D8.3: First periodic report of GAMER

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Presentation of the deliverable

This deliverable presents the overall objectives of the GAMER project and provides a summary of some of the results generated during the first 18 months of the project.

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Additional information can also be found on GAMER website: https://www.sintef.no/projectweb/gamer/

GAMER is a European research project co- financed by the European Union's Horizon 2020 research and innovation program and the Fuel Cells and Hydrogen Joint undertaking under grant 779486

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1 Introduction

1.1 The GAMER project

The GAMER project aims at developing a novel cost-effective tubular Proton Ceramic Electrolyser (PCE) stack technology integrated in a steam electrolyser system to produce pure dry pressurized hydrogen. The electrolyser system will be thermally coupled to renewable or waste heat sources in industrial plants to achieve higher AC electric efficiency and efficient heat valorisation by the integrated processes (figure 1). The project aims at establishing a high volume production of novel tubular proton conducting ceramic cells. The cells will be qualified for pressurized steam electrolysis operation at intermediate temperature (500-700°C). They will be bundled in innovative single engineering units (SEU) encased in tubular steel shells, a modular technology, amenable to various industrial scales. GAMER focuses on designing both system and balance of plant components with the support of advanced modelling and simulation work, flowsheets of integrated processes, combined with robust engineering routes for demonstrating efficient thermal and electrical integration in a 10 kW electrolyser system delivering pure hydrogen at minimum 30 bars outlet pressure.

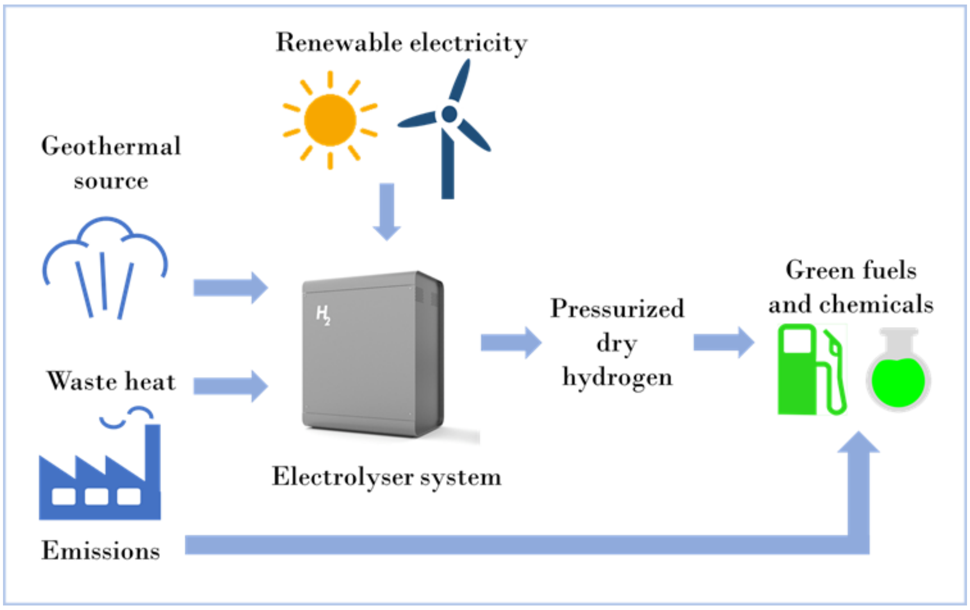

Figure 1: Conceptual schematics of PCE integration with renewable sources in GAMER

Partners of GAMER are:

Partner (short name)	***Country***
SINTEF (SINTEF)	*Norway*
Coorstek Membrane Science AS (CMS)	*Norway*

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CSIC, Instituto de Tecnología Química (CSIC)	*Spain*
Carbon Recycling International (CRI)	*Iceland*
University of Oslo (UiO)	*Norway*
MC2 Ingenieria y Sistemas SL (MC2)	*Spain*
Shell Global Solutions International B.V. (SGSI)	*The Netherlands*

The consortium covers the full value chain of the hydrogen economy, from cell and SEU manufacturer (CMS), system integrators (MC2, CRI), through researchers (SINTEF, UiO, CSIC), to end users in refineries, oil and gas, chemical industry (CRI, SGSI, with advisory board members YARA and Air Liquide). All along the project, these experienced partners will pay particular attention to risk management (technical, economic, logistic, business) and ensure progress of the technology from TRL3 to TRL5. The overall consortium will perform strategic communication with relevant stakeholders in order to ensure strong exploitation of the project's results.

