

# PROJECT FINAL REPORT

## Publishable summary

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Project acronym: **EDEN**

Project title: **High energy density Mg-Based metal hydrides storage system**

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## Executive Summary

**EDEN** aims at the realization of a solid-state hydrogen storage technology for the specific sector of stationary applications and an overall integrated Power-to-Power (P2P) system at support of distributed level applications.

The request for energy storage systems and power-to-power technologies is growing as fast as the energy availability from renewable sources is increasing in penetration on the energy networks. Consequently, the market is demanding for storage solutions more performing, safer and economic.

It is emerged from the past EU projects that the hydrogen storage in solid state is one of the better solutions to seek. Between the materials studied for solid state hydrogen storage, Magnesium based systems represent nowadays one of the best candidates able to meet the industrial storage targets: they have proper gravimetric and energetic density (typical  $>7$  wt.%,  $\geq 100$  kg H<sub>2</sub>/m<sup>3</sup>) and suitable charging and discharging time and pressure.

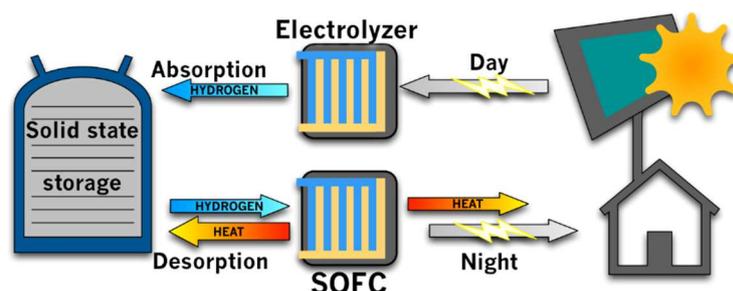
The main barrier to the wide use of the Magnesium based materials in hydrogen storage system is represented by two limitations: the working temperature of about 300°C and the high heat of reaction, around 10Wh/g.

Four main themes have led to the development of **EDEN technology**:

- (i) Delivering continuous energy to buildings, small dwellings, micro-communities, by integrating intermitted thermal and electrical power sources with hydrogen storage systems;
- (ii) Mitigating the problem of intermittent energy delivered to the grid. Higher storage capacity at the local level reduces the need to expand the grid;
- (iii) Providing safe, reliable and high-density energy storage for domestic applications. Mg-based metal hydrides can configure as a safe material and technology, with high energy density (more than 2000 Wh/l);
- (iv) Provide the market with a viable complete system for hydrogen storage that will compete with the available storage systems in terms of costs and performances.

The **overall scope** of **EDEN** is to advance the actual state of the art of hydrogen based power-to-power systems, with reversible HT technologies for the production of hydrogen from renewable sources and conversion back to electricity, integrated with a solid state storage in form of Mg-based material, reduced in costs and enhanced in thermodynamic and kinetic properties.

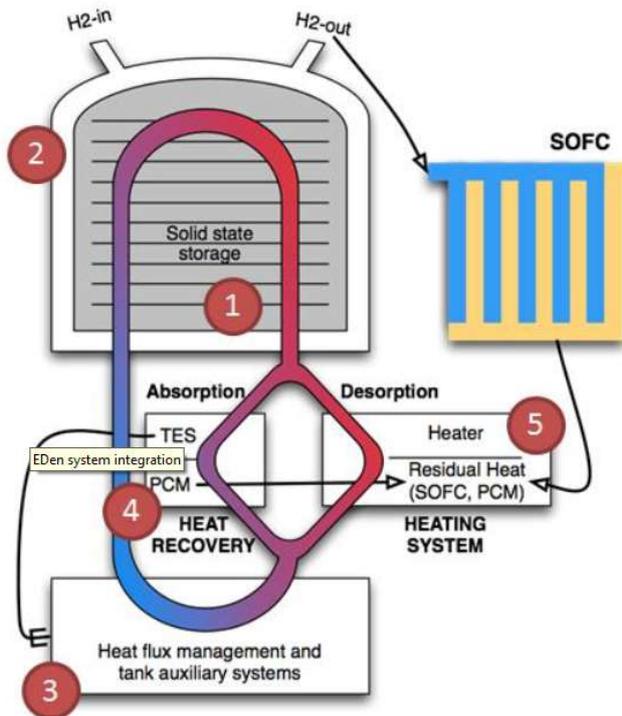
The novel storage material, provided of with high hydrogen storage capacity, will be manageable in real-time, included on a specifically designed storage tank. The overall **EDEN system** will have an integrated thermal and fuel management and it will be interlinked to an energy provision system able to match intermittent energy sources with local energy demand (buildings or small dwellings) for distributed level applications.



## Summary description of project context and objectives

### Project context

EDEN project has the aim to develop a POWER-to-POWER (P2P) system consisting of: (1) a new storage material with high hydrogen storage capacity, for distributed level applications, included on (2) a specifically designed storage tank, integrated with (3) an energy provision system able to match local energy sources with energy demand in form of reversible solid oxide cell.



EDEN realizes a full scale prototype composed by a storage tank, a SOC operating in reversible mode and an overall integrated system provided of fuel and thermal management in a full P2P energy system.

The system architecture will combine five main sub-systems:

- 1) The storage material, compacted in pellet with specific design
- 2) A light, thermal insulated tank
- 3) The heat flow managing system, heat carrier and pumps
- 4) The heat recovery system, equipped by TES and PCM (active during hydrogen absorption)
- 5) The heating system (active during hydrogen desorption) connected with the SOFC

The request for energy storage systems is growing as fast as the energy availability from renewable sources, consequently the market is demanding for storage systems more performing, safer and economic.

It is emerged from the past EU projects that the hydrogen storage in solid state is one of the better solutions to seek. Between the materials studied for solid state hydrogen storage, Magnesium based systems represent nowadays the major candidate able to meet the industrial storage targets: they have proper gravimetric and energetic density (typical  $>7$  wt.%,  $\geq 100$  kg H<sub>2</sub>/m<sup>3</sup>) and suitable charging and discharging time and pressure. The main barrier to the wide use of the Magnesium based materials in hydrogen storage system is represented by two limitations: the working temperature of about 300°C and the high heat of reaction, around 10Wh/g.

Four main themes have led to the development of this project:

- (i) Delivering continuous energy (to buildings, small dwellings, micro-communities), by integrating intermitted thermal and electrical power sources with hydrogen storage systems;
- (ii) Mitigating the problem of intermittent energy delivered to the grid. Higher storage capacity at the local level reduces the need to expand the grid;

- (iii) Providing safe, reliable and high-density energy storage for domestic applications. Mg-based metal hydrides can configure as a safe material and technology, with high energy density (more than 2000 Wh/l);
- (iv) Provide the market with a viable complete power-to-power system for hydrogen storage that will compete with the available storage solutions in the medium term.

## Main objectives

The primary objective of EDEN project is to develop a new storage material with high hydrogen storage capacity, manageable in real-time, for distributed level applications, included on a specifically designed storage tank. It will be interlinked to an energy provision system able to match intermittent energy sources with local energy demand (buildings, small dwellings). The target performance values of the system under investigation are, respectively for material, tank and overall system:

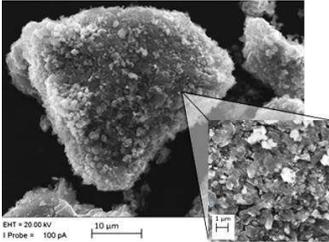
- **Material:** Hydrogen storage capacity: >6.0 wt.%, Hydrogen density: >80 g/l, Hydrogen desorption rate: >3 g/min, Material cost: <30€/kg;
- **Tank:** Hydrogen storage capacity: 4.0 wt.%, Hydrogen density: 40 g/l, Absorption heat recovery: 25%, Hydrogen stored: 600g, Desorption rate: 1,5g/min;
- P2P system (TANK coupled with SOFC/SOE): Heat recovery, Safety, SOFC performance: >300 mW/cm<sup>2</sup>, Performance loss: <10%/year.

Secondary objectives of EDEN project are: the improvement of the performance of the material by addition of catalyser via PVD on powder particles; the development of a proper compaction and activation process for the material; an efficient coupling of the tank with Solid Oxide Fuel Cell with utilization of the thermal energy on both the internal system and the end-user heating; determine the possibility of use of low grade or polluted hydrogen; demonstrate the validity of the concept for small scale applications.

As reported in FCH JU objectives and technical targets in Multi-Annual Implementation Plan 2008-2013, in the Hydrogen Production and Distribution application area (AA2), the targeted cost of hydrogen delivered to retail station is 5 €/kg. Since the EDEN system is a power to power system not delivering gaseous hydrogen, this target is not directly applicable, but project's objectives are however in line with this target: with a cost of 500 €/kg, a capacity of 0.6 kg H<sub>2</sub> and 100 cycles in system lifetime, the cost of stored H<sub>2</sub> at each cycle (and released to produce energy) will result 5 €/kg. The Hydrogen storage system cost (CAPEX) per kg capacity @ mass production (estimate) will be around 300 €/kgH<sub>2</sub>.

## Description of main S&T results/foregrounds

During the whole duration of the project EDEN consortium - in collaboration with the Technology Transfer Board (TTB) settled up during the project - have been focused on all the three main topics of the project: material development and optimization, system components improvement (hydrogen storage tank, energy recovery system, FC compatibility, etc.) and the overall system integration to build a first prototype of complete P2P power system and its demonstration in real environment. Finally, EDEN consortium could achieve improved performances on material development and address with success most of the initial objectives, as outlined in the project proposal:



Development of H<sub>2</sub> storage material in form of Mg-based metal hydrides nano-composites, with high H<sub>2</sub> uptake capacity, improved of catalyst layers. Mg-based powder produced by High Energy Ball Milling, with 7.1 wt.% H<sub>2</sub>/MH storage capacity and desorption rate > 1 gH<sub>2</sub>/min/kg at 320 °C and 1.2 bar



Development of a high reliable storage tank for the specific proposed material.

Intermediate and full Storage Tanks realized, integrated by thermal and hydrogen management system capable to release more than 1,5 l/min;



Integration of additional sub-components for the improvement of the efficiency profile (i.e. heat recovery system through thermal fluid and/or by thermos-electric device)

Consolidation method of Mg-based powder, suitable for enhancing thermal and mechanical properties, to full exploit the storage properties of the tank



Integration with a SOFC to realize and test a full-scale POWER TO POWER system (HT electrolyzer / fuel cell and solid state integrated storage) for stationary, portable and stand-alone applications.

System integration layout comprised of all auxiliaries to properly manage hydrogen and thermal power between the hydrogen tank and the SOFC.



Market Deployment Plan for high volume industrial production for distributed applications. Preliminary business cases investigated.

In the following table are summarized the main results achieved in the EDEN project towards the objectives declared at the beginning of the project.

	<b>OBJECTIVES DECLARED</b>	<b>RESULTS ACHIEVED</b>
<i>Hydrogen storage material</i>		
<i>Hydrogen storage capacity [wt. %]</i>	6.0	<b>7.1</b>
<i>Hydrogen density [g/l]</i>	80	<b>130</b>
<i>Hydrogen desorption rate [g/min]</i>	3	1.5
<i>Material cost [€/Kg]</i>	< 30	<b>28</b>
<i>Hydrogen storage tank and Integrated system</i>		
<i>Hydrogen storage capacity [wt. %]</i>	4.0	2.0
<i>Hydrogen density [g/l]</i>	40	37
<i>Absorption heat recovery [%]</i>	25	<b>26.5</b>
<i>Hydrogen stored [g]</i>	600	<b>815</b>
<i>Desorption rate [g/min]</i>	1.5	1

## 1. DEVELOPMENT OF IMPROVED MATERIAL FOR HYDROGEN STORAGE

The material development started from the production by HEBM of many material variants, considering different process parameters and involving different milling energy conditions. Moreover, different additives amounts have been tested, to select the most promising material variants. During a first stage the Nb<sub>2</sub>O<sub>5</sub> catalyst has been introduced by HBEM, to include its effect during the material development process. During a second stage, the selected variants have been produced by HEBM without addition of catalyst and then processed by PVD for its deposition.

Three main processes were performed to achieve the final results: identification of the best candidate, the upscaling of the Mg-based hydride production for the EDEN prototype at the intermediate (2,5 kg) and full (10 kg) scales, the validation and upscaling of the PVD catalyst addition to the Magnesium up to the kg-scale.

### 1. Identification of the Best candidate material and consolidation process

The best candidate material from High Energy Ball Milling (HEBM) production with Nb<sub>2</sub>O<sub>5</sub> catalyst was selected between several material variants, considering the best balance between the physical properties resulted from the material validation process.

