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Start date : 2022-09-01 Duration : 36 Months

Description of techno-economic assessment of energy policies and relations among hybrid energy systems

Authors : Mr. Víctor AMEZCUA (EAI), Miriam Minchole Lapuente (EAI), Francisco Javier Gallo (EAI), Alfonso Junquera (EAI),Clément Liegeard (CEA), Stéphanie Crevon (CEA), David Proult (CEA), Olli Soppela (VTT), Tomi J. Lindroos (VTT), Ville Tulkki(VTT), Jussi-Pekka Ikonen (VTT), Alain Ruby (CEA), Michele Frignani (ANN), Gabriele Firpo (ANN), Andrei Goicea (NUCLEAREUROPE), Caroline Bono (EDF), Giorgio Simonini (EDF), Olivier Authier (EDF), Franck David (EDF), Christophe Schneidesch (TRACTEBEL), Vincent Megank (TRACTEBEL), Lubor Zezula (UJV), Michael Fuetterer (JRC)

TANDEM - Contract Number: 101059479

Project officer: Angelgiorgio IORIZZO

Document title	Description of techno-economic assessment of energy policies and relations among hybrid energy systems
Author(s)	Mr. Víctor AMEZCUA, Miriam Minchole Lapuente (EAI), Francisco Javier Gallo (EAI), Alfonso Junquera (EAI), Clément Liegeard (CEA), Stéphanie Crevon (CEA), David Proult (CEA), Olli Soppela (VTT), Tomi J. Lindroos (VTT), Ville Tulkki (VTT), Jussi-Pekka Ikonen (VTT), Alain Ruby (CEA), Michele Frignani (ANN), Gabriele Firpo (ANN), Andrei Goicea (NUCLEAR EUROPE), Caroline Bono (EDF), Giorgio Simonini (EDF), Olivier Authier (EDF), Franck David (EDF), Christophe Schneidesch (TRACTEBEL), Vincent Megank (TRACTEBEL), Lubor Zezula (UJV), Michael Fuetterer (JRC)
Number of pages	37
Document type	Deliverable
Work Package	WP1
Document number	D1.3
Issued by	EAI
Date of completion	2023-04-05 10:37:47
Dissemination level	Public

Summary

Identification task for the two hybrid system configurations; the approach will rely on a reasonable deployment timeline as European boundary conditions will certainly evolve. Each partner will provide support in the definition of energy scenarios and in the definition of Figures of Merits.

Approval

Date	By
2023-04-06 11:12:32	Dr. Christophe SCHNEIDESCH (ENGIE)
2023-04-06 11:38:20	Dr. Claire VAGLIO-GAUDARD (CEA)

TANDEM

D1.3 - Description of techno-economic assessment of energy policies and relations among hybrid energy systems

WP1 - Task 1.3

March 2023 [M7]

Miriam Mincholé (EA), Francisco Javier Gallo (EA), Víctor Amezcua (EA), Alfonso Junquera (EA), Clément Liegeard (CEA), Stéphanie Crevon (CEA), David Proult (CEA), Alain Ruby (CEA), Olli Soppela (VTT), Tomi J. Lindroos (VTT), Ville Tulkki (VTT), Jussi-Pekka Ikonen (VTT), Michele Frignani (ANN), Gabriele Firpo (ANN), Andrei Goicea (NUCLEAR EUROPE), Caroline Bono (EDF), Giorgio Simonini (EDF), Olivier Authier (EDF), Franck David (EDF), Christophe Schneidesch (TRACTEBEL), Vincent Megank (TRACTEBEL), Lubor Žežula (UJV), Michael Fuetterer (JRC)

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History

Date	Version	Submitted by	Reviewed by	Comments
28/02/2023	V1	M.Mincholé	S.Crevon S.Lorenzi	

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Table of Contents

Funded by the European Union

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List of Figures

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List of Tables

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Abbreviations and Acronyms

Acronym	Description
AHG	Auxiliary Heat Generation
APP	Alternative Product Plan
β_c	Cost per unit of greenhouse gas emission
CAPEX	Capital Expense
C_{Cap}	Capital cost
$C_{ghg,k}$	Cost for direct greenhouse gas (GHG) emission
CHP	Combined Heat and Power
$C_{O\&M,k}$	Operation and maintenance cost
DA_k	Depreciation and Amortization at year k
DAM	Day-Ahead Market
DC	District Cooling
DH	District Heating
E_t	Electricity generation in year t
ESE	Energy Storage Systems
ETS	Emission Trading System

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Acronym	Description
F_t	Cost of fuel in year t
FCFF	Free Cash Flow to Firm
FoM	Figures of Merit
GHG	GreenHouse Gas
HES	Hybrid Energy System
H_t	Heat generation in year t
HTE	High Temperature Electrolyzer
HTSE	High Temperature Steam Electrolyzer
$H2_t$	Hydrogen generation in year t
i	Inflation rate
IRR	Internal Rate of Return
I_t	Investment expenditures in year t
LCOE	Levelized Cost Of Electricity
LCOH	Levelized Cost Of Heat
$LCOH_2$	Levelized Cost Of Hydrogen
LTE	Low Temperature Electrolyzer
MACRS	Modified Accelerated Cost Recovery Systems

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Acronym	Description
M_c	Emission rate of greenhouse gas
MILP	Mixed-Integer Linear Programming
M_t	Running costs (fixed and variable) in year t
NG	Natural Gas
NPV	Net Present Value
PHG	Primary Heat Generation, including Power Cycle
p.u.	Per unit
PV	Photovoltaic
R_k	Revenue at year k
REN	Renewable Energy Input
RES	Renewable Energy System
r_R	Discount rate used in computing weighted average cost of capital (WACC)
RTM	Real-Time Market
SMR	Small Modular Reactor
T_{pb}	Payback period
σ	Tax rate

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Acronym	Description
WACC	Weighted Average Cost of Capital

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Executive Summary

The TANDEM project aims at assessing nuclear safety, techno-economics and operationality of Hybrid Energy Systems (HES) integrating Light-Water Small Modular Reactors (LW-SMRs). For this purpose, the project will analyse the integration of LW-SMRs in two different Hybrid Systems configurations, focusing on different localizations and final uses: the first one aims to supply a district heating network and a power grid, for a Northern and Central Europe region; the second one, instead, is an energy hub which aims to provide power to the grid and produce valuable goods (such as hydrogen) in Southern Europe.