1.2 The novel tubular SEU

In the GAMER project, we focus on the demonstration of an innovative, low cost and modular hydrogen production technology utilising *tubular proton conducting ceramic cells* and their inherent advantages for steam electrolysis:

- *Scalability and modularity* of the electrolyser system: the electrolyser is designed for scale (small, medium, large);
- *Reduced operation and maintenance costs* compared to planar stack towers: possible to "isolate" one or several SEUs from the system without shutting it done completely; possibility to change some SEUs;
- *Reduced risks* in case of leakage due to low volume of SEU;
- *Lower operating temperature* (600°C) than SOE reducing degradation associated to cation diffusion, and enabling use of lower cost steel for pressure vessel;
- *Production of pure dry hydrogen* at the anode side, preventing risk of oxidation encountered in SOE (see figure 2);
- *Increased safety*: In PCE, any increase in pH_2O increases the pH_2. In contrast, the SOE must have a high pO_2 alone at one electrode to balance the pH_2O+pH_2 at the opposite electrode. Pure hot high pressure O_2 is risky;
- *Increased robustness of tubular cells*, in particular, when exposed to pressure differentials compared to planar cells;
- *Reduced sealing area* compared to planar cells.

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This novel design concept has also challenges, which are addressed in GAMER:

- Current collection is challenging compared to planar technology. This is alleviated in GAMER by the use of lower current density cells.

- Lower current density of the cells compared to SOE. This is compensated in GAMER by increased surface area and lower cost of PCE cells.

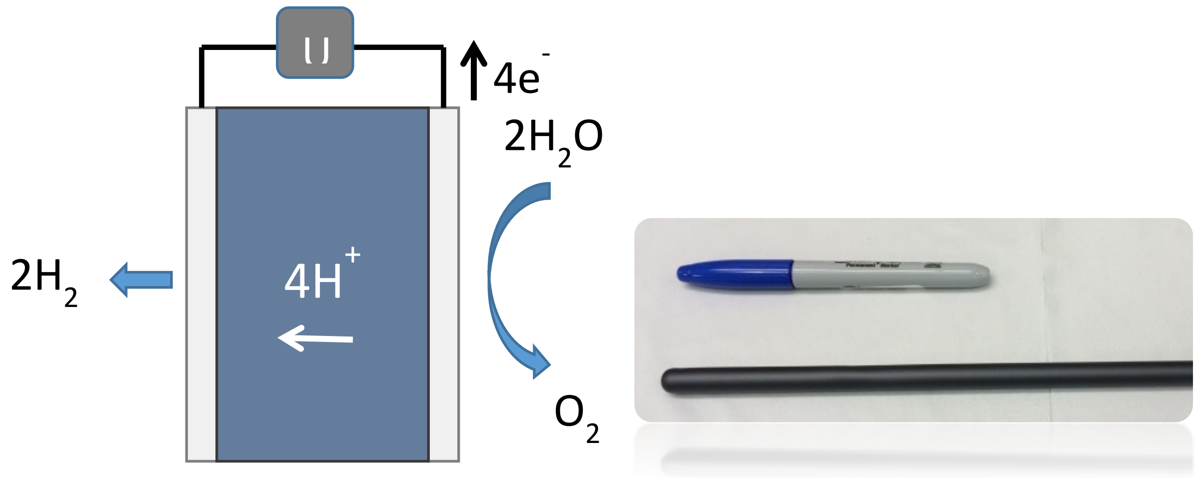

Figure 2: Schematic of PCE cell to be developed in GAMER (left); camera picture of tubular half-cell in GAMER.

The tubular cells in GAMER integrate a proton conducting electrolyte based on Y-doped Ba(Zr,Ce)O_3 (BZCY). The cells will consist of a porous Ni-BZCY cathode for the H_2 side (also ensuring mechanical strength), a thin dense BZCY-based electrolyte, a porous anode for the H_2O+O_2 side, and a current collector system. They are assembled in a vessel enabling safe pressurized operation of at least 30 bars and 700 °C in high steam content.

