Future energy structures needed for the energy transition

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Outline

- The European energy context

- Energy structures required for clean energy transition and TANDEM

European energy context

EU Green Deal

- Climate change and environmental degradation pose an existential threat to Europe and the world
- Carbon neutrality is the main way to address these challenges
  It is a concept for legislators and the public as a target to be reached
- To overcome these challenges, the **EU Green Deal** will transform the EU into a modern, resource-efficient and competitive economy, ensuring:
  - Net zero greenhouse gas emissions by 2050
  - Economic growth decoupled from resource use
  - No one and no place left behind

- The objectives of the Green Deal are supported by a **set of policy initiatives** that aim to put the EU on the path to a green transition

[A European Green Deal (europa.eu)](https://ec.europa.eu)

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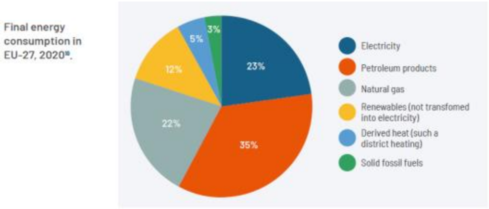
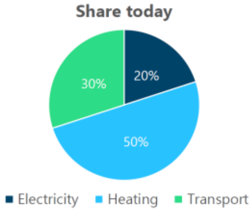
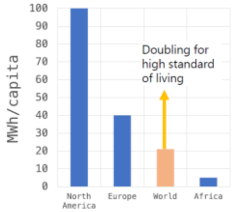
EU path to a green transition

- One of the policy initiatives to put the EU on the path to a green transition aims at **Clean, Affordable and Secured energy**
  - 75% of the EU's greenhouse gas emissions come from energy consumption and production, **decarbonizing the energy sector** is a crucial step towards a climate-neutral EU
  - The transition strategy relies heavily on substantial electrification of many sectors, replacing fossil fuels, supported by the accelerated deployment of renewable electricity generation capacity
  - Electricity currently accounts for only a fraction of final energy consumption (20% worldwide, 23% EU-27)
  - Heating and cooling constitute about 50% of the final energy demand in Europe and represent by far the most significant energy sector to be decarbonized



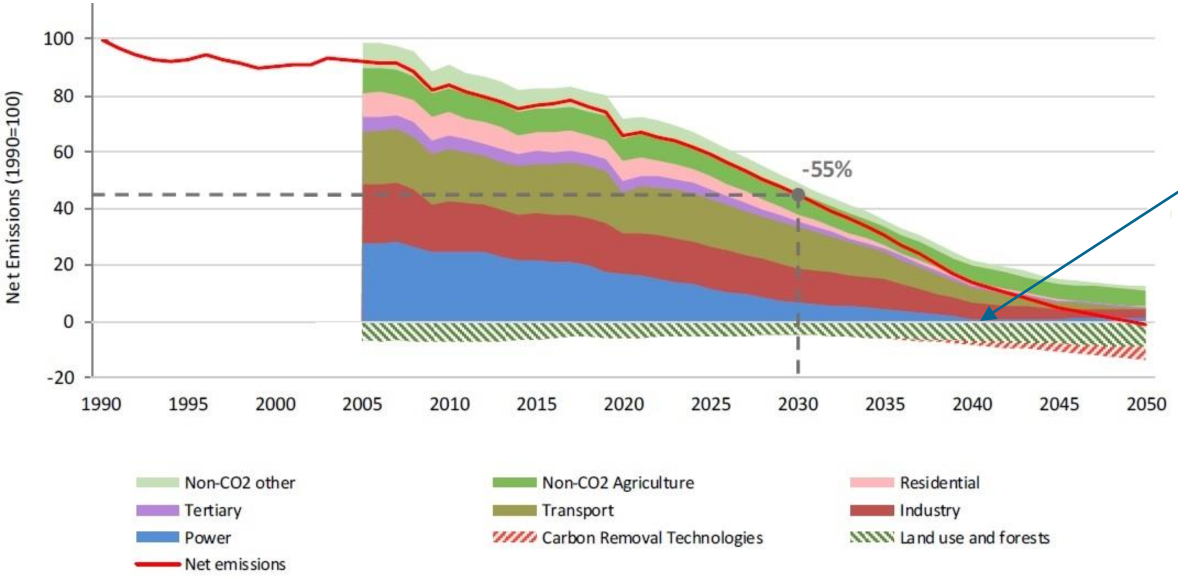
Source : EERA Manifesto





EU pathway to climate neutrality

- The EU has set very ambitious targets to achieve the decarbonization of the economy for both 2030 (55% reduction in GHG emissions) and 2050 (net-zero emissions)



The EU's pathway to climate neutrality, 1990-2050

The electricity sector is one of the first to be decarbonized by 2040

[*Stepping up Europe's 2030 climate ambition*]