WP1 of the TANDEM project focuses on the "Characterization of the studied hybrid systems", aiming at defining the energy scenarios to be adopted in the studies, the technologies that shall be considered and implemented in the HES outlined, their techno-economic description, as well as the definition of the figures of merit (FoM) to be considered for the techno-economics and operationality assessment in WP3. In this framework, this document provides these figures of merit and the main techno-economic and environmental parameters, as a set of criteria and data to take into account in WP3 studies.

Keywords

SMR, Hybrid Energy Systems, Figures of Merit, energy market, heat market, HTSE, techno-economic parameters, environmental parameters.

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1 Introduction

Small Modular Reactors (SMRs) can be hybridized with other energy sources, storage systems and energy conversion applications to provide electricity, heat and hydrogen. SMR technology thus has the potential to strongly contribute to the energy decarbonisation in order to achieve climate-neutrality in Europe by 2050. However, the integration of nuclear reactors, particularly SMRs, in hybrid energy systems (HES) is a new R&D topic to be investigated. In this context, the TANDEM project aims to provide assessments and tools to facilitate the safe, secure and efficient integration of SMRs into smart low-carbon hybrid energy systems.

TANDEM intends to focus on two main study cases corresponding to hybrid system configurations covering the main trends of the European energy policy and market evolution: a district heating network and power supply in an urban area, and an energy hub serving energy conversion systems, including hydrogen production, in a local territorial perspective.

The aim of this task is to define a set of criteria, referred to as figures of merit (FoM), as well as techno-economic and environmental parameters of interest, to assess the economic viability of selected HES configurations and optimize economically the operation of HES under variable renewable energy generations and market volatility.

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2 Literature survey

There are several references in the literature about techno-economic assessment of HES to be considered with interest in this work to defined the FoM and techno-economic and environmental parameters. For example in [1] and [2], the optimization of hybrid energy system configurations is developed varying the price of energy and price of product output (H2, fresh water, gasoline, etc.). In both studies, Net Present Value (NPV) is the parameter used to check the configuration profitability.

Economic and technical Figure of Merits (FoM) relative to Nuclear/Hydrogen Hybrid Systems are analyzed in [3].

In work [4], the financial performance of three HES configurations is analyzed. The first configuration includes a High Temperature Electrolyzer (HTE) to produce hydrogen that utilizes heat from a nuclear reactor and electricity from the thermal power cycle, a wind power plant, and/or the grid. The second and third configurations use Low Temperature Electrolyzers (LTE) that only utilize electricity. In this case, electricity can come from the thermal power cycle, the wind power plant, and/or the grid. The difference between the two LTE scenarios is the electrolyzer's capital cost and efficiency. The profitability is assessed for each configuration by calculating NPV of cash flows over a 25-year project financial life considering revenues generated through sales of electricity and hydrogen and expenses incurred for system installation, operation and maintenance, and fuel purchases. Positive NPVs (equivalent to a 10% nominal rate of return) are considered profitable. The study concludes that, to be profitable, the examined HES configurations including LTE and HTE require higher electricity prices, more electricity price volatility, higher natural gas prices, or higher capacity payments than those of the reference case.

In article [5], two hybrid power and desalination systems, one powered by SMR and the another one by a natural gas plant equipped with a system that performs carbon capture and geological sequestration, are analyzed and compared using the Levelized Cost of Electricity (LCOE).

A comparative review of hydrogen production technologies in Hybrid Energy Systems (HES) including nuclear reactors is provided in [6], where it is concluded that current hybrid technologies are not cost effective, and will require either increased electricity prices, CO2 subsidies, or increased hydrogen prices to overcome capital costs.

In paper [8], USA grid technical and economic characteristics are described followed by how hybrid energy systems can help to create a system that can produce economic variable electricity.

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Paper [10] describes the method for calculating the economic potential of efficient district heating (DH) in Austria under different energy scenarios, assuming the full decarbonisation of the heating sector by 2050.

3 Figures of Merit

3.1 Economic Figures of Merit

3.1.1 Operation, optimization and economic evaluation

The economic Figures of Merit (FoM) can be used as objective functions for operation optimization and economic evaluation. In this work, they might be used in the following way:

a) **Net Present Value (NPV)** is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. The equation to be used is given below:

$$NPV = \sum_{k=0}^{N} \frac{FCFF_{R,k}}{(1+r_R)^k}$$

where N is the year of operations of the NHES, r_R is the discount rate used in computing weighted average cost of capital (WACC) and $FCFF_{R,k}$ is the real discounted Free Cash Flow to Firm (FCFF) for year k, defined as

$$FCFF_{R,k} = (R_k - C_{O\&M,k} - DA_k(1+i)^{-k}(1-\sigma) + DA_k(1+i)^{-k} - C_{ghg,k} - CAPEX_k \ \forall\ k\ 1..N$$

where σ is tax rate, i is inflation rate and $CAPEX_k$ (Capital Expense) only occurs when k=0, i.e., year 0 given by $CAPEX_0 = C_{Cap}$, and $CAPEX_k = 0$ for all k>0.

