DELIVERABLE REPORT

PROJECT FULL TITLE	Highly efficient power production by green ammonia total oxidation in a membrane reactor
PROJECT ACRONYM	HiPowAR
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Deliverable No.: D6.1

Cost estimation, lifetime and recycling costs of all HiPowAR devices

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Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group specified by the consortium (including the	
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Deliverable 6.1

Cost estimation, lifetime and recycling costs of all HiPowAR devices
is assigned to Task 6.1

Objective: This deliverable aims at giving estimations for costs, lifetime and recycling costs of all HiPowAR devices.

Background: The HiPowAR concept is to be compared with other NH3-based systems for energy supply in terms of economic efficiency. For this purpose, estimates must be made of the likely costs for the HiPowAR system respectively the various subsystems and components.

Results: For the cost estimates, the HiPowAR concept was divided into 5 subsections, starting with the actual MIEC reactor, the expander system, the major hardware components, other hardware and the controls hard- and software needed for an appropriate system. Costs are estimated based on literature and the expertise of companies, partners and colleagues. For the estimation a range is given in which the costs are expected. The identified specific costs show high shares for the reactor and the expander systems. These are also the subsystems with the greatest uncertainties. Assuming the minimum expected costs from today's point of view, the costs of HiPowar are in the range of those for NH3 fueled SOFC and NH3 fueled ICE if pre-cracker and SCR are included. The estimated costs presented in this deliverable are the basis for LCOE calculations, which will be performed in the further course of the project.

Deviations/delays: Recycling costs are not given in detail, but it turned out that recycling is not a critical aspect for the HiPowAR system. A large proportion of the components used are made of steel, stainless steel or aluminum and can therefore be recycled. The MIEC membranes can be recycled easily by milling and using the substrate again. No special recycling costs are expected. Detailed information and costs relating recycling will be given in the frame of the LCA, which is done later in the project.

Annex:-

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1. Introduction

New concepts and innovative systems must not only make sense from an energetic-technical point of view and have advantages over existing systems. In addition, the costs are an important factor in the evaluation of an innovation. For the evaluation, the investment costs must be estimated in a first step. The service life and maintenance costs also have an influence on the economic viability. Last but not least, the disposal and, where possible, the recycling costs are also an important consideration, as a look at nuclear power shows. Based on these costs, the LCOE can be determined and a comparison can be made with plants of different technology. This deliverable focuses on the estimation of the investment costs and lifetime of the HiPowAR devices.

2. HiPowAR system

2.1. Approach

Various challenges arise when determining the costs for the HiPowAR concept. First no clear power class has yet been defined. Exemplary assumptions are made for the sizes 100 kW_{el} and 1 MW_{el}. The smaller power class corresponds to mobile applications and the most widely used power spread for CHP units from 50 to 250 kW [1]. The second power class corresponds to the second most widely used CHP from 500 to 2000 kW_{el}. Based on this power class estimates for power in the double-digit MW range can be determined via extrapolation. In the triple digit MW range of 100 MW or more there is no informative cost estimation possible up to now. Before this can be done to get reasonable results questions of reactor and system design for high power outputs must be solved.

The plant design as well as the reactor concept, which is the most innovative part of the HiPowAR-concept, have not been fully determined at this early stage. Cost estimates for the reactor will be based on the design determined for the test reactor from WP1. The plant design is based on highly simplified flowsheets that allow cost estimations of the components required. The whole system will be divided into several subsystems.

2.1.1. Subsystems

In order to perform the cost estimations, the system was divided into subsystems (see Figure 1). The first is the reactor consisting of the MIEC membranes and the reactor shell including insulation and seals.

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The second subsystem corresponds to the actual power generation unit, i.e. the expander with generator. This unit has relatively high specific costs and is therefore considered separately from the components in the third area.

The third subsystem contains the larger and correspondingly cost-intensive components that are required in the concept. These include e.g. pumps, heat exchangers, fans or condensers. All these components are commercially available components, but some of them have to be designed for the performance data specified by the HiPowAR, such as pressures, temperatures or mass flows.

The fourth subsystem includes the components needed in any power system, such as valves, sensors, fittings, and piping. Since the plant design is not yet fixed and no flowsheet set up, the quantity of components is roughly estimated here and average cost values are applied.

The fifth and last area includes the control technology (hardware and software) as required for example when using a programmable logic controller (PLC), commissioning tests as well as documentation and approval.

Required labor hours are added to the respective subsystems. Location factors (development, foundation, container...) are neglected as well as engineering and profit. These points may have to be considered when comparing with competing systems such as SOFC and ICE in detailed scenarios or specific applications.

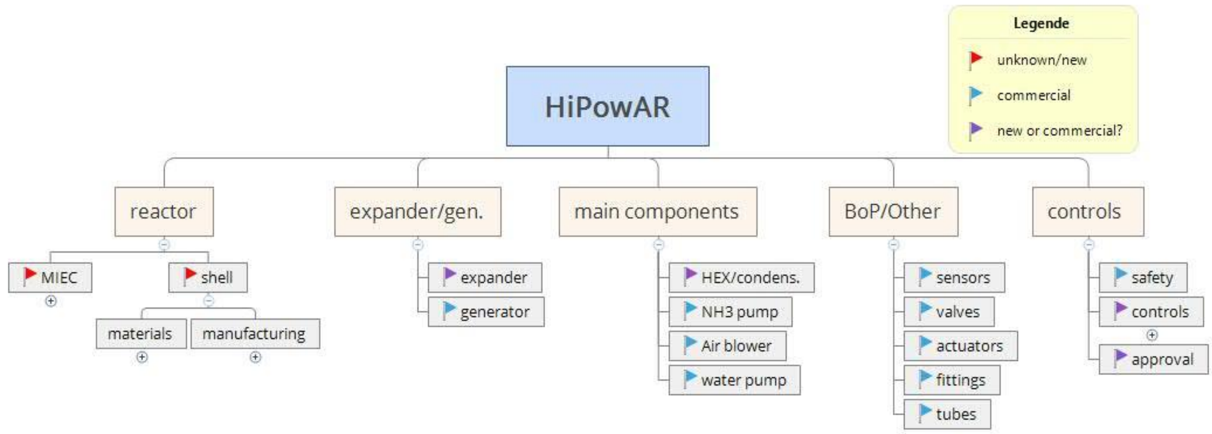

Figure 1: Subsystems of HiPowAR

2.1.2. Input data

For carrying out a cost estimation various input is required. For the reactor cost estimation performance data of the MIEC and the reactor design is needed. Information about system pressure and temperature are as important as information about unit sizes and dimensions.