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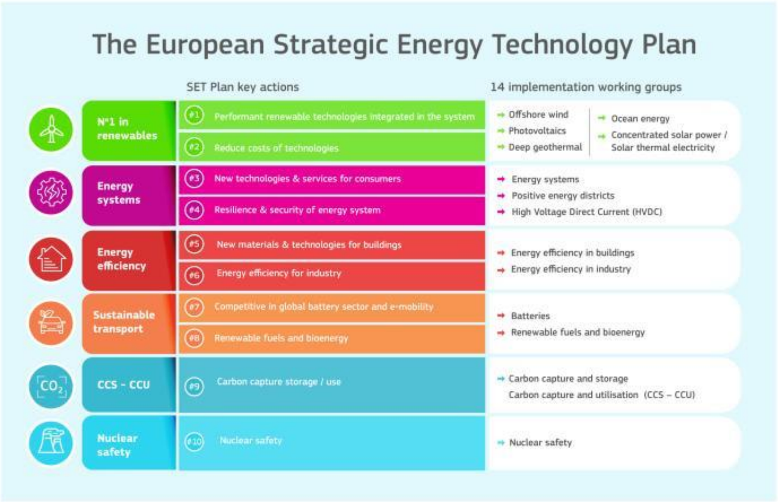
The SET-plan

- The SET-plan supports the EU's energy and climate objectives to make Europe a world leader in low-carbon energy and energy efficiency technologies

The integrated SET-plan identifies 10 actions in favour of research and innovation.

Actions cover the entire innovation chain, from research to market uptake, and address both funding and the regulatory framework



[Strategic Energy Technology Plan (europa.eu)]

EU revisited strategic plan

- The security crisis that followed the unexpected and unprecedented Russian invasion of Ukraine threatens the very continuity of economic activity and social stability in the EU
  - Lasting paradigm shift resulting from a major redefinition of the global geopolitical order
  - At the same time, tackling global warming remains at the heart of the EU's long-term strategy
- In the context of the energy crisis, the EU has revisited its strategic plan to **change its energy profile** and increase the use of low-carbon products and maximize energy efficiency gains (revision of the SET-plan)
  - The REPowerEU plan aims to reduce the use of oil and gas
    It complements actions relating to energy security of supply and storage and mostly implies a faster replacement of fossil fuels (mostly gas) by a mix of carbon neutral sources
  - REPowerEU addresses the multiple challenges of maintaining energy security in the short term and tackling energy affordability, while maintaining its 2050 climate neutrality targets and building a strong strategic autonomy of the EU

REPowerEU: affordable, secure and sustainable energy for Europe (europa.eu)

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The energy trilemma

- The EU ambitious targets to achieve the decarbonization are driven by the energy trilemma (**environmental sustainability, energy security, energy equity**)

Sustainability

The ENERGY trilemma

The **decarbonized energy mix** must be diversified to be **robust and versatile**

Security of supply

Security of supply and **sovereignty** are strategic features

Affordability

The **total system costs** must be such that it allows competitiveness of the industry

.... Which also drives the energy market

Energy market trends

- Decarbonized energy production CO_2
- Variable renewable energy
- Decentralized energy production
- Emerging sectors/countries

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The energy market

- Decarbonized energy needs beyond Electricity Generation are enormous….

Heat

~3000 TWh_{th}/y
Europe Heat Market

> 60% market
Heat < 550°C

89 GW_{th}
Plug-in Cogen applications

>1000 Mt CO_{2eq}
EU27 ETS industrial emissions in 2007 (excl elec)

>100
Identified compatible Industrial sites in Europe

Source: EUROPAIRS – EU-funded research project, May 2011

Hydrogen….

>280 Mt H_2/y
Worldwide Market Estimate for 2050

>5500 TWh_e/y
Clean electricity estimate to produce half of that hydrogen

~1650 Mt CO_2
Hydrogen-related emission savings in 2050

Source: IEA – Energy Technology Perspectives 2020, September 2020

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HES for energy transition

- Traditional power systems based on **single-generation sources** to support a **single energy demand** do not match economical and technical efficiency requirements for clean energy transition
- The future of energy landscape is based on **Hybrid energy systems (HES)** that have emerged as prominent solutions to address the challenges of energy sustainability
- **HES** are relying on the integration of multiple energy generation, storage, conversion, transportation and distribution technologies to achieve net-zero goals
  - Allows cost savings and enhanced capabilities, value, efficiency, or environmental performance relative to the independent "traditional" alternatives
  - Offers increased flexibility by integrated hybrid energy systems and can expedite the penetration of additional renewable energy into the grid to meet the 2035 zero carbon grid goal
  - Can specifically target hard to decarbonize applications in the industrial and transportation sectors through hybrids producing thermal energy, hydrogen, or other renewable fuels

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Low carbon energy production

- Facing

Sustainability

The energy mix must be diversified to be robust and versatile

The ENERGY Trilemma

Security of supply

Security of supply and sovereignty are strategic features.