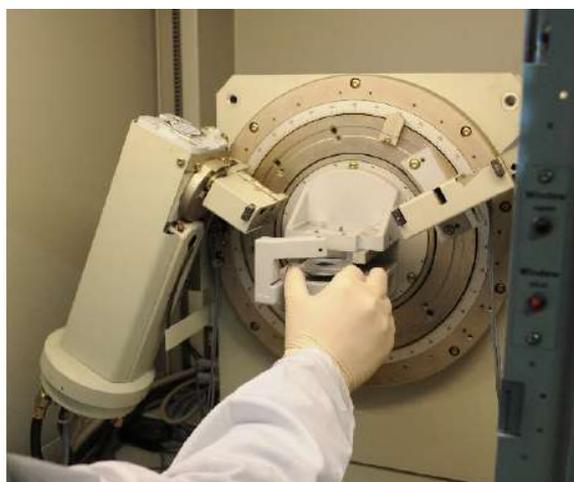
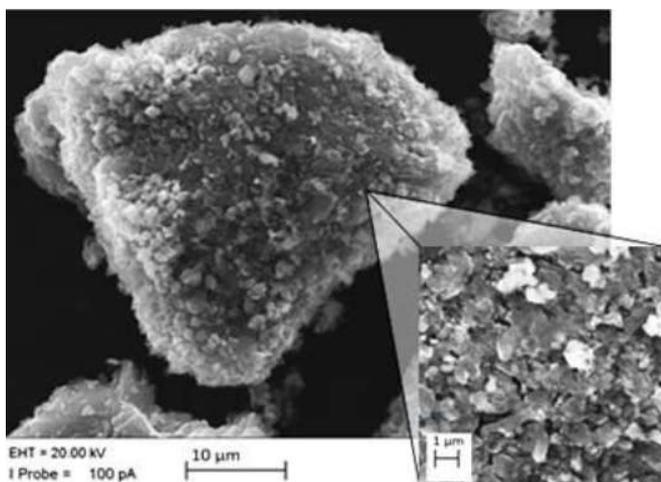
The best candidate material is a nanostructured Mg-based powder, produced with addition of 7 wt.% of graphite and 3 wt.% of Nb<sub>2</sub>O<sub>5</sub> catalyst. This material fulfils project targets for storage properties: gravimetric capacity 7,1 wt.% (H<sub>2</sub>/MH); hydrogen density 130 gH<sub>2</sub>/l; desorption rate 1 gH<sub>2</sub>/min (1kg of material, at storage tank working conditions).

The reproducibility of material synthesis process was verified, in view of the scale up of production and the realization of the prototype.

The main issues along the definition of the material are:

- high energy ball milling leads to a nanostructured material, achieving an homogenous dispersion of catalysts and enhancing powders reactive surface, even introducing active lattice defects;
- Nb<sub>2</sub>O<sub>5</sub> addition in bulk, in the range of 2-5 wt.%, resulted the best catalyst for magnesium based solid state hydrogen storage, gathering a transition metal effect and a surface oxide effect;
- carbon additives in the range of 1-10 wt.%, e.g. graphite powder (C), act as both ball milling process additive and co-catalyst for magnesium storage properties;
- physical deposition is a useful technique for surface modification, since the main catalyst effect is a surface effect;
- a uniform coating of powders can be achieved by employing a vibration device for their mixing during deposition process.

Particularly the evaluations of storage capacity and desorption rate were obtained by independent measurements performed by FBK in Trento, MATRES in Treviso and JRC in Petten, obtaining similar values for the material performances at pressure and temperature values close to working storage tank conditions.



## 2. PVD decoration of catalyst on Magnesium powders

A catalytic effect Nb<sub>2</sub>O<sub>5</sub> was observed for both ball milled Mg-catalyst and PVD coated Mg. A comparison was made between the powder behaviours, in terms of H<sub>2</sub> sorption kinetics, when catalysed either with Nb<sub>2</sub>O<sub>5</sub> as milling additive or as a coating. The utilization of the catalyst on the Mg powders ranges from the ppm scale for the PVD coated powder versus few wt.% for the powder with Nb<sub>2</sub>O<sub>5</sub> incorporated as HEBM additive. Tests performed demonstrated a similar reaction kinetics of the storage material in both the configurations. This represents a significant catalyst weight reduction.

To select the material variants, the obtained powders have been characterized by:

- mechanical sieving, to evaluate the process yield in fine granulometric fractions, which are more active and homogenous than coarse fractions; a 45-mesh sieve (354 μm) has been selected as distinctive;
- XRPD, to evaluate crystal size by Scherrer formula, hence the nanostructure of the obtained material;
- SEM imaging, to evaluate the morphology, measure the particle size distribution and the catalyst dispersion and dimensions;
- Evaluation of the Nitrogen sorption and BET: the value obtained for the as milled material is very low (0.2 m<sup>2</sup>/g), the one measured for activated material is 15.4 m<sup>2</sup>/g for hydrogenated and 18.8 m<sup>2</sup>/g for de-hydrogenated;

- Validation of thermodynamic and kinetic properties: the selected variants of powders were characterised by SolTeF laboratory of JRC Petten, employing an agreed test protocol and focusing on the achievement of thermodynamics and kinetics data:
  - specific use of dedicated equipment, e.g. volumetric and gravimetric instruments;
  - testing conditions: the materials testing conditions were following an agreed testing protocol including condition for equilibrium during PCI measurements;
  - materials sampling: the samples of all materials were taken from a vials “as received”, without any special treatment like sieving or grinding;
  - thermodynamics: PCI curves and Van’t Hoff plots: For each set of the conditions the first measurement was PCI in order to obtain the plateau pressure. Each PCI measurement was performed using dosing volume of  $\sim 11.6 \text{ cm}^3$ ; pressure step of 1 bar; max. time to equilibrium of 3 h (at 280 °C prolonged up to 10 h) with the automatic recognition of the reaction begin and equilibrium reached (test begin after 15 min.);
  - kinetic curves: The Avrami method was used to calculate the kinetic constant of the reaction. The kinetic data was represented as fraction of the reacted material. The Arrhenius method was used to calculate the activation energy of the dehydrogenation reaction;
  - storage properties: this confirms the best candidate material ED011 A3, which has, as well as a good balance between thermodynamic and kinetic properties, the highest gravimetric capacity ( $\text{H}_2/\text{MH}$ ) and an intermediate desorption rate, particularly considering the data at 320 °C and 1 bar, close to future tank working conditions.

Following the powder consolidation process, the material selected variants, particularly focusing on the best candidate, have been characterized in form of pellets. The following aspects were investigated:

- Nitrogen sorption, BET and specific surface;
- Thermal conductivity measurements;
- Sorption properties measurements.

The best candidate material was developed in two different variants:

- The first is the bulk-catalysed variant, that was obtained by high energy ball milling (HEBM) process only, introducing the catalyst at this stage in order to obtain the amount of storage material needed to be used for the tank prototype realization.
- The second is the surface-catalysed variant, produced by HEBM without catalyst addition, then processed by physical vapour deposition (PVD) for catalyst deposition on powder surface. This process resulted to enhance sorption rate of powder and will be tailored to achieve the targeted hydrogen storage properties, evaluating its effect on powder particles.

The bulk-catalysed best candidate material variant presents a **gravimetric capacity of 7.1 wt.% ( $\text{H}_2/\text{MH}$ )**, a **hydrogen density of 130 g/l** and a **desorption rate of 0.11 wt.% / min**, measured at tank working conditions.

The best candidate material produced by HEBM has been tested as consolidated in form of cylindrical pellets, obtained by cold uniaxial pressing and with the consolidating fillers selected during the material development. The obtained pellets present enhanced mechanical stability and thermal conductivity, even after 50 absorption/desorption cycles or when scaled up by size. Considering the anisotropy of thermal conductivity of pellets, due to the presence of ENG as filler, only the axial conductivity was evaluated, since it is lower than radial conductivity.

The main properties of this material are reported in the following list, specifying the relative characterisation performed and the selection criteria. Particularly the evaluations of storage capacity and desorption rate

were obtained by measurements independently performed in two different laboratories, obtaining similar values for the material performances at pressure and temperature values close to future working storage tank conditions.

Below a summary of performances, indicating (1) the specific property, (2) the measured value, (3) the characterization method, (4) the selection criteria for the specific value.

- Hydrogen Storage gravimetric capacity: **7.1 wt.%** ( $H_2/MH$ ), Volumetric and flow-meter based Sievert analysis, Highest value;
- Desorption rate: **0.11 wt.% / min**, Sievert analysis, measured at 320 °C and 1 bar, Intermediate value;
- Absorption Enthalpy,  $\Delta H_{abs}$ : - **75,8 kJ mol<sup>-1</sup>**, PCI curves at 280, 300, 320, 340 °C and Van't Hoff plot, Lowest absolute value;
- Desorption Enthalpy,  $\Delta H_{des}$ : **78.3 kJ mol<sup>-1</sup>**, PCI curves at 280, 300, 320, 340 °C and Van't Hoff plot, Lowest absolute value;
- Absorption Entropy,  $\Delta S_{abs}$ : **136.0 J K<sup>-1</sup> mol<sup>-1</sup>**, PCI curves at 280, 300, 320, 340 °C and Van't Hoff plot, Lowest absolute value;
- Desorption Entropy,  $\Delta S_{des}$ : **139.9 J K<sup>-1</sup> mol<sup>-1</sup>**, PCI curves at 280, 300, 320, 340 °C and Van't Hoff plot, Lowest absolute value;
- Desorption Activation Energy,  $E_{act,des}$ : **230 kJ mol(H<sub>2</sub>)<sup>-1</sup>**, Kinetic curves at 1 bar and 300-320-340 bar, Intermediate value
- Projected cost of material: **28 €/kg**, Evaluation of raw material and process costs, Best cost-properties balance. *ED005 (A1) will cost 10 €/kg more, but storage capacity is lower; ED007 (A2) will cost 5 €/kg less, but generally material storage properties are worse;*
- Crystal size: **35 nm**, XRPD and Scherrer formula, not considered for selection;
- Specific surface: **15-19 m<sup>2</sup>/g**, Nitrogen sorption and BET, on activated material (hydrogenated – dehydrogenated), Not considered for selection;
- Size range of dispersed catalyst particles: **< 1-2 μm**, SEM imaging, not considered for selection.

The best candidate material was characterised also in consolidated pellet obtained by cold uniaxial pressing at different conditions: with and without selected consolidating fillers and in smaller and larger pellets (diameter from 18 mm to 70 mm). The material storage properties resulted to be maintained also in consolidated form, with improved mechanical stability and axial thermal conductivity, and with a good cyclability, measured up to 50 cycles. This allows to consider a pellet size for the tank layer design between the explored diameters.

### 3. Scaling-up of the magnesium PVD decoration with catalyst to industrial level.

In the project, three stages for upscaling were followed, producing 5 g, 40g and 400g of the material coated with catalyst. The activity was performed with external support of a supplier.

The PVD process for surface-catalysed best candidate material variant production was optimized, evaluating the effect of the catalyst deposition on material kinetics, to achieve target properties on catalyst reduction at same kinetic properties. This material was compared with the bulk-catalysed variant. For the final optimization step of PVD process the use of a more limited nano-sized particle distribution of powder from HEBM will be considered, to perform a further tailoring for vibrating PVD conditions, avoiding too small or too big particles.

The possibility to produce master batches by PVD was considered too, to limit the amount of material to be processed. Validation of the properties was performed by JRC in Petten, focusing on hydrogen storage wt.%, thermodynamics and kinetics.



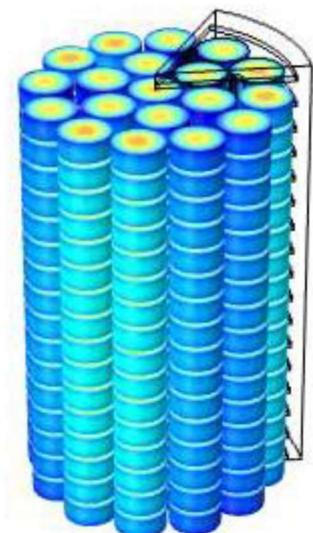
The best bulk-catalysed candidate material is going to be produced by HEBM and then consolidated by MBN to fill the storage tank prototype that was realised and tested along the second period of the EDEN project. The amount of ED011 powder produced by MBN is around 12 kg. Finally, around 100 pellets were produced to store hydrogen in the tank prototype.

## 2. DEVELOPMENT OF THE STORAGE TANK

The design of the EDEN storage tank followed several steps, starting from the modelling with a multi scale and multi physic approach. The following step moved to the definition of materials and components and the overall engineering design, lasting with prototyping and validation steps, first at the small scale, followed by an intermediate storage tank at 25% of final size. Last development was performed at the full scale, including integration and testing in the EDEN final system.