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The input data regarding the MIEC come from project partner IKTS. For the reactor design the discussions of WP1 were followed.

For the cost estimation of the expander and the other hardware components information such as temperatures, pressures and mass flows are needed. To get these data project partner POLIMI did some simulations for the power range of 15 kW which is related to the test system and for 100 kW and 1 MW systems. Results were the mass flows, temperatures and pressures at the inlet and outlet of the reactor, the expander, the pumps and the heat exchangers. With the help of these data, inquiries could be made to colleagues and companies offering the corresponding hardware. Information from literature reviews were incorporated as well. Costs for the not so detailed specified hard – and software base on experiences from projects done before at the partner institutes.

2.1.3. Output/results

Excel sheets were developed where all relevant input is gathered. The absolute costs (€) and the specific costs (€/kW_{el}) are calculated for the different subsystems of the HiPowAR system as well as for the entire unit. Additionally, graphics are created to get a quick overview. New or updated data can be entered and the results will change directly. This is important and helpful in so far as aspects as efficiency, reactor design, pressure levels or temperature are not fixed yet for the HiPowAR system. Thus, it is possible to modify cost estimations to get updated specific costs with not too much effort during the project duration.

Costs for components and controls normally show a wide range based on different offers and information. The same applies to the efficiency assumed up to now. That is why working with minimum and maximum values is reasonable to show the potential range of the specific costs.

2.2. MIEC and reactor

A central component of the HiPowAR concept are the MIEC membranes (details to MIEC in WP3). The final composition of the MIEC is not fixed yet but will be investigated during the project. Membranes so far consist of e.g. BSCF (Ba0.5Sr0.5Co0.8Fe0.2O3-). Up to now, IKTS is the only manufacturer of the MIEC membranes and so costs for the membranes are given by the project partner with 15 €/double capillary and 10 €/capillary. Assumptions for the prices for mass production are at least 6 €/capillary.

For a fuel power of 1 kW approx. 12 double capillaries are needed [pers. communication IKTS]. This means that with an electrical efficiency of 60% about 2000 double capillaries are required for an electrical power of 100 kW, accordingly 10 times for 1 MW. Figure 2 shows the costs for the minimum and maximum price for assumed system efficiencies of 40 to 60%.

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The specific costs thus vary between 120 and 450 €/kW for the membranes only. Assuming that the lower price assumed for mass production can be applied in the future, the differences based on the number of membranes due to the different system efficiencies are between 120 and 180 €/kW.

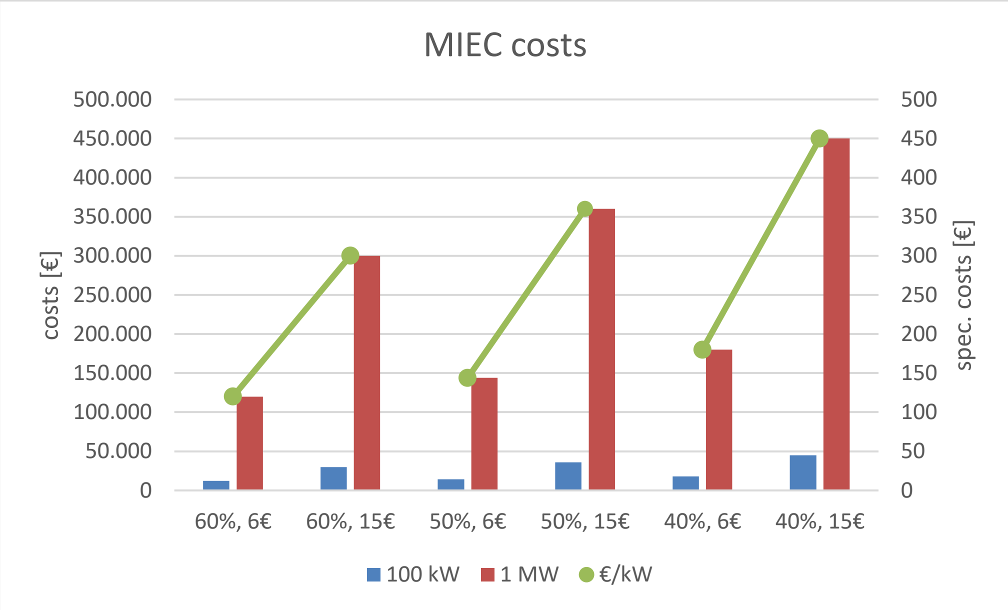

Figure 2: Total and specific costs for the MIEC

The reactor design for the HiPowAR system has not yet been finalized. In particular, experiences from the test reactor will still have an influence on the design. Different variants were discussed for the design of the test reactor (see deliverable D2.1). The last decision focused on a test reactor design in which 127 MIEC capillaries are arranged around the NH3 feed. The combustion chamber is lined with ceramic insulation so that the actual reactor shell is exposed to temperatures less than 200°C, eliminating the need to use expensive high temperature resistant steels. The capillaries can be accommodated with silicone seals, since at the seal location the cool air is blown in and keeps the temperatures below the maximum permitted for silicone. The requirements for the reactor are therefore the design, i.e. the accommodation of capillaries, the pressure resistance with a nominal pressure of at least 50 bar and the good assembly possibility.

For a required power of 100 kW_{el}, a total of 2000 capillaries are needed at an efficiency of 60%. With the reactor design described above with 127 capillaries each, 16 individual modules are therefore required. A modular system is assumed, in which individual reactors are connected together. This would still ensure good mixing of fuel and oxygen in the reactor and the materials would not have to withstand high temperatures. Therefore, for the

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cost calculations the price of one reactor is estimated and multiplied accordingly. The minimum price without MIEC is estimated at about 1400 €/reactor and the maximum price at almost 5000€/reactor. Apart from the materials, especially the tolerances during manufacturing and the compressive strength have an influence on the costs. The cost estimation was carried out on the basis of apparatus and reactor constructions carried out at the ZBT. The estimated costs include materials, manufacturing and assembly of reactor as well as pressure tests and any certificates required.

For estimations of lifetime more tests with MIEC under the specific conditions in HiPowAR must be performed.

