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1 Load following of Small Modular Reactors (SMR) by
2 cogeneration of hydrogen: a techno-economic analysis
3
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1 **ABSTRACT**

2 Load following is the possibility for a power plant to adjust its power output according to the demand
3 and electricity price fluctuation throughout the day. In nuclear power plants, the adjustment is usually
4 done by inserting control rods into the reactor pressure vessel. This operation is inherently inefficient
5 as nuclear power cost structure is composed almost entirely of sunk or fixed costs; therefore, lowering
6 the power output, does not significantly reduce operating expenses and the plant is thermo-
7 mechanical stressed. A more attractive option is to maintain the primary circuit at full power and use
8 the excess power for cogeneration. This paper aims to present the techno-economic feasibility of
9 nuclear power plant load following by cogenerating hydrogen. The paper assesses Small Modular
10 nuclear Reactors (SMRs) coupled with: alkaline water electrolysis, high-temperature steam
11 electrolysis, sulphur-iodine cycle. The analysis shows that in the medium term hydrogen from alkaline
12 water electrolysis can be produced at competitive prices. High-temperature steam electrolysis and
13 even more the sulphur-iodine cycle proved to be attractive because of their capability to produce
14 hydrogen with higher efficiency. However, the coupling of SMRs and hydrogen facilities working at
15 high temperature (about 800 °C) still require substantial R&D to reach commercialisation.

16

17 **KEYWORDS**

18 SMR; Load following; Cogeneration; Hydrogen; Economics; Feasibility study

19

20 **LIST OF ACRONYMS**

21 AWE = Alkaline Water Electrolysis

22 DCF = Discounted cash flow

23 CAPEX = CApital Expenditures

24 HTGR = High-Temperature Gas Reactor

25 HTSE = High-Temperature Steam Electrolysis

26 LF = Load Following

27 LWR = Light Water Reactor

28 NPP(s) = Nuclear Power Plant(s)

29 NPV = Net Present Value

30 OECD = Organisation for Economic Co-operation and Development

31 OPEX = OPeration EXpenditures

32 R&D = Research & Development

33 SI = Sulphur-Iodine thermochemical

34 SMR(s) = Small Modular Reactor(s)

35 WACC = Weighted Average Cost of Capital

1 Introduction

2 1.1 The need for load following

3 The global demand for energy will increase by 48% from 2012 to 2040 primarily due to non-
4 OECD countries [1]. The journey towards sustainable energy production, therefore, faces
5 several challenges, with the contribution of different technologies to achieve this long-term
6 goal. Nuclear Power Plants (NPPs) can be deployed along with renewable power plants to
7 achieve the long-term perspective of sustainable development [2], [3].

8 Due to the predominance of fixed costs, NPPs are considered a base load power technology
9 [4]. NPPs have a lower marginal production cost than gas or coal. Since the demand for
10 electricity changes continuously during a single day, the adjustment on the offer-side is
11 usually obtained by manoeuvring gas or coal power plants. This is done since the 70s and it is
12 still mostly the case nowadays. However, given the expected substantial introduction of
13 intermittent sources of energy (i.e. solar, the wind), NPPs need to be able to follow the load
14 as stressed by OECD/NEA [5]:

15
16 *“a unit must be capable of continuous operation between 50% and 100% of its nominal power*
17 *(P_n), [...]. Load scheduled variations (should be) 2 per day, 5 per week and 200 per year”.*

18
19 Therefore NPPs planned today, and operating in the time frame 2025 – 2100 need to have
20 the manoeuvrability described in [5]. Several modern NPP designs implement enhanced
21 manoeuvrability, with the possibility of planned and unplanned load-following in a wide
22 power range and with ramps of 5% of nominal power rate per minute [5]. This is, for example,
23 the case of France, while older reactors in other countries (e.g. USA) have more limited
24 manoeuvrability. For example the standard Russian design “VVER – 1000” can perform ramps
25 of 3-4% their power rate per minute if the reactor is in the 10-70% of the fuel cycle or 1%-
26 1.5% their power rate per minute if the reactor is in the 70-100% of the fuel cycle [5].

1 1.2 Challenges in load following using nuclear power plants

2 Currently, NPP follows the electricity demand (from now on “Load Following” - LF) by
3 modifying the reactivity within the core, e.g. by inserting control rods made of neutrons
4 absorbers into the coolant [6]. By doing so, the power is reduced, with a waste of potential
5 energy and a thermomechanical stress on the plant. Moreover, the typical cost breakdown of
6 producing electricity with NPP is [4]:

- 7 • Investment, including interest: 59%
- 8 • Operation and maintenance: 25%
- 9 • Fuel (uranium mining, conversion, enrichment, fabrication): 12%
- 10 • Waste management and decommissioning: 4%

11 Besides investment costs, operation & maintenance costs (mainly personal and insurance)
12 are fixed and independent of the power rate. Therefore unlike fossil-fuelled power plants,
13 there is not a relevant cost saving in operating an NPP at a lower power level due to the
14 substantially fixed nature of nuclear costs. Again, opposite to conventional gas-fired plants,
15 where fuel accounts for approximately 70%-80% of the generation cost, nuclear fuel accounts
16 for only about 12% of generation costs [4]. Due to the complexity of the neutron dynamics
17 within the core (fission, absorption by all reactor materials, capture reactions, leaks,
18 poisoning, etc.), the proportionality between power produced and fuel consumed is not linear
19 [6]. A lower power rate does not translate into an equivalent fuel saving. Consequently
20 running a power plant at 50% of its power does not save more than few percentages of its
21 operating cost, while the loss of revenue is proportional to the electricity not produced.

22

23 1.3 Load following by cogeneration

24 As presented in [7] the fundamental idea of the “LF by Cogeneration” is to meet electricity
25 market demand fluctuation and avoid an economic penalty at the same time. In this
26 configuration, the NPP would work at its nominal power all the time, leaving the primary
27 circuit conditions unchanged. Cogeneration is therefore intended as the production of
28 electrical energy and another valuable product output [8], [9]. During the high load/high price
29 hours (usually day-time) the nuclear thermal power is entirely converted into electricity to
30 the grid, while during hours of low demand/low price (usually night-time) the excess thermal
31 energy would produce a valuable by-product. The coupling is particularly virtuous for those

1 co-products that are storable, that require large amounts of energy (heat or electricity) and
2 for which the energy supply represents a significant component of production cost [7].

3 Virtually *every* facility which requires electricity could be coupled with a standard NPP to
4 support the LF if:

- 5 • The power demand is in the region of 500 MW_e – 1 GW_e;
- 6 • There is an abundance of “input material” to be processed;
- 7 • There is relevant market for the end product;
- 8 • It can work at full power during the night, and operate at a much lower load during the
9 day. This means that the co-product is storable and daily power cycles do not damage the
10 facility in the long term;

11 In this paper, we investigate the case of co-production of hydrogen as recommended in [7].
12 Since electricity can be more easily transmitted than heat, the proximity with the NPP is not
13 imperative for a hydrogen facility using electricity only. Conversely, the coupling with a
14 hydrogen facility using thermal energy has tighter requirements. An auxiliary facility thermally
15 coupled with an NPP operating in LF mode should:

- 16 • Be located reasonably close to the NPP;
- 17 • Need a thermal power in the region of 1.5-3 GW_{th};
- 18 • Require adequate temperature.

19 Most of the Light Water Reactors (LWR - accounting for 89% of the global nuclear capacity
20 [10]) operate in the region of 300 °C; while future high-temperature reactors might operate
21 at higher temperature, for instance, 500 °C for the sodium-cooled fast reactors and 900 °C for
22 high-temperature gas reactors (HTGR) [11] like the GTHTR300C [12], [13]. The NPP
23 temperature is a key parameter because, as later explained (section 2.2), higher the
24 temperature more types of cogenerating facilities are available.

25

26 1.4 Why SMRs might be an ideal candidate technology

27 Small Modular Reactors (SMRs) are a relevant technology for the LF because the overall
28 power at the site level is fractioned. As explained in [6] and further developed in [7] a key
29 advantage of adopting multiple SMRs instead of a single large reactor is the intrinsic
30 modularity of an SMR site power output. It is possible to operate all the primary circuits of
31 the SMR fleet at full capacity and switch the thermal power of some of them only, for the

1 cogeneration of suitable by-products. The same could be made with a single large reactor, i.e.
2 some thermal power could be diverted and channelled to the cogeneration process, but
3 getting some steam out of the secondary circuit would compromise the efficiency of the
4 electricity conversion and this would translate into a technical and economic inefficiency.
5 With multiple SMRs, the LF strategy is realised at the site level, rather than at single plant
6 level, by diverting 100% of the electricity (or 100% of the thermal power) generated by some
7 SMRs to cogeneration purposes and let the remaining SMRs produce power for the electricity
8 market at full regime; in this way the optimal fine tuning of the secondary power circuit is not
9 compromised. Either in the case of full electricity conversion or in full cogeneration operation
10 mode, the efficiency would be maximised, letting the secondary circuits working by-design:
11 indeed, some SMRs could run at the full nominal power and maximum conversion efficiency,
12 while some other would give up producing electricity.

13 The size of the cogeneration facility is optimised according to the thermal power rate made
14 available by the SMRs. E.g. considering four SMRs, the electric power rates at site level would
15 be approximately 0%, 25%, 50%, 75% and 100% corresponding respectively to the following
16 cases: none of the four SMRs produces electricity for the grid, or alternatively, one, two, three
17 or all SMRs produce electricity for the grid. These steps in power rate could be made available
18 by SMRs, with gas plants providing further fine matching with the electricity market demand.
19 By using smaller SMRs, the possible power rates steps could be made smoother.