Affordability

The total system cost must be such that it allows competitiveness of the industry

- Only Renewable HES?
  What about Nuclear?

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Nuclear for energy transition

- Industry requires responses to the trilemma at lowest cost and strongest political and financial stability aligned with the mandatory energy decarbonization

Industry must strive to become climate neutral, ideally by 2050. **Electrification** of processes **is a key part** of achieving this goal

Industrial companies **need stable volumes of electricity at a stable price and a stable regulatory environment** to remain competitive

Industry will require **significant amounts of carbon-neutral electricity** to power these processes

While **renewables** can contribute, they have **drawbacks such as intermittency, high grid connection costs**, and the need for backup solutions

The **urgency for affordable energy** and a stable framework is high if we want industries to remain in EU

To ensure competitively priced and secure electricity availability, a **complementary technology to RES** is essential

Ref. KPMG survey for Belgium transition

⇨ There is NO unique specification to answer "Industry Needs"

⇨ **Nuclear Hybrid Energy Systems (NHES)** including SMRs/AMRs can deliver solutions defined on a case-by-case basis depending on local/regional features and the domain of the industry; heat, power, CHP, hubs with several vectors

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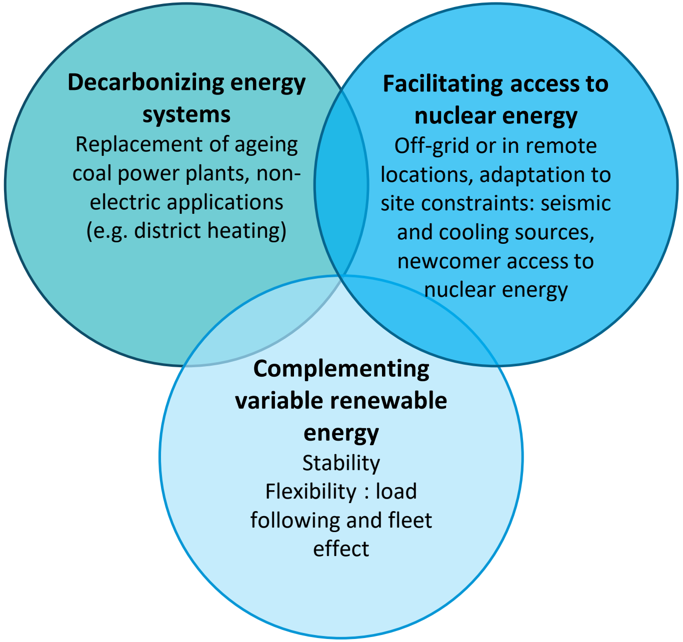
Nuclear for energy transition

- Nuclear power generation technologies and SMRS in particular offer overarching carbon-neutral opportunities to be cornerstones of tomorrow's energy ecosystems



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Energy structures and TANDEM

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Characterization of the studied hybrid systems

Objectives

- TANDEM aims to demonstrate the technical and economical adequacy of safe SMR penetration in hybrid energy systems (HES) for various regional & national frameworks in an EU policy perspective
- To cope with the multiplicity of HES configurations matching end-uses needs, the **TANDEM demonstration purposes** require to fix representative configurations based on
  - **credible assumptions** with respect to known EU energy directives and plans, to reach net-zero carbon emissions by 2050
  - the **best SoA technologies** supporting carbon-neutral energy mix, mature as available or with credible projectable highest TRL (Technical Readiness Level)
- The first task in TANDEM is to define and characterize basic concepts for configuring demonstrative hybrid energy systems **within reference scenarios**

  ⇨ provide data with the aim of drafting European energy scenarios, technical characteristics of hybrid systems for modelling, techno-economic data for optimization for SMR HES integration

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Characterization of the studied hybrid systems

Frameworks

- In TANDEM, energy scenarios refer to the energy frameworks where demonstrations cases will be defined and analyzed
  - Many scenarios present strategic plans for evolution of energy transitions at different levels (national, regional and EU)
  - EU’s clean energy transition strategy heavily relies on **substantial electrification of many sectors**, supported by the accelerated deployment of renewable electricity generation capacity
  - Heating and cooling constitute about 50% of the final energy demand in Europe and represent by far the **most significant energy sector to be decarbonized**
  - Therefore the TANDEM SMR deployment integrates SMR technologies into these energy scenarios as a **combined electricity and heat provider to end-user segments applications**