The capital cost C_{Cap}, operation and maintenance (O&M) cost $C_{O\&M,k}$, cost for greenhouse gas (GHG) emission $C_{ghg,k}$ and revenue R_k, for year k, will be defined for each of the HES configurations.

Depreciation and amortization for year k considering tax deduction under Modified Accelerated Cost Recovery Systems (MACRS), i.e., DA_k, is calculated by $DA_k = \rho_{da,k} C_{Cap}$, where $\rho_{da,k}$ is DA rates at year k.

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The cost for direct Greenhouse gas (GHG) emission is given by $C_{ghg} = \int_0^T M_c \beta_c dt$, where M_c is the emission rate of GHG and β_c is the cost per unit of GHG emission. The cost per unit of GHG emission allows to study different scenarios: it can be zero (assuming that there is no tax on CO_2 emissions), thus CO_2 emissions will not be included in NPV calculation. However, if it is different from zero, it should be the object of a sensitivity study to assess the impact of a given CO_2 tax on the architecture sizing.

The capital cost C_{Cap} and O&M cost $C_{O\&M,k}$ can be split relatively to five major components, i.e., PHG (Primary Heat Generation, including Power Cycle), AHG (Auxiliary Heat Generation), REN (Renewable Energy Input), ESE (Energy Storage Systems) and APP (Alternative Product Plant), and are given by:

$$C_{Cap} = C_{phg} + C_{ahg} + C_{ren} + C_{ese} + C_{app}$$

$$C_{O\&M,k} = O\&M_{phg} + O\&M_{ahg} + O\&M_{ren} + O\&M_{ese} + O\&M_{app}$$

For all these components, under the form of an investment per hour, the replacement cost is considered within the O&M cost after a life time number of operating hours.

The Revenue $R_k$for year k comes from the sale of electrical energy in Day-Ahead Market (DAM), electrical energy in Real-Time Market (RTM), ancillary services in DAM and alternative product.

$$R_k = R_{dam,e} + R_{rtm,e} + R_{dam,as} + C_{app}$$

b) **Levelized total costs**: is based on the same calculation as the NPV but revenues are not taken into account. So it requires no assumption on the sell price of the products.

c) Payback period (T_{pb}): refers to the period of time required to recoup the expense of an investment. For a fixed discount rate, it is defined as the years of operations such that NPV equals 0.

d) **Internal Rate of Return (IRR):** corresponds to the discount rate at which the NPV for the period of analysis is zero.

Additionally, other parameters, as LCOE for electricity generation, LCOH for heat production, or $LCOH_2$ for hydrogen production can be considered to assess the financial viability in specific conditions by just comparing directly the LCOE, LCOH and $LCOH_2$ with the price at which electricity, heat and hydrogen could be sold.

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The levelized cost is a good indicator of cost-effectiveness, because it can be calculated without requiring any assumptions about the price at which the electricity can be sold to the grid or to an end-user, as is the case when calculating the Payback period or the net present value. This price affects directly the viability of an investment but varies significantly between different markets (by a factor of 10 or more) or over time.

a) **Levelized Cost of Electricity (LCOE):** It is defined as the price at which the generated electricity should be sold for the system to break even at the end of its lifetime [5]. It can be calculated using the following equation:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where, t refers to the year t with t = 0 for the start of the plant construction,
n is the plant lifetime,
r is the discount rate,
I_t is the investment expenditures in year t,
F_t is the cost of fuel in year t,
M_t is the running costs (fixed and variable) in year t,
E_t is the electricity generation (in kWh) in year t, assuming constant output.
The amount of electricity generated by each technology is based on a capacity factor.

b) For the energy scenarios with district heating, **Levelized Cost of Heat (LCOH)** is used to compare each potential DH areas [10].
Adapting the LCOE formulation for heat production, LCOH can be expressed as:

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

Where, t refers to the year t with t = 0 for the start of the plant construction,
n is the plant lifetime,
r is the discount rate,
F_t is the cost of fuel in year t (if applicable),
I_t is the investment expenditures in year t,
M_t is the running costs (fixed and variable) in year t,
H_t is the heat production (in kWh_{th}) in year t, assuming constant output.

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c) The **Levelized Cost of Hydrogen ($LCOH_2$)** can be used to compare the different hydrogen production systems. $LOCH_2$ includes calculation of current costs of production of hydrogen via water electrolysis. It can be expressed as:

$$LCOH_2 = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t + M_t + E_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

Where, t refers to the year t with t = 0 for the start of the plant construction,
I_0 is the Initial investment for the system in €,
n is the plant lifetime,
r is the discount rate,
A_t is the Annual costs (operation and replacement) in year t in €,
M_t is other operational expenditures in year t,
E_t is the electricity consumed in year t including generation costs (wholesale price), grid costs and taxes when applicable, and electrolyzer stack degradation,
H_{2t} is the hydrogen production in year t.

3.1.2 Tax and tax reliefs in electricity and heat markets

Taxes and tax reliefs can significantly impact the simulation results of techno-economic modeling. Taxation of fuels, electricity consumption, different generation methods, transmission and distribution affect the production and purchase prices of electricity. Especially asymmetric (i.e. technology-specific) taxation of different phases in the value chains can change the market dynamics and market competitiveness of technologies. Taxation of fuels is an obvious example, where a higher tax on a fuel can directly affect competitiveness of the fuel. Same can apply when different taxes are imposed on certain technologies or methods. Taxes are an effective way of imposing different technologies through political ambitions while making the transition to be economy-driven. On the other hand, tax credits and incentives for low carbon energy production can increase their competitiveness and cost-effectiveness, making them more attractive target for investments.