2.3. Expander

A steam-nitrogen mixture with a pressure of 50 bar and a temperature of approx. 750°C is generated in the reactor chamber. The expansion of this mixture can take place on the one hand via a steam engine and on the other hand via a steam turbine. The mechanical work can then be converted into electric current via a generator. The selection of the expander type depends on the power range. Steam engines are mainly used for industrial purpose with a power output below 1000 kW, whereas the typical power range of steam turbines begins at 1 MW [2]. Accordingly, a steam engine was considered for the 100 kW cost estimation. For the 1 MW (and perspective following scale up) a steam turbine is considered for cost estimation.

For the given application case and boundary conditions, few suppliers for steam engines were identified. Often, appropriate steam engines are integrated in combined heat and power units (CHP) from the biogas sector. Inquiries to appropriate manufacturers resulted in offered prices of 95.000 €/engine package with an output of 100 kW. Included are the steam engine, the generator and the regulation etc. as well as profit of the company. For the cost estimation, this price was assumed to be the maximum price, because it was the offer for just one unit. If larger quantities are purchased or included in the overall HiPowAR concept, 30% lower prices seem to be possible and were therefore assumed for the minimum price.

Inlet conditions for the HiPowAR expander system differ from conventional power generation steam inlet conditions. Therefore, the applicability of state-of-the-art power plant equipment with known price ranges needs to be checked carefully.

A comprehensive comparison of conventional steam turbine power plant technology against the HiPowAR requirements is given in Deliverable 5.1. In summary, due to the high amount of steam in the working fluid, a comparison against commercial steam turbines is appropriate. Targeted pressures are well within the range of conventional power plants.

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Contrary the targeted reactor outlet temperatures are above state of the art inlet conditions of powerplants. The steam turbine inlet temperature is generally limited by the mechanical and chemical material properties.

Major powerplant manufacturer state the following range of inlet conditions as current state of art: 600 - 650°C, 280 - 330bar (e.g. [3]). Therefore, specific costs for available turbine hardware potentially underestimates hardware cost for combination with HiPowAR reactors due to higher temperature requirements. However, development of advanced turbine hardware for further efficiency increase due to increased inlet temperature is currently done. Higher process temperature increases the efficiency and is therefore favorable from thermodynamic perspective. Development of turbine hardware, capable of handling inlet temperatures of 700° and higher, is present as a globally funded research area. Demonstration plants are intended to start 2021. Examples are given in [4] [5]. Further increase of inlet temperatures up to 700°C and higher requires a change of e.g. the material to Nickel based alloys.

A thermodynamic process, at least regarding turbine inlet conditions, comparable to HiPowAR is the implementation of the Allam Cycle as described in [6] with 717°C / 310 bar inlet conditions. Toshiba combined availably gas turbine and steam turbine technology to enable the turbine hardware for those conditions. Unfortunately, costs are nondisclosed.

This large-scale ongoing research might lead to a midterm elevation of the 'state of the art' – conditions of power plant turbine hardware to a level required for the aspired HiPowAR reactor outlet conditions. Even when estimation of cost for power plant hardware for HiPowAR is currently of uncertainty, with the assumption stated above, it is rated as reasonable to use available cost information of state-of-the-art hardware.

The EIA [7] gives a comprehensive overview about specific costs and cost structures of power plants. It needs to be remarked that most specific cost values for power plant equipment refer to the complete power plant package. From conventional investment perspective this is reasonable. For this cost assessment a more detailed cost breakdown is required as multiple cost intense components are not required, e.g. the heat recovery steam generator (HRSG) or the condenser system (as it is covered separately in this report). As shown in [8] gas- and steam turbine represent approx. one third of the total costs. This is in good agreement with [7] where turbine hardware is approx. one third of the total capital cost, as well.

Prices of complete systems, including condenser and other cost intensive components, were provided by the project partner PBS in a range between 550€/kW_{el} and 1200€/kW_{el}. In addition, information from personal communication was used as a basis for determination

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of minimum and maximum prices for the overall package of turbine, generator and control system. The data were subject to large price ranges, which cannot be explained solely by differences in performance. In summary, assuming that conventional technology is used, only a wide price window can be set for the turbines, with a minimum price of 300 €/kW_{el} up to a maximum of 1000 €/kW_{el}. If high temperature turbines or special designs are needed, costs above the maximum are possible.

Steam turbines for power generation or industrial purpose often have lifetime of multiple decades. Depending on the region lifetime of 30 – 50 years are not uncommon. [9, 10] During this period intensive maintenance and overhauling of components, e.g. rotating parts is necessary. Beginning with daily inspections and monthly analyzing of lube oil and hydraulic fluid and ending with major overhauls with an duration of 4-8 weeks after 50.000 equivalent operating hours (EOH) (see [11]).

2.4. Main hardware components

In a further step, the cost estimates for the various hardware components were carried out (see gray shaded areas in Figure 3). The first ones to be mentioned are the pumps, i.e. the ammonia pump, the water pump for the process water, and the pump for cooling water.