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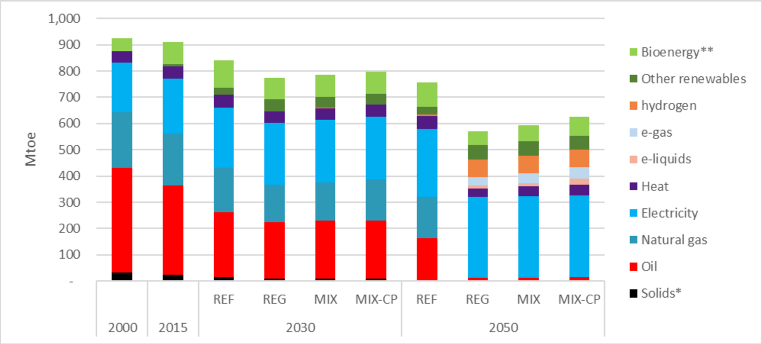
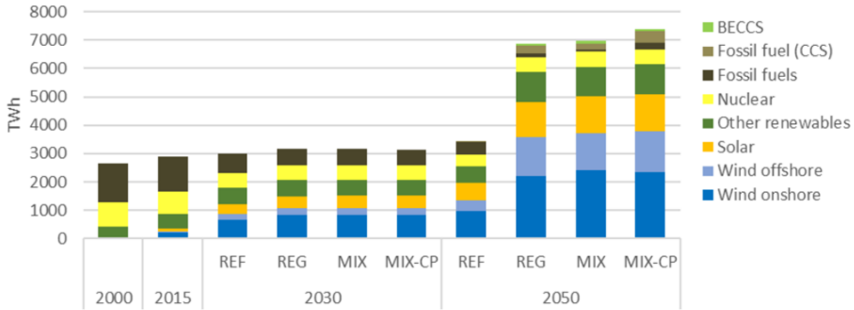
Characterization of the studied hybrid systems

Reference scenarios

- Even if the gross energy consumption is called to decrease, the overview of how the EU's gross electricity generation might develop on long term leads to the conclusion that **the electricity needs will double by 2050** in any of the analyzed scenarios



Share of energy carriers in final energy consumption; Source ESTAT, PRIMES



Gross electricity generation in the EU; Source EUROSTAT, PRIMES

Electricity share doubles 2020→2050

Nuclear contribution rather constant beyond 2020

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TANDEM demonstration cases

- For TANDEM, the scenarios aim 2 timeframes, 2035 and 2050, based on most probable (and available) energy mix projections to demonstration technical adequacy of SMR penetration
- For the gross electricity mix projection, TANDEM baseline relies on one of the net-zero options, where the nuclear capacity share will not vary significantly

  ⇨Possible impact on the economical properties of system components

- Therefore, with respect to SMR penetration
  - Only 2 scenarios will be considered, with emphasis on the SMR technologies
  - The 2 scenarios will have the same fixed figure for the large reactors installed capacity, the only variable being the SMRs installed capacity
  - Considering a fixed gross production capacity per timeframe, SMR penetration will have to be combined with variations of other sources

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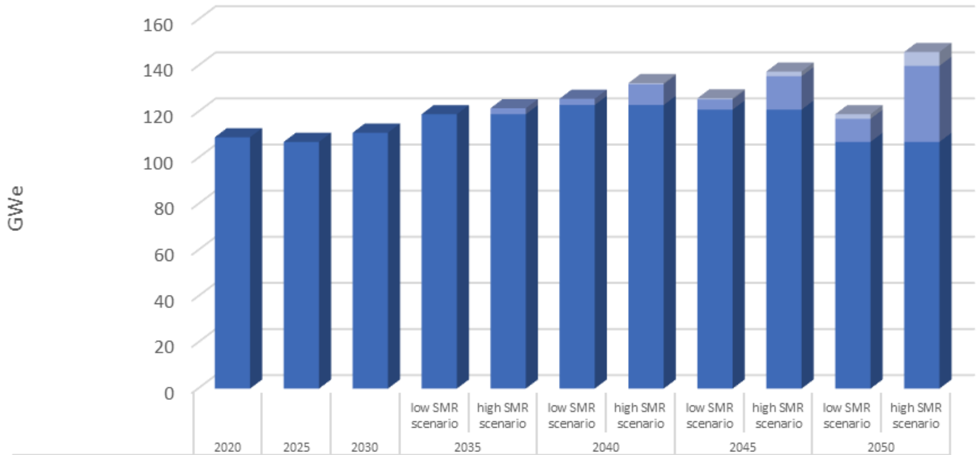
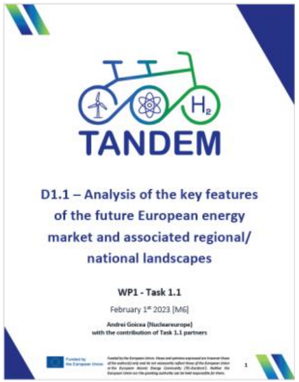
Integration in the future European energy scenarios

- The nuclear scenario (EU-27) from Nucleareurope's Vision 2050 looks conservative enough – 132 GW installed capacity reflecting more or less the current trend of LTO and new build (including c. 25 GW of SMR and <1 GW of Gen-IV)



	2020	2025	2030	2035 low SMR scenario	2035 high SMR scenario	2040 low SMR scenario	2040 high SMR scenario	2045 low SMR scenario	2045 high SMR scenario	2050 low SMR scenario	2050 high SMR scenario
SMR for heat production							0.5	0.5	2	2	6
SMRs for power production					2.6	2.7	9	4.4	14.5	10	33
Large reactors	109	107	111	119	119	123	123	121	121	107	107