2 Summary of the first period

2.1 Summary of the context and overall objectives of the project

The concept of sustainable development has evolved into a guiding principle for a liveable future world where human needs are met while keeping the balance with nature. In this context, a hydrogen-based energy system is regarded as a viable and advantageous option for delivering high-quality energy services in a wide range of applications in an efficient, clean and safe manner, while meeting sustainability goals. Hydrogen provides an ideal complement to electricity. Both are premium quality energy carriers, do not contain carbon and generate little or no polluting emissions at the point of use. Electricity, however, is at disadvantage when storage is required while hydrogen could be well suited for those applications. The introduction of highly efficient and clean hydrogen-based end-use technologies would help to reduce final energy consumption and, in addition, could provide local and

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regional environmental benefits (e.g. regarding air pollution). Furthermore, hydrogen can be produced from carbon-free resources or from fossil fuels combined with carbon separation and sequestration. Thus, hydrogen could contribute substantially to the reduction of greenhouse gas (GHG) emissions. Hence, hydrogen economy can confer energy security, along with environmental and economic benefits. Achieving such a goal, however, will require significant cost and performance improvements in production, storage, conversion, transportation and end-use technologies.

In the GAMER project, we focus on the demonstration of an innovative, low cost and modular hydrogen production technology utilising tubular proton conducting ceramic cells and their inherent advantages for steam electrolysis. High temperature electrolysis (HTE) can potentially replace fossil fuel energy input with renewable electricity for the generation of hydrogen, for example in refineries and chemical industries, whereby available (waste) heat from the plant could improve the efficiency of the electrolysis process. The main objective of GAMER is to design, build and operate for 2000 hours in relevant environment a low cost 10 kW proton ceramic conducting based electrolyser system delivering at least 30 bar output dry H_2 using standard industry components for balance of plant (BoP) for efficient thermal management with renewable, heat sources and steam available in industrial plants.

2.2 Work performed and main results achieved so far

During the first period of GAMER (January 2018-June 2019), the work has focused on establishing a multi scale multi physics modelling platform to optimize the design of the electrolyser system (see Figure 3). This modelling framework addresses materials, electrochemistry and flows spanning from cells, SEUs, electrolyser and BoP. It has been implemented as an excel tool (GES.VI) and has been used to dimension the 10kW prototype considering energy balance and power demands of each component, using experimental data sets for materials, cells and SEUs performance collected in the project. An optimized design of the electrolyser system has been established meeting the efficiency target set by GAMER. It includes highly integrated SEU racks mounted in a hot-box. The blueprints of the electrolyser system necessary for its construction are available. A HAZOP exercise has been performed to validate the design with respect to HAZards and OPerational aspects. A public bidding process has been carried out, and a preferred vendor has been identified for building the 10kW prototype, based on best value for money as well as technical capabilities.

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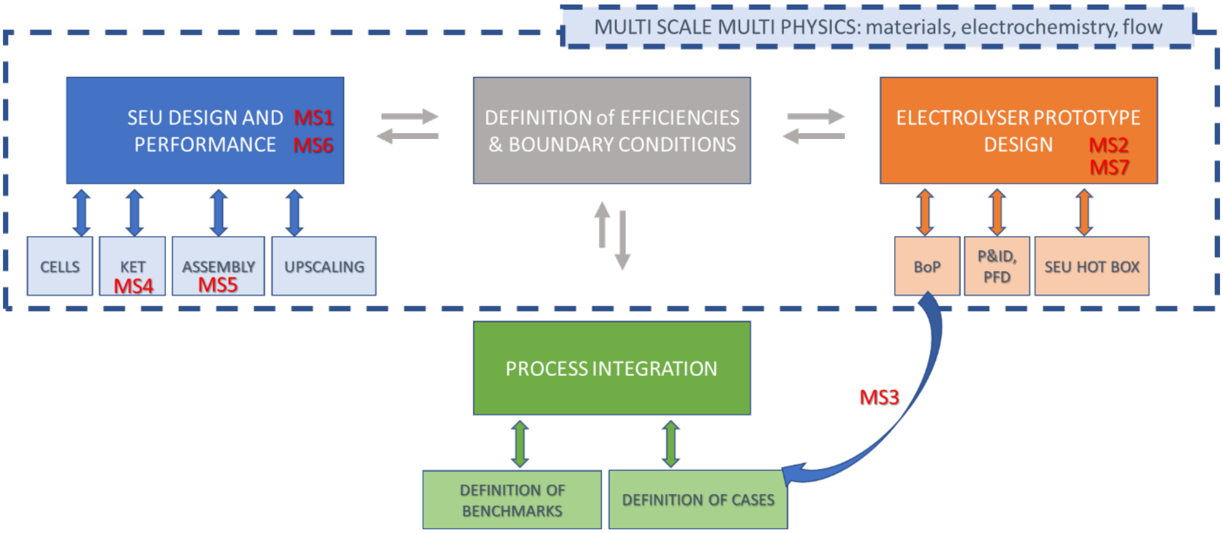

