imposed by the receiver shell at high temperatures (see figure 4).

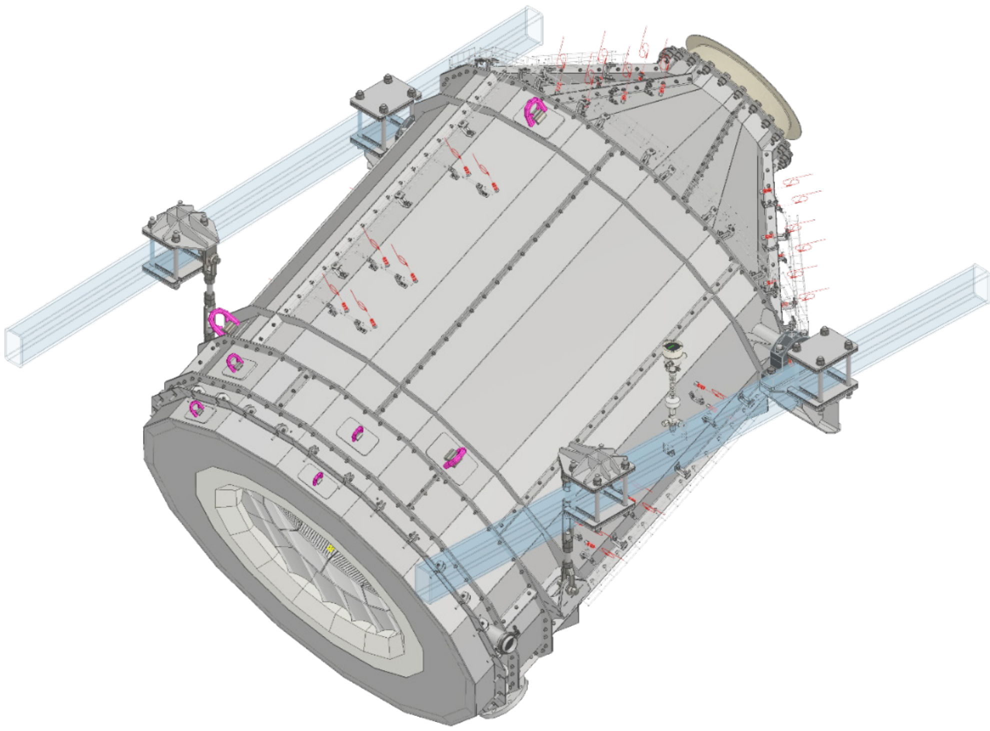


Figure 3: Key components of the receiver metallic shell: thermocouple sleeves, cable ducts, lifting lugs and consoles at the front and rear for fixing and tilting the receiver to the tower beam structure.

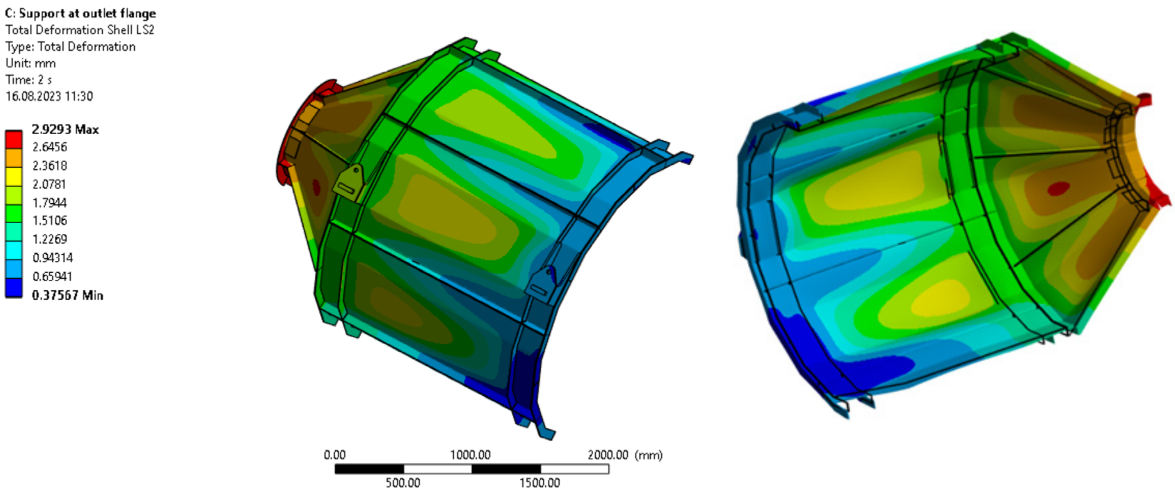


Figure 4: Representative result of a thermo-mechanical simulation to guide the design of the receiver metallic shell connections to the tower structure via consoles at the front and rear.

3.2.2 Active thermal insulation (ATI) system

A different solution for insulating the receiver and for feeding the HTF through the cavity was proposed and evaluated. It consists of a tubes bundle, integrated into the solid receiver insulating material, located at a predefined radial distance from the internal cavity lateral wall. In the rear part of the receiver, a HTF manifold is exploited to homogeneously feed the HTF through all the pipes. Once in the pipes, the HTF flows from the rear part of the receiver to the front entering therefore into the cavity near the aperture. Figure 5 shows a schematic representation of the ATI integrated into the receiver. Referring to that, it's worth to mention that the HTF manifold is only idealized for representation purpose; it still has to be designed and, highly likely, its geometry will be different than the one represented here (anulus with a square cross-section).