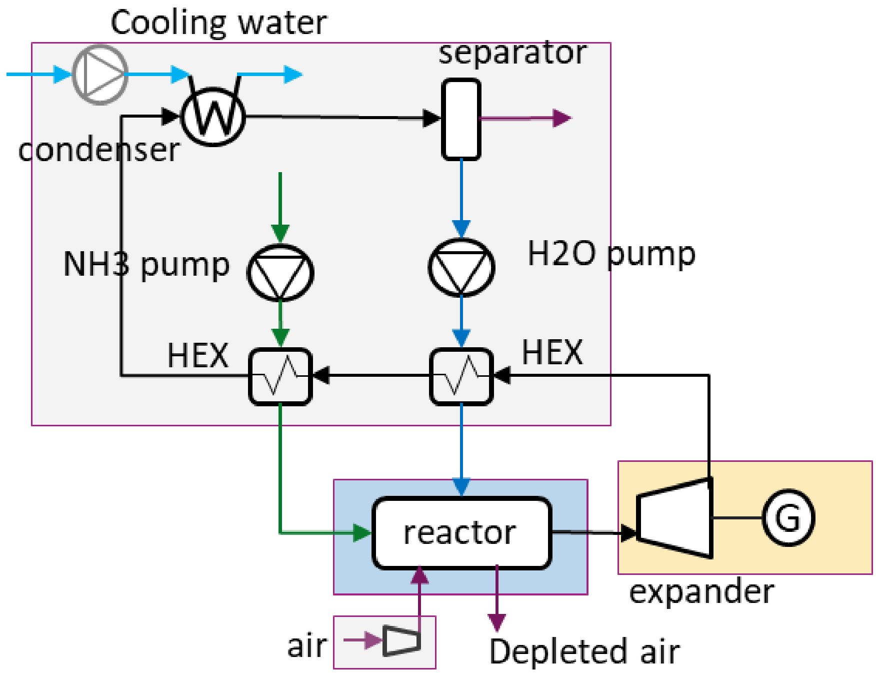

Figure 3: Rough schematic of HiPowAR system

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The water pump and the ammonia pump must each bring the media to a pressure of 50 bar. For ammonia pumps, prices between 20.000 € and 45.000 € were quoted for the 100 kW range, and between 20.000 € and 70.000 € for the 1 MW range. For the process water pump, the offers ranged from 2.200 € to 28.000 €. However, this value falls far outside the range, so that 10.000 € for lower and 12.000 € for higher power was taken as the maximum price quotation. No concrete offers were requested for the cooling water pump, since no mass flows are known here. These depend on the cooling water temperature, which has not yet been further specified and may depend on the location. There are no high pressure or temperature requirements for the cooling water pump. Therefore, prices of 500 to 2000 € were used, which correspond to data for pumps from other projects carried out.

An air blower is required to supply air to the reactor. For this the price quotations were similarly widely spread as for the process water pump. The cheapest variant for 100 kW was 325 €, while the most expensive was 11.300 €. Here, too, the highest offer was neglected and costs of 325 to 2000 € were considered.

Furthermore, different heat exchangers and a condenser are required. In the first HEX water at a pressure of 50 bar is heated up by using the expanded vapor/nitrogen mixture that exits the expander at near ambient pressure. This cooled down mixture then is used in a second HEX to vaporize the ammonia that is fed at 50 bar to the HEX. The cost estimation for the heat exchangers to be used proved to be difficult, as these are normally designed and calculated for the respective applications. Companies only gave rough values for costs. For both the water/water and NH3/water heat exchangers, prices were quoted in the range of at least 700 € for the 100 kW variant and at least 100 0€ for the 1 MW power class. The pressure rating of 50 bar can be critical at temperatures above 200°C. Here a pressure frame is supposed, which has to be estimated at approx. 1000 €.

A condenser and nitrogen separator were requested as well. In principle, the condenser is also a heat exchanger. In some cases, this price was included in the steam turbines, but in the steam engines which were also considered for comparison, a condenser had to be considered additionally. The prices here were between 3680 € (100 kW) and 9200 € (1 MW). These are far below the prices of the turbine manufacturers which were indicated with 140 to 390 €/kW_{el}. This is due to the different pressures. For the HiPowAR concept the pressures after the expander were supposed to be near ambient pressure resulting in simple and cheap HEX. Conventional power plants work below atmospheric pressure to reach better efficiencies [12] which means more expensive condensers.

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Both, the offer prices and experiences from other projects showed partly very high ranges. As before, the minimum and maximum figures are listed, so it can be assumed that the estimated costs are within these limits.

2.5. Other Hardware

The estimation of the costs for further typical components such as valves, controllers and sensors can only be carried out roughly, since there is no RI flow chart yet. Based on the flow diagrams created for the test stand, 15 valves and 10 controllers as well as 5 sensors were calculated. Depending on the required temperature, pressure and material resistance, there are often large price differences depending on measurement accuracy and tolerances. For the sake of simplicity, average prices were used; the corresponding tables are in the appendix. Also, the cost share of fittings and piping etc. is roughly estimated based on experience from other systems and the corresponding prices. Especially for smaller systems the components described here have an influence on the specific price, for larger systems the influence is smaller.

2.6. Controls

Every system needs control. Pressures, temperatures or mass flows must be checked and adjusted. Critical conditions must be detected and lead to appropriate shutdowns. For this it needs on the one hand the appropriate hardware, which records and/or processes the data. On the other hand, software and thus programming is needed. The hardware e.g. programmable logic controllers (PLC), are needed for each system. For the software the costs are strongly dependent on the number of systems. The development of the software is time-consuming and accordingly expensive. However, this development can be allocated to a correspondingly large number of systems. The minimum cost approach assumes at least 20 systems to which the software can be distributed. The maximum cost approach considers only one system. Lump sums for documentation and any certificates or approvals required were also added to the costs.

2.7. Labor costs

A difficult area to estimate are the labor costs. The corresponding times and costs are already included in the individual components. The labor costs therefore essentially comprise system assembly and commissioning. In the minimum case, 100 hours were estimated for this, assuming that packaging, connections and test protocols are coordinated. In the maximum case 180 h of work are estimated so that imponderables are included. The hourly wage was assumed to be 40 €/h, since qualified specialists are required here.

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2.8. Others

Costs such as transport, installation and integration were not considered, as these are mostly not included in the prices of the comparison systems either, and only the pure module costs are considered.

2.9. Results

2.9.1. Cost estimation for 100 kW system

The different values for the costs for the 100 kW system were summed up. Figure 4 shows the minimum and maximum cost scenarios of the different parts of the system for an assumed efficiency of 60%. Based on the knowledge up to now the specific costs will lay somewhere between 1600 €/kW in the best case and more than 3700 €/kW in the worst case. In the minimum cost scenario, the subsystem 'expander' has the biggest share on costs, but this part as well has high uncertainties for the price. More experience with the test rig expander and resulting better-defined process parameters will help to find optimized expander systems with better defined prices. In the worst case the MIEC reactor has the highest share on cost due to materials, manufacturing and membrane costs followed by the expander system. The maximum costs for the hardware components based on the numbers from offers. In this case hardware components account for a high proportion of the specific costs as well as the controls.