The currently collected taxes and fees in the heat and electricity markets may include some of the following:

- Value Added Tax,
- Energy Content Tax,

- Carbon Dioxide Taxes, which are ideally to be replaced with the Emission Trading System (ETS),
- Strategic Stockpile fee,
- Transmission and distribution fees,
- Renewable subsidy taxes,
- Heat and electricity taxes and so on.

In Europe, many countries have already introduced taxation based on carbon emissions or environmental impact. The European Union and its Member States have committed to implementing the Paris Agreement. The energy taxation framework in the EU Member States should: support the clean energy transition, contribute to sustainable and fair growth, and reflect social equity considerations. However, the overall taxation percentage can vary quite a lot in each Member State, and additionally, the taxation can be industry specific. For example, the EU's energy taxation framework states that the taxation of energy products and electricity used for combined heat and power generation is optional [26].

The above logic also applies to the heat market, as nearly all heat is produced by using either fuels or electricity as the source of the energy. Additionally, tax structuring of the installation and use of district heating networks can affect the competitiveness of the solution [27]. However, lower taxation for the use of smaller very common combustion boiler installations may also create incentive barriers for transition towards more sustainable heating options.

In the heat markets, the ETS requirements are restricted to thermal power installations above 20 MW which covers most of district heat network capacity but excludes individual and block boilers that use fossil fuels [28]. This arrangement lowers the incentives to replace very common fossil block heaters with more resource-efficient and flexible district heating options. For example, in Germany in 2020, it was still cheaper to heat households with low-cost fossil gases rather than free electricity and heat pumps, due to the high additional tax-related cost components in the household electricity bill. Regarding the electricity market, ETS has a direct impact on fuel usage prices, and thus, the economics of the electricity markets and the merit order in which the generators will activate during the auctions.

3.2 Technical Figures of Merit

Additionally to economic FoM, technical FoM should be considered:

- Sizing of the components of the HES,
- Share of each technology in the load demands or productions (electricity, heat, H2),
- Electrical/heat cogeneration share of SMR.

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These elements can be used to have a technical view of the three study cases.

3.3 Environmental Figures of Merit

Additionally to economic and technical FoM, at least one environmental FoM should be considered, CO_2 emissions.

Even if CO_2 emissions are taken into account in the NPV calculation, showing the CO_2 emissions specifically allows a comparison with other forecasted energy systems. Pareto fronts showing the levelized total cost of the system compared to CO_2 emissions (built from parametric optimization with several CO_2 emissions constraints) are very interesting FoM, as usually done (see PlaMES platform[1]).

Regarding the calculation of CO_2 emissions, it could cover both direct emissions (from consumption of resources) and grey emissions (including CO_2 emissions due to construction and deconstruction of facilities that need to be built in the project). Accounting for grey emissions tends to prevent from introducing new technologies except if they yield really decisive reduction of direct CO_2 emissions. In a first approach, only direct emissions could be considered.

3.4 Merit order in electricity and heat markets

Merit order is a market-based solution that enables efficient resources allocation in the energy grid [24]. The merit order ranks electricity producers based on their marginal costs of production. These costs are composed of both operating expenses (OPEX) and capital expenditures (CAPEX).

Factors contributing to the OPEX of a power plant include:

- Fuel costs such as uranium in nuclear power plants and natural gas in peaking power plants,
- Labour costs such as salaries and training of the personnel,
- Maintenance and repair costs such as acquisition of spare parts and labour during the maintenance breaks,
- Environmental compliance costs such as waste management,
- Taxes and regulatory fees,
- Decommissioning and disposal costs.

Factors contributing to the CAPEX of a power plant include:

- Design and engineering costs such as planning of the power plant,
- Land acquisition costs,

[1] https://plames.eu/

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- Installation and construction costs such as site preparation, civil engineering, and labour,
- Equipment and material costs such as turbines, generators, and transformers,
- Environmental mitigation costs such as pollution control,
- Financing costs such as loan payments and interest rates.

The OPEX and CAPEX varies widely depending on the type of power plant. For example, the capital expenditures of a peaking gas power plant is fairly low, but operating expenses high due to fuel costs. Capital expenditures of a nuclear power plants on the other hand are very high and operation expenditures are lower since the cost of nuclear fuel, uranium, is low compared to the fossil fuels used in conventional power plants. Variable renewable systems, such as wind and solar power, use no fuel at all, so their operating expenses become very low. The goal of the merit order is to reduce the overall electricity system costs to the customers. This is achieved by replacing higher cost, for example, fossil-fuel power plants with more cost-efficient energy systems such as renewable energy systems or even nuclear power plants [25].

The merit order is imposed with the so-called pay-as-clear auction. The pay-as-clear auction procedure takes in bids from buyers and sellers and the electricity exchanges clear the auctions with the assistance of the Euphemia-algorithm, the auction bids and available interlinkage capacity [29]. Separately agreed merit order practices in the electricity auctions can provide advantage for certain generation technologies, such as renewable generation is enjoying in European Union at the moment. This means that same price electricity sales offers can favour certain technologies.

Heat markets are not yet evolved to have open entrance for producers, thus still working as monopoly markets with regulatory risk management needs. Open market network development is considered in some densely populated areas, such as the Helsinki Capital Region.