The reasons behind the development of this alternative insulating solution were mainly two: (i) to pre-heat the HTF prior entering the cavity by exploiting a fraction of the heat that would have been otherwise lost to the environment and (ii) to reduce the receiver thermal inertia having therefore a consequent beneficial impact on the receiver transients.

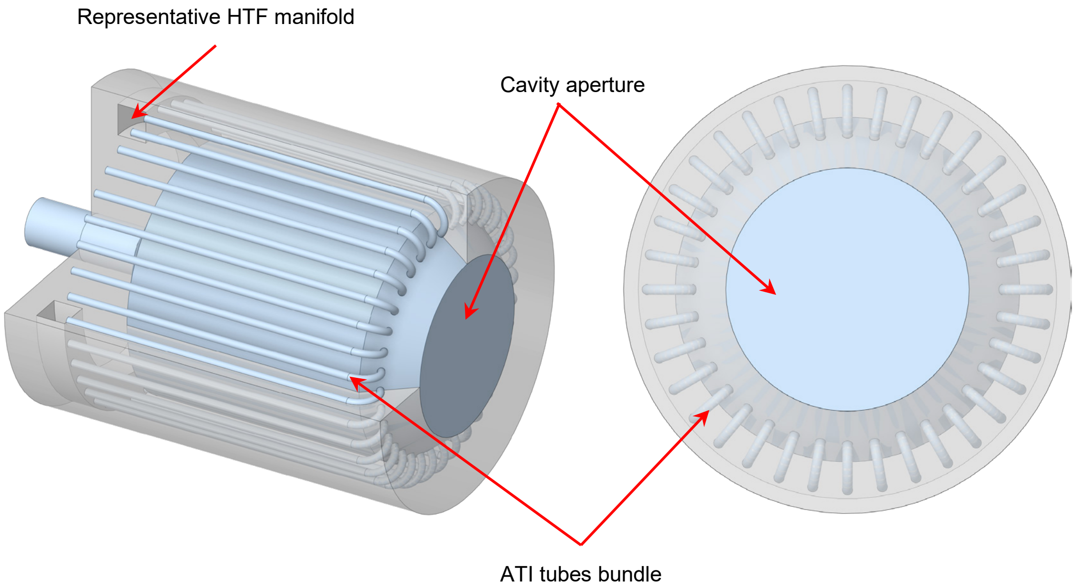


Figure 5: Schematic of the ATI integrated into the receiver.

Receiver with ATI – Effect of tubes number

To properly design the ATI, an extensive CFD-based analysis has been conducted considering two different ATI configurations, in terms of tubes number (36 and 64), and two reference receiver operating conditions (i.e., full load and part-load operations). To finally evaluate the impact of the ATI on the receiver performance, the CFD simulations results obtained, in terms of receiver thermo-fluid dynamics behaviour and efficiency, were then compared with those referred to a conventional absorbing gas receiver operating without ATI.

Table 1 summarizes the main boundary and operating conditions considered for the CFD simulations, along with some representative results obtained. By looking at these results from a macroscopic standpoint it can be concluded that, operating the receiver in part load has a remarkable detrimental effect on its performance. Moreover, still focusing on the receiver subjected to part load steady operations, it can be seen that the ATI doesn't have a noticeable impact on the receiver behaviour if compared to the conventional design (i.e., no ATI). The situation is different if the receiver is operated at steady nominal condition (i.e., full load); in this case, the ATI integration shows a beneficial effect on its performance with the 36 tubes configuration that should be preferred to maximize the efficiency.

Table 1: Summary of boundary conditions and relative results of the receiver operating, in part load and full load, without ATI and with ATI constituted by 36 and 64 tubes respectively.

	Part load operation			Full load operation		
	No ATI	36 tubes	64 tubes	No ATI	36 tubes	64 tubes
HTF mfr [g/s]	82.9	83.95	83.2	220.4	244.1	226.4
$T_{HTF,in}$ [K]	973	973	973	973	973	973
Input power [kW]	272	272	272	544	544	544
$T_{HTF,out}$ [K]	1'474	1'473	1'472	1'474	1'472	1'473
$T_{HTF,in,cavity}$ [K]	//	1'022	1'031	//	1'010	1'022
$\eta_{receiver}$ [-]	0.373	0.377	0.373	0.496	0.545	0.508

Receiver with ATI – Effect of tubes bundle radial position

An additional CFD simulations campaign was also conducted with the aim of investigating the effect of the ATI radial position on both the amount of energy recovered, and exploited to pre-heat the HTF, and on the overall receiver behaviour. Starting from a reference ATI position (i.e., the same considered for the previous analysis), two alternative designs were proposed and evaluated. In these designs, the radial position of the ATI was assumed to be 1 cm inwards (closer to the cavity) and 1 cm outwards (closer to the ambient) with respect to that of the reference position. As for the previous analysis, part- and full-load receiver operations were considered.