Low SMR vs High SMR : Low has no SMR in 2035 with weak penetration after
→ to be able to make a clear demonstration of SMR benefit from the 2 proposed scenarios



Configuring the hybrid systems

- Hybrid energy systems combine multiple types of energy generation and/or storage and are the key transitioners away from fossil fuel- based economies
  - Current needs for decarbonization highlight **two typical HES configurations**
    - an **energy hub** with downstream (industrial) applications or energy conversion systems as end-uses segments
    - a **district heating** structure
- SMR penetration in those HES to be considered as a **combined electricity and heat provider** to end-user segments applications
  - Complement RES and replace/substitute fossil fuelled **electricity/heat** sources
- SMR penetration driven on 2 timeframes scenarios, 2035 and 2050, based on most probable (and available) energy mix projections to demonstration technical adequacy of SMR penetration
  - Considering a fixed gross production capacity per timeframe, SMR penetration will have to be combined with variations of other sources
  - CO_2 intensive emitters replaces by low CO_2 emitters in a credible projection for the two timeframes

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Configuring the hybrid systems

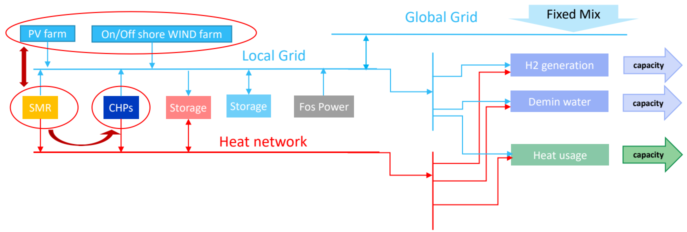
Initial schematic architecture & elements

- Selection of the energy carriers
  - Only **Power and Heat** fluxes will be considered
- Need to keep demonstration cases for HES using both electricity and heat vectors
  - Therefore, HES architectures must contain components allowing such demonstration
  - However, the level of detail for the Modelica library modules will be adapted to needs, i.e.
    1. very explicit for explicit downstream application requiring both power and heat
    2. simplified for those which are using only power.
- This will allow at the same time to reach “reasonable” complexity for the simulations while still keeping relevant driving outputs for the demonstration

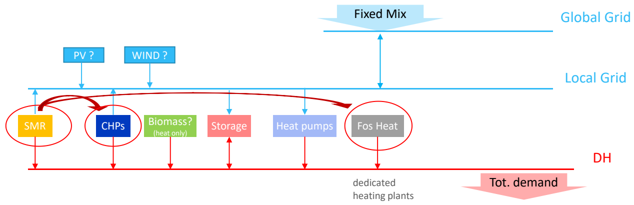
Configuring the hybrid systems

Initial schematic architecture & elements

- Energy hub case : complex distribution of in-out energy carrier fluxes
  - Coexistence of power and thermal systems must be considered
  - For demonstration purposes, we need to go beyond output fluxes and consider end-use cases
    - Hydrogen production with respect to current market evolution
    - Additional conventional or industrial end-user segments in option
  - Local storage capacity must be considered



- District heating case
  - Co-production of electricity and heat by CHP generation
  - Includes contributions from various sources (PV, Wind)
  - Separate production of heat is required by dedicated heating plants according to need at any given time
  - Production can be balanced with heat and cooling accumulators



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Configuring the hybrid systems

Initial schematic architecture & elements

- Components (the level of detail for the Library modules will be adapted to needs)
  - Energy production
    - PV (Solar Photovoltaic) : fixed as time dependent set of values
    - Wind : detailed to allow dynamic grid supply
    - SMR : one reactor with detailed core model to allow dynamic response to power/heat solicitations
    - CCGT (Combined Cycle Gas Turbine) /CHP (Combined Heat Power): play a role in the HES architecture, either as part of the complementary power generation assets or as part of those assets to be replaced by SMR
  - Energy conversion
    - CI (Conventional Island) /BOP (Balance of Plant) : detailed allowing heat storage, power production and heat production
  - Energy storage
    - E-batteries : simplified.
    - Hydro : simplified.
    - Thermal storage : detailed but the technologies will be adapted to HES to be considered hub certainly TES (Thermal Energy Storage) or DH (District Heating) where more options could be used.