4 Techno-economic and environmental parameters

To examine and optimize the profitability of the selected HES configurations based on NPV value, the following techno-economic and environmental parameters will be required. The list is not exhaustive and some parameters could be optimization variables.

4.1 Technical parameters

- Energy generation (SMR, Wind farm, PV farm, CHP)
  - Maximum power output (kW)
  - Minimum power output (kW)
  - Load change rate (kW/min)

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  - Capacity factor (-)/ share of RES
  - Life time
- Energy storage (Thermal energy and electrical energy)
  - Storage capacity
  - Life time
- Alternative Product Plant (H_2, potable water, district heating)
  - Maximum production rate (kg/s, kWh_{th})
  - Minimum production rate (kg/s, kWh_{th})
  - Load change rate (kW/min)
  - Maximum storage capacity, if any
  - Life time
- Loads (if any)
  - Demand (kg/s, kWh_{th})

4.2 Economic parameters

- Energy generation (SMR, Wind farm, PV farm, CHP)
  - Unit capital cost (€/kW)
  - Unit O&M cost (€/kW or %)
  - Electricity price (€/kW)
  - NG price (€/kg s^{-1})
  - Unit GHG emission cost (€/t_{CO2})
- Energy storage (Thermal energy and electrical energy)
  - Unit capital cost (€/kW)
  - Unit O&M cost (€/kW)
- Alternative Product Plant (H_2, potable water, district heating)
  - Unit capital cost (€/kW)
  - Unit O&M cost (€/kW)
  - Product revenue (€/kg.s^{-1} or €/kWh_{th})
- General
  - Inflation rate
  - Discount rate (WACC)
  - Depreciation and amortization (DA) rates
  - Tax rate

4.3 Environmental parameters

- Energy generation (SMR, Wind farm, PV farm, CHP)
  - Emission factor (t_{CO2}/kW), if any

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4.4 Techno-economic data of SMR

4.4.1 French data for SMR prospective exercises

The French Transmission System Operator (RTE [11]) retains the following open values in general prospective exercises:

Parameter		Units	Values	Ref.
Generalities	Net Power	MWe	350	[11]
	Construction period	months	46	
	Load factor	%	92	
	Lifetime	year	60	[12]
	Start-up year		2040	[11]
2040 to 2050	CAPEX (overnight)	€2022/kW	5710	
	Equipment	$€_{2022}$/kW	5500	[11]
	Owner	$€_{2022}$/kW	-	
	Decommissioning	$€_{2022}$/kW	210	*
	Hazards	$€_{2022}$/kW	-	
	OPEX fixed	$€_{2022}$/kW/year	-	
	OPEX variable	$€_{2022}$/MWh	23,0	[12]
	Combustible	$€_{2022}$/MWh	7	[13]

Table 1. Techno-economic data of French SMR prospective exercises

* The cost of decommissioning can be estimated at 15% of CAPEX, assuming the sum is invested at 2% for 70 years (decommissioning = 0.15 x CAPEX / [1.02] / 70).

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4.4.2 SMR Nuscale

For comparison with the previous data we remind that the Small Modular Reactor "NuScale" should be the first small-scale reactor to be commercialized, with a project to be implemented in Idaho Falls (USA). The principle of the nuclear power plant is to interconnect several modules of 74 MWe each (depending on the version) to produce electricity. The total power of the reactor can vary from about 296 MWe (coupling of 4 modules of 74 MWe) to 888 MWe (12 modules).

D. Schlissel [14] summarizes various estimates of the construction costs of this reactor in USA according to different sources. We reproduce below a figure that provides these estimates: these costs vary from $2850/MW estimated by the company NuScale for the Idaho Falls project to more than $6000/kW according to the US Energy Information Agency/DOE, or even $7700/MW according to American Electric Power.

W.R. Stewart [15][16] estimates the cost of NuScale reactors between 5700 $\$_{2020}$/kW and 7000 $\$_{2020}$/kW for a first series reactor, and between 3500 and 4100 $\$_{2020}$/kW for a tenth series reactor (depending on the version).