### 1. *Numerical modelling of the storage tank*

Numerical simulation was related to final optimization of internal tank components. The numerical modelling was performed considering a multi-scale and multi-physic approach. Numerical simulation has been performed to study the effect of each single component in the final complete performance of the hydrogen storage tank. This includes: thermodynamic and kinetic behaviour of the material, integration between the magnesium pellet with a thermal conductive porous Expanded Natural Graphite (ENG), to increase thermal distribution inside tank, overall heat transfer during the ads/desorption reactions, thermal insulation required for the tank. A completely new concept for the heat transfer was developed. Heat pipes with custom design were engineered for the use in hydrogen tanks. The heat distribution from the heat pipes to the storage material has also been ensured. A control system and measurement of temperatures, pressure and gas flow is considered.



## ***Modelling of the tank – Presentation***

Modelling of final tank requires a description of the physical phenomena progressing during uptake/release of hydrogen on candidate material inside the tank. From the phenomena, a physical model, able to properly describe the storage tank and the materials have been developed. The model describes the details relevant for the design of the final solution such as heat flow, temperature gradients during specific defined processes, fluid dynamic regimes.

Based on technological information available from the consortium and from the literature, an initial physical model has been developed to describe in an accurate way the profiles and trends of physical variables inside the tank during different operational conditions (e.g. hydrogen pressure, temperature gradient and distribution, heat flow) and provide feedback both on stationary and transient behaviours of the tank-system. To achieve this goal, a simple physical model of a single pellet was realized. From the basic model of a single pellet, a more complex problem has been developed and solved, including a single layer of the tank and the behaviour of the material in 2D simulation. Finally, the overall tank-system has been simulated in 3D to obtain the complete solution. Below a more detailed description of the modelling activity performed mainly in FBK are summarized in two main step:

### Step 1. Physical model of the material

Conjugate variables on EDEN material and tank have been modelled: temperature/heat, pressure/flow and mass/reacted fraction. For each of the conjugate variables a specific physics law describes the behaviour and trend have been modelled using specific COMSOL modules:

- *Fluid dynamics* module, specifically Darcy's module, which approximate with good accuracy fluid dynamics problem in porous media;
- *Heat transfer* module, specifically designed to model heat transfer between fluids and porous media;
- *Mathematical* module, particularly *Distributed ODEs* (Ordinary Differential Equations) and *PDEs* module (Partial Differential Equations), to simulate reaction kinetics of the material (the mathematic formulation of a reaction kinetic is a differential equation).

Parameters utilized to simulate tank are an important element of the overall modelling defined partly by characterization of material (MATRES and PANCO supplied parameters on reaction kinetics, thermodynamics and thermal properties of magnesium) and by scientific literature. The model of the designed EDEN tank-system has been validated against similar geometries achieving good agreement in the behaviour through different numerical simulation performed in COMSOL.

### Step 2. Modelling of the tank

The tank for hydrogen storage is one of the main and more important components of the EDEN P2P system. By this way, an optimal design of this component can enhance the reaction kinetics performance of the developed storage material and consequently of the overall storage system.

For these reasons, modelling of the tank is important to guarantee some important features:

- An optimal control and thermostatic conditions of the temperature inside the tank;
- An optimal system and flow directions for hydrogen;
- Safety, for pressurized conditions, for high temperatures, for the presence of hydrogen.

Preliminary simulations have been done to extract the main parameters necessary for the design and engineering of the first tank prototype. In addition, the model has been used after the preliminary tank

realization to validate the model itself and to optimize the design parameters for the engineering of the final tank.

## 2. Tank design and engineering

FBK, MATRES and PANCO collaborated to design, engineer and finalize the development of the hydrogen storage tank to optimize the heat transfer, the heat exchangers, the thermal management as well as the heat recovery system. A completely new concept for the heat transfer has been developed and was installed into the tank prototype to increase the overall energy performance.

The design has addressed particularly the thermal management of the tank, to supply the filling of the hydrogen storage material with adequate temperature management – provided by heating/cooling power - during the different operation phases of the tank (charge, discharge, start-up, transient). The tank has been designed based on:

- Characterization parameters of selected material;
- Thermal and gas proprieties of commercial ENG;
- Thermal and gas diffusion problem on metal hydride-tank.

The modelling of the tank address the development of the following elements and components:

- Tank external design in a cylindrical geometry: the benefits are the structural mechanical properties for pressurized vessels; a better distribution of temperature gradient respect other geometries; the simplicity and lower realization costs;
- Solid state material for hydrogen storage in form a consolidated pellet: simplicity in serial pellet production, pellets have similar geometry (e.g. no sharp edges) and can be easily designed with different sizes; pellets can be easily replaced inside the tank;
- Heat pipes for fast and concentrated heat transfer inside the storage tank. To realize a compact and light system, heat pipes have been identified as the best candidate components;
- Fins and thermal conductive material: Expanded Natural Graphite (ENG) is a high thermal conductivity material completely chemically inert to hydrogen; thermal and diffusion proprieties could be tuned by changing the density of material.

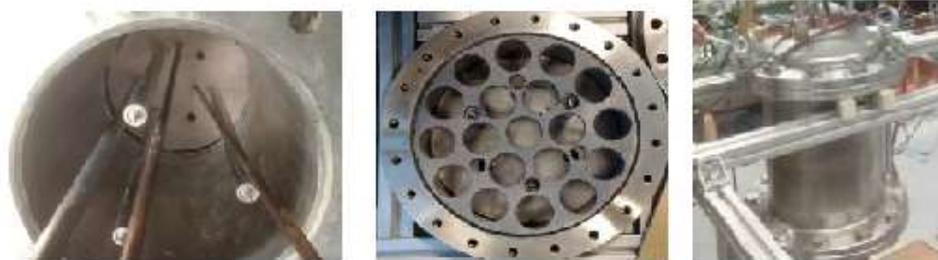
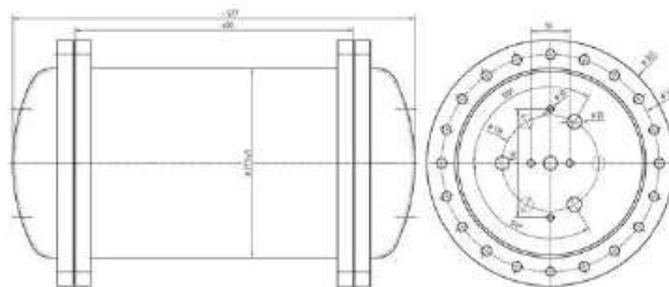
After a first rough design, optimization of the tank-design followed the below described method:

1. Detailed definition of the components (e.g. length of the heat pipe, total mass of magnesium);
2. Selection of the optimal distribution of pellets per layer, considering industrial production requirements and capabilities;
3. Optimization of single/multiple layer's geometry against gas and heat diffusion:
  - ✓ Identification and selection of thermal conductive material design (e.g. graphite);
  - ✓ Check for possible effect of composite material on gas permeability (e.g. conductive fin);
  - ✓ Optimization of single layer geometric parameters for both pellet and conductive elements;
4. Optimize final design of tank and its auxiliary necessary elements.

Once the best layout for a single layer of tank has been defined, the design of complete tank considers some main fixed parameters (e.g. height of overall tank, height of pellet, height of fins) to match tank's realization constraints. Particularly, height of tank is limited respect height of heat pipes.

### ***Realization and Validation of the intermediate tank***

The developed tank design, according to the features emerged from simulations and to described considerations, has been validated by the realization of an intermediate scale tank prototype. Distribution of pellet has been chosen to make a compromise between production capability and performance of pellet. Moreover, internal layout of the tank takes in account the thermal diffusion issues inside tank to guarantee a good thermal transfer between heat pipes and porous ENG (exploiting its overall length) and a good thermal transfer between pellets and high conductive fins. Finally, considering fixed parameters of tank (e.g. height of heat pipe, volumetric density) a final layout of tank has been decided, fixing the number of layers and fins (at least 33 with fin's thickness of about 2mm).



The main objective related to the realization of an intermediate scale tank prototype was to validate the tank design, to be suitable for material sorption properties exploitation. This includes:

- Components realization and assembly;
- Material loading and packing, by an embedding of pellets in layers suitable to ensure thermal contacts of the ENG matrix with both the storage material and the heat exchange components;
- Characterisation with a measurement equipment suitable for the tank size;
- Evaluation of storage performances (i.e. capacity, sorption rate) during tank cycling, also related to targeted properties;
- Thermal management evaluation, to ensure a suitable heat exchange during both absorption and desorption steps.

Preliminary tank vessel has been constructed per safety regulations. Heat pipes has been selected considering the required heat flows and working temperatures and a suitable commercially available lightweight thermal conductive ENG matrix has been used. Bulk catalysed best candidate material has been produced (2.4 kg) and consolidated in pellets, tailoring the pellet size per the defined layer design. Before the overall assembly of the tank, preliminary tests have been performed embedding small pellets on the selected ENG matrix and evaluating their mechanical and thermal behaviour. Data collected allows to improve further layer designs.

According to the defined design, the tank assembled with all the components was loaded embedding pellet layers with ENG matrix. Attention was addressed to properly allocate thermocouples for an optimal monitoring and control of the temperature behaviour inside the tank. Once fully assembled, the tank was connected to the electrical heat management system and to specifically developed device suitable for control and characterization of hydrogen flows. By this way, after some preliminary tests for leaks verification and a degassing step, the tank has been heated up, starting its activation to perform some charging/discharging cycles and evaluate hydrogen storage performances of the overall storage system.

### Tank characterization

Employing the MATH2 volumetric instrument, with the mass-flow control tool, 28 cycles of hydrogen absorption and desorption were performed. During the 8 cycles performed for tank activation, different sorption conditions has been tested, selecting a steady flow condition with self-regulating pressure to simulate the future needs of the final EDEN system. Once the storage material within the tank reached the expected gravimetric capacity, 20 absorption and desorption cycles has been performed, allowing the evaluation of tank sorption properties, testing different thermal management solutions and evaluating the storage properties at different conditions. To allow a simple comparison with the specific characterizations previously performed on the storage material, the sorption properties (i.e. gravimetric capacity, sorption rate) were referred to the amount of best candidate material inside the tank.

Since the storage tank will be integrated in the EDEN P2P system and coupled with a reversible SOFC, with this characterization activity the tank storage properties have been validated to verify capability of the tank in sustain inlet and outlet flows from the SOE/SOFC device during absorption and desorption phases. Different process parameters were settled and tested during the characterization campaign to extract the best operating conditions and parameters for maximizing the percentage of tank capacity. These parameters became validated working conditions for the design and engineering of the full-scale tank.

### Intermediate tank performances

This tank prototype presents a storage volumetric capacity of 20 gH<sub>2</sub>/l, considering the volume of the vessel and the time required to achieve the 95% of storage capacity, a desorption rate of 0.029 wt.%/min at 350 °C and 0.025 wt.%/min at 320 °C, corresponding to 0.70 g/min and 0.60 g/min respectively. The volumetric capacity of each layer can be estimated in 37 gH<sub>2</sub>/l.

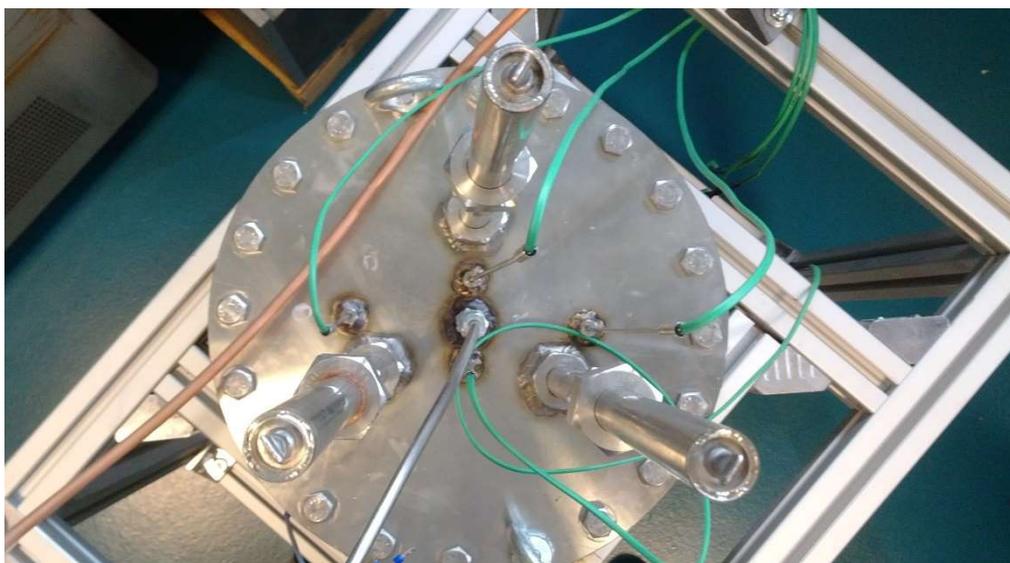
The work performed with the intermediate tank led to the acquisition of further knowledge that will be employed for the realization of the full-scale tank prototype, improving the design at different levels and allowing its integration with the other components of the overall P2P storage system.