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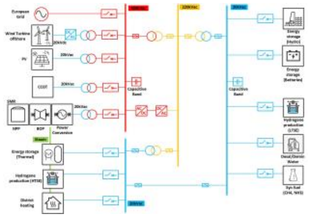
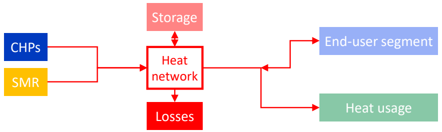
Configuring the hybrid systems

Initial schematic architecture & elements

- Components
  - Energy Distribution
    - Local grid : detailed to allow dynamic grid behaviour
      - ✓ Low/medium voltage
      - ✓ High voltage
      - ✓ Sub-Stations
    - Heat network : simplified as a point model (black box)
      Energy losses considered as arbitrary parameter (unknown layout configuration
  - Energy consumption
    - LTE (Low-Temperature Electrolysis) : simplified
    - Demineralizers : simplified – only osmosis tech retained as being the most popular one
    - E-molecules : not considered as it can be considered as talking part of the value chain of H2
    - HTSE (High Temperature Steam Electrolysis) : detailed to allow for H2 demonstration
    - Heat usage : defines any type of heat consumption, could be industrial, buildings, ….





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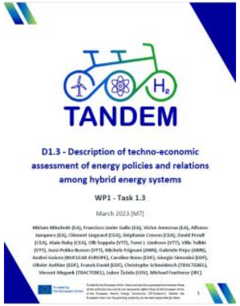
Configuring the hybrid systems

Specifications as deliverables

- The schematic architecture and composition of the selected demonstration cases lead to
  - The identification of the components to be integrated in the hybrid energy system for the two selected configurations and their characterization
    - to give model details in terms of
      - ✓ Recommendation for most relevant technologies
      - ✓ Interfaces with components/safety codes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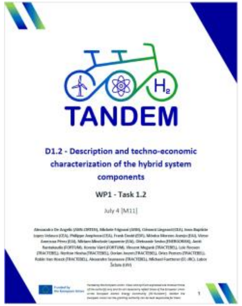
D1.3 - Description of techno-economic assessment of energy policies and relations among hybrid energy systems

WP1 - Task 1.3

March 2023 [M7]

  - The identification of the techno-economic characteristics of the components and of the global HES configuration
    - Provide a set of criteria, referred to as figures of merit (FoM), to assess the economic viability of the selected HES configurations and optimize economically the sizing and operation of HES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D1.2 - Description and techno-economic characterization of the hybrid system components

WP1 - Task 1.2

July 4 [M11]

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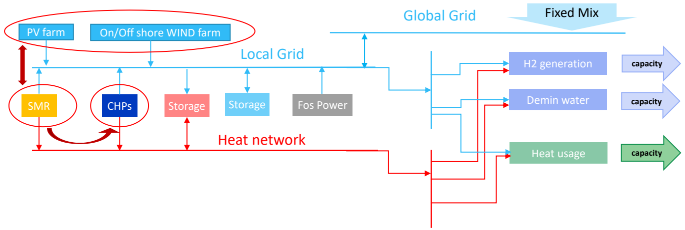
HES-study cases architecture

Energy Hub

- HES Energy hub as complex distribution energy carrier fluxes (electricity, heat, gas, hydrogen,…) locally produced and/or distributed among various end-use segments
  - There is an unlimited range of possibilities for defining our energy hub demonstration case
  - Target configuration : harbor-like architecture with typical end-use segments
    - Hydrogen production by **HTSE**



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HES-study cases architecture

Energy Hub

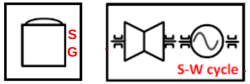
- Connectivity of the modules with the SMR
  - For the reference cases all HES modules are connected **to grid and heat network**, in particular HTSE
    - The reason is that if the HTSE is directly liked downstream to the SMR, the CI/BOP Modelica module will have a different structure than the one with grid and heat network connection
  - To avoid additional layers of modelling complexity, only **grid/network** connection will be considered for the Modelica architecture
- End-user segments definition
  - The value chain of the hydrogen production (as well as the value chain of any outcome of the industrial application/energy conversion module will not be taken into consideration) in the analysis
  - The production of H2 will be set as imposed output (full capacity) over a given time slot – the latter is set by WP3 which can use this as a variable boundary condition to perform sensitivity studies.
  - The level of H2 production will be a modelling choice in the form of a global (lumped) answer to the current understanding of the industrial users needs