Table 2 summarizes the main boundary conditions, considered for these simulations, along with relevant results obtained. According to these outcomes, it seems that the 1 cm inwards/outwards variation considered is too small for influencing the overall receiver performance. However, as expected, the closer the ATI is with respect to the internal cavity walls, the higher the amount of energy recovered by the HTF. Nevertheless, a slightly higher HTF inflow temperature leads, on average, to an increase of the temperature level in the region close to the aperture. This, in turn, causes an increment in the radiative losses to the ambient that balances the amount of thermal energy recovered by the HTF passing through the tubes bundle. As a result, the overall receiver efficiency remains unchanged.

Table 2: Summary of boundary conditions and relative results of the receiver operating, in part load (PL) and full load (FL), without ATI and with ATI at different radial positions with respect to the reference.

	NO ATI		Reference ATI position		ATI 1 cm in-wards		ATI 1 cm out-wards	
	PL	FL	PL	FL	PL	FL	PL	FL
HTF mfr [g/s]	82.9	220.4	83.2	226.4	83.2	226.3	83.2	226.2
$T_{HTF,in}$ [K]	973	973	973	973	973	973	973	973
Input power [kW]	272	544	272	544	272	544	272	544
$T_{HTF,out}$ [K]	1’474	1’474	1’472	1’473	1’472	1’476	1’473	1’476
$T_{HTF,in,cavity}$ [K]	//	//	1’031	1’022	1’050	1’033	1’014	1’013
Heat loss (lateral wall) [kW]	19.0	23.6	18.0	19.3	17.1	18.2	19.2	20.7
$\eta_{receiver}$ [-]	0.373	0.496	0.373	0.508	0.372	0.51	0.373	0.51

3.2.3 Receiver insulation

The receiver is internally insulated to maintain high temperatures across the cavity. Layers of different insulation materials were engineered together with the supplier. This involved determining the thickness of each material layer to ensure a temperature gradient across the insulation such that the metallic shell temperature is maintained above 100 °C to prevent condensation of steam that would percolate the porous insulation, while also preventing overheating to avoid excessive thermal strain. A thermal model was implemented to simulate the resulting temperature across the insulation and at the metallic shell. A temperature distribution, obtained from CFD simulations provided by SUPSI, was imposed on the cavity surfaces, while natural and forced convective cooling was imposed on the metallic shell surfaces. The CFD simulations performed by SUPSI were in turn based on absorbed solar power source terms obtained from Synhelion's LBL heat transfer model of the receiver.

3.2.4 Receiver aperture internal cooling system – Initial design

Given the receiver scaleup, along with the different solution developed for the quartz window (i.e., a series of laser-cut segmented quartz tubes next to each other rather than the conventional flat plate air-tight window), a proper aperture cooling system needs to be designed. To support the initial design of the component, a preliminary CFD simulation was performed. Concerning the latter, it was assumed that the steam cooling mass flow rate was equal to 10% of the total HTF mass flow rate through the receiver. Figure 6 shows an overview of the first results in terms of temperature distribution and heat transfer coefficient in the region close to the aperture. These preliminary results show that the cooling system design needs to be improved in order to enhance the interaction between cooling jets and aperture for a proper thermal management of this component.

3.2.5 Receiver window – Testing of materials at high temperature

The receiver front section contains mainly the window, which consists of 6 segments of quartz glass tubes placed next to each other. To check for the compatibility of the different materials in contact with each other at high temperatures, a part of the front section was fabricated at tested in an oven at 800 °C for 24 hours. Two different materials for the ceramic support structure were tested: polycrystalline fiber board and vacuum formed ceramic. The tests showed that both ceramic support structure materials are brittle and sensitive to surface abrasion, resulting in ceramic dust on the window segments and the ceramic pillows. The concept of using brittle ceramic parts for supporting the window seems non-ideal and costly.