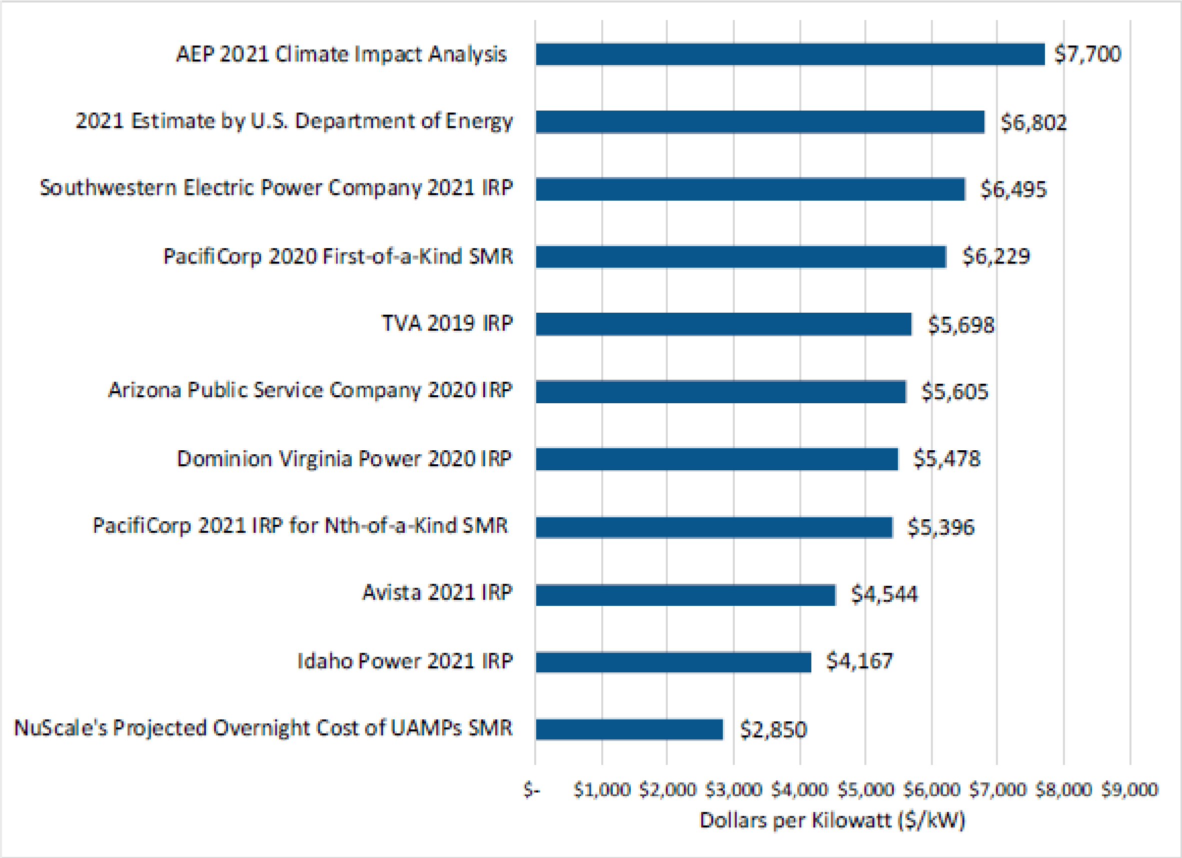

Figure 1 - Estimations of the constructions costs of Nuscale plant in USA.

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Nuscale Parameter		Units	Values
Generalities	Net Power	GWe	888
	Number of modules		12
	Construction period	months	65 (49-87)
	Load factor	%	95 (93-96)
	Lifetime	years	60
	Start-up year		2030
2040-2050	CAPEX	$€_{2022}$/kW	5930 (5100-6330)
	Equipment	$€_{2022}$/kW	
	Owner	$€_{2022}$/kW	-
	Decommissioning	$€_{2022}$/kW	210 (190-240)
	Hazards	$€_{2022}$/kW	-
	OPEX fixed	$€_{2022}$/kW/ year	-
	OPEX variable	$€_{2022}$/MWh	23.0 (21.0-25.0)
	Combustible	$€_{2022}$/MWh	7.0 (6.5-7.5)

Table 2. Techno-economic data of Nuscale plant

For OPEX and fuel, we maintain the values recommended in the previous section.

4.5 Techno-economic data for HTSE

The considered technology for HTSE is SOEC (Solid Oxide Electrolyser Cell). This technology is still under development. Economic and technical data for this technology given in the tables below

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are for Europe at horizon 2030 and at horizon 2050. Ranges of values are given in the tables but is recommended to use the reference value. The values are based on the literature [17], [18], [19], [20], [21], [22] and [23].

By now, there is not enough data to take into account size effect on CAPEX. Thus, this value corresponds to electrolysers with a nominal power higher than 20MWe.

Tables gather both technical and economic parameters that will be considered in WP3. Nevertheless, depending on the level of modelling, other technical data could be taken into account.

- 2030

Parameter	Value	Unit
Stack life time	50000	Hour
System life time	20	year
Electrical consumption	37	kWh/kg H_2
Heat consumption	8	kWh/kg H_2
Water consumption	18	kg H_2O /kg H_2
Nominal power	0.3	MW
Minimal operating power	60	%Nominal power
CAPEX	780	€$_{2022}$/kW
OPEX	2.5	%CAPEX/year

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Parameter	Value	Unit
Stack replacement costs	166.25	€$_{2022}$/kW

Table 3. Techno-economic data of HTSE for 2030

- 2050

Parameter	Value	Unit
Stack life time	90000	Hour
System life time	20	year
Electrical consumption	37	kWh/kg H_2
Heat consumption	8	kWh/kg H_2
Water consumption	18	kg H_2O /kg H_2
Nominal power	300	MW
Minimal operating power	60	%Nominal power
CAPEX	535	€$_{2022}$/kW
OPEX	2.5	%CAPEX/year
Stack replacement costs	107	€$_{2022}$/kW

Table 4. Techno-economic data of HTSE for 2050

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4.6 Techno-economic data of electricity and heat markets

Parameters used for Electricity Market modeling are presented in Table 5. The values associated with the parameters will be defined in WP3, depending on the local country, economic context, the time period and envisaged technologies in the study cases.

Total fuel cost consists of multiple elements. Currently, taxing of conventional power plants might vary depending on the plant type. In the future, the different types of taxes are going to be harmonized into the EU Emission Trading System (ETS). The EU ETS is the world's first and biggest major carbon market [28].

Grid fees and taxes specify the expenses utilities pay for the Transmission System Operator or the Distribution System Operators. These might vary quite a lot if the regulation changes in the future.