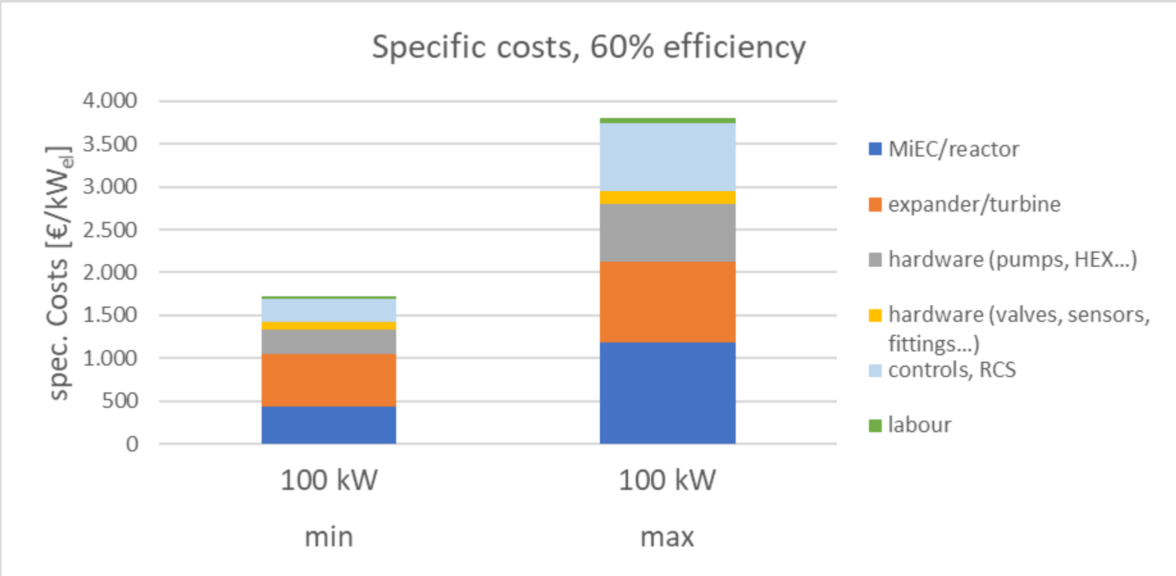

Figure 4: Share of subsystem on specific costs for 100 kW HiPowAR system

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In Figure 5 the specific costs for an efficiency of 40% are shown additionally. Here mainly the costs of the reactor are changed, because by decreasing efficiency the number of membranes must be increased as well as the reactor units to get a sufficient mass flow of steam and nitrogen. In principle the parameters for the hardware components change as well (mass flow), but this is supposed to be in the components working range and price. The specific costs with an assumed efficiency of 40% are between 2000 and 4000 €/kW.

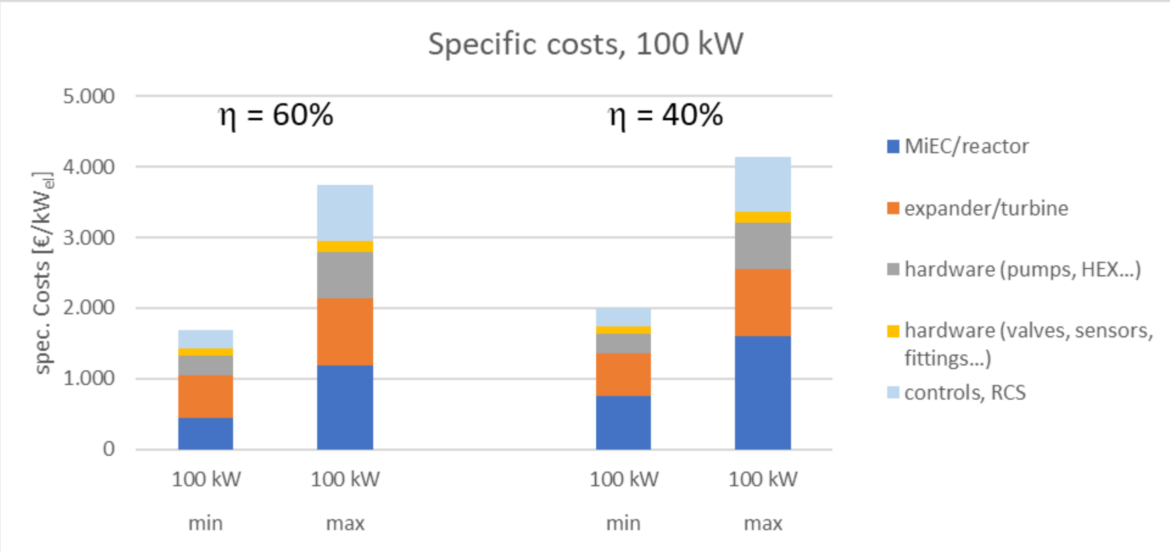

Figure 5: Specific costs for 100 kW HiPowAR system with different efficiencies

2.9.2. Cost estimation for 1 MW system

Often bigger systems have lower specific costs than smaller systems. In Figure 6 it can be seen, that the share of controls and hardware components is very low in contrast to the 100 kW system (see Figure 4). For example, for the minimum scenario the costs for the NH3-pump are the same for 100 kW and 1 MW system. The pump for process water for the 1 MW system costs only double and not 10 times the pump for the 100 kW system. Control strategies and software are the same for the different system sizes. Thus, the cost shares of these subsystems are lower than for smaller systems.

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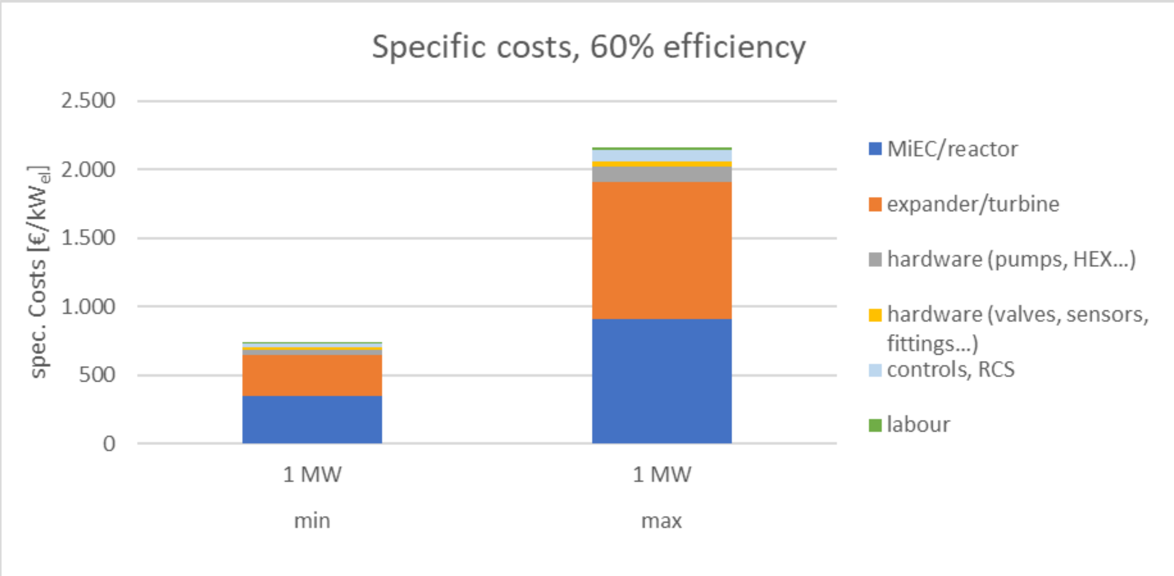

Figure 6: Share of subsystem on specific costs for 1 MW HiPowAR system

In the best case assumed for efficiencies of 60% the specific costs are estimated at about 750 €/kW and in the worst case at about 2200 €/kW$_{el}$. With lower efficiencies the specific costs rise up to 2800 €/kW. As mentioned before, the uncertainties for the turbine/generator part are relatively high showing specific costs in range between 300 and 1000 €/kW. Better knowledge of the system design will help to get better numbers.