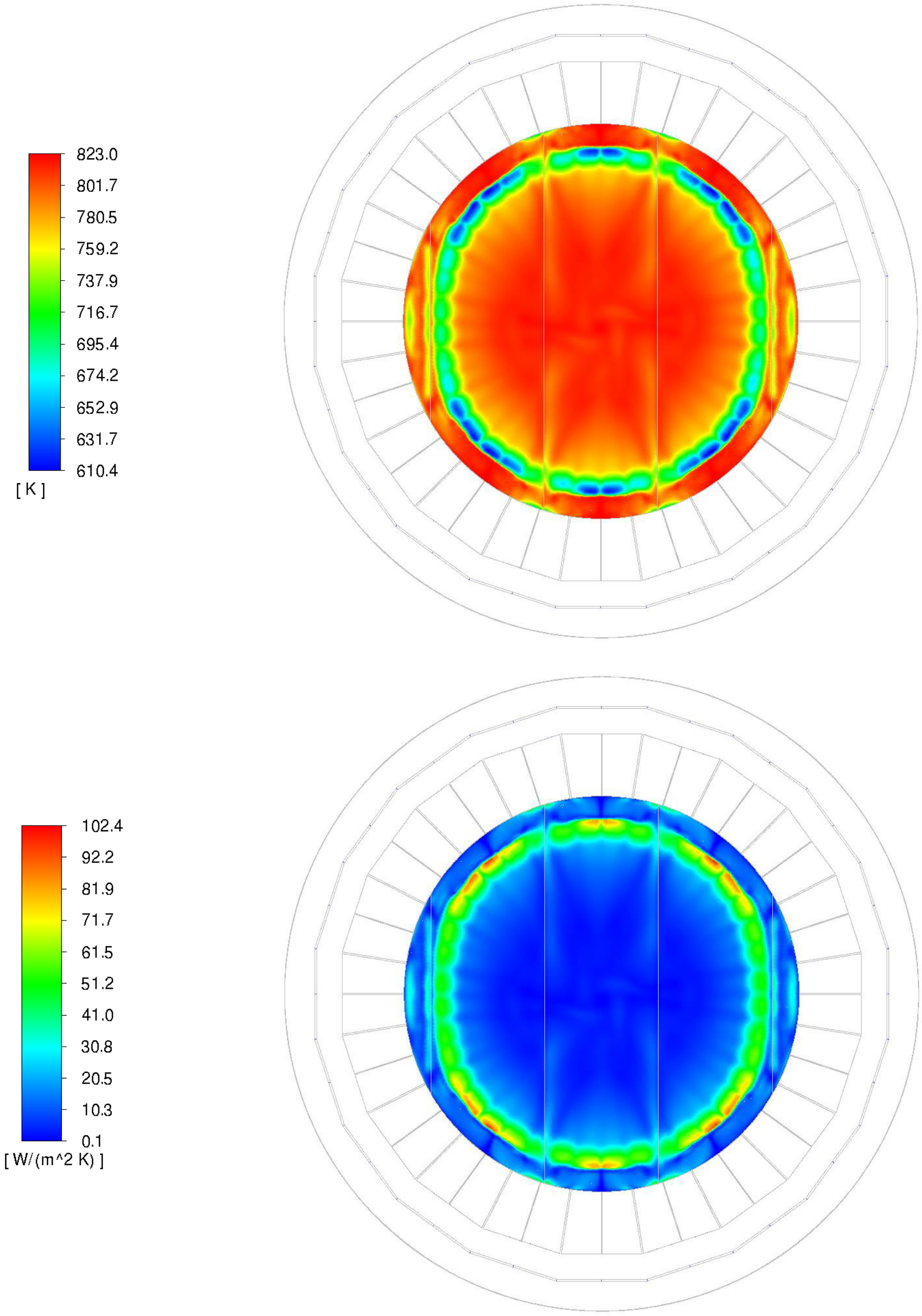


Figure 6: Resulting temperature (top) and heat transfer coefficient (bottom) contour plots in the region close to the receiver aperture, for the preliminary CFD simulation performed. Temperature values are [K] and heat transfer coefficient values are [W m^{-2} K^{-1}].

3.3 Construction and on-sun testing of 250 kW SM1D receiver prototype

3.3.1 Construction and assembly of 250 kW SM1D receiver prototype

The receiver front is composed of different components that are exposed to high solar irradiation. In the previous report [6], the engineering and testing of the secondary concentrators were described. Another critical component is the steam ring that is composed of four aluminium segments. The steam ring has two main functions: on the one hand, the steam ring holds the window in place in the receiver aperture; while, on the other hand, the steam that is injected into the steam ring exits radially over the window. The temperature of the exiting steam is lower than the window temperature. Therefore, the outgoing steam decreases the window temperature and thus prevents it from overheating. As mentioned above, the steam ring is also one of the most irradiated components of the front section since it is positioned directly around the receiver aperture where the highest solar flux is expected. To avoid overheating of the aluminium component, the surface of the steam ring is highly polished and coated to achieve a high surface reflectivity. Furthermore, the steam that is injected into the steam ring maintains the component in a safe temperature range.

Left-hand side of figure 7 shows the receiver during the front assembly process. In the upper part of the picture, the solar receiver can be seen without the front mounted. In the lower part of the picture, the front section of the receiver can be seen horizontally. In this position the receiver window and other front components are installed. Right-hand side of figure 7 shows the assembly of the polished and coated steam ring segments to the front section.