20 For the sake of clarity, let's compare a site with four "independent SMRs of 250 MWe" versus
21 a site of same total power (1000 MWe) produced by a single large reactor. If during the night,
22 the power needs to be reduced by about 50%, two SMRs can be disconnected from the grid
23 and used for the cogeneration of other products, while the two remaining will continue to
24 produce electricity at full power rate and maximum efficiency. In the case of a 1000 MWe,
25 the 50% power reduction will cause some components (e.g. pumps and turbine) to work
26 outside the most efficient operating conditions, with a lower efficiency of the electricity
27 conversion. Therefore, when operating in LF mode, the four SMRs would be more efficient
28 than a single stand-alone LR, at the plant level.

1 1.5 Aim and structure of the paper

2 Following the preliminary analysis of [7], the co-production of hydrogen seems a good
3 candidate technology for coupling with nuclear power, but the topic is under-researched. This
4 paper fills this gap assessing the technical and economic feasibility of coupling hydrogen
5 production facilities with SMRs.

6 This paper aims to present the techno-economic feasibility of SMRs performing the LF by
7 cogenerating hydrogen. Specifically, the paper assesses the case of multiple SMRs coupled
8 with three alternative hydrogen production facilities: alkaline water electrolysis, high-
9 temperature steam electrolysis, sulphur-iodine cycle.

10 The rest of the paper is organised as follows: Section 2 presents the literature review about
11 candidate technologies for both hydrogen facilities and SMRs. In 2.1 the paper focuses on the
12 most relevant aspects of the hydrogen production and market. In 2.2 it presents the three
13 most relevant technologies that can be coupled with SMRs to perform the “LF by
14 cogeneration”. These three technologies will be analysed and compared throughout the
15 paper. Section 3 explains the overall research method. Section 4 reports the technical
16 verification of coupling SMR with a hydrogen-producing facility on the basis of the literature
17 and experts’ interviews. Section 5 details a novel economic appraisal of the technically
18 feasible solutions. The results from these economic calculations are original from this
19 research. Section 6 summarises the most salient conclusions and provides insights for future
20 works.

1 2 Literature review

2 2.1 The market for hydrogen

3 The hydrogen world consumption is about 85 million tonnes, growing steadily [14]. This
4 market might increase dramatically if technologies such as fuel-cell vehicles would be widely
5 used [15]. Indeed the “hydrogen economy” is getting higher visibility and stronger political
6 support [16]. Nowadays, hydrogen finds many applications as a chemical product for [17]:
7 ammonia synthesis, methanol synthesis, direct reduction of iron ore, fossil fuel processing
8 (hydrocracking), Fischer-Tropsch hydrocarbon synthesis, methanation in long-distance
9 energy transportation, hydrogasification. Ammonia is the most important product, used as
10 fertiliser and in the petroleum industry. In the future, hydrogen might be utilised for ground
11 transport, aviation, marine applications, and railroad transport. If the whole demand of
12 hydrogen was satisfied by water electrolysis, with an energy input of 48.2 MWh/ton [15], then
13 4097×10^3 GWh of electricity would be necessary for its production. Considering that a
14 standard 1 GWe NPP can produce up to 8,760 GWh/year, almost 500 large NPPs would be
15 required to produce the same amount of hydrogen. This is more than the global NPP installed
16 capacity in 2018.

17

18 2.2 Hydrogen production methods overview

19 Nowadays, the breakdown of the hydrogen production methods is [18]:

- 20 • Steam Methane Reforming: 48%
- 21 • Oil/Naphtha Reforming: 30%
- 22 • Coal Gasification: 18%
- 23 • Water Electrolysis: 4%

24 The vast majority of hydrogen comes from fossil fuel because the energy demand in their
25 process is much lower than in water electrolysis [18]. Hydrogen can also be produced by
26 several other methods (thermolysis, radiolysis, thermochemical cycles, photolysis et al.), but
27 the status of economics and technology readiness prevented so far their large-scale
28 application [19].

29 The water electrolysis is the only non-fossil process giving a sensible contribution to the
30 industrial production of hydrogen. This method has “abundant material as input” (water) and

1 a large increasing market as output (see section 2.1). Requiring a significant amount of energy,
2 hydrogen from water is an ideal candidate for the LF application. According to the experts'
3 opinions and to the literature [17] Alkaline Water Electrolysis (AWE) is the standard
4 technology among those that use electricity as the unique energy input. High-Temperature
5 Steam Electrolysis (HTSE), and Sulphur-Iodine thermochemical (SI) cycle are the two most
6 promising technologies among those that make use of heat.

7 Therefore this paper investigates:

- 8 • AWE as proven, short-term, electricity only application;
- 9 • HTSE as medium-term heat and electricity application;
- 10 • SI as long-term, mostly thermal power application.

11

12 2.2.1 Low-temperature electrolysis: Alkaline Water Electrolysis (AWE)

13 The AWE consists in the decomposition of water molecules, under an electric field generated
14 between two electrodes immersed in an electrolyte. The process occurs in installations
15 commonly called electrolyzers. An electrolyser cell consists mainly of the water medium, the
16 electrodes and the diaphragm, which separates the cell into two compartments, anode and
17 cathode, where the two semi-reactions (reduction and oxidation) take place [20]. The
18 electricity creates an electric field over the electrolyte, which forces the negative ions (anions)
19 to move towards the anode (positive pole) and positive ions (cations) to the cathode (negative
20 pole). Hydrogen and oxygen develop separately on two electrodes. AWE is the most common
21 technology for the large-scale application. The electrical input is 3.5 [kWh/Nm³] in
22 theoretical conditions [26] however in real life real life operations, considering a reasonable
23 efficiency for industrial applications, a more reasonable value is 3.8 - 4.4 [kWh/Nm³]
24 according to [20] or 4.3 - 4.7 [kWh/Nm³] according to [27]. Several studies assert that AWE
25 is not economically competitive against hydrocarbon-based technologies because of the
26 electricity cost [21], [22]. In these studies, the electricity accounts for about 75% of the
27 hydrogen generation cost [15]. However, these studies consider an average annual cost of
28 the electricity or a combination with must-run power sources (like wind or photovoltaic) [23],
29 [24]. These studies do not consider the variation of the electricity price over the day. They
30 assume to feed the AWE with electricity at "market price", regardless its hourly variable value.

1 The novelty of this study is that the AWE cogeneration process is assumed to work only during
2 the period of low electricity market price, typically during the night-time. Assuming a “carbon-
3 free electricity” generation portfolio, i.e. a mix of nuclear and renewable, the electricity
4 production will be independent of the demand, creating an excess of energy during the night.
5 The idea of using “the surplus of electricity” is among the key innovative contributions of this
6 paper, as well as taking advantage of the SMRs plant modularity to produce different power
7 rates with optimal conversion efficiency.

8

9 2.2.2 High-Temperature Steam Electrolysis (HTSE)

10 It is possible to reduce the electricity required for the electrolysis by increasing the
11 temperature of the process. At the temperature of 2,500 °C, the electricity is unnecessary
12 because water breaks down into hydrogen and oxygen through thermolysis [25]. For the
13 whole range of temperatures between 0 and 2,500 °C, the energy input is a combination of
14 electricity and heat. The electrical and thermal energy inputs for the HTSE at 850 °C (a typical
15 value) are respectively 2.5 [kWh_e/Nm³] and 0.92 [kWh_t/Nm³] [26]. A solid oxide electrolyser
16 cell is the standard technology for HTSE. Since the HTSE is a high-temperature application, the
17 ideal solution is the coupling with high-temperature, GEN-IV SMRs [28], [29]. HTSE is in the
18 R&D phase, and most of the high-temperature SMRs are at the prototype/pilot phase.

19

20 2.2.3 Sulphur-Iodine thermochemical cycle (SI)

21 In the SI process, the sulphuric acid is heated to approximately 900 °C producing hydrogen
22 through a series of reactions described in [26]. This process is still under R&D, and different
23 options are considered [19], [30]. Within this process, the hydrogen is produced with an
24 overall efficiency of about 45% using thermal energy only [31]. Because sulphuric acid and
25 other elements are very corrosive, the selection of the structural materials is a relevant
26 research topic [32] [33]. Notably, R&D on the SI cycle is carried out in the USA, France, South
27 Korea and Japan [34]. Recently, researchers successfully demonstrated a stable and
28 continuous hydrogen evolution at laboratory scale [12]. [13] describes the technical aspects
29 of coupling a SI facility with high-temperature SMR design, such as the HTGR. The HTGR
30 generates up to 300 MW_e at 45-50% thermal efficiency by a direct cycle gas turbine power
31 conversion system and potentially up to 1.4 million Nm³ hydrogen/day at about 45%

1 efficiency with an SI process. The reactor has 600 MW_t thermal power and 850~950 °C reactor
2 outlet temperatures, ideal for the SI. Using an intermediate heat transport loop, a share of
3 the HTGR heat is the input of the adjacent hydrogen facility. As for HTSE, the hydrogen facility
4 should be sited close to the reactor building to reduce thermal loss and pipeline cost [13].

5

6 2.3 Other revenues: reserve services and energy storage

7 The coupling of a SMR with a facility producing hydrogen could allow the SMR to sell
8 electricity for balancing service. Each country has its balancing service market; the UK market
9 is selected as a reference because of the public availability of information and previous studies
10 [35], [36]. In the UK the “National Grid” procures balancing services to balance demand and
11 supply and to ensure the security and quality of electricity supply across the UK transmission
12 system. The National Grid manages the balancing service either accessing to sources of extra
13 power generation or demand reduction, to deal with unexpected demand increase and
14 generation unavailability. Different sources require different time scales to be ready to deliver
15 the services and different price [37]. The most important reserves for this studies are the so-
16 called “Fast Reserves” and “Short Term Operating Reserves” [36]. Fast reserves are used to
17 control frequency variations arising from sudden and unpredictable changes in generation or
18 demand. Active power delivery must start within 2 minutes of the dispatch instruction, and
19 the reserve energy should be sustainable for a minimum of 15 minutes; it must be able to
20 deliver a minimum of 50MW [38]. *“Providers of the service will receive an Availability Fee (£/h)*
21 *for each hour in a Tendered Service Period where the service is available. A utilisation fee*
22 *(£/MW/h) is payable for the energy delivered”* [38].