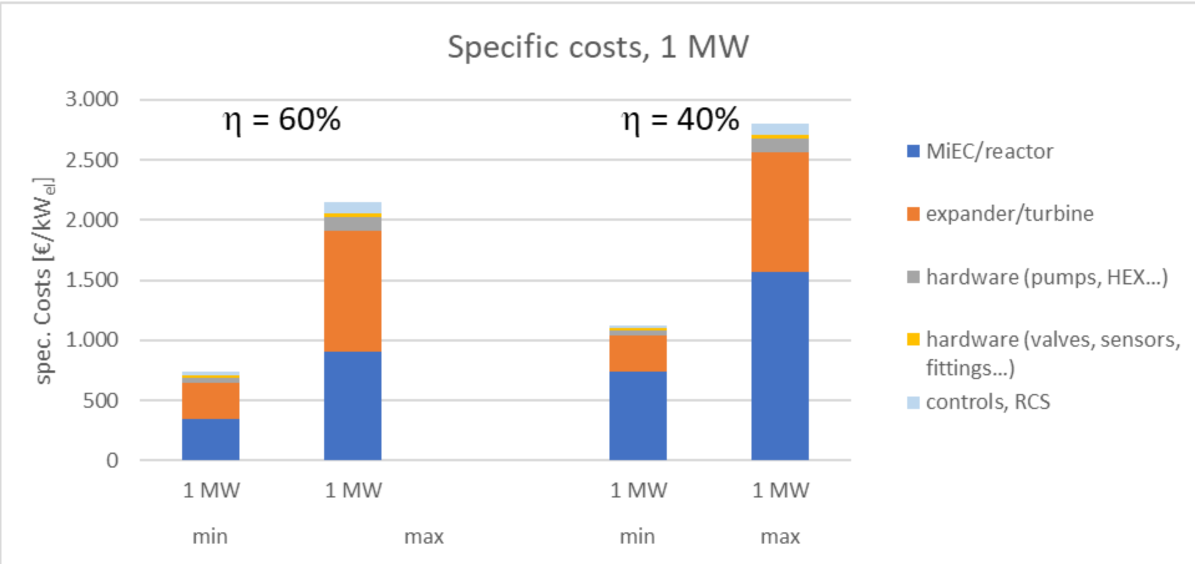

Figure 7: Specific costs for 1 MW HiPowAR system with different efficiencies

The share or the reactor itself with the high amount of MIEC capillaries and the modular concept with many small reactors has a share of more than 50% of the specific costs.

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Especially for higher power, a suitable reactor design must be found here to reduce costs. Possibilities are from other geometries (length) of the capillaries to bigger units for the reactor with more than the above mentioned 127 tubes in one unit.

2.9.3. Power > 10 MW

MIEC reactor and turbine/generator unit have the highest share on costs for higher power systems. For even higher power of 10 MW and more the inaccuracies will rise even more, on the one hand because of the reactor design and on the other hand because it is almost impossible to obtain meaningful prices for the expander unit in this order of magnitude.

If looking at the curves of cost over power of other energy systems such as gas power plants [10, 13] and CHP [1] the costs depending on power follow an exponential decay, so the costs will decrease slightly by higher power output.

3. Competitive systems

The costs found for the HiPowAR system are only meaningful if compared to other systems used for the same application. These other systems should be fed with ammonia as well and thus being carbon free. The HiPowAR will be compared thus to the NH3 fed SOFC and the NH3-fed ICE.

3.1. Solid Oxide Fuel Cell (SOFC)

An introduction to Solid Oxide Fuel Cells was given in Deliverable 5.1. Inhere only the cost related aspects especially for ammonia fed SOFC shall be mentioned. This means aspects related to Capex, such as materials, or aspects related to Opex such as efficiency and life time.

The solid oxide fuel cell (SOFC) is a high temperature fuel cell working at temperatures between 600°C and 1000°C. They use ceramic oxides as electrolyte. Due to the high temperatures the electrochemical reactions take place even without the presence of nobelmetalls e.g. Pt. Cheaper catalysts such as Ni work as well, which is advantages related to costs.[14] [15] Up to now there are no commercial ammonia fed SOFC. Most systems described in literature are used for testing e.g. for materials, electrolyte thickness, temperature , system operation and simulation validation. [16–20].

There are two relevant types of NH3 fed SOFC, the oxygen anion conducting SOFC-O and the proton conducting SOFC-H. The latter one is up to now not in a commercial state, so for the economic comparison the focus is on the SOFC-O. The electrolyte consists most of the times of an Yttria stabilized zirconia (ZrO2 + Y2O3) which transports the oxygen ions from

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cathode to anode at temperatures between 700 and 1000°C. At lower temperatures cerium gadolinium oxide (CGO) or lanthanum strontium gallate magnesite (LSGM) electrolytes can be used [21]. "The anode and cathode materials are usually Ni-YSZ and lanthanum strontium manganate-YSZ composites (LSM-YSZ), respectively."[17]

Here, the Ni at the anode serves additionally as catalyst to split NH3 into H2 and N2.

$$NH_3 \leftrightarrow \frac{1}{2} N_2 + \frac{3}{2} H_2$$

Due to similar materials the investment costs for ammonia fueled SOFC are similarly to those of NG-fueled ones.