### **Realization and Validation of the full tank**

The full-scale hydrogen storage tank prototype has been constructed by PANCO based on the design optimization raised from experience and characterization of the intermediate tank. The thermal management has been improved by using a new set of heat pipes and heat exchanger. The tank height and diameter have been increased to 400mm, the position of heat pipes for heating and cooling and the layer design were optimized through additional simulation done in COMSOL. Due to the objective declared at the beginning of the project (at least 600g of hydrogen stored) it arises that for the heating of this tank the heat provided by the SOFC – Dummy (limited by the commercial product available) was not sufficient, thus an

additional electrical heater (1kW power) was wound around the tank and properly controlled. Safety issues were considered too, particularly for the thickness and the material of the components.

The bulk-catalysed best candidate material for solid state hydrogen storage, developed within WP1 and validated in the intermediate tank, has been produced and consolidated in form of pellets by MBN. The pellets were produced with the selected consolidating fillers, for a total amount of 15 wt.%, per the previously defined layer design. A total number of more than 400 pellets, corresponding to 10.66 kg of bulk catalysed material (ED011), has been placed in 22 different layers, embedding them in a soft thermal conductive matrix of expanded natural graphite (ENG) during the tank filling operations. ENG matrix and fins are in contact with heating and cooling pipes. The contact of the graphite fins to the heat pipes has been improved using a zigzag shaped cutting of the graphite.



### Tank characterization

Once closed the tank, tests for leaks were performed both at room and at working temperatures with inert gases (N<sub>2</sub> up to 330 °C and 10 bar, Ar and He up 330 °C and to 4bar), followed by a degassing step. Then the characterization campaign has started.

A preliminary characterization set up has been implemented and used to verify material activation, consisting of 3 pressure sensors and 14 temperature sensors, with a multi-step volumetric approach. Following this approach, 5 absorption/desorption cycles have been performed for material activation, maintaining the material in hydride form after the 5<sup>th</sup> absorption and the tank in overpressure of inert gas at room temperature conditions, to proceed with whole system integration. During material activation and cycling the thermal management has been tested employing different heating and cooling conditions, evaluating temperature variations by a set of specifically placed thermocouples.

To fully characterize and validate the storage properties of the final tank, the activation and characterization activities proceeded after the setup of a complete measurement system performed in FBK using different mass flow controllers to verify the flow during charging of the tank (H<sub>2</sub> adsorbed must be consistent with working conditions of fuel cell in SOE mode) and discharging of the tank (H<sub>2</sub> desorbed must consistent with the gas flow required by fuel cell in SOFC mode).

### Full tank performances

The full tank prototype presents a storage volumetric capacity of 37 gH<sub>2</sub>/l, considering the volume of the vessel and the time required to achieve the 95% of storage capacity, a desorption rate of 1.00 g/min at 350 °C. The maximum volumetric capacity of the whole tank is 815 g of H<sub>2</sub>. The main performance values are included in the table below.

<b>Hydrogen storage tank performances</b>	
<i>Hydrogen storage capacity [wt. %]</i>	2.0
<i>Hydrogen density [g/l]</i>	37
<i>Absorption heat recovery [%]</i>	<b>26.5</b>
<i>Hydrogen stored [g]</i>	<b>815</b>
<i>Desorption rate[g/min]</i>	1

### **3. SYSTEM INTEGRATION and DEMONSTRATION**

FBK, PANCO and CIDETE cooperated in the P2P system integration initially performed in Germany and finalized in FBK, where all auxiliaries are assembled, tested and optimized on all the following components: reversible SOFC/SOE device, hydrogen burner, water removal system, hydrogen compressor, blower, steamer, heat exchangers, valves and components controls, electronic control unit (ECU) and power supply.



#### ***EDEN system integration***

The main issue addressed by FBK for a successfully development of a complete P2P energy storage system based on EDEN technology is the integration and efficient management of two main components: the hydrogen storage tank and the reversible SOFC/SOE device. This device can run in reversible mode: as an electrolyser (SOE mode) to produce hydrogen (using external electrical source – like renewable PV) and store it in the hydrogen storage tank developed in EDEN; as solid oxide fuel cell (SOFC mode) to re-convert the accumulated hydrogen into electrical and thermal power.

The integration layout between H<sub>2</sub> storage tank and SOFC/SOE device unit must consider the following points:

- Thermal management: this includes several requirements from the system in both SOFC and SOEC modes, requesting a proper sizing of heat exchangers, hydrogen burner as a balancing element for the heat transfer along the system;
- Hydrogen management;
- Water management;
- Air management;
- Power management.

To properly address this objective, physical and energy flow layout for the overall system have been identified and optimized considering the auxiliaries' characteristics and behavior, considering optimization of working parameters such as the fuel utilization, management of mass flows and measurement control of water percentage in the fuel supplied from and to the fuel cell. Therefore, integration between SOFC/SOE device and hydrogen storage tank includes the identification and sizing of auxiliary components for an efficient and integrated balance of plant (BoP) able to properly manage the fuel and heat moved through the system.

#### Thermal management in SOFC and SOE modes

The SOFC mode is the most critical to handle, due to the high amount of thermal energy involved. Some main considerations for heat transfer and related thermal fluid dynamic regimes are:

- even if the energy/power balance guarantees the self-sustainability of the system from a first principle point of view (8 kW of suitable thermal power from exothermic heat versus 7.5 kW required by inlet flows), the constraint introduced by the Pitch's temperature creates a reduction of available energy/power to preheat the inlet flows (both air and fuel);
- temperature of exhausted flows (after main heat exchanger) is about 170°C;
- Finally, energy/power balance is short of about 1.3 kW to guarantee self-sustainability of EDEN system.

In conclusion, despite the presence of excess thermal power in outlet flows, this is totally unusable because it is at too low temperature. So, to guarantee a correct heat exchange, there is the need to supply an additional thermal power. Different solutions have been studied and applied to identify the best solution for the problem. Finally, the design and technical consideration for a proper thermal management in SOFC mode and SOE mode are the following:

- SOFC mode:
  - ✓ Two separate heat exchanger are used to recover heat form air and fuel exhaust side;
  - ✓ Air exhaust from SOFC is utilized to heat the hydrogen storage tank, through heat pipes and their heat exchanger;
  - ✓ A hydrogen burner is utilized to increase temperature of exhausted. Non-reacted hydrogen and an additional amount of hydrogen is burned with the exhaust air coming from the fuel cell.
- SOEC mode:
  - ✓ Water is purified (softener) and vaporized in suitable steamer;
  - ✓ Air at room temperature and steam are pre-heated by outlet flows and heat exchangers;
  - ✓ Exhausted air from main heat exchanger is expelled from system, and it can be exploited for domestic using;
  - ✓ Hydrogen/steam flows are purified and compressed. Compressed hydrogen is introduced in the hydrogen storage tank.

### ***Evaluation of the storage tank heat recovery solution***

Thermoelectric devices (TE) for heat recovery was specifically designed to re-cover heat from the curved faces of the heat pipes during SOE mode, when absorption phenomena generate a considerable amount of heat. The design was optimized to reduce thermal losses and properly transmit the heat.

#### *Simulation of heat recovery system*

Heat from exothermic adsorption reactions, considered as wasted energy, could be used to improve the tank performances but also recovered to balance the overall power consumption of the system. Using COMSOL heat transfer simulation software, different ways to recover the highest amount of heat and convert it into electricity have been studied:

- 1<sup>st</sup> case – heat sink without TE modules;
- 2<sup>nd</sup> case – heat sink with TE modules on the top;
- 3<sup>rd</sup> case – TE modules re-covering the Heat Pipe.

#### *Testing the heat recovery system*

The design proposed for the heat recovery solution of the hydrogen storage tank must be validated. The same heat pipe to be installed into the tank have been used for the validation tests. Metallic components with a square section to recover heat from the curved faces of the heat pipes were designed. The design was optimized to fits tightly around the heat pipe and minimize thermal losses. In addition, between the heat pipe and the metallic blocks, we introduced thermal conductive grease to properly transmit the heat. Nevertheless, to ensure the correct performance of the TE modules, it is necessary to maintain enough temperature difference between the two faces of each TE device using specific TE geometry and distribution.

During in-lab testing the proposed heat recovery solution has been validated: a maximum temperature difference of about 95 °C, with 203 °C hot side temperature, have been measured obtaining a voltage around 18.5 V in open circuit and 1 A current.

#### *Integration between the heat recovery solution and Thermo-electric components with the SOFC system*

The integration between the TE heat recovery system and the SOFC is done with a small electronic control circuit (made of relays and thermostats and divided in two functional part: “part A” and “Part B”) properly controlled by the Electronic Control Unit (ECU) to change the working mode when the SOFC system changes from SOE mode to SOFC mode or vice versa.

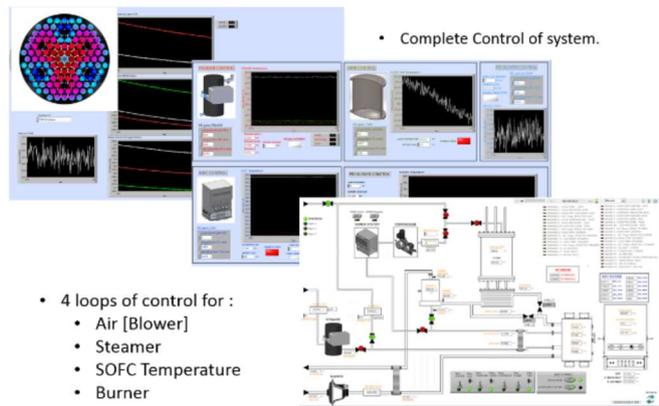
The “Part A” consists of a relay that is controlled by the ECU to decide in which way make work the TE modules (Seebeck or Peltier mode). The “Part B” is the fans control. Fans are designed to work always automatically in both modes; in SOE mode it is needed the maximum temperature gradient between the hot and cold side of the TE module to obtain as much power as possible, in the SOFC mode it is needed that the cold side of the TE module (the one in contact with the heat sink) is lower than 200 °C to avoid damages.

### ***Electronic Control Unit (ECU)***

A proper ECU has been developed to manage the overall EDEN P2P system. ECU includes a complete monitoring and controlling of system parameters, with a series of alarms and warning to make safe the system when dangerous events occur. ECU software includes some automations (PID algorithm and parameters management) to support the operator during working step.

The ECU has the objective to properly measure each single parameter of the system, both at a functional level to monitor the overall system under working condition and to collect data for safety reasons.

ECU provides continuous and real time monitoring to achieve optimal system functioning efficiency, preventing system malfunction and operating protection mechanisms when faults occur according to the different critical situation and the proper safety measure established during the Risk Assessment analysis. The full system control is done reading the value of different sensors installed in selected point of the EDEN system configuration, measuring electrical signals that are converted into engineering values by the control SW of the ECU to check the main functional parameter. In addition to the data acquisition and system control objectives, the ECU manages all the electrical power supply and the electric energy produced by SOFC and consumed by SOE (in electrolyze mode), also important to prevent damage of the SOFC/SOE apparatus. More info regarding the ECU architecture and functionalities are reported in D3.4, while the performances evaluation and control unit validation have been conducted continuously during the test and the assembly of the system to verify, step by step, the correct implementation of the SW.