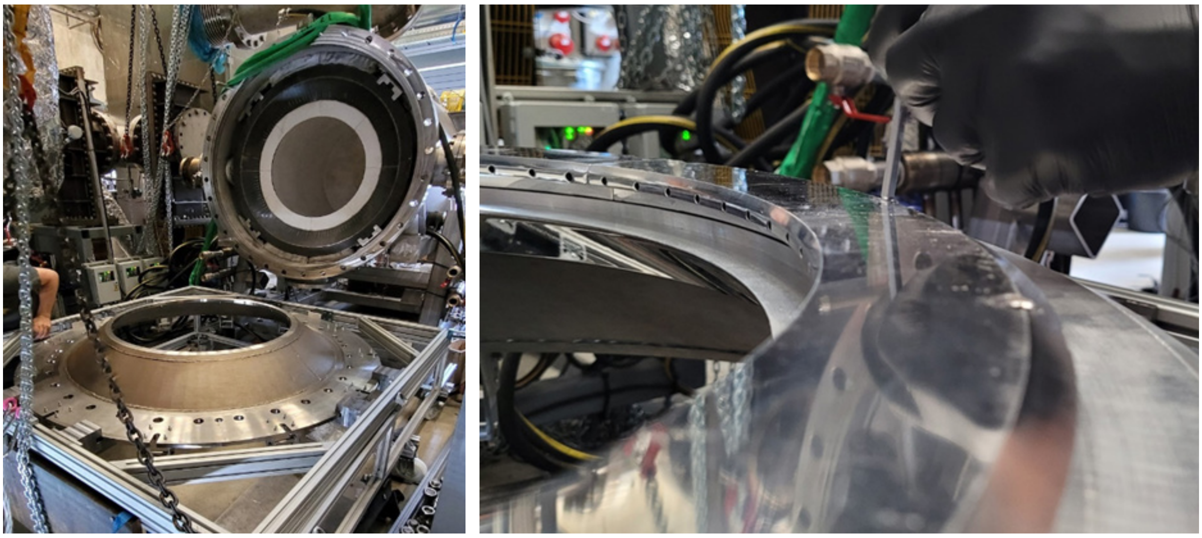


Figure 7: The receiver front is placed horizontally in front of the receiver for the assembly of front components (l.h.s.); mounting of the polished and coated steam ring segments where, on the inner side of the segments, the circular steam outlets can be seen (r.h.s.).

Figure 8 shows three critical components in the test chamber. On the left-hand side of the picture, the solar receiver can be seen. At the back of the receiver a tee-piece connector is mounted. The steam exiting the receiver can either be guided to the left side into the stack or to the right side into the gas heated reformer (GHR). The GHR is a shell and tube heat exchanger type reformer. The tubes are filled with an industrial catalyst to perform the desired steam reforming reactions. On the shell side, the overheated steam from the receiver is injected at the lower part of the GHR to power the endothermic reforming reactions. The steam exits at a lower temperature at the upper part of the GHR. At that position is another tee-piece connector where the steam can either be flown to the stack or to the high-temperature blower. The high-temperature blower is a centrifugal blower that enables a closed-loop operation of the system. In closed-loop operation the steam exiting the GHR is pushed back into the solar receiver by the high-temperature blower and thus closing the steam circuit.