23 For Short Term Operating Reserve the minimum capability requirements are [39]:

- 24 • 3MW minimum power generation;
- 25 • 240 minutes maximum response time, although typical contracts are for 20 minutes or
26 less;
- 27 • Delivering the contracted MW for a continuous period of minimum 2 hours;
- 28 • Not more than 1200 minutes as recovery period after the reserve provision;
- 29 • Being able to deliver at least three times per week.

30 There are two forms of payment that National Grid makes as part of the Short Term Operating
31 Reserve. *“Availability Payments (£/MW/h): service providers are paid to make their unit/site*

1 available for the [Short Term Operating Reserves] service within an Availability Window.
2 Utilisation Payments (£/MWh): service providers are paid for the energy delivered as
3 instructed by National Grid. This includes the energy delivered in ramping up to and down
4 from the Contracted MW level" [39]. This paper assesses the economic relevance for SMR
5 coupled with a hydrogen facility operating in the reserve market, assuming the market prices
6 in the UK. Regarding the technical aspects is unclear if a stand-alone SMR can adjust its power
7 output, on a regular basis, in the timeframes required. Conservatively the paper considers
8 this options for AWE only. In case of AWE, the SMR produces electricity 100% of the time, so
9 the Short Term Operating Reserves and Fast Reserve service is provided by simply
10 disconnecting or reducing the power in one (or more) of the electrolyser modules. This
11 electrical switch operation is compatible with the requested flexibility timeframe.

1 3 Methodology

2 This research is based on two steps.

- 3 1. The technical verification of the possible coupling solutions, on the basis of the literature
4 and experts' interviews (Section 4).
- 5 2. A novel economic appraisal of the technically feasible solutions. The results from these
6 economic calculations are original from this research (Section 5).

7

8 3.1 General framework for the economic analysis

9 Traditional methods for project economic appraisal are based on the Discounted Cash Flow
10 (DCF) analysis that is grounded on the estimation of costs and revenues over the facility life.
11 A detailed and clear explanation of the DCF analysis in energy and research facility is available
12 in [40]. This section explains the equations used in the research presented in this paper.
13 Because of the time value of money, each cash flow produced during the plant lifetime is
14 discounted back to current value, using the formula:

15

$$PV_t = \frac{FV_t}{(1 + WACC)^t} \quad (1)$$

16 Where:

17 FV = future value of the cash flow;

18 PV = present value of the cash flow;

19 WACC (Weighted Average Cost of Capital) = discount rate per time period, i.e. weighted
20 average remuneration rate expected for the financing sources mix invested in the project;

21 t = number of the time periods.

22 The project Net Present Value (NPV) is the sum of the PVs of all the cash inflows and cash
23 outflows over the life of the project:

24

$$NPV = \sum_{t=0}^T PV_t = \sum_{t=0}^T \frac{FV_t}{(1 + WACC)^t} \quad (2)$$

25

1 Therefore the DCF analysis calculates future free cash flow projections (revenues and costs)
2 and discounts them in a lumped NPV, which is used to evaluate the capability of the project
3 of generating net economic value for the investors.
4 If the discounted cash inflows are higher than the all the discounted costs, then the NPV is
5 positive, and therefore the investment is considered “profitable”. A heuristic decision maker
6 rule is, therefore, to invest in the project (i.e. building the hydrogen cogeneration facility) if
7 NPV is positive. Therefore the NPV is usually a synthetic value calculated as the lump sum of
8 the annual net cash flows over the entire life cycle of the facility (i.e. “T” in the equation 2 is
9 the total number of years and “t” is the year index). The following charts in Figure 1 and Figure
10 2 show the cumulated net cash flows calculated at each year of the life cycle of the facility.
11 The value in the final year is the NPV of the overall project. An important indicator related to
12 the DCF is the “Payback time”. The Payback time is the length of time (usually years) required
13 to recover the cost of an investment.
14 The main limitation of the aforementioned NPV method is that all costs and revenues over
15 the facility lifecycle should be estimated with reasonable confidence. This is possible for the
16 case of AWE, but not for HTSE or SI. When key data are missing it is common practice to
17 reverse the equation: the NPV calculation can be implemented in a spreadsheet and, with a
18 “goal seek function” assuming $NPV = 0$, it is possible to calculate breakeven values of the key
19 variables, (e.g. the construction capital cost) that are the threshold values for the technology
20 profitability. Table 8, Table 9 and Table 11 are built with this criteria and provide a complete
21 sensitivity analysis respect to different parameters.

22

23 3.2 Key Hypothesis for the economic analysis

24 The goal of this economic analysis is to support the investment appraisal of building a
25 hydrogen production facility for the LF. This paper assumes that the decision to build the SMR
26 is already taken. In the perspective of the SMR owner, the paper assesses the chance to add
27 economic value by building a hydrogen production facility coupled with the SMR, to perform
28 the LF with the help of the cogeneration process. Therefore the economic analysis focuses
29 only on the hydrogen production facility and is presented in differential terms compared to
30 the case of a SMR 100% dedicated to the electricity production for the grid.

1 Compared to a SMR full-electricity operation mode, the analysis considers three main
2 elements:

- 3 • Revenues: from the sale of hydrogen and from backup capacity (Fast Reserve and
4 Short Term Operating Reserves – for AWE only).
- 5 • Capital expenditures (CAPEX), including all the costs to design and build the hydrogen
6 production facility.
- 7 • Annual operation expenditures (OPEX), including all the costs to run the hydrogen
8 production facility, i.e. personnel, materials & spare parts. We assume that the OPEX
9 expenditures include the “opportunity cost” from the loss of the electricity sales.

10 Since the analysis is differential to the full-electricity operation mode, revenues from
11 electricity sale are not considered. Conversely, the paper considers the “opportunity cost” of
12 giving up the revenues from electricity sales, to use the nuclear thermal power to produce
13 hydrogen. The “opportunity cost” is not a cash cost, but a loss of revenue and is equal to the
14 wholesale price of electricity (0.05 €/kWh) when the SMRs are in LF mode. As presented later,
15 the “opportunity cost” is a very important parameter driving the overall economics.

16 The paper also assumes that the electricity sold to the grid by the combined nuclear-hydrogen
17 plant is roughly 100% SMR site nominal power during the day (8.00 am to 12.00 pm), and
18 roughly 50% during the night (0.00 am to 8.00 am). This is called “Base Case 8” i.e. a case with
19 8 hours of low electricity demand and price. A sensitivity analysis is performed on a “Base
20 Case 12”, that assumes a longer 12 hours night (8 pm – 8.00 am).

1 4 Technical verification

2 Table 1 lists the key characteristics of a typical LWR SMR [41] (according to the IRIS reactor
3 concept [42]), and an HTGR SMR (according to the GTHTR300 [12]) resized to 335MW_e for a
4 fair comparison.

5

6

PLEASE INSERT TABLE 1 HERE

7

Table 1: SMRs technical characteristics [34], [31]

8

9 Assuming that the electricity required by the grid is roughly 100% SMRs nominal power during
10 day-time and roughly 50% at night-time the power available night-time for the cogeneration
11 auxiliary facility will be 670 MW_e from both IRIS and GTHTR300 designs, or 2000 MW_t and
12 1456 MW_t from the IRIS and GTHTR300 sites respectively. The power split between the grid
13 and the hydrogen production facility, for each case, is calculated as follows:

- 14 1. During the night, 50% power is diverted to the hydrogen facility.
- 15 2. If the SMRs cannot provide the necessary enthalpy to the cogeneration process, natural
16 gas is burned to increase the steam temperature.
- 17 3. The ratio between the nuclear and the natural gas thermal contribution is determined by
18 the enthalpies (i.e. by temperatures reached in the two thermal power sources).

19

20 4.1 Alkaline Water Electrolysis

21 4.1.1 Choice of the electrolyser module

22 Alkaline electrolysers are a standardised item and several manufacturers are available. The
23 efficiency of an electrolyser measures the rate of hydrogen production per unit of electrode
24 active area; it is inversely proportional to the cell potential, which is determined by the
25 current density [43]. Consequently, a higher voltage would result in more hydrogen
26 production, but at a lower efficiency. Typically, the cell voltage is about 2 V, but a lower
27 nominal voltage (as low as 1.6 V) can be used to raise the efficiency. Currently, commercial
28 large-size electrolysers have electric power inputs usually between 0.35 MW_e and 3.35 MW_e.
29 Considering that the cogeneration facility has to absorb all the excess power coming from the
30 SMR, the AWE facility will be composed of several electrolysers cells (or modules).

1 [15] presents a list of electrolysers models, technical data on efficiency degradation (typically
2 between 0.25 to 1.00 %/year) and stack lifetime (between 78,840 to 96,000 hours). According
3 to [20] [27], the energy input varies from 3.8 KWh_e/Nm³ to 4.7 KWh_e/Nm³. After several
4 interviews with electrolyser manufacturers, the researcher selected a standard module with
5 a size of 2.2 MWe and an electricity consumption of ranging from 3.8 to 4.4 KWh_e/Nm³ with
6 4.3 KWh_e/Nm³ as the expected value. This module is the NEL A. 485, produced by NEL
7 Hydrogen [27] with the features presented in Table 2

8

9

PLEASE INSERT TABLE 2 HERE

10

Table 2: AWE technical parameters [27] [15]

11

12 It is necessary to take into accounts some degradation of the electrolyser efficiency, i.e. the
13 energy required to produce 1 Nm³ of hydrogen increases. According to the experts he
14 efficiency degradation ranges between from 0.7% to 1.5 %/year, with an expected value of
15 1.0 %/year. After ten years, the excessive degradation of performance requires a replacement
16 of the electrolysers stacks. The availability of the electrolysers is typically high (about 98%)
17 since there are no moving parts. The planned maintenance can mostly be done during the
18 day-time with a negligible impact on the production.