Figure 3: Overview of the activities carried out in GAMER during M1-M18 addressing the milestones (MS) of GAMER (primarily conducted in WP1 and WP6).

An optimized SEU design based on single *tube-in-shell* configuration has been developed in GAMER and is currently under patenting action. It is expected to reduce manufacturing risks and operational mechanical failures of SEUs due to the reduced number of components and therefore, junctions. At M18, the production of the new SEU design is being established at laboratory scale and a few SEUs have been delivered to the project. The supply chain for volume scale production of SEUs have also been defined, involving external supply of some KET components and some welding work, as planned in the DoW. Current efforts are focusing on establishing yields based on routine production practice.

Supply of cells, key enabling technology (KET) components (seals, vessels, feedthroughs, risers) and SEUs for qualification and testing in the project have been conducted. Dedicated protocols and criteria for qualification with respect to functional properties and stability under operating conditions or near-operating conditions of KET components, assemblies and cells have been established (WP3). Assemblies of pairs of KET towards SEU assembly have also been evaluated with respect to performance (mainly polarisation resistance or contact resistance) and stability. This evaluation enabled to down-select KET components.

Electrochemical testing of the tubular cells has been conducted, highlighting the need for optimization of the steam + oxygen electrodes to reach these criteria: (a) ASR < 0.2 Ω $.cm^2$ at 600°C in pressurized electrolysis operation enabling to achieve a cell exhibiting (b) high faradaic efficiency > 90% with (c) current density at thermoneutral voltage above 200 $mA.cm^{-2}$ and (d) the cells should be produced using scalable manufacturing route for volume scale production. Two electrode sets are currently developed in GAMER, each of which fulfilling 2 criteria (LSM/BZCY: a, d) or 3 criteria (BGLC/BZCY: a, b, c). Focused efforts are currently targeting these 4 criteria for both sets of electrodes and it is considered realistic to validate the suitability of at least one set of electrodes by M21.

In order to test the SEUs, strong efforts were focused on defining a current collection system, which is one of the main challenges of GAMER. Viable routes to current collection and connectivity have been

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identified using three main routes with variable risk/reward impact (in terms of scaling up): 1) Ag based current collection system has lower risk/reward impact; 2) new current collection systems with higher risk/reward impact (under patenting action). The former system has been integrated in SEUs using the reference LSM/BZCY electrodes.

Partner CMS has upgraded the SEU testing station available to accommodate for the new SEU design. One new test station is also being implemented at CSIC to increase testing capacity. SEUs testing protocols have been defined in collaboration with GAMER partners, including performance testing, long term stability and cycling tests. By M18, three SEUs based on LSM/BZCY electrodes have been tested at CMS. Leakages in welding points and negatrode feedthrough were observed for these SEUs upon operation: this prevents measuring hydrogen production rate and Faradaic efficiency. It was, however, possible to conduct electrochemical characterization of the SEUs and compare the results with those acquired on cell's evaluation. Post-characterisation of the tested SEUs was conducted to support the interpretation of experimental testing data. These data enabled to validate the manufacturing scaling up from short cells to long cells. As new SEUs integrating BGLC/BZCY or LSM/BZCY improved electrodes are being produced in GAMER using improved electrodes and current collection, more testing results will be generated in the coming months to establish quantifiable data on SEU performance.