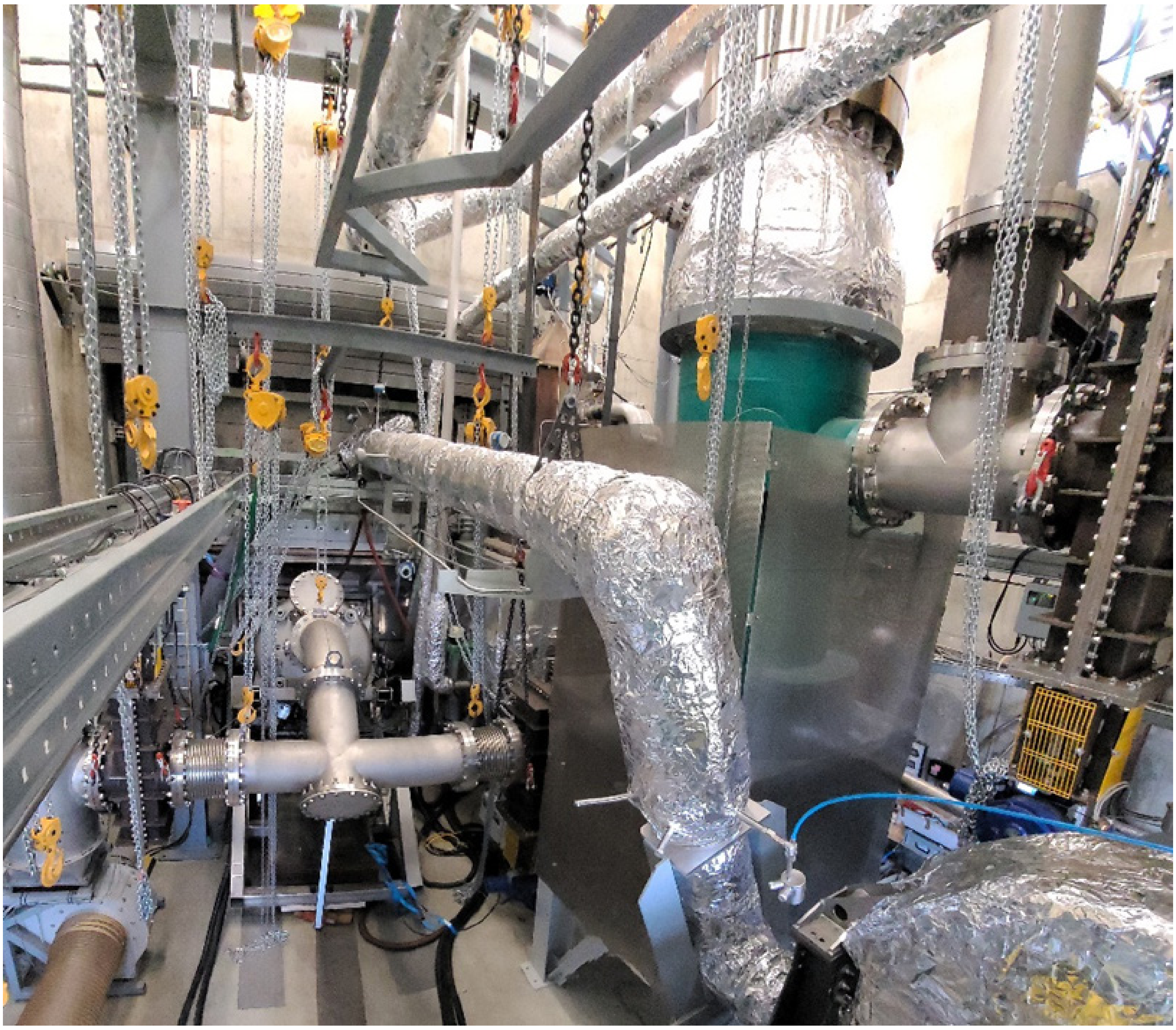


Figure 8: Picture of the test chamber. The solar receiver can be seen on the left-hand side. The receiver outlet is connected to the gas heated reformer (GHR) on the right side. At the bottom right corner of the image, the blower, used to circulate the HTF from the GHR outlet back to the receiver inlet, can be seen.

3.3.2 On-sun operation of 250 kW SM1D receiver prototype

In this paragraph, an operation day in August 2023 is described in more detail. During this experimental test, the solar receiver was operated at the beginning of the day in an open-loop configuration with the steam exiting the through the stack. Simultaneously, the GHR was preheated with a gas burner. As soon as the receiver outlet temperature reached the desired outlet temperature of 1’100 °C, the gas burner was stopped and the steam from the receiver was guided through the GHR. From that point onwards, the high temperature blower was used to control the steam mass flow rate to the solar receiver.

The graph in figure 9 shows the temperature curves during the operation day. The red line shows the receiver outlet temperature. The on-sun operation of the solar receiver started around 09:00 a.m. After one hour, the desired receiver outlet temperature of 1’100 °C was reached. The GHR inlet temperature is shown in green. At 10:00 a.m. roughly, a temperature drop can be seen. At this time the burner was stopped and the steam from the receiver was guided toward the GHR to power the reforming reactions. The GHR inlet temperature was kept relatively constant at 980 °C during the solar operation. Only a few clouds, around 12:30 a.m., caused temporary temperature drops. The GHR outlet temperature, shown in blue, slowly increased from 500 °C to 575 °C during the on-sun operation. The graph in figure 10 shows the rotational speed setpoint of the high temperature blower. As mentioned above, during the closed-loop operation the rotational speed of the blower is the main lever to control the steam mass flow rate through the solar receiver and thus to control the receiver outlet temperature. It can be seen in figure 10 that the blower setpoint was constantly adjusted to maintain the receiver outlet temperature relatively constant at the desired 1’100 °C.

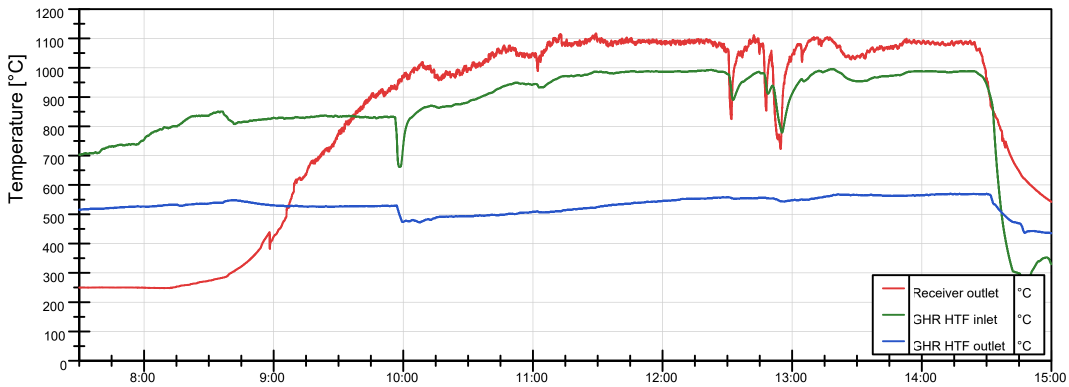


Figure 9: Measured temperature evolution at the receiver outlet (red), GHR inlet (green) and outlet (blue).