Parameters	Power plants and SMR units	Storage units	Transmission
Fuel Use Cost (€/t):	x		
- Fuel Market Price (€/t)	x		
- ETS cost of Fuel (€/tCO_2_eq emitted)	x		
- Fuel Tax (%€/t)	x		
- Fuel Logistics Cost (€/t/km)	x		
- Fuel Security of Supply Fee (€/t)	x		
Capacity of Interconnector (MW/h)			x
Capacity factor of Interconnector (%)			x
Interconnector Transmission Losses (%)			x
Grid fee (€/MWh)			x

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Parameters	Power plants and SMR units	Storage units	Transmission
Grid tax (%€)			x
Grid Frequency (Hz)			x
Electricity Demand Profile of Market Area (MWh/h)			(x)
Electricity Tax in Market Area (%€/MWh)	(x)	(x)	(x)
Wind Power Production Profile of Market Area (%/MW_wind_capacity/h)			(x)
Solar Power Production Profiles of Market Area (%/MW_pv_capacity/h)			(x)
Power Plant Parameters:			
- Maximum electrical power (MWe)	x	x	
- Minimun electrical power (MWe)	x		
- Electricity efficiency, at max. Power (%)	x		
- Electricity efficiency, at min. Power (%)	x		
- Electricity efficiency, at constant (%)		x	
- Reduction, max. (MW)	x		

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Parameters	Power plants and SMR units	Storage units	Transmission
- Ramping limit (p.u. / h)	x		
- Minimiun online time (h)	x		
- Minimun offline time (h)	x		
- Maintenance break (days)	x	x	
- Investment cost (k€/MWe)	x	x	
- Fixed O&M (k€ / MWh_e)	x	x	
- Start cost (€)	x		
- Storage size (MWh)		x	
- Storage capacity (MW)		x	
- Storage losses (% /h)		x	

Table 5. Parameters used for Electricity Market modeling

Parameters used for District Heating Market modeling are presented in table 6. The parameters 'Reduction', 'Reduction, max' and 'Power-to-heat ratio' are solely used for Combined Heat and Power (CHP) plants. 'Reduction' determines how much of the thermal energy produced in a CHP plant can be diverted from its electricity production to its heat production. 'Reduction, max.' defines the maximum amount of heat production. 'Power-to-heat ratio' defines the ratio between electricity from cogeneration and useful heat when operating in full cogeneration mode.

The electricity market price affects the profitability of CHP plants, electric boilers, and heating pumps. Electric boilers and heating pumps consume electricity, while CHP plants produce it. Energy tax varies depending on the type of power plant. For example, CHP plants and boilers depending on their size each have different scheme for taxing.

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Parameter	Power plants and SMR units	Other production units	Storage units	District Heating network
District Heating Demand Profile of Market Area (MWh/h)				x
District Cooling Demand Profile of Market Area (MWh/h)				x
Maximum thermal power (MWth)	x	x	x	
Minimun thermal power (MWth)	x			
Electricity, DH, and DC efficiency, at max. Power (%)	x			
Electricity, DH, and DC efficiency, at min. Power (%)	x			
Electricity, DH, and DC efficiency, at constant		x	x	
Reduction (MW)	x			
Reduction, max. (MW)	x			
Power-to-heat ratio (%)	x			
Market price of the Electricity (€/MWh)	x	x		

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Parameter	Power plants and SMR units	Other production units	Storage units	District Heating network
Energy tax (%€)	x			
Ramping limit (p.u. / h)	x			
Ramping constrains (p.u./ model specific time unit)	x	x	x	
Minimiun online time (h)	x			
Minimun offline time (h)	x			
Maintenance break (days)	x	x	x	
Investment cost (k€/MWth)	x	x	x	
Fixed O&M (k€ / MWhth)	x	x	x	
Start cost (€)	x			
Storage size (MWh)			x	
Storage losses (% /h)			x	

Table 6. Parameters used for District Heating Market modelling

5 Methodology of techno-economic and environmental evaluation

5.1 Optimization analysis

The optimization process is based on the minimization of an objective function (NPV, Levelized Total Cost) by finding an optimal sizing of system components and an optimal control of the system to meet 1 year demands at a given time step (typically 1 hour). This optimization process

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may be enriched by additional constrained, like for instance maximum integrated CO_2 emissions over the life of the system, or over a smaller time horizon.

A case study in WP3 will consist of the following:

- A HES architecture,
- a geographical location, with its policies,
- a time line, with its policies,
- and a set of technical and economic data.

In WP3, two architectures of HES will be studied through three study cases at three different locations. A first architecture of HES with a district heating will lead to two study cases:

- Northern European case that will be investigated with BACKBONE,
- Central Europe case that will be investigated with PERSEE.

A second architecture of NHES with an energy hub will lead to one study case:

- Southern European case that will be investigated with PERSEE.

BACKBONE and PERSEE are two modelling frameworks for conducting techno-economic and environmental analysis owing to a MILP formulation. They allow to optimize the sizing of components (the number of SMRs, the installed capacity of wind turbines, the size of the HTSE, the size of the storage capacity (if any)) and their operation to minimize or maximize an objective function. In techno-economic analysis, generally, the objective function is the NPV that should be maximized but it could also be the total levelized costs of the system.

The way to consider the system to analyse can be different depending on the study case. For example, for the Northern European case, a district heating network and power supply in an urban area will be considered. In this case, thermal loads are pretty well known, so the thermal energy required for district heating as well as selling prices will be fixed assuming values on the horizon (2035-2050), being able to perform sensitivity analyses at a subsequent stage to check the impact of the assumptions on the final results.