### ***Control of the EDEN P2P technology***

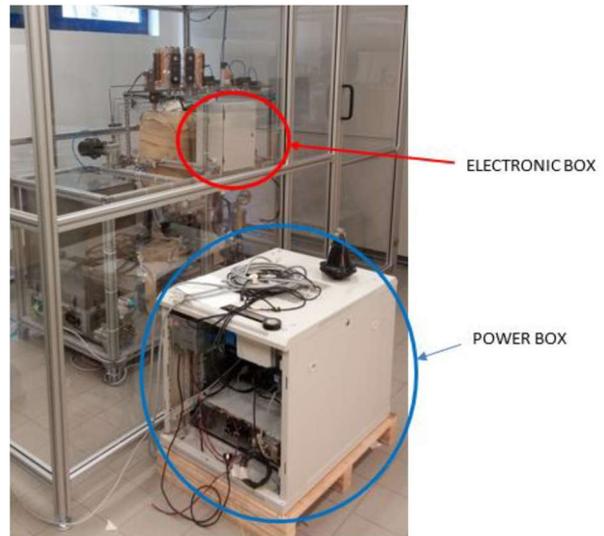
The EDEN power to power technology is composed by several components working together in a controlled manner: solid-state hydrogen storage tank, solid oxide bidirectional fuel cell – electrolyser, catalytic burner, water removal system, vaporiser, hydrogen compressor, heat exchangers, blower, and other components such as valves, sensors, fittings. In addition, this system can work in two modes: SOFC mode producing electricity from the H2 stored inside the tank or SOE mode producing H2 and storing it inside the tank.

ECU hardware includes:

- **ELECTRONIC BOX.** Core of ECU, it includes: main electronic platform (software runs over that), electronic boards for signal conditioning and power supply for the sensor transducers.

Electronic box is responsible of signal acquisition, valves control, PID tuning algorithms and sensors power supply. Electronic box is supplied only with low voltage (24 V, 12 V and 5V).

- **POWER BOX.** It includes, power relays for every device, SSRs (Solid State Relays) to control electrical heater, main power supply (PU) for SOE mode, UPS, Electronic control unit for valve engines and monitoring PC.



Power Box is responsible for the handling of power supply for all device in EDEN system (mainly, for the devices with high current consumption (heater, SOE, etc..)). It is externally placed respect to EDEN system box, for safety reasons, to maintain high voltage handling outside to possible explosive atmosphere.

Considering safety conditions for EDEN system, ECU implements a series of alarms making in safe side the system, for possible emergency and possibility of danger for things or people. Every alarm has a warning state to recover the nominal conditions.

#### ***Demonstration of the EDEN components and subsystems (in-lab @ FBK)***

To complete system integration reducing uncertainty and avoiding undesired problems during the test of the full system and the future test in real environment, different test n the single components – where reasonable – have been performed.

The tests included the following components:

- Hydrogen storage tank: The full-scale hydrogen storage tank prototype for EDEN project has been constructed, filled with the consolidated best candidate material ED011, powdered up and fully characterized. More detailed on complete characterization are reported in D2.3;
- SOFC/SOE characterization: The SOFC/SOE unit was properly integrated with the thermal management system and the corresponding auxiliary control system to guarantee the complete functionality of the overall prototype. Test and integration of the SOFC/SOE unit provided by SOLID POWER was completed following the specific operating guidelines supplied by Solid Power, which request additional architecture implementation and process evaluation for the switching phases from SOE to SOFC mode and vice versa;
- H2 Burner: Catator has designed a burner for catalytic combustion of hydrogen on the request of Bruno Kessler Foundation (FBK) to be installed in the full system architecture under development. The flow rate of hydrogen requested is 20 – 25 slpm, which corresponds to a heat output of around 4.5 kW. The hydrogen flow is mixed with a similar steam flow and the mixture enters the reactor at 800°C. Air enters the reactor at a flow rate of 400 slpm and 650°C. The device has been tested completely using Mass Flow Controllers (MFC) to control the gas flow of air and hydrogen (H2) to the burner. The temperatures after the primary catalyst and on the exhaust outlet were recorded. More data are available in D4.1;

- Water removal system: this component is necessary to maintain stable and cyclable properties on the storage material. The water removal system has been tested completely by FBK, verifying the pressure loss behaviour which depends on used dryer agent and the residual humidity of dried product gas. Dew point of  $-60^{\circ}\text{C}$  was measured, corresponding to less than 100 ppm of water content in the gas stream, as agreed among partners;
- Hydrogen compressor: hydrogen compressor has been configured as a subsystem able to maintain the necessary pressure drops in the system, both upstream and downstream. A parallel retrofitting piping was installed and properly controlled by a modulating valve;
- Blower: the blower is an important part. Air flow is the thermal vector of system as well as the oxygen carrier for the SOFC reaction. Pressure drop of pipeline and valves in EDEN system is about 10-30 mBar, at nominal flow of 150-250 NL/min;
- Steamer: dedicated tests were performed to demonstrate the proper control of the steamer, following the suppliers' instructions.

The EDEN integrated system was tested on both SOE and SOFC reverse modes. FBK solved several issues emerged during the integration of the different components, particularly in the below reported elements:

- SOFC mode: automatic tuning of hydrogen mass flow;
- Pressure drop during the compressor working time;
- Procedure of start-up;
- Procedure of shut down.

#### ***Demonstration of the EDEN system prototype (in-field @ Barcelona, Spain)***

The demo activities were partly performed in FBK and partly performed in-field in Barcelona, by a site selected in collaboration with the Barcelona Energy Agency (AEB). The activities in FBK, after demonstration of the correct behaviour of each single component in a lab environment, have been conducted to complete a first preliminary test of the full integrated system performance and control before the final shipping to the demo site in Barcelona. A dedicated risk management procedure was implemented in the ECU to give the proper alarm following the risk assessment document developed by EDEN partners in collaboration with Fire Fighter Department of Barcelona and AEB).



The final step demonstrated a simplicity of installation and configuration of the overall system (< 1day for full installation, assembly and start up procedure), evaluating the installation procedure of such kind of system in case of future market deployment.

Finally, hydrogen absorption and desorption cycles were performed with EDEN P2P system connected to local electrical load to evaluate performances of the prototype in real environment. Good results have been

achieved considering the overall cycle efficiency and the hydrogen storage capacity. A final electrical cycle efficiency of 5% (including the auxiliaries' consumption, not optimized due to the prototypal nature of EDEN technology) has been achieved with about 800 g of hydrogen storage in the final tank prototype. Unfortunately, due to the limited time available and the degradation process of the storage material, three complete cycles at the full-scale tank storage capacity have been performed.

## Potential impact and main dissemination activities and exploitation results

### 1. INTRODUCTION

The use of hydrogen as an energy carrier is relatively new and, as such, may be vulnerable to inaccurate public perception. Social acceptance is vital to the successful deployment of any technology and can be achieved by heightening awareness of the risks and benefits offered by each specific technology. For hydrogen technologies, through knowledge dissemination and education during research project duration as EDEN, providing information on safety and emphasizing the environmental advantages of hydrogen as a fuel could contribute at creating opportunities to traduce the EU investment in potential impact at economic and social level. Only with a good social acceptance and proper regulation package, a successful market deployment of innovative technologies could be addressed with consequent positive economic impact on the overall European community.

In order to contribute at this objective, EDEN consortium have done a consistent number of dissemination initiative (more than 60 %) as public press releases, media communication events and public events to address a huge public audience - from politicians to citizens - in order to stimulate social acceptance of hydrogen technologies. In addition, the transnational cooperation prompted by EDEN consortium has managed to mobilise and promote the sharing of knowledge and capabilities (in terms of expertise, institutions and resources such as laboratories) among the whole scientific community, collaborating with other research project (like BOR4STORE, SSH2S, HYPER), participating in different FCH-JU initiatives (review days, presence at fairs, etc.). The project has produced valuable impact on the related industry and research disciplines, participating at international conferences and congress where members of the EDEN consortium presents project objectives and results. Feedback from the audience and stakeholders can be distinguished and summarized in the following main categories:

- Research: people asking for information on the project to complete research papers, dissertations, for use in related research prototypes or to be better informed about the project innovations and objectives;
- Industrial: people ask for information on future market deployment of the hydrogen storage technology, to estimate possible future market participating as a components supplier/provider or as partner in a new joint venture initiative;
- End-users: people asking for information as potential end-users willing to try out the project results;
- Working/collaborations: people and companies declaring interest for collaborating in new initiatives;
- Commercialisation: established Technology Transfer Board (TTB) evaluate how to collaborate to move EDEN prototype from TRL4 to TRL9 and develop a product to address preliminary market opportunities.

It is also important to note that impacts of research, capacity building and innovation projects like EDEN are also long-term in nature and the contribution to socio-economic development can not only unfold with immediate direct results, but also via indirect ones that may become visible only years after research activities have ended. Besides the obvious impact in terms of new technologies/products produced, EDEN has also helped in ensuring further knowledge sharing and capacity building projects between typically unconnected research partners established especially in South Europe - thus contributing towards the development of skills and institutional capabilities of partners. Similarly, some effort has been undertaken to generate and influence policy makers (in Spain and Italy), while promoting policy dialogue and learning in the topic of hydrogen technology and in the general energy applications towards the objectives outlined in the H2020 programs.

## 2. TOWARDS COMMERCIALISATION of EDEN TECHNOLOGY

As reported in detail in the Market deployment plan (MDP), the EDEN technology has been tested in intended environment achieving a TRL5 level according with the FCH-JU TRL level definition.

MBN, as material producer, will exploit commercial opportunities related to Mg-based storage material developed inside the EDEN project, in form of powder and/or pellets, for different hydrogen storage systems. Particularly, after some improvements and optimizations of the “ED011 Nanostructured Magnesium” developed during the project, commercialization of the storage material is expected by first quarter of 2017 addressing mainly the European markets of solid state H<sub>2</sub> storage systems. By upscaling the material production in the range of 10-20 ton/year, it is estimated that first material selling could be done in the price range of 28-30€/kg, that could be successively decreased in function of the increasing number of order for material production.

In addition to the short-time market availability of the storage material, there are several additional options to commercialize the EDEN technology, varying from selling it as a standalone product or incorporating it (or part of the technology developed) into existing products. These following important steps are envisaged to increase the opportunity of the market deployment, especially for the improvement and final product development of a complete integrated P2P system after the basic and applied research conducted during the project:

- Improve performances of the already available ED011 storage material;
- Scaling-up the industrial material production process (hundreds of tons/year) - in form of powder and/or pellets;
- Improve tank efficiency (control process, insulation and energy recovery) and tank weight reduction;
- Miniaturisation of ECU and safety systems;
- Involvement in the TTB of a company capable to operate as system integrator with expertise to properly address future market deployment;
- Influence policy makers for the necessity of a common national and/or international standards and regulation on solid state hydrogen storage, to facilitate the diffusion of hydrogen storage technologies and applications;
- CE marking;

In the EDEN Market Deployment Plan (MDP), a complete market analysis has been done and preliminary business cases for real deployment of EDEN P2P system have been envisaged. Here are reported, as feasible business cases, the exiting market that could be addressed in a short time:

- OFF-GRID TELECOMMUNICATION TOWER;
- HYDROGEN BALANCE FOR REFINERIES;
- GRID MITIGATION;
- HYBRID SYSTEM FOR DAILY TIME SHIFTING AND RESIDENTIAL mCHP.

Three to five years is estimated as a reasonable amount of time to improve the technology as previously outlined, to decide the commercialization pathway and collect the funding for preliminary installation of the EDEN P2P system products.

On the other side, some issues remain unsolved for the commercialization of the complete P2P solution and further R&D activities are necessary to bring the developed technology at higher TRL levels.

FBK has the intention to set up again the EDEN system inside a new laboratory under preparation in the institute in Trento. FBK has already installed a new stack supplied by SOLID POWER, to recover the previous faulty cell, and signed an agreement to continue the related research on this topic. The new set up will allow further tests on the EDEN system, to complete pending issues such as:

- Cyclability and long term tests;
- Optimization of auxiliaries;
- Connection and utilization of the heating recovery system.

The follow up of EDEN project is indeed planned to properly prepare a further initiative (in form of public project or private investment) to evaluate, according to the business cases individuated in the Market Deployment Plan, proper partnership to address preliminary industrial pre-production, installation and evaluation at distributed level.

### 3. POTENTIAL COMMERCIALISATION PATHWAYS

There are several options to commercialize the EDEN platform. Potential commercialization pathways for EDEN technology include:

1. Outright sale Simple, immediate income;
2. Consulting thanks to the expertise developed during the project;
3. Licensing Exclusive or not, long term income, simple;
4. Joint Venture company with TTB members: agreed equity stakes, sharing in future development;
5. Independent Spin-out company: agreed equity stakes, best returns including from future R&D.

The final Exploitation Plan is the result of a concertation process conducted by the project consortium in the last twenty months of the project, collected in two main documents: Market Deployment Plan (MDP) and the Common IPR Agreement (IPR). In the following paragraph about exploitation results are briefly summarized the details included in these two important documents for future market deployment of the EDEN technology.