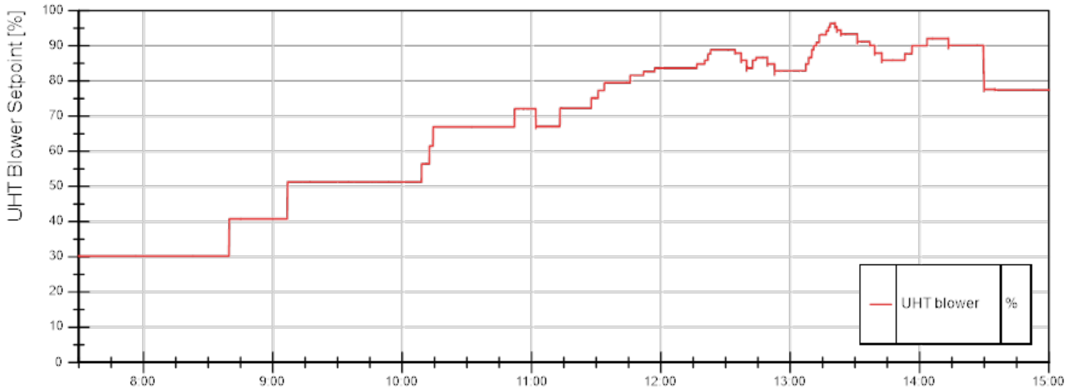


Figure 10: The curve shows the rotational speed setpoint of the high temperature blower. In closed-loop operation the steam mass flow rate, entering the receiver, is mainly controlled by the blower rotational speed.

4 Evaluation of results to date

The original time schedule of the project is reported in figure 11 where the red line indicates the actual date. Here is a schematic evaluation of results achieved within the project:

- WP 1: nothing to note; the foreseen activities were carried out as planned.

- WP 2: tasks 2.1 and 2.2 were successfully completed. Tasks 2.3 was put in idle due to the low priority of this activity; while, task 2.4 is started and it is still ongoing since the 0.6-1 MW precommercial receiver design is yet to be finalized.

- WP 3: task 3.1 was completed. The milestone M 3.1 (SM3 pre-commercial scale receiver fully engineered) is delayed and will be reached after the end of the project. A high degree of novelty for various components of the receiver, and the associated calculations, engineering, and testing to validate the concepts, is the main reason for the delay. Construction of the SM3 receiver is expected to start after the end of the project. Test operation with solar irradiation is expected to start in summer 2024.

- WP 4: task 4.1 is complete (see paragraph 3.3); the receiver prototype construction started on time but the foreseen on-field experimental campaigns were postponed to spring-summer 2023.

- WP 5: was considered complete with the answer that a reliable windowless design still needs further efforts.