Nowadays system costs are in a range of about 2000 to 3000 €/kW_{el} for systems up to 100 kW (pers. communication). Batelle [22] did a very detailed cost estimation for 100 and 250 kW-CHP fuel cell systems based on NG for production of 100 up to 50.000 units/year. When subtracting prices for fuel processor and heat recovery (which might be an interesting option later on as well for HiPowAR) prices for the 100 kW System are in range of 1000 €/kW down to 600 €/kW for mass production. 250 kW-Systems are cheaper with 826 €/kW to 530 €/kW (mass production). Figure 8 shows some cost estimations from different literature.[18, 22–26]

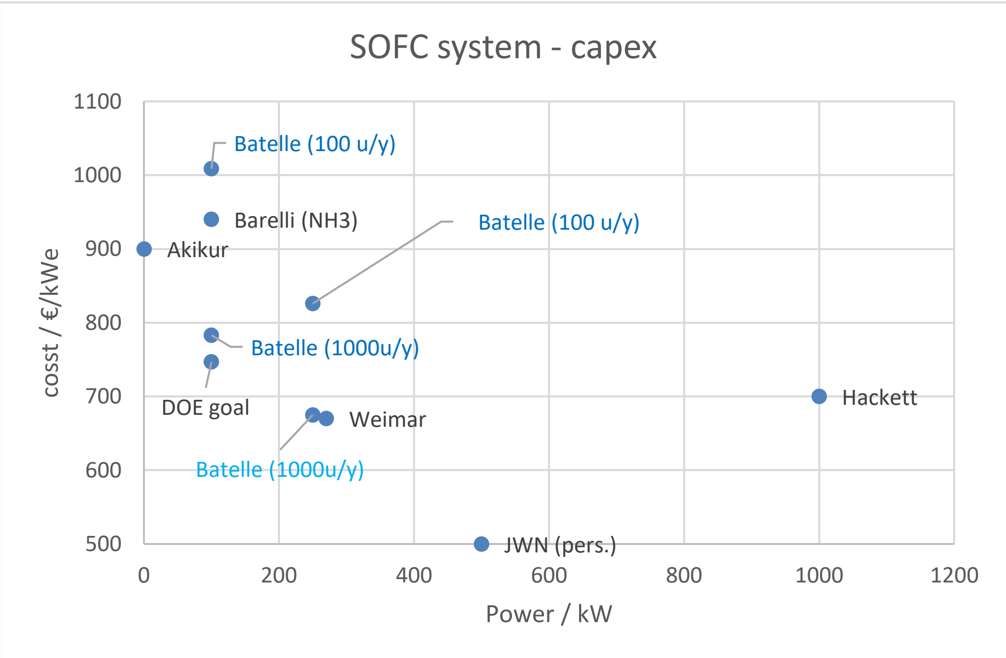

Figure 8: SOFC investment costs

Most of the systems investigated are in an order of less than 300 kW of power. Higher power for fuel cell systems are mostly reached by modular systems, where several modules are combined. [27]

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One of the important values needed for estimating the operational costs is the efficiency, because this has influence on the amount of fuel needed to get a defined electrical energy output. As mentioned above there are no commercial NH3 fed systems available up to now. Efficiencies are only given for test systems. In some literature ammonia fueled systems seem to be better than hydrogen in other it is vice versa. But mostly it is thought to get efficiencies in the same range as for NG fueled systems somewhere between 50 and 60% depending on material, thickness and temperature optimization as well as on size.

The second important value for OPEX calculations is the lifetime. SOFC systems normally show a degradation over lifetime. DoE goal for that is less than 0,2% over 1000 hours [24]. Degradation for ammonia fueled systems must be investigated further but for calculation the goal will be used as a first guess. Lifetime of SOFCs vary a lot from 20.000 h for up to 100.000 h [28]. The DOE goal here is 40.000 h which seems to be accessible and will be used for further calculations. This time frame is valid only for the stack. The BoP components normally have lifetimes of 10 years or more.

One advantage of most fuel cell systems is the lower maintenance effort in comparison to motors or turbines due to not rotating parts and the lack of lubrication systems.

3.2. Internal Combustion Engine (ICE)

A comprehensive overview about the Internal Combustion Engine technology itself and ongoing research activities regarding combustion of Ammonia was presented in Deliverable 5.1. Key statements from cost perspective are:

- Specific capital costs are highly sensitive to nominal power output
- Enabling ICEs to burn NH3 fuel is of high interest for multiple producers for different industries
- Short term commercial availability of NH3 fueled engines is expected.
- Promising concept for Ammonia: Spark ignition and NH3-H2 mixture.
- No major changes in core engine design required.

As stated above, the core design of available ICEs remains mainly identical when changing fuel to ammonia [29] . Engine package changes mainly refer to the storage system and supply line system. As ammonia storage and piping is present in the HiPowAR baseline system as well, it doesn't' need to be considered as an additional cost position for this comparison.

A recent publication regarding two-stroke ammonia ICE by MAN [30] confirms small amount of required changes on the core engine and potential possibility of retrofit engines. It

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describes the changes to enable ammonia as a fuel as an add-on for available engine designs, comparable to available add-ons as liquid gas propane or methanol. The required supply pressure will be approx. 70bar.

Similar costs for enabling core internal combustion engines to burn Ammonia and LNG can be expected. This coincides with other literature as [31, 32] , where identical costs for NH3 and LNG fueled ICEs are expected. However, materials such as copper, brass or zinc alloys should not be used for ammonia due to corrosion [32]. Efficiencies for stationary ICEs often operated optimum are expected to be about 35 to 45%. Lifetime for NG-fueled ICEs on is about 80.000 [1] to 100.000 hours [33], but good maintenance and general overhauls after 30.000 to 60.000 hours are necessary.

In [7] a cost overview of a 21,4 MW power plant with natural gas fueled internal combustion engines (4 pieces) is given. For the engines itself the specific costs are approx. 700 €/kWel. In [1] specific costs for CHP modules with ICE are given for different fuels such as NG, biogas or Sewage gas are given. These costs dependent on the power range and ranges from, 400 €/kW_{el} for a 2 MW) module up to 4000 €/kW_{el} for 5 kW modules.

For ammonia fueled ICE it could be helpful to perform a kind of pre-cracking of the ammonia to get some hydrogen for better combustion processes. In addition, exhaust gas aftertreatment to reduce nitrogen oxides using SCR may be necessary. These components will increase the costs of the NH3-fueled ICE.

Regarding operational costs it is assumed that these are similar to conventional NG fueled system, which are typically given in relation to electricity produced. The values range from 0,5 ct/kWh for multi-MW-systems to 4 ct/kWh for kW-systems [34].