All the options the consortium considers viable are described in the IPR Agreement. Since today, EDEN project has assessed not only the technological development, but also the aspects related to the regulatory frameworks and standards which allows customisation of the final prototype to match the requirements for the development of a marketable product. These may include:

- Safety related standards;
- Maintenance procedure standardisation: instructions related to the maintenance procedure for the system (definition of lifetime of each spare component and/or system, definition of terms of use for the system);
- Regulatory framework assessment.

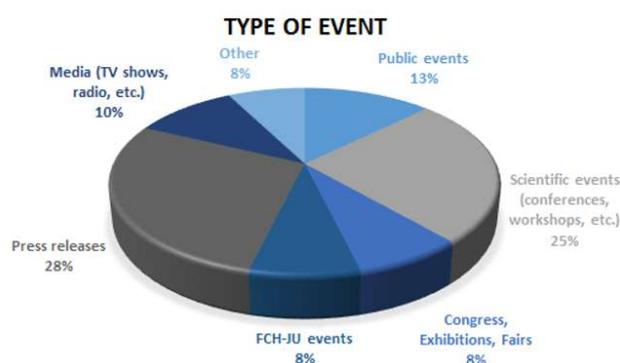
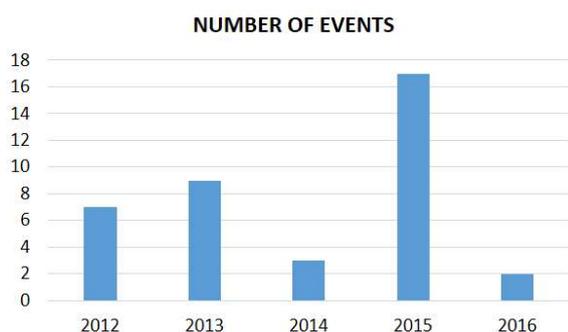
**Now, it is deemed that the commercialisation pathways best suited for the EDEN results are primarily the spin-out route and the licence route, with the opportunity of outright pending IP applications for the single components or process.**

#### 4. DISSEMINATION ACTIVITIES

During the whole duration of the project (October 2012 – June 2016) more than 35 dissemination actions (average value of 0.8 event/month) have been taken by the project consortium under the WP5, following a common agreed dissemination plan - with at least one event each three months - in order to maintain a constant attention on project advancement and activities. As reported in the following figure, the dissemination actions have been distributed using different media channels to address a huge audience, from the scientific community, to industrial sectors and policy makers, until the possible final users (citizens, companies, etc.). More details on each event are reported in the tables at paragraph 4.2. In parallel, the EDEN official websites published in February 2013 (M5) have been constantly updated and completely restyled at the end of 2014 (M26). Additional dissemination material (a new brochure with detailed information about the system applications, postcards, rollup, etc.) have been developed in order to better address the interest of energy sector actors and stakeholder and diffused in trade fairs, conferences, exhibitions and face to face meetings.



Looking at the following picture, it should be noticed that a consistent number of dissemination activities have been done in 2015, since preliminary results on the whole system architecture was available only during the first quarter of 2015 and that the project end was initially planned at September 2015, with the Final Dissemination Event in Trento already organized and publicized. Due to the technological and shipment delay occurred at the end of 2015, two additional dissemination events in Barcelona during project extension in 2016 have been organized as EDEN closing events after the test campaign in real environment.



## 5. EXPLOITABLE FOREGROUND

Exploitable foreground and relative applications, as a non-exhaustive list, are here summarized:

- Modelling, simulation and design of hydrogen systems for complex production - storage - usage of hydrogen;
- Modelling and simulation of hydrogen storage in solid state materials with multi-scale models and multiphysics phenomena analysis of hydrogen storage in solid state material for R&D activities, industrial innovation, new product productions, educational and academic courses;
- Improved knowledge on Mg-based hydrogen storage material characterization - in powder and particularly as consolidated pellets - as services for material industrial production, for measurements of storage performance (gravimetric capacity, sorption rate) and for solid state hydrogen storage material development;
- Development of synthesis route by high energy ball milling for nanostructured Mg-based powder for hydrogen storage;
- Plasma deposition of ultrathin films onto powders for catalysis in energy sector application (photocatalysis for H<sub>2</sub> production), sintered powder consolidation in electrodes for fuel cells or for electrodes in OLEDs applications;
- Catalyst application by physical vapor deposition onto Mg for H<sub>2</sub> sorption kinetics improvement for catalysis in energy sector application (photocatalysis for H<sub>2</sub> production), sintered powder consolidation in electrodes for fuel cells or for electrodes in OLEDs applications;
- Production procedures of consolidated pellets including consolidating fillers enhancing thermal conductivity and mechanical stability, specifically developed for tank used in high temperature hydrogen storage systems;
- Testing equipment and procedures for medium to large amounts of solid state hydrogen storage materials;
- Development of safe and cost effective procedures for material production in inert atmosphere and correlated procedures for transportation and commercialization;
- Hydrogen tank design with proper heat pipes geometry for solid state hydrogen storage systems;
- Measurement instrumentation and characterization procedures for hydrogen storage tanks;
- Design, development, assembly and control of a heat recovery solution for industrial applications;
- Expertise in power-to-power (P2P) system development for energy storage applications, grid management, residential and industrial scalable solutions based on hydrogen;

- Safety requirements and procedures for hydrogen storage system installation in industrial and residential applications.

## **6. FOREGROUND TO BE PROTECTED AND EXPLOITED COMMERCIALY**

The list below illustrates the major innovative developments achieved:

- Catalyst application by physical vapor deposition onto Mg for H<sub>2</sub> sorption kinetics improvement
- Hydrogen storage tank for integration in P2P system
- Complete P2P system architecture based on solid-state hydrogen storage solution

Patent application is under evaluation by the consortium, as outlined in details in the IPR Agreement.

## **7. SETTING UP of TECHNOLOGY TRANSFER BOARD**

The Technology Transfer Board is a horizontal structure defined at the beginning of the project between the Project Coordinator, the project partners and external industrial parties interested in exploitation of the project results and in developments after the project closure. The TTB's task is to ensure full exploitation of the project results. Today, the actual TTB is participated by 14 European and international entities with more than 70% representing European SME.

As a first results of the collaboration, SOLID POWER and FBK are preparing a collaboration agreement specific to the topic of HT Electrolysers and reversible Solid Oxide technologies.

Based on updated expression of interest of the TTB members to exploit the EDEN technology, partners involved for deployment of the technology will meet again to evaluate future collaboration pathways.

## **8. COMMERCIALIZATION REQUEST & EXPRESSION OF INTEREST**

Commercialisation requests and further funding opportunities collected are here summarized:

- Request to collaborate with the SOLID POWER company in the field of HT electrolyzes and reversible Solid Oxide systems;
- Request to collaborate with the HZG company in research and development of new hydrogen storage materials and systems;
- Interest of local municipality of Isera in Italy for the installation of a prototype unit in the municipality renewable energy station, based on solar PV and hydrogen generation system;
- EDEN was requested to provide information at local municipality of Borgo Valsugana (Italy) to better understand advantages, environmental and social impact of the EDEN technology;
- EDEN was requested to provide information at Barcelona Energy Agency (BEA) in Barcelona, Spain to better understand advantages and applications of the EDEN technology in big smart cities;
- EDEN was requested to provide a feasibility study and a full prototype for a potential installation by a private user in a rural family building requiring 3Kw of power;
- EDEN was requested to provide collaboration in teaching courses at industrial and technological schools in Italy (progetto Alta Formazione).

## Address of project public website and relevant contact details

Website: <http://www.h2eden.eu/>

Relevant contact details:

Mr. Luigi CREMA

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CMM – Centre for Materials and Microsystems

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# PROJECT FINAL REPORT

## Use and dissemination of foreground

FCH JU Grant Agreement number: **303472**

Project acronym: **EDEN**

Project title: **High energy density Mg-Based metal hydrides storage system**

Funding Scheme: **JTI-CP-FCH - Joint Technology Initiatives - Collaborative Project (FCH)**

Period covered: **from 2012.10.01 to 2016.06.30**

Name of the scientific representative of the project's Coordinator, Title and Organization:

**Dr. Luigi Crema**

**FONDAZIONE BRUNO KESSLER**

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Project website address: <http://www.h2eden.eu/>

## Section A (public)

### Publications

#### LIST OF SCIENTIFIC PUBLICATIONS (STARTING WITH THE MOST IMPORTANT ONES)

No.	Title/DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifier (if available)	Is/Will open access provided to this publication?	Type
1	Nb2O5 deposition on Mg by plasma technique for hydrogen storage applications	R. Bartali, et al.	NANOENERGY 2015 - International Conference on Nanotechnology, Nanomaterials & Thin Films for Energy Applications			Manchester, United Kingdom	June 1-3, 2015			NO	Poster
2	DEVELOPMENT OF A EXPERIMENTALLY VALIDATED MODEL FOR SOLID STATE HYDROGEN STORAGE DESIGN OF MATERIAL AND TANK	M.Testi et al.	EFC2013 - Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference			Rome, Italy	December 11-13, 2013			YES	Conference Proceedings
3	EDEN: NOVEL POWER-TO-POWER SYSTEM FOR ENHANCED HYDROGEN STORAGE IN SOLID STATE	L. Crema et al.	EFC2015 - Sixth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference			Naples, Italy	December 16-18, 2013			YES	Conference Proceedings
4	NEW CONCEPT FOR THERMAL MANAGEMENT IN A HYDROGEN TANK	D. Platzek et al.	9th International Symposium Hydrogen & Energy			Emmetten, Switzerland	January 25-30, 2015			YES	Conference Proceedings

Not considered in this table the different scientific presentations (7) presented at the FCH-JU projects on hydrogen storage Joint Workshop, October 2013, Tenerife, Spain

## LIST OF DISSEMINATION ACTIVITIES

No .	Type of activities	Main Leader	Title of the event	Date/Period	Place	Type of audience	Size of audience	Countires addressed
	Press release	FBK	KICK OFF MEETING- EDEN PROJECT	12/10/2012	Italy	Public	>1000 media members	National/international
	Self-published Press release	FBK	PROVIDING HYDROGEN ENERGY TO HOMES	15/10/2012	Italy	Public	> 50000/year	National/international
	TV show	FBK	TV show "Dedalo" on Ada Channel <a href="https://www.youtube.com/watch?v=TdLuMaMxEtE">https://www.youtube.com/watch?v=TdLuMaMxEtE</a>	24/10/2012	Italy	Public	>20000	Italy / National
	Daily Newspaper	FBK	Weekly press insert on scientific dissemination. Article entitled "La casa pulita è a idrogeno e sta nascendo a Trento"	07/11/2012	Italy	Public	n.a.	National
	Workshop	FBK	IPHE Workshop - Hydrogen Storage <a href="http://www.iphe.net/events/workshops/workshop_2012-11.html">http://www.iphe.net/events/workshops/workshop_2012-11.html</a>	14-16/11/2012	Seville, Spain	Research, Industry	>100	Spain / International
	Congress	MATRES	National Congress on Energy and Hydrogen European program – H2IT Association <a href="http://www.fast.mi.it/H2IT/ppt_convegno13dicembre2012/Presentazioni.htm">http://www.fast.mi.it/H2IT/ppt_convegno13dicembre2012/Presentazioni.htm</a>	02/12/2012	Milano, Italy	Research, Industry, Government bodies	>50	Italy / National
	Video news release	FBK	National TV – RAI – TG2 (Radio Televisione Italiana) – news programme - EDEN project presentation	14/12/2012	Italy	Public	n.a.	Italy / National
	Self-published Press release	MBN	AVVENIRE newspaper - Article entitled "Nanotecnologie, l'Italia è sul treno"	12/01/2013	Italy	Public	n.a.	National
	Website	FBK	EDEN website online	24/02/2013		Public		
	Daily Newspaper	FBK	Article entitled "Più idrogeno per dare energia alle abitazioni"	25/02/2013	Italy	Public	n.a.	National
	Congress	CIDETE	International Congress on Materials and Renewable Energy (MRE) <a href="http://www.energy-conference.co.uk">http://www.energy-conference.co.uk</a>	01-03/07/2013	Athene, Greece	Research	>500	Greece / International
	Congress & Exhibition	MBN	Euro PM2013 Congress & Exhibition – European Powder Metallurgy Association <a href="http://www.epma.com/euro-pm2013">http://www.epma.com/euro-pm2013</a>	15-18/09/2013	Gothenburg, Sweden	Research, Industry	>800	Sweden / International
	Daily Newspaper	MBN	Milano Finanza – Economical newspaper - Article entitled "Micropolveri, grandi numeri"	18/09/2013	Italy	Public	n.a.	National
	FCH-JU Workshop	ULL (hosting organization) ALL PARTNERS	FCH JU Joint Workshop participation to the workshop is restricted to partners of EDEN, HYPER, SSH2S and BOR4STORE projects <a href="http://ares.fbk.eu/events/fch-ju-joint-workshop">http://ares.fbk.eu/events/fch-ju-joint-workshop</a>	02/10/2013	Tenerife, Spain	Research	>70	Spain / International