See below in Figure 2 a scheme of the potential architectures of current and future (2035 and 2050) energy and heat producers for Northern European case:

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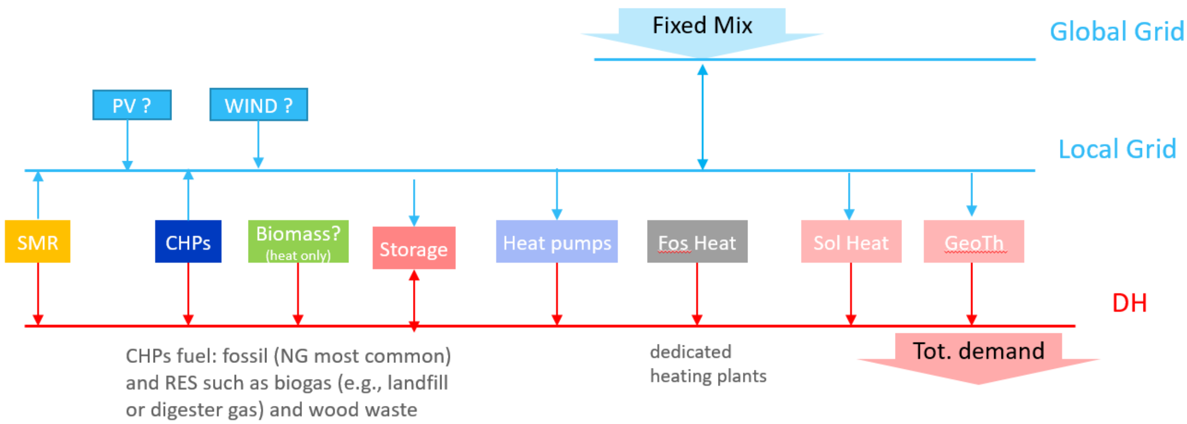

Figure 2 - Example of hybrid energy systems including a DH network.

A potential HES architecture for the Southern European case will be an energy hub. In this case the alternative product (H_2, fresh water, clean molecules, etc.) production and its storage will be defined as a variable to be optimized. See below in Figure 3 a scheme of the potential architectures, considering the current situation and the future one (2035 and 2050).

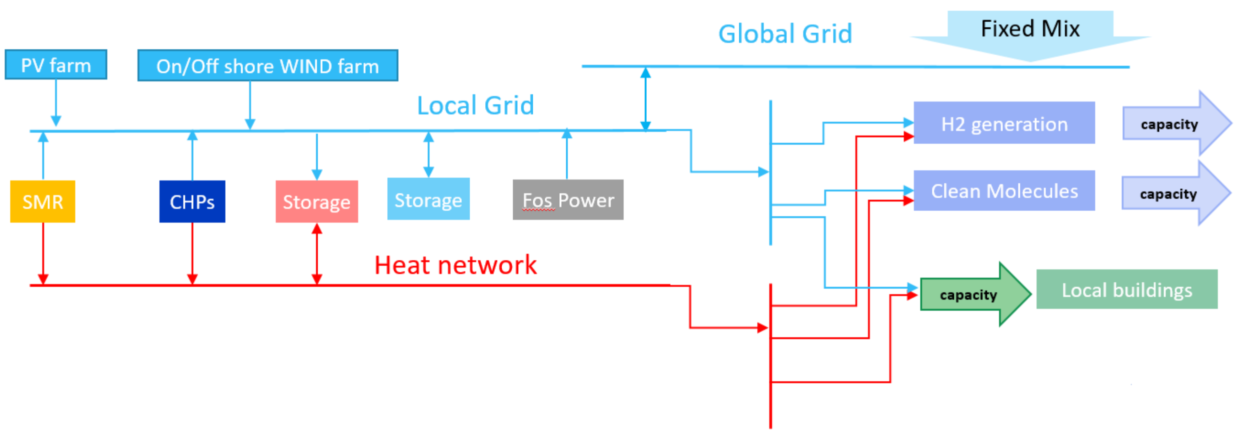

Figure 3 - Example of an energy hub.

5.2 Sensitivity analyses

Sensitivity analyses will be performed in order to check the impact of main parameters and hypotheses on the results.

Hypotheses such as electricity, product prices, capital costs and inflation rate at horizon 2035-2050 can have an important impact on the economic assessment. Therefore, at least the following sensitivity analyses will be performed in Task 3.2 with the aim of quantifying the risks of considered assumptions:

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1. Sensitivity to component parameters:

   Due to the wide range of CAPEX values for both SMR or HTE, sensitivity studies should be conducted on this parameter. These sensitivity studies could also include other parameters such as plant life.

   Furthermore, on the Southern European case, HTSE will use heat and electricity from SMR. The connectivity hypotheses between the HSE various components must be defined but it could be the object of a sensitivity study and of a depth investigation in Task 3.4.

2. Sensitivity to system parameters

   These sensitivity studies should challenge the resilience of the architecture to external parameters impacted by the local economic and political context:

- Electricity price,
- Alternative product price (H_2, fresh water, thermal power, etc.),
- Greenhouse gas emission (impact of GHG emission cost or subsidy on green energy),
- Discount rate,
- Inflation rate,
- Tax rate.

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6 Conclusion

Once the HES configurations are selected in WP1, each of them will be analyzed in a specific local political and economic context through three different case studies in WP3. As regards the political context, the European energy market trends will be taken into consideration, as well as the application of subsidies for the use of green energy and the penalties for GHG emissions.

As regards economic context and based on the literature referenced, the net present value seems to be the most relevant FoM to analyze the profitability of the HES configurations.

LCOE, LCOH and $LCOH_2$ are good indicators of cost-effectiveness, because they can be calculated without requiring assumptions about the electricity, heat or hydrogen prices, as it is the case when calculating the payback period or the net present value. Therefore, LCOE, LCOH and $LCOH_2$ are good indicators for comparison between HES architectures, but as they are strongly linked to the HES architecture, they should not be used to perform any extrapolation to other energy scenarios and should be estimated for each one.

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