HES-study cases architecture

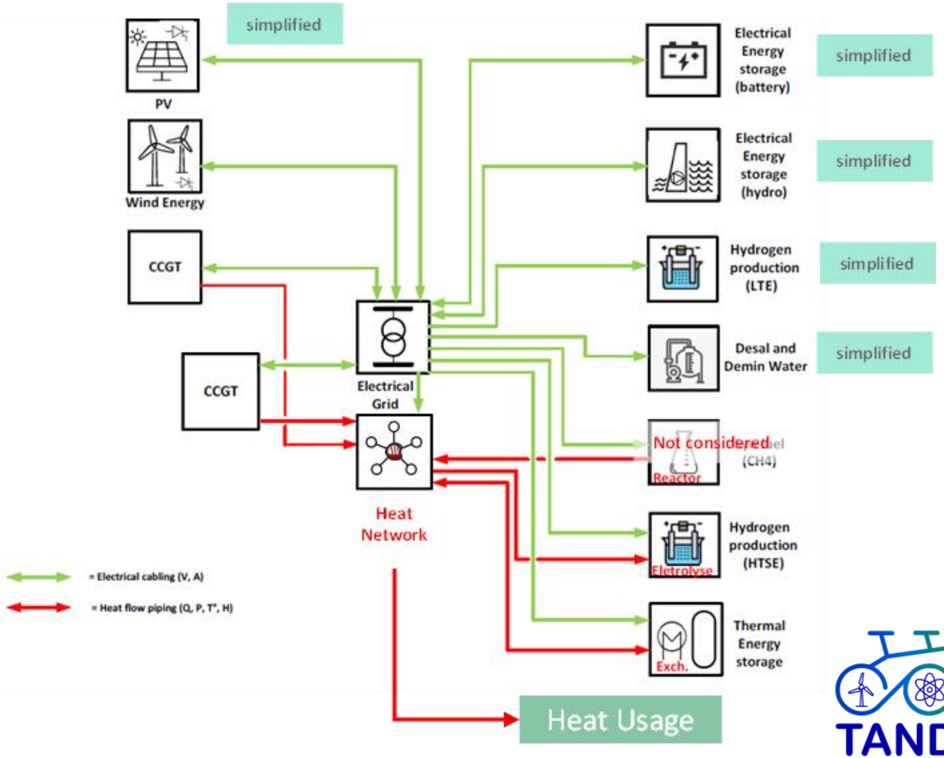
Energy Hub

- Schematic overall architecture
  - Reference case
    power/heat by CCGT/CHPs
  - SMR penetration case :

SMR
to replace
CCGT/CHP



  - 2035 one CCGT/CHPs power/heat replaced by SMR
  - 2050 two CCGT/CHPs power/heat replaced by two SMRs
  - Question still need for third CCGT for heat production needs balance?



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HES-study cases architecture

District heating

- General considerations
  - DH relies on co-production of electricity and district heat by CHP generation
    - Boiler/steam turbine CHP systems can utilize nearly any type of gas, liquid, or solid fuel, but the technology is typically used when low cost solid or liquid fuels are available (e.g., coal, biomass, or process waste).
  - DH production means also includes contributions from PV, nuclear power, hydro power, fossil power and wind power, most of those are “exogeneous sources”, i.e. production out of the district area
  - Heat from the CHP plants is not enough in cold weather conditions, separate production of heat is required by dedicated heating plants according to need at any given time
    - Short operating times of heating plants at the annual level, sometimes only a few hundred hours
  - Production can be balanced with heat and cooling accumulators
    - Heat consumption is not steady: heat is needed more during the day than at night
    - In the night, heat produced with cogeneration is stored in large water tanks to be discharged when needed
- DH demonstration case should be based on **real infrastructure** which has been analysed and **reconfigured/ simplified** to include **key components for relevant tech/economic demonstration**

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HES-study cases architecture

District heating

- The choice of heating solutions depend on the area where DH is used. DH is mainly a solution in northern and central Europe with growth for specific technology deployment conditioned by resource limits (biomass, wind).
- Trends from EU scenarios and market evolution for district heating evolution towards net-zero
  - Global demand of energy should be lower → capacity reduction
  - Favour heating plants that deliver higher heating efficiencies → increased efficiency
  - Maximize the use of CHP → increase CHP penetration but with low-carbon fuels
  - Scale up the use of individual heat pumps → increased electricity share but may be limited
    - Heat typically extracted or inserted into ambient air or ground, can be used to utilize waste heat which temperature is low (< 100°C)
  - Develop large-volume seasonal heat storage to accommodate fluctuating supply and demand from RES → increased heat storage penetration

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HES-study cases architecture

District heating

- Implementation
  - Aim at general composition of a DH configuration and not be a specific case
    - This general composition addresses a **rather large urban area** and not a (tiny) local community
    - Focus also goes on **heat transportation effects**
  - Because of **large urban area**
    - Distribution across separated areas and significant distance between production and consumers
    - Each separated area has its specific combination of production means
    - There could be bottlenecks in transporting heat between the separated areas
    - Need to consider "small thermal storage effect " due to inertia of infrastructures
  - Evolution of the initial reference configuration model as follows
    - Distribution across separated areas : 2 DH blocks
    - Specific production means but keeping for each area required trends : TES heat pumps HOB for intermittent capacity
    - Small thermal storage effect in DH block properties
    - Modelling of Bottlenecks in transporting heat by properties of interconnecting heat network between 2 DH