4. Conclusion

The costs of a system that has not yet been fully planned and designed always contain numerous inaccuracies. Nevertheless, the specification of expected minimum and maximum costs enables a statement to be made about the range in which the costs for the HiPowAR concept are to be located. The breakdown into subsystems shows that, on the one hand, the innovative reactor is a cost driver from today's perspective. There is cost reduction potential here through appropriate design changes or also material and manufacturing variants for the MIEC. On the other hand, the expander system including the generator is responsible for a large part of the costs. At the same time, the costs for this system are strongly dependent on the process parameters, which have not yet been definitively determined or whose adjustment can still be influenced, for example, by a maximum temperature. With regard to costs, a balance must be struck here between efficiency and

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system costs. With specific costs in the range of 1700 to approx. 4000 €/kW$_{el}$ for the 100 kW system and 700 to 2800 €/kW$_{el}$ for the 1 MW$_{el}$ system, the estimated investment costs are in the range of SOFC systems. Compared to ICE, the costs are somewhat higher, but if a pre-cracker and the SCR required after the combustion are taken into account, the specific costs are also relativized here. For economic comparability not the investment costs are decisive but the LCOE which will be calculated next in the ongoing project.

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5. Literature

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6. Appendix

Power 100 kW	lower range (60% efficiency)			higher range (60% efficiency)		
parts	**quantity**	**price/unit**	**total price**	**quantity**	**price/pce**	**total price**
MIEC reactor			*44.080*			*118.160*
miec membranes	2.000	6	12.000	2.000	15	30.000
reactor			*32.080*			*88.160*
socket miec	16	300	4.800	16	600	9.600
silicon plug in sealings	2.000	0,1	200	2.000	1	1.000
reactor shell	16	1.500	24.000	16	4.000	64.000
Sealing of reactor	16	5	80	16	10	160
ceramic insulation	16	25	400	16	50	800
fittings	160	5	800	160	10	1.600
assembly whole system	10	40	400	160	50	8.000
testing	10	40	400	20	50	1.000
certificates	1	1.000	1.000	1	2.000	2.000
expander/turbine			*60.000*	0		*95.000*
expander (all in)	1	60.000	60.000	1	95.000	95.000
generator (drehstrom sync	0	2.000	0	0	4.000	0
NH3 system			*20.000*	0		*45.000*
NH3 pump	1	20.000	20.000	1	45.000	45.000
water system			*2.218*	0		*10.000*
water pump	1	2.218	2.218	1	10.000	10.000
product system			*450*	0		*650*
product valve	2	100	200	2	200	400
product drainvalve	1	250	250	1	250	250
cooling water			*500*	0		*1.000*
pump	1	500	500	1	1.000	1.000
Hex/Cond			*5.280*			*8.900*
HEX Steam/NH	1	700	700	1	1.700	1.700
HEX steam/H2O	1	700	700	1	1.700	1.700
HEX cooling water	1	200	200	1	500	500
condenser	1	3.680	3.680	1	5.000	5.000
air system			*325*			*600*
air blower	1	325	325	1	600	600
Valves/sensors			*7.250*			*11.500*
Valves	15	150	2.250	15	300	4.500
sensor, conroler	10	300	3.000	10	400	4.000
safety	5	400	2.000	5	600	3.000
fittings/tubes			*2.500*			*3.750*
fitting a	100	10	1.000	100	15	1.500
fitting b	50	20	1.000	50	30	1.500
tubes	10	50	500	10	75	750
Controls			*23.500*	0		*74.000*
controls (SPS...)	1	20.000	20.000	1	50.000	50.000
Hardware	1	2.000	2.000	1	4.000	4.000
Software	1	1.500	1.500	1	20.000	20.000
RCS			*2.500*	0		*5.000*
documentation	1	500	500	1	1.000	1.000
approval	1	2.000	2.000	1	4.000	4.000
labour			*4.000*			*7.200*
system assembly	60	40	2.400	120	40	4.800
system testing	40	40	1.600	60	40	2.400
Total costs			**172.603**			**380.760**
Specific costs			**1.726**			**3.808**

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Power 1MW	lower range (60% efficiency)			higher range (60% efficiency)		
parts	quantity	price/unit	total price	quantity	price/unit	total price
MIEC reactor			*344724*			*909080*
miec membranes	20000	6	120000	20000	15	300000
reactor		1422	224724		3854,9	609080
socket miec	158	300	47400	158	600	94800
silicon plug in sealings	20000	0,2	4000	20000	0,5	10000
reactor shell	158	1000	158000	158	3000	474000
Sealing of reactor	158	3	474	158	10	1580
ceramic insulation	158	25	3950	158	50	7900
fittings	1580	5	7900	1580	10	15800
assembly whole system	40	40	1600	40	50	2000
testing	10	40	400	20	50	1000
certificates	1	1000	1000	1	2000	2000
expander/turbine			*300.000*			*1.000.000*
turbine (all in)	1	300000	300000	1	1000000	1000000
generator (drehstrom syn	0	20000	0	0	40000	0
NH3 system			*20000*			*70000*
NH3 pump	1	20.000	20000	1	70.000	70000
water system			*5733*			*13000*
water pump	1	5.233	5233	1	12.000	12000
water injection 2	1	500	500	1	1000	1000
product system			*1250*			*2500*
product valve	2	500	1000	2	1000	2000
product drainvalve	1	250	250	1	500	500
cooling water			*1000*			*5000*
pump	1	1000	1000	1	5000	5000
Hex/Cond			*11700*			*18000*
HEX Steam/NH	1	1000	1000	1	2000	2000
HEX steam/cooling water	1	1000	1000	1	2000	2000
HEX steam/water	1	500	500	1	1000	1000
condenser	1	9200	9200	1	13000	13000
air system			*1200*			*2000*
air blower	1	1200	1200	1	2000	2000
Valves/sensors			*14000*			*27000*
Valves	15	400	6000	15	800	12000
controles	10	500	5000	10	1000	10000
safety	5	600	3000	5	1000	5000
fittings/tubes			*5850*			*9800*
fitting a	100	25	2500	100	50	5000
fitting b	50	40	2000	50	60	3000
tubes	15	90	1350	15	120	1800
Controls			*26500*			*84000*
control (SPS...)	1	20.000	20000	1	50.000	50000
Hardware	1	2.000	2000	1	4.000	4000
Software	1	1.500	1500	1	30.000	30000
RCS			*2500*			*5000*
documentation	1	500	500	1	1000	1000
approval	1	2000	2000	1	4000	4000
labour			*5600*			*11200*
system assembly	80	40	3200	160	40	6400
system testing	60	40	2400	120	40	4800
Total costs			**737.057**			**2.156.580**
Specific costs			**737**			**2.157**

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