FCH-JU review days 2013	FBK, PANCO	FCH-JU programme review days and General Assembly JTI FCH <a href="http://www.fch-ju.eu/">http://www.fch-ju.eu/</a>	11-14/11/2013	Brussels, Belgium	Research, Industry	>200	Belgium / International
International Conference	FBK	EFC 2013 – European Fuel Cell - Piero Lunghi Conference <a href="http://www.europeanfuelcell.it/">http://www.europeanfuelcell.it/</a>	11-13/12/2013	Rome, Italy	Academia, Research Industry, Government bodies, Public sector	>500	Italy / International
Press release	ULL	Mid term results of the EDEN project presented at Brussels	10/06/2014	Spain	Public	>1000 media members	National/international
Congress & Exhibition	MBN	Euro PM2014 Congress & Exhibition, – European Powder Metallurgy Association <a href="http://pm2014.epma.com/">http://pm2014.epma.com/</a>	21-24/09/2014	Salzburg, Austria	Research, Industry	> 800	Austria / International
Public Symposium	FBK	1° Summit Energetico “Europa Domani” - Quale Energia per il futuro?	06/11/2014	Castelfranco Veneto, Italy	Industry, Policy makers	> 50	Italy
Symposium	PANCO	9th International symposium on hydrogen and energy <a href="http://hesymposium.ch/">http://hesymposium.ch/</a>	25-30.01.2015	Emmetten, Switzerland	Research, Industry	> 50	International
Newsletter	FBK	FBK-CMM NEWS	01/04/2015	Treviso, Italy	Research, Industry	1000	International
Fair	FBK	Hannover Messe – FCH-JU stand	13-17/04/2015	Hannover, Germany	Industry, Policy makers	> 100000	International
Conference	FBK	NANOENERGY 2015 - International Conference on Nanotechnology, Nanomaterials & Thin Films for Energy Applications	01-03/06/2015	Manchester, United Kingdom	Academia, Research Industry, Policy makers	> 200	International
Personal invitation	FBK	EDEN FINAL DISSEMINATION EVENT – Invitation to event	16/06/2015	Italy	Academia, Research Industry, Policy makers	> 1000	National/international
Symposium	ULL (organizer), FBK	HYCELTEC 2015 - Iberian Symposium on Hydrogen, Fuel Cells and advanced Batteries	05-08/07/2015	Tenerife, Spain	Research, Industry	> 100	Spain / International
Self-published Press release	FBK	EDEN FINAL DISSEMINATION EVENT	14/09/2015	Italy	Public	> 50000/year	National/international

	Press release	FBK	HYDROGEN TO SUPPLY POWER FOR HOMES AND PUBLIC SPACES	14/09/2015	Italy	Public	>1000 media members	National/international
	Video news release	FBK	Regional TVs services (RTTR and RAI TGR Trentino Alto Adige) – news programme	23/09/2015	Italy	Public	n.a	Italy / National
	Press Conference	FBK	EDEN FINAL DISSEMINATION EVENT	24/09/2015	Trento, Italy		12 journalists	National
	Radio	FBK	Radio Trentino InBLU – Interview to Luigi Crema on EDEN	24/09/2015	Trento, Italy	Public	n.a	Italy / National
	Public event	FBK	EDEN FINAL DISSEMINATION EVENT	24-25/09/2015	Trento, Italy	Academia, Research Industry, Policy makers	> 50	International
	Public event	FBK	European Researchers' Night 2015	25/09/2015	Trento, Italy	Public	> 4000	National / International
	Public event	FBK	BOR4STORE Final Event	28/09/2015	Hamburg, Germany	Research Industry,	> 50	Germany / International
	Conference	FBK	3rd DRESDEN CONFERENCE “ENERGY IN FUTURE”– Materials for Energy	10-11/11/2015	Dresden, Germany	Research Industry, Policy makers	>500	Germany / International
	FCH-JU review days 2015	FBK	FCH-JU programme review days and General Assembly JTI FCH <a href="http://www.fch-ju.eu/">http://www.fch-ju.eu/</a>	17/11/2015	Brussels, Belgium	Research, Industry	>200	Belgium / International
	International Conference	FBK	EFC 2015 – European Fuel Cell - Piero Lunghi Conference <a href="http://www.europeanfuelcell.it/">http://www.europeanfuelcell.it/</a>	16-18/12/2015	Naples, Italy	Academia, Research Industry, Government bodies, Public sector	>500	Italy / International
	Private event	CIDETE	EDEN system presentation to Barcelona policy makers	21/06/2016	Barcelona, Spain	Government bodies, Public sector,	15	Local
	Public event	CIDETE	EDEN demo final event	28/06/2016	Barcelona, Spain	Public,	>20	National

## Section B (Confidential or public: confidential information marked clearly)

### Part B1

#### LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, UTILITY MODELS, ETC

Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. Patent EP123456)	Subject or title of application	Applicant(s) as reported on the application
Patent	Yes	19/12/2013	WO2013186417	ELECTRICAL GENERATOR FOR EXPLOITING HEAT RESERVOIRS USING A RING-BASED THERMOELECTRIC SYSTEM	CIDETE
Trade secret	YES	n.a.	Patent application is under evaluation	Catalyst application by physical vapor deposition onto Mg for H2 sorption kinetics improvement	FBK
Trade secret	YES	n.a.	n.a.	Development of synthesis route by high energy ball milling for nanostructured Mg-based powder	MBN nanomaterialia SpA

## Part B21

### OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND

Type of Exploitable Foreground.	Description of Exploitable Foreground	Confidential	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measures(s)	Sector(s) of application	Timetable for commercial use or any other use	Patents or other IPR exploitation (license, etc.)	Owner and Other beneficiary (s) involved
Knowledge and Technology	Plasma deposition of ultrathin films onto powders	NO	n.a.	Coated powders by dry processes and characterization	Powders for catalysis in energy sector application (photocatalysis for H2 production), sintered powder consolidation in electrodes for fuel cells), for electrodes for OLEDs.	Already available		FBK
Technology	Catalyst application by physical vapor deposition onto Mg for H2 sorption kinetics improvement	YES	n.a.	Specific deposition technology for H2 sorption kinetics improvement	Powders for catalysis in energy sector application (photocatalysis for H2 production), sintered powder consolidation in electrodes for fuel cells), for electrodes for OLEDs.	n.a.	Patent application is under evaluation	FBK
Knowledge	Modelling, simulation and design of hydrogen systems	NO	n.a.	Expertise and tools for R&D activities and industrial production	System engineering for the design of complex production - storage - usage of hydrogen	Already available		FBK
Knowledge and technology	Power-to-power system development	NO	n.a.	Expertise and tools in the development of control architectures of power to power systems based on hydrogen	Energy storage solutions, Grid management, Residential and Industrial applications based on hydrogen	Already available		FBK
Knowledge	Modelling and simulation of hydrogen storage in solid state materials	NO	n.a.	Expertise and tools for the development of multi-scale models and multiphysics phenomena of hydrogen storage in solid state	R&D activities, Industrial innovation for new product production, Educational and Academic courses	Already available		FBK
Knowledge and technology	Hydrogen tank design with proper heat pipes geometry	YES	n.a.	Operation principle of heat exchange in tank. The design with the heat pipes is the preferred solution with the highest efficiency and dissemination output instead of conventional	Solid state hydrogen storage systems	n.a.	Patent application is under evaluation	PANCO

				tube design or plate heat exchangers				
Knowledge	Improved knowledge on Mg-based hydrogen storage material characterization, in powder and particularly as consolidated	YES	n.a.	Service for measurements of storage performance (gravimetric capacity, sorption rate) validated by JRC	Solid state hydrogen storage material development	Already available		MATRES S.r.l.
Equipment and procedures	Testing equipment and procedures for medium to large amounts of solid state hydrogen storage material	YES	n.a.	Measurement instrument and characterization procedures "MATH2" specifically developed for activation and testing of medium to large amounts of storage material and for characterization of storage tanks	Solid state hydrogen storage systems	2017		MATRES S.r.l.
Procedures and knowledge	Development of synthesis route by high energy ball milling for nanostructured Mg-based powder for hydrogen storage and cost effective production procedures in inert atmosphere	YES	n.a.	ED011 – Nanostructured Magnesium, powder specifically catalyzed for hydrogen storage applications	High temperature hydrogen storage systems	2017	Background knowledge on ball milling and equipment mechanosynthesis principles are already protected.	MBN nanomaterialia S.p.A.
Procedures and knowledge	Production procedures of consolidated pellets made by nanostructured powder for hydrogen storage including consolidating fillers enhancing thermal conductivity and mechanical stability, within an inert atmosphere chain	YES		Bulk nanostructured magnesium pellets specifically developed for tank for hydrogen storage	High temperature hydrogen storage systems	2018	Patent application is under evaluation	MBN nanomaterialia S.p.A.

## ADDITIONAL TEMPLATE B2: OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND

Description of Exploitable Foreground	Explain of the Exploitable Foreground
Plasma deposition of ultrathin catalyst coating on Mg powders	<p>It has been engineered a process to deposit ultrathin coatings of metals, metal-organic and other compounds by a physical vapour deposition process directly onto powders, such as Magnesium or other compounds. This deposition allows the realization of few nanometre coating able to functionalize the target material minimizing the use of catalysts or precious metal by order of magnitudes.</p> <p>The process has been validated using an own developed coating equipment. The process can be transferred to other applications in the energy domain, such as electrodes, catalyst layers in fuel cells, supercapacitors and batteries, and outside the specific sector of energy, such as in OLED electrodes.</p>
Catalyst application by physical vapor deposition onto Mg for H2 sorption kinetics improvement	<p>Different tests for the optimization of the production process toward cost reduction has been conducted, and the recovery of fraction of powders not suitable for the subsequent processes that is between 90 and 500µm.</p> <p>The routes explored for smallest particle recovery allows to individuate the solution of re-process with other batches of material and the agglomeration of particles with Spray Dryer which allows to have particles that are more suitable for the catalyst PVD deposition with more homogeneous particle size distribution.</p> <p>From an economical point of view resulted more effective to re-work the finest fraction in other fresh material batches, the drawback of introducing more oxygen trough these smallest particles are compensated by the recovery of a waste that would be difficult to treat.</p>
Modelling, simulation and design of hydrogen systems	<p>Competences and expertise acquired by personnel in modelling, simulation and design of hydrogen system could be used in further research project and R&amp;D activities – as expert consultant in collaboration with industrial partners- in the development of new processes and products. Specific for the modelling of hydrogen systems is the lumped and dynamic analyses, looking for the more efficient configuration.</p>
Power-to-power system design and development	<p>Competences and expertise acquired by personnel in design and development of complete P2P system architecture is the results of a long trainee and practice period of the personal during the project. The setting up of a complete P2P solution is a complex process which may consider not only the technological aspects solved during the R&amp;D activities, but also the selection of the right components off-the-shelf available on the market, the electronic and user interfaces for the management and control of the system, the safety regulation for the installation and maintenance of the system, etc. This expertise could be an added value in future EU research project where system integration and demo activities in real environment is required, but also as consultancy activities for company that face the market of different energy storage solution (hydrogen, flow batteries, etc..) as support for prototype and product development.</p>
Modelling and simulation of hydrogen storage in solid state materials	<p>Competences and expertise acquired by personnel in modelling and simulation of hydrogen storage, especially in the case of solid state materials, could be used in further research project and R&amp;D activities – as expert consultant in collaboration with industrial partners- in the development of new procedure and products. The modelling was performed on the concept of multi-scale (not just an application of commercial tools) and multi-physic (contemporary analysis of different physical environments).</p>
Hydrogen tank design with proper heat pipes geometry	<p>Competences and expertise acquired by personnel in the design of tank with heat pipes is suitable for a proper management of the thermal energy during the charge and discharge of the tank, which is fundamental to guarantee the required performances in hydrogen storage solution independently by the dimension of the tank. This expertise is the results of a long trainee and practice period of the personal during the project. This could be an added value when R&amp;D activities are requested for the development of new products in the specific field of highly efficient heat transfer.</p>