Process integration of PCE in various industrial plants and techno-economic study of steam electrolyser using various scenarios for supply of electricity, steam generation from various heat sources (renewables or waste), and for hydrogen pressurization has started. This work involves GAMER partners, as well as GAMER advisory board members. Process information is collected to define efficient thermal integration of the electrolysis technology with the partners industrial plants, and has so far concerned geothermal steam, nitric acid and ammonia production (CRI and Yara business cases). Requirements of the commercial scale electrolyser system with regards to the CRI methanol process have been defined with respect to hydrogen delivery conditions, capacity turndown, ramping (rate of change of capacity) and plant interface. Analysis of industrial integration of PCE technology in CRI plant has started using GES.VI tool, which is being updated for predicting performance of a PCE electrolyser at commercial scale (SEUs in hot box), while initial Aspen simulations are being created for dimensioning required BoP in the different integration scenarios.

An overview of the results from the technical work packages is given in the figure below. It highlights completed milestones, and those which require additional activities in GAMER.

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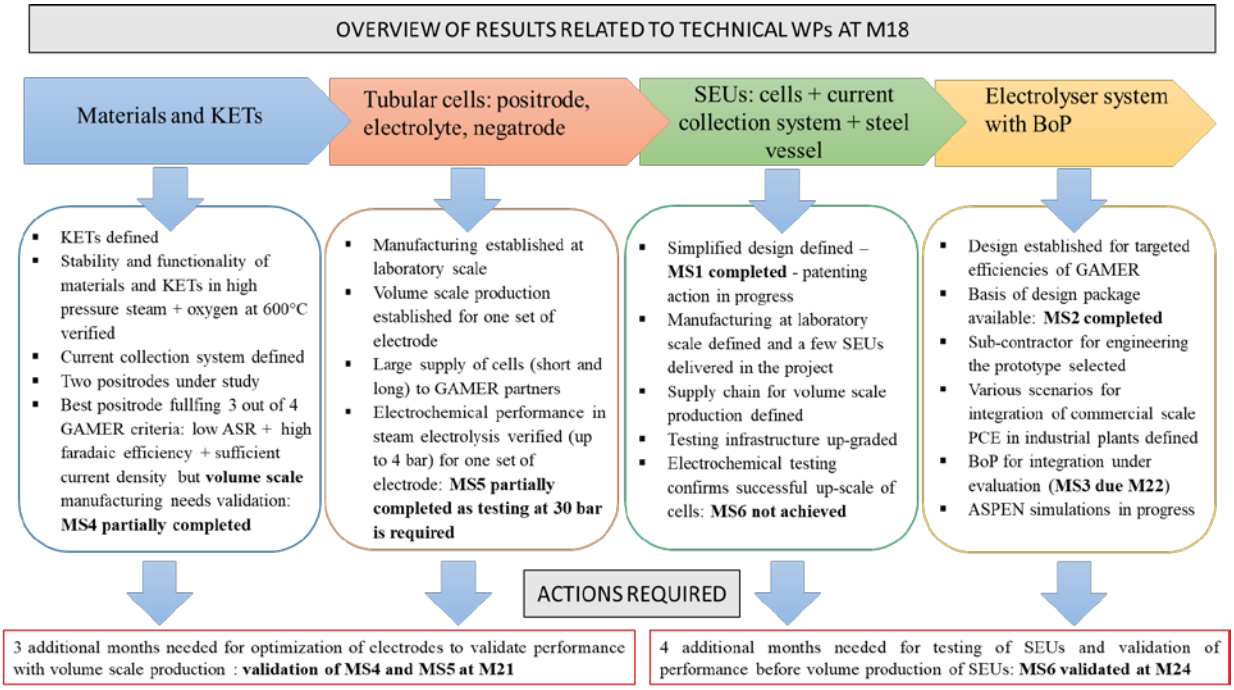

Figure 4: General overview of GAMER results generated by M18 from the technical WPs, with corresponding milestones, and actions required to meet GAMER milestones.

Tools for dissemination of the project's results have been implemented to reach specialized as well as large audience (presentations in conferences, flyer, twits, project webpage, press releases, publication) in a dedicated work package (WP). Dissemination activities are overseen in a dissemination and communication plan, continuously monitored in the project. This WP has also overlooked education of GAMER partners, notably through the organization of GAMER webinars. So far, the project has contributed with 14 oral and poster presentations in international conferences, 3 press releases, 1 flyer and one article in Nature Materials.