19

20 4.1.2 Sizing the Alkaline Water Electrolysis facility

21 Since the available power from the SMRs is approximately 670 MWe, 304 electrolyser units
22 are installed. During the night the electrolysers operate at their maximum operating load. On
23 the opposite, according to alkaline electrolysers manufacturers, the repeated shutdown of
24 the AWE facility during day-time would cause a rapid degradation of the electrolysers
25 performances. Therefore, following the manufacturer's recommendations, the paper
26 assumes that the minimum operation level for the AWE facility is 20% of its nominal capacity.
27 Considering the reserve market, the dynamic response becomes essential in the case of “Fast
28 Reserve Operation” and “Short Term Operating Reserve”. According to electrolysers
29 manufacturers, in the event of a request, electrolysers can be rapidly brought to the minimum
30 operating level and the electricity made available to the grid within two minutes, without
31 damaging the AWE system.

1 4.2 High-temperature steam electrolysis facility

2 Currently, there are no commercial HTSE facilities in operations. Therefore it is not possible
3 to refer a “standard” set of input data. Efficiency degradation is one of the most serious
4 problems affecting the HTSE and is highlighted in Table 3. Moreover, LWR SMRs (like IRIS)
5 cannot supply a steam temperature high enough for the HTSE. Therefore, natural gas could
6 be burned to increase the steam enthalpy. The techno-economic feasibility of this facility
7 might be challenging. On the contrary, the steam produced by HTGR SMR (like GTHTR300)
8 complies with the requirement in terms of temperature, and therefore no extra heating
9 source is necessary. The stack lifetime is hardly predictable at this stage of knowledge, so a
10 sensitivity analysis will be done on this parameter (see section 5).

11 Also in this case, the repeated shutdown of the facility during day-time would cause a rapid
12 degradation of the electrolyzers performances. Therefore the paper assumes that the
13 minimum operation level for the HTSE facility is 20% of its nominal capacity. Table 3 presents
14 the key technical parameters of the HTSE. The HTSE requires a combination of electric and
15 thermal energy (about $2.5 \text{ kWh}_e + 0.92 \text{ kWh}_t$) [26]; therefore electricity is largely the most
16 important input for the HTSE as well. The HTSE is still in the R&D phase, and its key challenge
17 is the fast degradation issue.

18

19 PLEASE INSERT TABLE 3 HERE

20 **Table 3 HTSE technical parameters**

21

22 4.3 Sulphur-iodine cycle thermochemical facility

23 All the considerations about uncertainties on technical parameters applicable to the HTSE
24 apply to the SI as well. The thermal energy input of the SI cycle is $5.99 \text{ kW}_t/\text{Nm}^3$. The need for
25 a heat transfer fluid at 850°C , makes the usage of an LWR reactor unrealistic since the
26 enthalpy of the steam is by far too low for the process. Therefore this work focuses on the
27 coupling of SI with HTGR. Whether an SI facility would be flexible enough to perform LF is not
28 an easy question to answer. Realistically, this facility would present the typical problems of
29 thermal inertia and low flexibility, which characterise large thermochemical facilities.
30 However, the process is under R&D, and there is not enough information to confirm nor
31 dismiss this assumption. Moreover to avoid the thermal dynamic stress a conservative

1 hypothesis and in analogy with the AWE and HTSE, a load factor of 20% has been assumed
2 for the day-time operation. The SI process requires thermal energy only: 5.9 kWh_t/Nm³ [26].
3 Table 4 presents the key technical parameters of an SI facility.

4

5

PLEASE INSERT TABLE 4 HERE

6

Table 4: Sulphur-Iodine facility model technical parameters

1 5 Economic analysis

2 5.1 Alkaline water electrolysis facility

3 5.1.1 Cost analysis

4 The AWE capital cost ranges between 1,000 to 1,200 €/kW_e, but it is expected to decrease to
5 760—1,100 €/kW_e in the next years [44]. A more significant cost reduction is expected in the
6 medium term, which could be fostered by the growing penetration of hydrogen as a fuel in
7 the automotive market. The expected capital cost in the long term is 600 €/kW_e, with an
8 optimistic forecast of 370 €/kW_e [44]. Much of the cost reduction will come from an improved
9 supply chain and from increased production volumes with more cost-efficient production
10 techniques [44]. Substantial capital cost reductions are possible by the economy of scale
11 applied to larger auxiliary systems shared by electrolyzers. [45] reports that the scaling of
12 compressors, gas holding tanks, transformers and balance of plant equipment might reduced
13 capital cost at 60% or 25% of its current value. All this considered and following discussions
14 with the manufacturers we assumed an interval from 730 to 880 €/kW_e as CAPEX cost.

15 Considering OPEX, the stack replacement is the substitution of the electrolyser components
16 where the electrochemical reactions take place. Stack cost typically represents about the half
17 of the overall costs of the alkaline electrolysis [44]. According to the vendors, the AWE system
18 lifetime is estimated to 40 years, but the stacks have to be replaced every ten years. According
19 to [44], other OPEX ranges between 2%-5% of the CAPEX, while manufacturers suggested that
20 for the middle term a value of around 1.0% and 1.5% is more reasonable.

21

22 5.1.2 Inputs

23 In this research, revenues come from:

- 24 • The hydrogen sale
- 25 • The electricity sold as Short Term Operating Reserve or Fast Reserve (*Utilisation*
26 *Payments*)
- 27 • The payment for the plant *Availability* related to the Short Term Operating Reserve only.

28 The costs are represented by CAPEX and OPEX (including the electricity opportunity cost) as
29 aforementioned discussed. Table 5 summarises the annual costs and revenues from the

1 participation to the Short Term Operating Reserve and the Fast Reserve markets, assuming
2 50% reduction in the electricity supply to the grid during 8 hours night-time.
3 The CAPEX values are reported in Table 6. As for the OPEX and Stack Replacement, the
4 expected values are derived from the literature [44] and the interviews with some
5 manufacturers. The WACC - Discount Rate is 5% as suggested by [40].

6

7

PLEASE INSERT TABLE 5 HERE

8

Table 5: Cost and Revenues description during different operation periods, for Short Term Operating Reserve and Fast Reserve

9

10

11

12

PLEASE INSERT TABLE 6 HERE

13

Table 6: AWE Inputs from [44] and the interviews with the manufacturers

14

15 The electricity price changes over the day as well as over the year. The electricity price
16 distribution of the UK Day Ahead electric market is available from [46], [47]. The hydrogen
17 selling price is very complex to define since it is usually not traded, but produced and
18 consumed in situ [48]. A reference price provided by experts is around 0.30 - 0.40 €/Nm³.

19

20 5.1.3 Results

21 Figure 1 gives a long-term perspective showing that with a hydrogen price of 0.30 €/Nm³ the
22 NPV is negative for all the scenarios; therefore the hydrogen production is not economically
23 viable in the long term. Considering a hydrogen price of 0.40 €/Nm³, the three scenarios
24 present very different results: indeed, in the “optimistic case” the Payback Time is about nine
25 years; in the “expected scenario” is 25 years, while the “pessimistic scenario” forecasts a non-
26 profitable investment (Payback Time never occurs).

27 Figure 2 gives a short-term perspective showing the hydrogen/electricity breakeven prices,
28 according to the two Base Case scenarios: Base Case 8 and Base Case 12, i.e. when the
29 hydrogen is produced respectively for 8 or 12 hours/day. Considering, for instance, the
30 “Expected Base Case 8” the figure reveals that the production of hydrogen is reasonable when
31 the demand and price for electricity is particularly low. In fact, given a certain Hydrogen price,
32 there is a break-even price for electricity, above which it becomes more profitable to produce

1 electricity. For instance, if the price of Hydrogen is 0.30 €/Nm³, the electricity breakeven price
2 is about 0.05 €/KWh_e. In other words at hydrogen 0.30 €/Nm³ and electricity 0.05 €/KWh_e is
3 economically equivalent, in the short term, to produce hydrogen or electricity.
4 Data and consequent revenues for Short Term Operating Reserve and Fast Reserve are
5 presented in Table 7 (with original data converted in €).

6

7 PLEASE INSERT FIGURE 1 HERE

8 **Figure 1: NPV for the Base Case 8 operation, taking the Hydrogen price at 0.40 €/Nm³ (solid line) and 0.30**
9 **€/Nm³ (dotted line).**

10

11

12 PLEASE INSERT FIGURE 2 HERE

13 **Figure 2: Deterministic Breakeven Hydrogen price depending on electricity Price: Expected value, Optimistic**
14 **and Pessimistic curves. Base Case 8 and Base Case 12 operation mode. BC = Base case. Operating life 20 years**
15

15

16

17 PLEASE INSERT TABLE 7 HERE

18 **Table 7: Short Term Operating Reserves and Fast Reserve - Revenue calculation (data converted in €)**
19

19

20 The Short Term Operating Reserve operation gives a weak extra value to the investment, due
21 to the lower unit economic value is given to this reserve type compared to the Fast Reserve.
22 The Fast Reserve operation is more profitable (from 3.5 M€/y for availability to 7 M€/y for
23 utilization), provided that the efficiency degradation is relatively low. However, these values
24 do not substantially change the overall economics of the facility.

25

26 5.2 High-temperature steam electrolysis facility

27 5.2.1 Inputs

28 The only relevant differences respect to the DCF model of the AWE investment case are:

- 29 • The natural gas fuel cost (LWR + Natural Gas case);
- 30 • The reserve market is not considered because the flexibility of the HTSE facility is not
31 known yet.