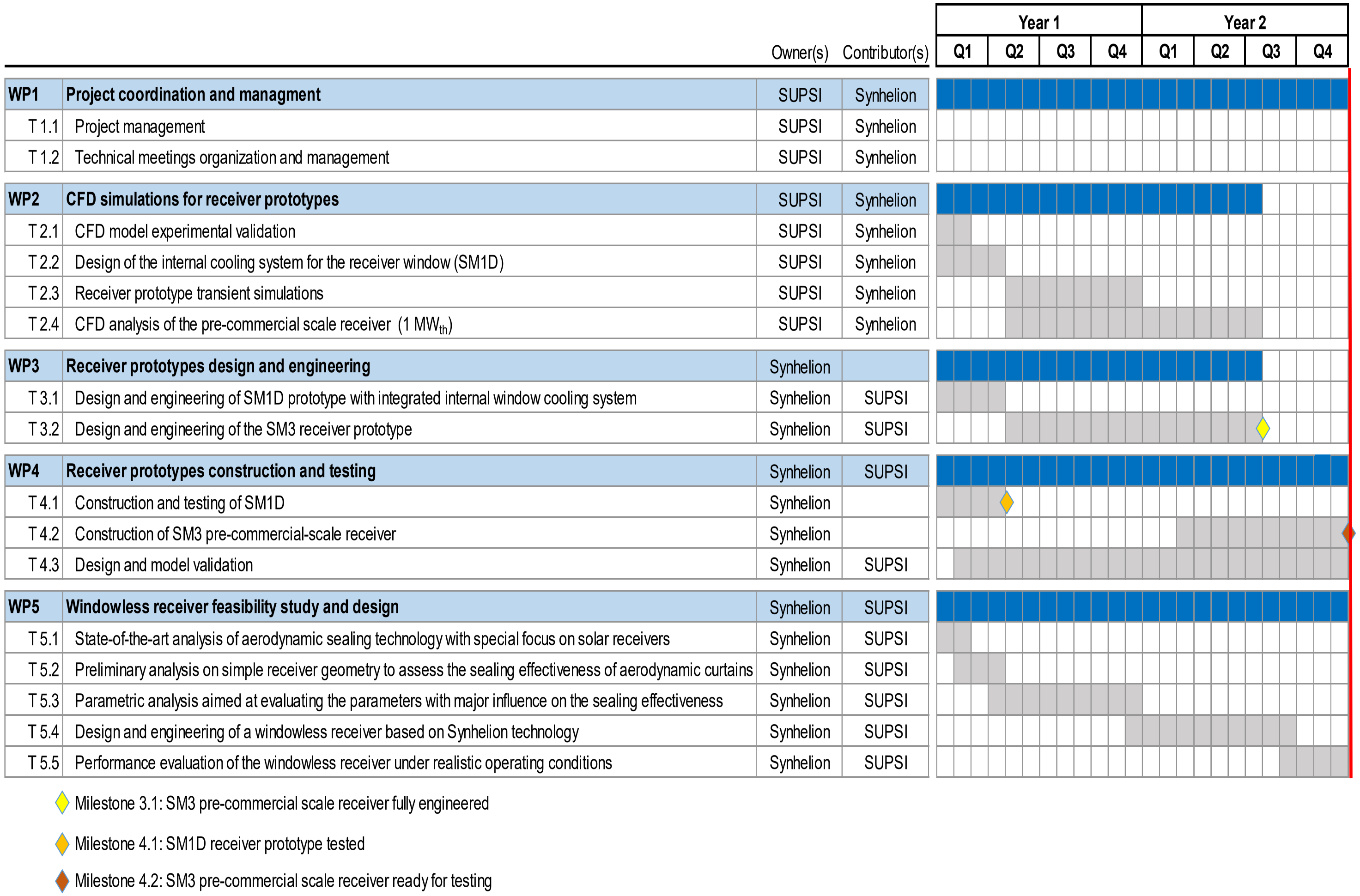


Figure 11: Gantt chart of FUELRECII project.

5 Conclusions and next steps

From the results obtained during this project, several learnings are deduced that would help in the further development of the receiver technology.

- It was concluded that a windowless design is currently not feasible with the set of assumptions and measures taken. Further work is required to enable an effective separation of the gases in the receiver (steam and CO_2) from the atmosphere and thus to prevent excessive mixing of the two, resulting in a less favorable absorption of solar radiation and hence a drop in receiver efficiency. Possible solutions could comprise a partly-covered aperture by standard quartz-window components in combination with sophisticated cooling methods.
- The choice of materials at the receiver front, where the insulation joins the window mount, is crucial to prevent material embrittlement, deposition on the window, and subsequent performance degradation of the receiver due to material failure or reduced absorption of solar radiation. More material combinations and potential solutions to prevent material degradation in the high-temperature zone around the aperture should be investigated to ensure sustained and stable performance of the receiver in future implementations.
- The ideal configuration of receiver insulation both using standard insulation materials and tube bundles preheating the HTF should be further investigated. Pre-heating of the HTF promises to increase the performance of the receiver by using heat otherwise lost to the environment but a reliable and efficient configuration has yet to be found and should be further analyzed in more simulations varying the size and position of the tubes and the HTF mass flow rate.
- The cooling of the windowed aperture requires continued attention for further optimization according to the chosen configuration. The window has to be kept at temperatures below a threshold to prevent failure, and the ideal position of the nozzles and mass flow of the cooling fluid depend on the overall design of the cavity and the window, as well as the operation mode of the receiver.
- A scale-up of the receiver technology towards several MW of thermal input power should be prepared with CFD simulations and design of the components.

As a next step, also the other components not covered in this project should be taken into account.

- There is the need for simulations and design of the thermal energy storage component, a cornerstone of the solar fuel technology that will enable around-the-clock operation. As a high-temperature component in contact with the HTF, this component requires detailed attention through simulations and preliminary computational design.
- As another central component, the thermochemical reactor that converts biogas into syngas using solar heat has to be simulated with a special attention to heat transfer and potential favorable reactor configurations is needed.
- Analysis of the HTF piping that connects the receiver, the thermal energy storage, and the thermochemical reactor with a focus on CFD and minimal heat loss. Also, the interaction between these components under different operating conditions will have to be investigated.

As final considerations, the activities developed in the framework of this project allowed the authors to deepen the knowledge in the field of solar receiver, high temperature heat transfer, thermal radiation heat transfer, numerical modeling and validation, experimental tests and others, representing a strong basement on which rely for the follow up activities not only related to this project but also to other potential projects covering similar topics. Furthermore, this know how will also be transferred to mechanical engineering students at SUPSI enriching their education.

6 Publications

Some of the results, obtained in the framework of FUELRECII projects, were presented at various editions of SolarPACES conference, the foremost worldwide symposium on concentrated solar technologies:

Zavattoni S.A., Good P., Geissbühler L., Rutz D., Toffanin R., Montorfano D., Ambrosetti G., Barbato M.C., “Performance Evaluation of the Pressurized Synhelion Absorbing Gas Receiver”, 28th SolarPACES conference, Albuquerque NM (USA), September 27 - 30, 2022.

Zavattoni S. A., Montorfano D., Good P., Geissbühler L., Rutz D., Ambrosetti G., Barbato M.C., “Synhelion absorbing gas solar receiver - Design advancement”, SolarPACES conference, online event, September 27 - October 1, 2021.

7 References

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[2] SUPSI-DTI-MEMTi, Synhelion SA, “ReceiverSIM - Modelling of absorbing gas receiver for solar applications,” Final report, 2018.

[3] S. A. Zavattoni, D. Montorfano, P. Good, G. Ambrosetti and M. C. Barbato, "The synhelion absorbing gas solar receiver for 1'500 °C process heat: CFD modeling," *AIP Conference Proceedings,* vol. 2303, no. 030037, 2020.

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[7] SUPSI-DTI-MEMTi, Synhelion SA, "Solar receiver for the production of solar fuels from water, carbon dioxide and methane – Part II, BFE-project FUELREC II (SI/502256-01), Annual Report," March 2023.