Improved knowledge on Mg-based hydrogen storage material characterization, in powder and particularly as consolidated	Expertise in testing and validation of the storage materials. Along the upscaling of the material, several characterizations at different scales of the Mg-based hydride were performed. There is a full know how developed on techniques to test the material's physical properties, including thermodynamics and kinetic behaviour. A new differential instrument was developed alongside the project by FBK. Intermediate storage tank was validated in lab environment by MATRES at 25% of the final volume for storage material.
Testing equipment and procedures for medium to large amounts of solid state hydrogen storage material	Expertise in management of instrumentation and in the definition of characterization procedures for hydrogen storage materials could create commercial opportunities for storage materials design and testing and for storage tanks activation and testing. These competences could be applied and extended at the whole hydrogen storage market.
Development of synthesis route by high energy ball milling for nanostructured Mg-based powder for hydrogen storage and cost effective production procedures in inert atmosphere	<p>MBN, as material producer, will exploit commercial opportunities of Mg-based storage materials, in form of powder and/or pellets, for different hydrogen storage systems. Particularly, MBN will commercialize "ED011 Nanostructured Magnesium" product after some improvements and optimizations beyond the Eden project purposes, addressing mainly European markets of solid state H2 storage systems.</p> <p>A new process is capable to uniform the particle dimension and increase performances of the storage material. The biggest particle is reduced by a second milling process at milder condition. The optimization of the process has been realized by designing and realizing a special milling chamber for tumbling process, in which were possible to perform in the same time, dispersion of Expanded Natural Graphite and big particle reduction.</p> <p>This chamber was designed to have a fast link with vials for Mg-material transportation to be easily filled and discharger. These industrial improvements allowed to estimate a reliable material price at industrial level production (corresponding to 28-30 €/kg for productions bigger than 10-20 tons/year) and allowed to define a business plan for the exploitation of the results on material development.</p>
Production procedures of consolidated pellets made by nanostructured powder for hydrogen storage including consolidating fillers enhancing thermal conductivity and mechanical stability, within an inert atmosphere chain	<p>Expertise in consolidation of the Mg hydride in form of a pellet, able to maintain the form and the aggregated layout after several (tens) tests and cycles.</p> <p>This has been validated along the project.</p>
Safety requirements for a hydrogen installation	There is different regulation for each member state regarding the installation of hydrogen based system in real environments. The expertise achieved in defining the requirements (safety control system, ventilation, power supply, etc.) and implement the safety procedure will be a valuable support in the definition of EU standard for safety and in the realization of new products and prototype compliant with the actual regulation.
Relation and procedures with the administration	Expertise in relationship with public administration and territorial security services. Identification of procedures to agree on risk assessment, contractual forms, agreement on testing procedures and phase.
Heat recovery	To recover the biggest amount of wasted heat during the charge/discharge of the tank, a heat recovery system based on thermoelectric (TE) devices have been realized. TE modules in between aluminium efficient heat sinks and metallic flat surfaces. More specifically, the heat pipes (HP) efficiently transport the heat inside or outside the tank. During the charging phase of the tank, an exothermic reaction takes place and it is necessary to dissipate such amount of heat as efficiently as possible. Recovering part of this heat and transform it in electrical power by means of thermoelectric (TE) devices allows to contribute at the electrical balance of plant (BoP) of the entire P2P system. During the discharging phase (desorption, SOFC mode), the TE modules can maintain the high temperature inside the tank to guarantee the proper hydrogen velocity. Finally, the heat recovery solution will contribute at the overall electrical balance of plant (BoP) of the entire P2P system, increasing the overall system performances and reducing the power consumption necessary to manage the system.

## Explanation to exploitable foreground

MBN, as material producer, will exploit commercial opportunities related to Mg-based storage material developed inside the EDEN project, in form of powder and/or pellets, for different hydrogen storage systems. Particularly, after some improvements and optimizations of the “ED011 Nanostructured Magnesium” developed during the project, commercialization of the storage material is expected by first quarter of 2017 addressing mainly the European markets of solid state H<sub>2</sub> storage systems. In addition to the short-time market availability of the storage material, there are several additional options to commercialize the EDEN technology, varying from selling it as a standalone product or incorporating it (or part of the technology developed) into existing products. These following important steps are envisaged to increase the opportunity of the market deployment, especially for the improvement and final product development of a complete integrated P2P system after the basic and applied research conducted during the project:

- Improve performances of the already available ED011 storage material;
- Scaling-up the industrial material production process (hundreds of tons/year) - in form of powder and/or pellets;
- Improve tank efficiency (control process, insulation and energy recovery) and tank weight reduction;
- Miniaturisation of ECU and safety systems;
- Involvement in the TTB of a company capable to operate as system integrator with expertise to properly address future market deployment;
- Influence policy makers for the necessity of a common national and/or international standards and regulation on solid state hydrogen storage, to facilitate the diffusion of hydrogen storage technologies and applications;
- CE marking;

In the EDEN Market Deployment Plan (MDP), a complete market analysis has been done and preliminary business cases for real deployment of EDEN P2P system in the exiting market that could be addressed in a short time are here reported:

- OFF-GRID TELECOMMUNICATION TOWER;
- HYDROGEN BALANCE FOR REFINERIES;
- GRID MITIGATION;
- HYBRID SYSTEM FOR DAILY TIME SHIFTING AND RESIDENTIAL m-CHP.

Three to five years is estimated as a reasonable amount of time to improve the technology as previously outlined, to decide the commercialization pathway and collect the funding for preliminary installation of the EDEN P2P system products.

All the options the consortium considered viable solution for the deployment of the technology are described in the IPR Agreement. Since today, EDEN project has assessed not only the technological development, but also the aspects related to the regulatory frameworks and standards.

Now, it is deemed that the commercialisation pathways best suited for the EDEN results are primarily the spin-out route and the licence route, with the opportunity of outright pending IP applications for the single components or process.

# PROJECT FINAL REPORT

## Societal implications

FCH JU Grant Agreement number: **303472**

Project acronym: **EDEN**

Project title: **High energy density Mg-Based metal hydrides storage system**

Funding Scheme: **JTI-CP-FCH - Joint Technology Initiatives - Collaborative Project (FCH)**

Period covered: **from 2012.10.01 to 2016.06.30**

Name of the scientific representative of the project's Coordinator, Title and Organization:

**Dr. Luigi Crema**

**FONDAZIONE BRUNO KESSLER**

**Applied Research on Energy Systems**

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E-mail: [crema@fbk.eu](mailto:crema@fbk.eu)

Project website address: <http://www.h2eden.eu/>

## 4.3 Report on societal implications

### A. General Information

FCH JU Grant Agreement Number	303472
Title of Project	EDEN - High energy density Mg-Based metal hydrides storage system
Name and Title of Coordinator	Dr. Luigi Crema

### B. Ethics

<b>1. Did your project undergo an Ethics Review (and/or Screening)?</b>	<b>NO</b>
If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final reports?	
<b>2. Please indicate whether your project involved any of the following issues:</b>	
<b>RESEARCH ON HUMANS</b>	
Did the project involve children?	<b>NO</b>
Did the project involve patients?	<b>NO</b>
Did the project involve persons not able to consent?	<b>NO</b>
Did the project involve adult healthy volunteers?	<b>NO</b>
Did the project involve Human genetic material?	<b>NO</b>
Did the project involve Human biological samples?	<b>NO</b>
Did the project involve Human data collection?	<b>NO</b>
<b>RESEARCH ON HUMAN EMBRYO/FOETUS</b>	
Did the project involve Human Embryos?	<b>NO</b>
Did the project involve Human Fetal Tissue / Cells?	<b>NO</b>
Did the project involve Human Embryonic Stem Cells (hESCs)?	<b>NO</b>
Did the project on human Embryonic Stem Cells involve cells in culture?	<b>NO</b>
Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	<b>NO</b>
<b>PRIVACY</b>	
Did the project involve processing of genetic information or personal data (e. g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	<b>NO</b>

Did the project involve tracking the location or observation of people?	<b>NO</b>
<b>RESEARCH ON ANIMALS</b>	
Did the project involve research on animals?	<b>NO</b>
Were those animals transgenic small laboratory animals?	<b>NO</b>
Were those animals transgenic farm animals?	<b>NO</b>
Were those animals cloned farm animals?	<b>NO</b>
Were those animals non-human primates?	<b>NO</b>
<b>RESEARCH INVOLVING DEVELOPING COUNTRIES</b>	
Did the project involve the use of local resources (e. g. genetic, animal, plant)?	<b>NO</b>
Was the project of benefit to local community (e. g. capacity building, access to healthcare, education)?	<b>NO</b>
<b>DUAL USE</b>	
Research having direct military use	<b>NO</b>
Research having potential for terrorist abuse	<b>NO</b>

### C. Workforce Statistics

**3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).**

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	0	6
Experienced researchers (i.e. PhD holders)	2	7
PhD student	1	1
Other	2	7

<b>4. How many additional researchers (in companies and universities) were recruited specifically for this project?</b>	3
Of which, indicate number of men	2
Of which, indicate number of women	1

## D. Gender Aspects

<b>5. Did you carry out specific Gender Equality Actions under the project?</b>	<b>YES</b>
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<b>6. Which of the following actions did you carry out and how effective were they?</b>	
Design and implement an equal opportunity policy	Almost effective
Set targets to achieve a gender balance in the workforce	Not effective
Organize conferences and workshops on gender	Not Applicable
Actions to improve work-life balance	Very effective
Other:	FBK has developed an internal policy on Gender aspects through the project FP7 -FESTA (nr. 287526). Women involved in the projects have been assigned of responsibility in tasks and activities. This action involved: - FBK: Nadhira Laidani as responsible of research for FBK in WP1, Gloria Gottardi as researcher in the material development - CIDETE: Silvia Ortega as responsible for technical activities performed by the partner and contacts with local authorities of Barcelona Municipality. Almudena Marquina as responsible for reporting activities and management activities - JRC: Patra Karagounis, main contact for management activities.

<b>7. Was there a gender dimension associated with the research content - i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?</b>	<b>No</b>
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## E. Synergies with Science Education

<b>8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?</b>	<b>YES</b>
If yes, please specify:	Collaboration with students involved also in activities under the Graphene Flagship, Dissemination event at Researcher Night 2015, collaboration with local technical 2nd schools with seminar and presentation of the EDEN technology, included the visit at FBK laboratories used in the project. EDEN technology was included in a thesis of a local secondary school.

<b>9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?</b>	<b>NO</b>
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## F. Interdisciplinarity

<b>10. Which disciplines (see list below) are involved in your project?</b>	
Main discipline:	1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
Associated discipline:	1.3 Chemical sciences (chemistry, other allied subjects)

## G. Engaging with Civil society and policy makers

11a. Did your project engage with societal actors beyond the research community?	YES
11b. If yes, did you engage with citizens (citizens' panels/juries) or organised civil society?	YES
11c. In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	NO
12. Did you engage with government / public bodies or policy makers?	YES During its demonstration period in Barcelona, EDEN was engaged with the Barcelona City Council and different departments inside it: local energy agency, environment department, safety department...
13a. Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	YES The Barcelona City Council was very interested on hydrogen technology, both for storage or power production, and this project was an interesting training for them on the topic.

## H. Use and dissemination

<b>14. How many Articles were published/accepted for publication in peer-reviewed journals?</b>	<b>4</b>
To how many of these is open access provided?	4
How many of these are published in open access journals?	3
How many of these are published in open repositories?	1
To how many of these is open access not provided?	0

<b>Please check all applicable reasons for not providing open access:</b>	
publisher's licensing agreement would not permit publishing in a repository	NO
no suitable repository available	NO
no suitable open access journal available	NO
no funds available to publish in an open access journal	YES
lack of time and resources	NO
lack of information on open access	NO
If other - please specify	

<b>15. How many new patent applications ('priority filings') have been made? ("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).</b>	1
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<b>16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).</b>	
Trademark	0
Registered design	0
Other: Trade secret	1

<b>17. How many spin-off companies were created / are planned as a direct result of the project?</b>	0
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<b>18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:</b>	Safeguard employment, in small and medium-sized enterprises
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<b>19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs:</b>	Difficult to estimate / not possible to quantify
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## **I. Media and Communication to the general public**

<b>20. As part of the project, were any of the beneficiaries professionals in communication or media relations?</b>	YES
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<b>21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?</b>	YES
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<b>22. Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?</b>	
Press Release	YES
Media briefing	YES
TV coverage / report	YES
Radio coverage / report	YES
Brochures /posters / flyers	YES
DVD /Film /Multimedia	NO
Coverage in specialist press	YES
Coverage in general (non-specialist) press	YES
Coverage in national press	YES
Coverage in international press	YES
Website for the general public / internet	YES
Event targeting general public (festival, conference, exhibition, science café)	YES

<b>23. In which languages are the information products for the general public produced?</b>	
Language of the coordinator	YES
Other language(s)	YES
English,	YES
Spanish	YES