32 Since the HTSE technology is not ready for commercialisation, the economic analysis will
33 provide a plausible CAPEX for the HTSE model, to be compared with some information

1 provided by the literature. Thus, for this technology (as well as for the SI cycle in section 5.2.2),
2 the most interesting research output is the break-even CAPEX. This is the maximum cost for
3 an HTSE module, which would let a minimum required profitability (i.e. 5% WACC) and
4 justifies the construction of this facility. Mathematically, the breakeven corresponds to a NPV
5 equal to zero, i.e. the investment returning a profitability rate which is exactly equal to the
6 WACC.

7

8 5.2.2 Results

9 Table 8 shows the results of the coupling the HTSE facility with an IRIS SMR and a superheater.
10 Results are given in terms of breakeven capital costs, that is the minimum WACC for the
11 hydrogen cogeneration facility that makes the investment profitable, given the electricity and
12 hydrogen market prices. Table 9 refers to the coupling between the HTSE facility and an HTGR.
13 The two cases (IRIS + Natural Gas; HTGR) produce very similar results. The difference is due
14 to the additional cost of the natural gas presented only in the first case. The values have a
15 trend:

- 16 • The values increase with the increase of the hydrogen price, which is the most important
17 variable since it is the only revenue. The correlation is almost direct: increasing the
18 hydrogen price, the breakeven capital cost increases by roughly the same percentage.
- 19 • The values decrease with the increase in the electricity price. The reason is that if the price
20 of electricity is high the “opportunity cost” of producing hydrogen increases; therefore
21 the production of hydrogen is convenient only if capital cost of the facility is low.
- 22 • The values decrease with the efficiency degradation increase. If the facility degrades
23 quickly, it is convenient to build the facility only if the CAPEX cost “is low”. In particular is
24 important to keep the degradation under 8%-10% per year.

25

26 PLEASE INSERT TABLE 8 HERE

27 **Table 8: HTSE + External Heater Breakeven Capital Cost, in the case of coupling between the HTSE facility**
28 **and an LWR, with the Steam Superheating provided by natural gas (Neg = Negative NPV)**

29

30 PLEASE INSERT TABLE 9 HERE

31 **Table 9: HTSE Breakeven capital cost, in the case of coupling between the HTSE facility and an HTGR (Neg =**
32 **Negative NPV)**

33

1 5.3 Sulphur-Iodine cycle thermochemical facility

2 5.3.1 Inputs

3 The relevant differences of the HTSE DCF model from the previous ones are:

- 4 • No Stack replacement cost, because of the different nature of the facility;
- 5 • No natural gas fuel cost, because the LWR+Natural Gas case is considered unfeasible (see
6 section 4.3);

7 The economic inputs for the SI cycle DCF are listed in Table 10

8

9 PLEASE INSERT TABLE 10 HERE

10 **Table 10: SI cycle Deterministic DCF Inputs**

11

12 5.3.2 Results

13 Table 11 shows the results of the SI facility and an HTGR coupling. The table is conceived in
14 the same way as the HTSE case; the only difference is represented by the OPEX costs
15 expressed as a percentage of the CAPEX in place of the efficiency degradation rate. Most of
16 the comments made for the HTSE case remain valid here: the electricity price is a key driver,
17 and the efficiency degradation must be carefully assessed since above 8%-10% per year the
18 investment might be hardly profitable.

19

20 PLEASE INSERT TABLE 11 HERE

21 **Table 11: Sulphur-Iodine Breakeven Capital Cost, according to hydrogen price, electric price and OPEX cost**
22 **scenarios (Neg = Negative NPV)**

23

24

25 5.4 Discussion and summary of the results

26 If the hydrogen price is low (below 0.15 €/Nm³) and electricity above 0.06 €/kWh_e, both the
27 HTSE and SI processes are not competitive as is. It is necessary need to decrease their capital
28 cost to become a profitable investment.

29 With a hydrogen price of 0.30 €/Nm³ and an electricity price of 0.06 €/kWh_e the HTSE begins
30 to be profitable if the efficiency degradation rate is between 2%/year and 5%/year. With
31 these market prices for hydrogen and electricity, the SI facility is always a profitable

1 investment. The SI facility is potentially profitable even for medium-high electricity prices as
2 far as the hydrogen price reaches 0.15 €/Nm³ and OPEX costs are lower than 6%.
3 The HTSE becomes profitable with hydrogen prices above 0.30 €/Nm³, particularly if efficiency
4 degradation rate remains below the 5-10 %/year. In the case of 20 % efficiency loss per year,
5 the HTSE struggles to be competitive. Table 12 summarises all these results.

6

7

PLEASE INSERT TABLE 12 HERE

8

Table 12: Summary of the results

1 6 Conclusions e future developments

2 NPPs have been historically used for base load electricity production. However, the energy
3 portfolios evolution towards increasing share of renewables and the new requirements set
4 by institutions, will require NPPs to be able to work in LF mode. NPP, including SMRs, are
5 capital intensive, and almost all of their costs are fixed or sunk costs. Therefore, this paper
6 proposes to use the excess energy available during periods of low demand / low electricity
7 price (usually night-time) to produce hydrogen as a valuable by-product.

8 Three different hydrogen production electrolysis technologies have been investigated: AWE,
9 HTSE and the SI. Among these, AWE is the only one commercially developed. HTSE and the SI
10 are at different stages of R&D.

11 Considering the technical aspects, the paper shows that the AWE, as an electric application,
12 is a flexible technology that can be easily coupled with SMRs. The investment can be
13 profitable, mostly depending on electricity and Hydrogen prices. With AWE, the Short Term
14 Operating Reserve is sustainable for electrolyzer and does not damage the facility. Fast
15 Reserve operation puts a strain on the electrolyzer, which however is capable of performing
16 fast shutdown and rapid recovery. This operation would reasonably cause an increase of the
17 efficiency degradation, and given the limited contribution to the overall economics, the
18 investor should carefully consider this option and carry out further research for an informed
19 decision.

20 HTSE is mostly an electric application even if requires thermal power. HTSE can be coupled
21 with an HTGR, but this SMRs concept still requires substantial R&D. The coupling of HTSE with
22 a LWR SMR might be technologically challenging due to the difference in temperature
23 between the steam produced by the SMR and the cogeneration process requirements. The
24 LF with HTSE might also be challenging because the capability of the 850 °C operating facility
25 to adapt to periodical changes in power input need further investigation. However, the
26 feasibility of this coupling cannot be excluded a priori. Moreover, the modular nature of the
27 facility (made by hundreds of HTSE) could be an advantage.

28 The SI facility uses predominantly thermal power and can be coupled with an HTGR for
29 cogeneration purposes. The coupling with an LWR and a natural gas burner is not feasible
30 since the natural gas heating system should provide at least 1,000 MWth. The use of a LWR

1 as a thermal power source seems unrealistic, since the steam enthalpy is too low respect to
2 the SI operating conditions. Also, the SI facility and the HTGR are in their R&D stage.

3 Considering the economic aspects, this research shows that the production of hydrogen with
4 an AWE facility is profitable if the hydrogen price is at least hydrogen price of 0.40 €/Nm³ and
5 the electricity price (i.e. the opportunity cost) is relatively low. This applies in particular when
6 the period of “low price” is longer: the 12 hours low price scenario is considerably more
7 profitable than the 8 hours low price scenario. The Short Time Reserve operation gives a weak
8 extra value to the investment, while the Fast Reserve operation gives a more significant
9 additional value to the investment, as far as the electrolysers efficiency degradation rate is
10 low (<2% per year). However, the reserve market, with the typical value of the UK scenario,
11 does not significantly change the overall project economics. It is interesting to note that HTSE
12 becomes profitable for high hydrogen prices, i.e. in the range of 0.30 - 0.45 €/Nm³ or above,
13 but only if efficiency degradation rate keeps below 5-10 %/year. The SI is potentially very
14 profitable, meaning that its capital cost can be higher than a water electrolyzer, even for
15 medium-high electricity prices, as far as the hydrogen price reaches 0.30 €/Nm³. Therefore
16 there is an economic rationale for a SMR to co-generate hydrogen for LF purposes if the price
17 of electricity is low enough during night-time. Moreover, the development of more advanced
18 technologies, such as SI, that use thermal energy only, is interesting from the technical-
19 economic point of view, since the conversion loss from thermal to electric power is avoided.

20 This research paves the way for a number of future developments. Regarding the technical
21 aspects, the most innovative, are related to the further development of SI facility and HTGR.
22 Regarding the economic aspects, the next step is to develop a Monte Carlo analysis with a
23 real options approach. This would allow to better quantify the risks in the investment and the
24 value of the degrees of freedom available to the investor. Regarding the policy aspects, the
25 study of the contracting schemes to enable the most reasonable risk allocation among the
26 stakeholders involved would be of extreme interest. Under this perspective, particularly
27 relevant would be the proposal of a government scheme to foster the construction of a pilot
28 facility and, eventually, the commercial production of the facilities investigated in this
29 research.