Exploitation of innovations from the project are addressed in an exploitation plan, where dedicated strategies are being established based on stakeholder mappings, interactions with GAMER advisory board members, organization of workshops and preliminary identification of exploitation pathways for each partner. One internal exploitation workshop has been conducted in May 2019 at SGSI and contributed to the preparation of stakeholder maps for three different exploitation pathways: GAMER implementation, PCE up-scale, use of proton ceramic reactors for other technologies (see D7.4). An engagement plan is also available for the first map to take actions towards the identified stakeholders (scientific, regulatory, funding, technical, public, political), and is currently being applied by GAMER partners (see D7.4). Three consultations have already been carried out with the AB members: Yara and Air Liquide to broaden the possibilities for integration of PCE technology in other industrial plants and scales than those represented by GAMER partners CRI (Methanol production) and SGSI (refineries). The meetings have so far been used to present GAMER, define industrial cases and boundary conditions for integration of PCE (with information provided by AB members on available steam/heat

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at their plants), as well as evaluation parameters of relevance for AB members. Further meetings are scheduled to discuss results of efficiency of integrated processes.

2.3 Progress beyond the state of the art, expected results until the end of the project and potential impacts

The proton ceramics offer several potential advantages for electrolysis – especially steam electrolysis. The direct production of dry hydrogen is a first advantage. Furthermore, the production of undiluted dry hydrogen (i) removes the risk of oxidation of Ni commonly used in H_2-side electrodes (cathodes) of high temperature electrolysers and (ii) enables the direct use of the hot pressurized H_2 produced, which helps in reaching high system and overall-plant energy efficiency. Additionally, the proton moves with a smaller activation energy than oxide ions enabling operation in an intermediate temperature range (400 – 700ºC), which is considered beneficial for efficient thermal coupling with renewable or waste heat. Finally, operation at high pressure requires a fairly balanced total pressure of the two sides of the cell in the stack. The PCE has the benefit of a high pressure of hydrogen balanced with the sum of steam and oxygen, while the SOE must use a high pressure of solely oxygen to balance steam and hydrogen, making it more challenging to reach the same produced hydrogen pressure. In addition, there is potential hazard of high pressure undiluted O_2 in the SOE, which may cause runaway or explosive oxidation with many materials, while the O_2 in the PCE is at a lower pressure and is diluted with steam which chokes oxidation, similarly as N_2 does in air. **In GAMER, we are currently focusing on demonstrating how these advantages can be leveraged in an innovative tubular cell and single engineering unit (SEU) design for the direct delivery of dry pressurized H_2.**

The tubular cells in GAMER integrate a proton conducting electrolyte based on Y-doped $BaZrO_3$ (BZY). The cells will consist of a porous Ni-BZY cathode for the H_2 side (also ensuring mechanical strength), a thin dense BZY-based electrolyte, a porous anode for the H_2O+O_2 side, and a current collector system. Innovation is brought in the project with the development of optimized H_2O+O_2 electrode and current collection system enabling designing a new SEU. A patent application is currently in progress to protect this invention.

Testing of the tubular cells in pressurized electrolysis mode have demonstrated performance and stability of operation beyond state-of-the-art for tubular proton ceramic based cells. Furthermore, it is expected that the new SEUs integrating the optimized material solutions will also achieve similar performance and stability, contributing to breakthrough development in HTE.

At present, there is no stack prototype of PCE developed worldwide. The design of the 10kW prototype already constitutes an important innovation of GAMER. Its building and testing in the second period of GAMER will generate important knowledge in PCE technology, which will have significant impact on stakeholders: this will result in an important proof-of-concept demonstration of the technology at TRL5/6. This is necessary to reach the next demonstration stage or deployment of the technology by industry. In parallel of this work, techno-economic studies will be carried to define relevant integration

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scenarios of PCE in industrial plants. These will be followed by LCA study. These will help defining potential socio-economic impacts of GAMER.

3 GAMER : further information and contact

Since April 6th 2018, GAMER 's website is online and features various options (https://www.sintef.no/projectweb/gamer/).

- A welcome page to GAMER's project with introduction information about the project,
- a *News and events* page to present the last news and events related to the project,
- an *Objectives* page to describe in more details the main objectives of GAMER,
- a *Consortium* page to present the seven partners of GAMER with a link to their webpage, country of origin and key role in GAMER,
- a *Reports and publications* page to list public reports and scientific publications resulting from the work performed in GAMER (which can be downloaded),
- a *Contact* page to give contact information with name and e-mail address of the coordinator and partners.
- A flyer is also available for download

4 Acknowledgements

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