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9 References

- 10 [1] DOE, "International Energy Outlook 2016," Washington, D.C. :, 2016 [Online].
11 Available: [https://www.eia.gov/outlooks/ieo/pdf/0484\(2016\).pdf](https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf)
- 12 [2] IAEA, "Nuclear Power and Sustainable Development," Vienna, 2016 [Online]. Available:
13 <http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1754web-26894285.pdf>
- 14 [3] D. MacKay, *Sustainable Energy-without the hot air*. UIT Cambridge, 2009.
- 15 [4] NEA/OECD, "Nuclear Energy Today 2nd edition," 2012 [Online]. Available:
16 <http://www.oecd-nea.org/pub/nuclearenergytoday/6885-nuclear-energy-today.pdf>
- 17 [5] NEA - OECD, "Technical and Economic Aspects of Load Following with Nuclear Power
18 Plants," 2011 [Online]. Available: [https://www.oecd-nea.org/ndd/reports/2011/load-](https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf)
19 [following-npp.pdf](https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf)
- 20 [6] G. Locatelli, S. Boarin, F. Pellegrino, and M. E. Ricotti, "Load following with Small
21 Modular Reactors (SMR): A real options analysis," *Energy*, vol. 80, pp. 41–54, 2015.
- 22 [7] G. Locatelli, A. Fiordaliso, S. Boarin, and M. E. Ricotti, "Cogeneration: An option to
23 facilitate load following in Small Modular Reactors," *Prog. Nucl. Energy*, vol. 97, pp.
24 153–161, 2017.
- 25 [8] G. Locatelli, S. Boarin, A. Fiordaliso, and M. Ricotti, "Load following by cogeneration:
26 Options for small modular reactors, gen IV reactor and traditional large plants," in *25th*
27 *International Conference on Nuclear Engineering, ICONE 2017; Shanghai; China, 2017*,
28 vol. 3.
- 29 [9] M. Leurent, F. Jasserand, G. Locatelli, J. Palm, M. Rämä, and A. Trianni, "Driving forces
30 and obstacles to nuclear cogeneration in Europe: Lessons learnt from Finland," *Energy*
31 *Policy*, vol. 107, pp. 138–150, Aug. 2017.
- 32 [10] IAEA, "PRIS - Reactor status reports - Operational & Long-Term Shutdown - By
33 Type." [Online]. Available:

- 1 <https://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx>.
- 2 [Accessed: 16-Feb-2017]
- 3 [11] G. Locatelli, M. Mancini, and N. Todeschini, "Generation IV nuclear reactors: Current
4 status and future prospects," *Energy Policy*, vol. 61, pp. 1503–1520, 2013.
- 5 [12] K. Kunitomi, X. Yan, T. Nishihara, N. Sakaba, and T. Mouri, "Jaea'S Vhtr for Hydrogen
6 and Electricity Cogeneration : GTHTR300C," *Nucl. Eng. Technol.*, vol. 39, pp. 9–20, 2007.
- 7 [13] IAEA, "Status report 101 - Gas Turbine High Temperature Reactor (GTHTR300C),"
8 2011.
- 9 [14] WNA, "Transport and the Hydrogen Economy - World Nuclear Association," 2017.
10 [Online]. Available: [http://www.world-nuclear.org/information-library/non-power-
11 nuclear-applications/transport/transport-and-the-hydrogen-economy.aspx](http://www.world-nuclear.org/information-library/non-power-nuclear-applications/transport/transport-and-the-hydrogen-economy.aspx).
- 12 [Accessed: 29-Aug-2017]
- 13 [15] M. Felgenhauer and T. Hamacher, "State-of-the-art of commercial electrolyzers and
14 on-site hydrogen generation for logistic vehicles in South Carolina," *Int. J. Hydrogen
15 Energy*, vol. 40, no. 5, pp. 2084–2090, 2015.
- 16 [16] IAEA, "Non-Electric Applications of Nuclear Power : Seawater Desalination , Hydrogen
17 Production," no. April, pp. 16–19, 2007.
- 18 [17] IAEA, "Advanced Applications of Water Cooled Nuclear Power Plants," 2008. [Online].
19 Available: [http://www-
20 pub.iaea.org/MTCD/Publications/PDF/te%7B_%7D1584%7B_%7Dweb.pdf](http://www-pub.iaea.org/MTCD/Publications/PDF/te%7B_%7D1584%7B_%7Dweb.pdf)
- 21 [18] M. Balat, "Potential importance of hydrogen as a future solution to environmental and
22 transportation problems," *Int. J. Hydrogen Energy*, vol. 33, pp. 4013–4029, 2008.
- 23 [19] I. E. Agency, "Hydrogen Production and Storage," *Energy*, vol. 13, p. 392, 2006.
- 24 [20] M. Passolunghi, "Analisi e sviluppo di un elettrolizzatore in media pressione per la
25 produzione di idrogeno e ossigeno," 2010 [Online]. Available:
26 <https://www.politesi.polimi.it/handle/10589/86624>
- 27 [21] F. Mueller-Langer, E. Tzimas, M. Kaltschmitt, and S. Peteves, "Techno-economic
28 assessment of hydrogen production processes for the hydrogen economy for the short
29 and medium term," *Int. J. Hydrogen Energy*, vol. 32, pp. 3797–3810, 2007.
- 30 [22] R. G. Lemus and J. M. Martínez Duart, "Updated hydrogen production costs and parities
31 for conventional and renewable technologies," *Int. J. Hydrogen Energy*, vol. 35, no. 9,
32 pp. 3929–3936, May 2010.

- 1 [23] A. Ursúa, I. San Martín, E. L. Barrios, and P. Sanchis, "Stand-alone operation of an
2 alkaline water electrolyser fed by wind and photovoltaic systems," *Int. J. Hydrogen*
3 *Energy*, vol. 38, pp. 14952–14967, 2013.
- 4 [24] a. G. Dutton, J. a M. Bleijs, H. Dienhart, M. Falchetta, W. Hug, D. Prischich, and a. J.
5 Ruddell, "Experience in the design, sizing, economics, and implementation of
6 autonomous wind-powered hydrogen production systems," *Int. J. Hydrogen Energy*,
7 vol. 25, pp. 705–722, 2000.
- 8 [25] Y. Yürüm, *Hydrogen energy system : production and utilization of hydrogen and future*
9 *aspects*. NATO scientific affairs division, 1995.
- 10 [26] X. L. Yan and R. Hino, "Nuclear Hydrogen Production," 2011.
- 11 [27] N. Hydrogen, "NEL A. Series Technical Data." [Online]. Available:
12 <http://nelhydrogen.com/product/electrolysers/#a-range-title>
- 13 [28] C. M. Stoots, J. E. O'Brien, K. G. Condie, and J. J. Hartvigsen, "High-temperature
14 electrolysis for large-scale hydrogen production from nuclear energy - Experimental
15 investigations," *Int. J. Hydrogen Energy*, vol. 35, no. 10, pp. 4861–4870, 2010.
- 16 [29] S. Fujiwara, S. Kasai, H. Yamauchi, K. Yamada, S. Makino, K. Matsunaga, M. Yoshino, T.
17 Kameda, T. Ogawa, S. Momma, and E. Hoashi, "Hydrogen production by high
18 temperature electrolysis with nuclear reactor," *Prog. Nucl. Energy*, vol. 50, pp. 422–
19 426, 2008.
- 20 [30] R. B. Gupta, *Hydrogen Fuel: Production, Transport, and Storage*. CRC Press, 2008.
- 21 [31] M. Richards, "H₂-MHR conceptual designs based on the sulphur–iodine process and
22 high-temperature electrolysis," *Int. J. Hydrog. Prod. Appl.*, 2006.
- 23 [32] P. Trester and H. Staley, "Assessment and investigation of containment materials for
24 the sulfur–iodine thermochemical water-splitting process for hydrogen production,"
25 1981 [Online]. Available: <https://www.osti.gov/scitech/biblio/6748668>
- 26 [33] K. Onuki, H. Nakajima, I. Ioka, M. Futakawa, and S. Shimizu, "IS process for
27 thermochemical hydrogen production," 1994 [Online]. Available:
28 https://inis.iaea.org/search/search.aspx?orig_q=RN:26072660
- 29 [34] S. Shiozawa, M. Ogawa, and R. Hino, "Development status on hydrogen production
30 technology using high-temperature gas-cooled reactor at JAEA, Japan." 2006 [Online].
31 Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:37057911
- 32 [35] G. Locatelli, E. Palerma, and M. Mancini, "Assessing the economics of large Energy

- 1 Storage Plants with an optimisation methodology,” *Energy*, vol. 83, pp. 15–28, 2015.
- 2 [36] G. Locatelli, D. C. Invernizzi, and M. Mancini, “Investment and risk appraisal in energy
3 storage systems: A real options approach,” *Energy*, vol. 104, pp. 114–131, 2016.
- 4 [37] National Grid, “What are Reserve Services,” 2017. [Online]. Available:
5 <http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/>.
6 [Accessed: 03-Jul-2017]
- 7 [38] National Grid, “Fast reserve | National Grid,” 2017. [Online]. Available:
8 [http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/fast-
9 reserve/](http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/fast-reserve/). [Accessed: 16-Aug-2017]
- 10 [39] National Grid, “Short Term Operating Reserves - Market Information,” 2017. [Online].
11 Available: [http://www2.nationalgrid.com/uk/services/balancing-services/reserve-
12 services/short-term-operating-reserve/](http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/short-term-operating-reserve/). [Accessed: 25-Jul-2017]
- 13 [40] European Commission, “Guide to Cost-Benefit Analysis of Investment Projects -
14 Economic appraisal tool for Cohesion Policy 2014-2020,” 2014 [Online]. Available:
15 http://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf
- 16 [41] M. D. Carelli, G. Locatelli, C. W. Mycoff, P. Garrone, M. Mancini, M. E. Ricotti, A. Trianni,
17 and P. Trucco, “Competitiveness of small-medium, new generation reactors: a
18 comparative study on capital and O&M costs,” in *16th International Conference on
19 Nuclear Engineering*, 2008, vol. 4, pp. 1–8.
- 20 [42] M. D. Carelli, L. E. Conway, L. Oriani, B. Petrović, C. V. Lombardi, M. E. Ricotti, A. C. O.
21 Barroso, J. M. Collado, L. Cinotti, N. E. Todreas, D. Grgić, M. M. Moraes, R. D. Boroughs,
22 H. Ninokata, D. T. Ingersoll, and F. Oriolo, “The design and safety features of the IRIS
23 reactor,” *Nucl. Eng. Des.*, vol. 230, no. 1, pp. 151–167, 2004.
- 24 [43] S. a. Sherif, F. Barbir, and T. N. Veziroglu, “Wind energy and the hydrogen economy-
25 review of the technology,” *Sol. Energy*, vol. 78, pp. 647–660, 2005.
- 26 [44] L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden, and E. Standen, “Study on
27 development of water electrolysis in the EU,” 2014 [Online]. Available:
28 http://www.fch.europa.eu/sites/default/files/study_electrolyser_0-Logos_0_0.pdf
- 29 [45] E. R. Morgan, J. F. Manwell, and J. G. McGowan, “Opportunities for economies of scale
30 with alkaline electrolyzers,” *Int. J. Hydrogen Energy*, vol. 38, no. 36, pp. 15903–15909,
31 2013.
- 32 [46] Ofgem, “The GB electricity wholesale market | Ofgem.” [Online]. Available:

1 <https://www.ofgem.gov.uk/electricity/wholesale-market/gb-electricity-wholesale->
2 [market.](https://www.ofgem.gov.uk/electricity/wholesale-market/gb-electricity-wholesale-) [Accessed: 10-Jun-2017]
3 [47] Epexspot, “EPEX SPOT in the UK | EPEX SPOT | Welcome.” [Online]. Available:
4 [https://www.apxgroup.com/trading-clearing/apx-power-uk/.](https://www.apxgroup.com/trading-clearing/apx-power-uk/) [Accessed: 10-Jun-2017]
5 [48] J. D. Holladay, J. Hu, D. L. King, and Y. Wang, “An overview of hydrogen production
6 technologies,” *Catal. Today*, vol. 139, pp. 244–260, 2009.
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8

1 Figures and tables

2

3 TABLE 1

| | LWR | HTGR |
|-----------------------------------------------------------------------|-------|-------|
| Thermodynamic efficiency | 33% | 46% |
| 1 SMR nominal Electric Power [MW _e] | 335 | 335 |
| Number of SMRs in the site | 4 | 4 |
| Overall <i>electric</i> power available night-time [MW _e] | 670 | 670 |
| Overall <i>thermal</i> power available night-time [MW _t] | 2,000 | 1,456 |
| Load Factor | 95% | 95% |

4

5

6 TABLE 2

| | Optimistic | Expected value | Pessimistic |
|-------------------------------------------------------------------------------|---------------------|------------------------------------------|-------------------------|
| Initial energy Input per Nm ³ [kWh _e /Nm ³] | 3.8 | 4.3 | 4.4 |
| Efficiency degradation_ Full operation | 0.7% | 1.0% | 1.50% |
| Efficiency degradation_ Fast Reserve operation [%/y] | Expected value *90% | Scenario variable: {2%; 5%; 10%; 20%} | Expected value *110% |
| Stack power [MWe] | 2.2 | | |
| Nominal Generation capacity [Nm ³ /h] | 485.0 | | |
| Stack lifetime [h] | 87,600 (10 years) | | |
| Availability [h/y] | 8,585 | | |

7

8

9 TABLE 3

| | Expected value |
|---------------------------------------------------------------------------------------------|-----------------|
| Initial Electric Energy Input per Nm ³ [kWh _e /Nm ³] [26] | 2.5 |
| Efficiency degradation: scenario variable [%/y] | {2%;5%;10%;20%} |
| Stack power [MWe] | 2 |
| Nominal Generation capacity [Nm ³ /h] | 800 |
| Availability [h/y] | 8,585 |
| Operating range (day - night) as explained in 4.1.2 | 20%—100% |

10

11 TABLE 4

| | Expected value |
|-----------------------------------------------------------|----------------|
| Thermal Energy Input [kWh _t /Nm ³] | 5.99 |
| Power Input [MW _e] | 1454 |
| Nominal Generation capacity [Nm ³ /h] | 242,700 |
| Facility lifetime [y] | 20 |
| Availability [h/y] | 7,008 (80%) |
| Operating range (day-night) | 20%—100% |

12

13

1 TABLE 5

| | Operation set up | Cost items | Revenues items | Hours |
|-------------------------------|-------------------------------------------------------|-----------------------------------|------------------------------------------------------------------------------|-------|
| Short Term Operating Reserves | Day operation: (279 electrolyzers at 20%) | Electricity used: 122 MW | Hydrogen production (from 122 MW) | 5,840 |
| | Availability – ready state (25 electrolyzers at 100%) | Electricity used: 55 MW | Hydrogen production (from 55 MW) Availability payment | 3,864 |
| | Electricity sale - Short Term Operating Reserve | Hydrogen Not produced (from 55MW) | Utilization payment: electricity sold on Short Term Operating Reserve market | 78 |
| Fast Reserves | Day operation: (259 electrolyzers at 20%) | Electricity used: 114 MW | Hydrogen production (from 114 MW) | 5,840 |
| | Availability – ready state (45 electrolyzers at 100%) | Electricity used: 99 MW | Hydrogen production (from 99 MW) Availability payment | 4,223 |
| | Electricity sale - Fast Reserve | Hydrogen Not produced (from 99MW) | Utilisation payment: electricity sold on Fast Reserve market | 365 |

2

3 TABLE 6

| | Optimistic | Expected value | Pessimistic |
|----------------------------------------------|---------------------------------------------------------------|----------------|-------------|
| CAPEX [€/kW _e] | 730 | 810 | 880 |
| OPEX [% CAPEX] | 1.0% | 1.25% | 1.5% |
| Variable non electrical cost [% total costs] | 0.9% | 1.0% | 1.1% |
| Stack Replacement [% capex] | 45% | 50% | 55% |
| Hydrogen price [€/Nm ³] | 0.30 or 0.40 in Figure 1, calculated as breakeven in Figure 2 | | |
| Electricity price [€/kWh _e] | Sensitivity analysis: {0; 0.02; 0.04; 0.06; 0.08; 0.10} | | |
| Discount rate | 5% | | |

4

5 TABLE 7

| | | Availability (contracted) | Utilization | Not Contracted |
|---------------------------------------------|------------------------------------------------|---------------------------|-------------|----------------|
| Short Term Operating Reserve Data from [39] | Hours per year | 3,864 | 78 | 4,818 |
| | Unitary payment [€/MWh] | 3.36 | 212 | 0 |
| | Total year revenue for 55 MW _e [k€] | 714 | 909 | 0 |
| Fast Reserve Data from [38] | Hours per year | 4,223 | 365 | 4,912 |
| | Unitary payment For a 99 MW Reserve Facility | 814 [€/h] | 192 [€/MWh] | 0 |
| | Total year revenue for 99 MW _e [k€] | 3,551 | 7,000 | 0 |

6

7 TABLE 8

| | | HTSE + External Heater BREAKEVEN CAPITAL COST [K€/(Nm ³ /h)]: IRIS+Natural Gas | | | | | | | | | | | |
|-----------------------------------------|------|-------------------------------------------------------------------------------------------|------|------|------|-------------------------------------|------|------|------|-------------------------------------|------|------|------|
| | | Hydrogen price [€/Nm ³] | | | | Hydrogen price [€/Nm ³] | | | | Hydrogen price [€/Nm ³] | | | |
| | | 0.15 | 0.15 | 0.15 | 0.15 | 0.30 | 0.30 | 0.30 | 0.30 | 0.45 | 0.45 | 0.45 | 0.45 |
| Efficiency degradation [%/year] | | 2% | 5% | 10% | 20% | 2% | 5% | 10% | 20% | 2% | 5% | 10% | 20% |
| ELECTRICITY price [€/kWh _e] | 0.02 | 2.79 | 2.32 | 1.73 | 1.09 | 6.48 | 5.41 | 4.05 | 2.55 | 10.17 | 8.49 | 6.36 | 4.01 |
| | 0.04 | 1.37 | 1.12 | 0.82 | 0.52 | 5.06 | 4.21 | 3.13 | 1.97 | 8.75 | 7.29 | 5.44 | 3.43 |
| | 0.06 | Neg | Neg | Neg | Neg | 3.60 | 2.97 | 2.19 | 1.38 | 7.29 | 6.06 | 4.50 | 2.84 |
| | 0.08 | Neg | Neg | Neg | Neg | 2.13 | 1.73 | 1.24 | 0.79 | 5.82 | 4.82 | 3.55 | 2.24 |
| | 0.10 | Neg | Neg | Neg | Neg | 0.69 | 0.51 | 0.31 | 0.20 | 4.38 | 3.60 | 2.62 | 1.66 |

8

9

1 TABLE 9

| | | HTSE BREAKEVEN CAPITAL COST [k€/Nm ³ /h]: HTGR | | | | | | | | | | | |
|-----------------------------------------|---------------------------------|-----------------------------------------------------------|------|------|------|-------------------------------------|------|------|------|-------------------------------------|------|------|------|
| | | Hydrogen price [€/Nm ³] | | | | Hydrogen price [€/Nm ³] | | | | Hydrogen price [€/Nm ³] | | | |
| | | 0.15 | 0.15 | 0.15 | 0.15 | 0.30 | 0.30 | 0.30 | 0.30 | 0.45 | 0.45 | 0.45 | 0.45 |
| ELECTRICITY price [€/kWh _e] | Efficiency degradation [%/year] | 2% | 5% | 10% | 20% | 2% | 5% | 10% | 20% | 2% | 5% | 10% | 20% |
| | 0.02 | 2.82 | 2.35 | 1.75 | 1.10 | 6.51 | 5.43 | 4.06 | 2.56 | 10.20 | 8.52 | 6.38 | 4.02 |
| | 0.04 | 1.29 | 1.05 | 0.76 | 0.48 | 4.98 | 4.14 | 3.07 | 1.94 | 8.67 | 7.22 | 5.39 | 3.40 |
| | 0.06 | Neg | Neg | Neg | Neg | 3.40 | 2.80 | 2.06 | 1.30 | 7.09 | 5.89 | 4.37 | 2.76 |
| | 0.08 | Neg | Neg | Neg | Neg | 1.82 | 1.47 | 1.03 | 0.66 | 5.51 | 4.55 | 3.35 | 2.12 |
| | 0.10 | Neg | Neg | Neg | Neg | 0.26 | 0.15 | 0.03 | 0.03 | 3.96 | 3.24 | 2.35 | 1.49 |

2

3 TABLE 10

| | Value |
|-----------------------------------------|----------------------------------------------------------|
| CAPEX [k€/kilo Nm ³ /h] | Research goal |
| OPEX [% capex] | Different scenarios texted: 2.5%; 5%; 7.5%; 10% |
| Variable non electrical cost [% capex] | 1% |
| Hydrogen price [€/Nm ³] | Different scenarios texted: 0.15; 0.30; 0.45 |
| ELECTRICITY price [€/kWh _e] | Different scenarios texted: 0.02; 0.04; 0.06; 0.08; 0.10 |
| DISCOUNT RATE | 5% |

4

5 TABLE 11

| | | SULPHUR-IODINE BREAKEVEN CAPITAL COST [k€/Nm ³ /h] | | | | | | | | | | | |
|-----------------------------------------|--------------------|---------------------------------------------------------------|------|------|-------|-------------------------------------|------|------|-------|-------------------------------------|------|------|-------|
| | | Hydrogen price [€/Nm ³] | | | | Hydrogen price [€/Nm ³] | | | | Hydrogen price [€/Nm ³] | | | |
| | | 0.15 | 0.15 | 0.15 | 0.15 | 0.3 | 0.3 | 0.3 | 0.3 | 0.45 | 0.45 | 0.45 | 0.45 |
| ELECTRICITY price [€/kWh _e] | Fixed OPEX [€/kWh] | 2.5% | 5.0% | 7.5% | 10.0% | 2.5% | 5.0% | 7.5% | 10.0% | 2.5% | 5.0% | 7.5% | 10.0% |
| | 0.02 | 4.5 | 3.6 | 3.0 | 2.6 | 9.3 | 7.5 | 6.3 | 5.4 | 14.2 | 11.5 | 9.6 | 8.3 |
| | 0.04 | 2.9 | 2.3 | 1.9 | 1.7 | 7.7 | 6.2 | 5.2 | 4.5 | 12.6 | 10.2 | 8.5 | 7.3 |
| | 0.06 | 1.2 | 1.0 | 0.8 | 0.7 | 6.1 | 4.9 | 4.1 | 3.5 | 10.9 | 8.8 | 7.4 | 6.4 |
| | 0.08 | Neg | Neg | Neg | Neg | 4.4 | 3.6 | 3.0 | 2.6 | 9.3 | 7.5 | 6.3 | 5.4 |
| | 0.1 | Neg | Neg | Neg | Neg | 2.8 | 2.2 | 1.9 | 1.6 | 7.6 | 6.2 | 5.2 | 4.4 |

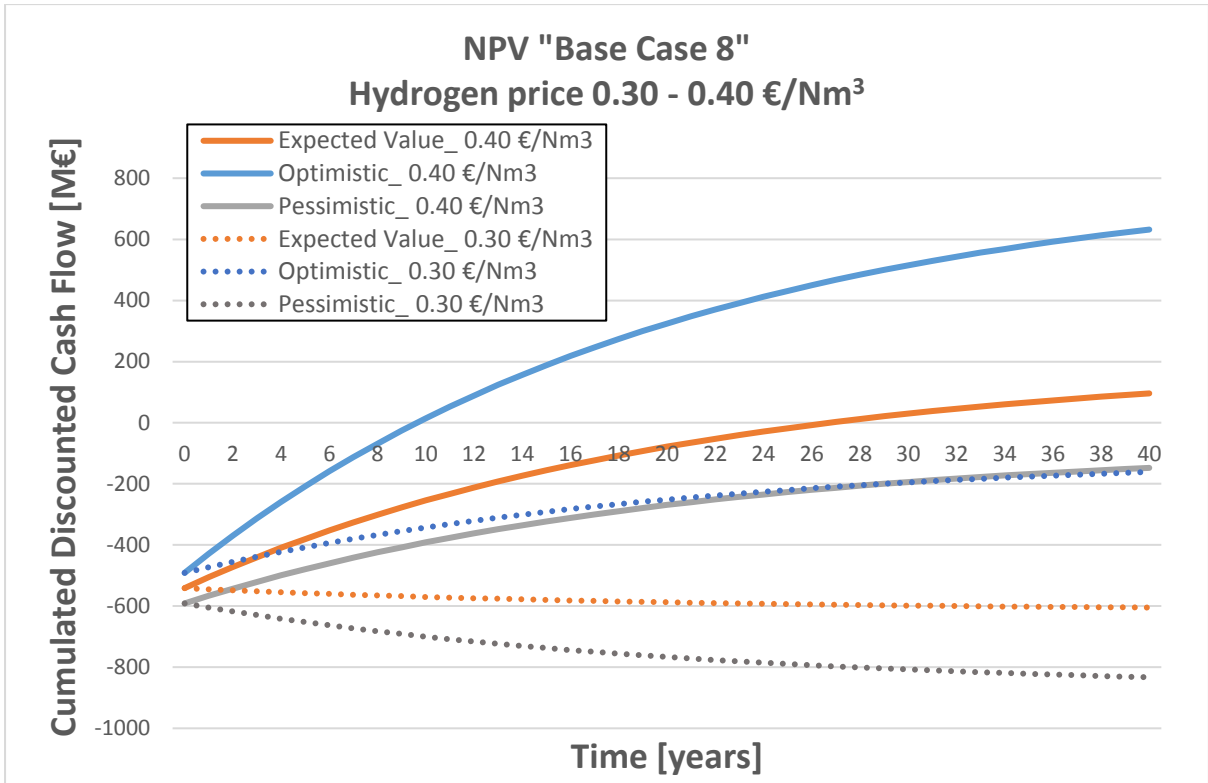
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7 TABLE 12

| Hydrogen Production Method | Process Temp. | Energy Input [kWh/Nm ³] | SMR coupled | Technical feasibility | Economic profitability |
|--------------------------------------------|---------------|-----------------------------------------------------------------|-----------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alkaline Water Electrolysis (AWE) | 80 °C | 4.3 kWh _e Electricity only | LWR | All Feasible | Depends on electricity and Hydrogen prices. All electric sources are equivalent. No advantage with SMR |
| | | | HTGR | | |
| High-Temperature Steam Electrolysis (HTSE) | 850 °C | 2.5 kWh _e + 0.92 kWh _t Mostly electricity | LWR + External Heater | Feasible in theory, Extra Heating required → natural gas solution. Technical challenges HTSE under R&D. | Depends on CAPEX, in electricity and Hydrogen price scenario |
| | | | HTGR | HTSE and HTGR under R&D | Depends on CAPEX, electricity and Hydrogen price scenario |
| Sulphur-Iodine Thermochemical cycle (SI) | 850 °C | 5.9 kWh _t Thermal energy only | LWR | Not Feasible. 4 GWh _t of natural gas heating required and very large heat exchanger | --- |
| | | | HTGR | SI cycle and reactor under R&D | Depends on CAPEX, in electricity and Hydrogen price scenario. In general electricity price might be 0.06 €/kWh _e or less and the Hydrogen price 0.3 €/Nm ³ or more. |

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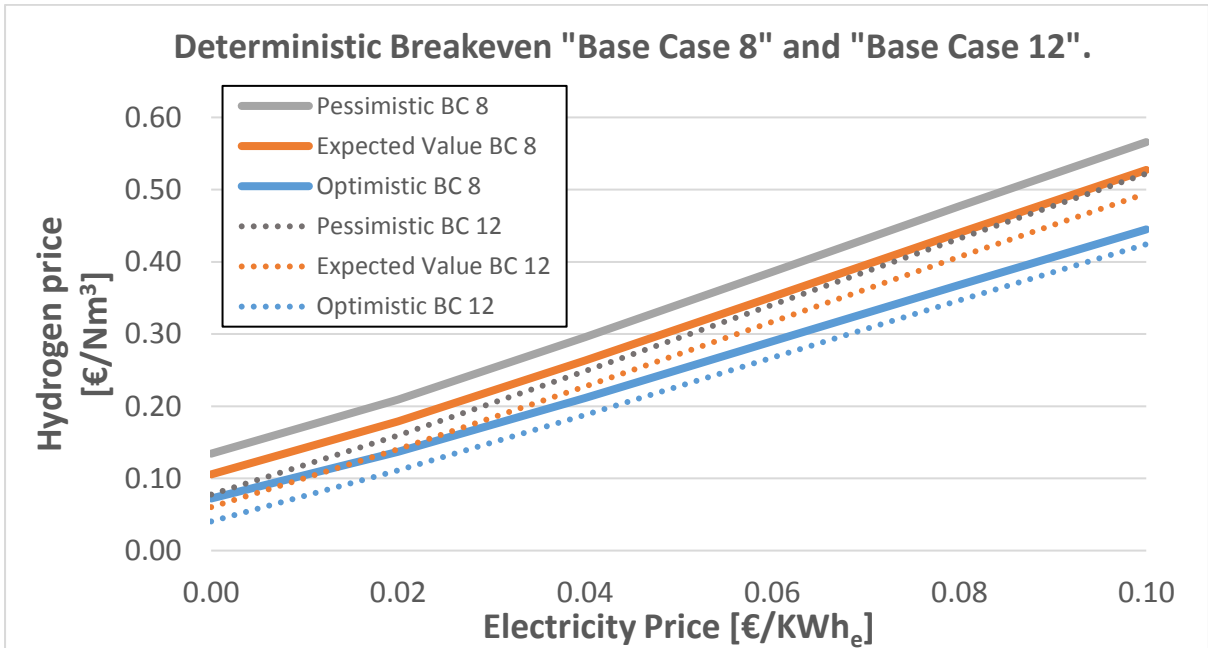
2 FIGURE 1



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5 FIGURE 2



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