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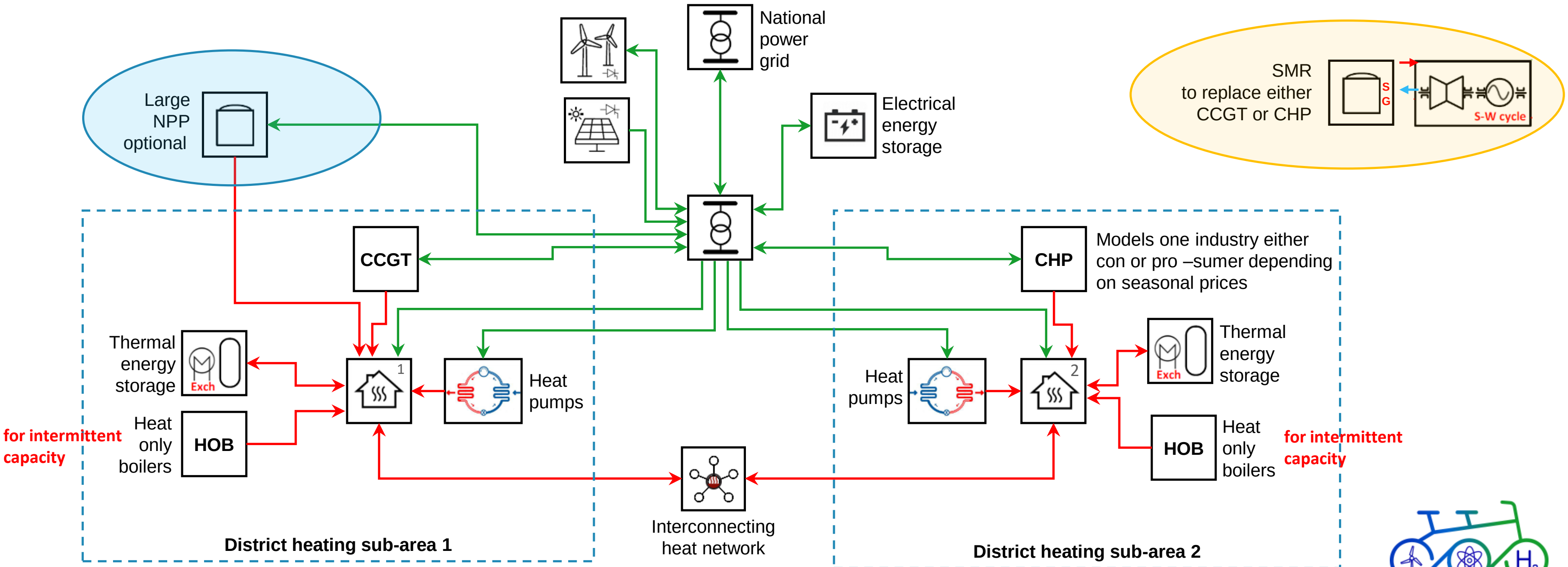
HES-study cases architecture

District heating – conceptual layout



Specific needs in power
Specific needs in heat

Each DH sub-area has its specific properties, including implicit heat storage capacity from thermal inertia

Specific needs in power
Specific needs in heat

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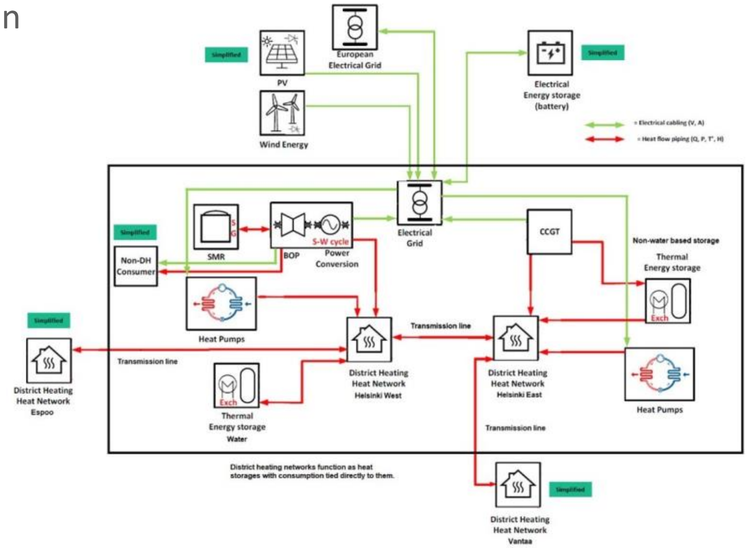
HES-study cases architecture

District heating : national priorities - Northern Europe variant

- Finland configuration : DHS decarbonization in the metropolitan area of Helsinki, which includes the large cities of Espoo and Vantaa
  - Separate companies responsible for DH production
    - Helen Ltd. in Helsinki
    - Fortum Ltd. in Espoo
    - Vantaa Energia Ltd. in Vantaa
  - Limited transfer capacity between Helsinki DH network and Espoo /Vantaa DH networks
  - Replace fossil fuel-based DH production
    - Heat Only Boiler Small Modular nuclear Reactors (HOB-SMR)
    - Combined heat and power SMRs (CHP-SMR)
    - Combination of HOB-SMR and CHP-SMR
  - Optional H2 scenario where hydrogen would be exported and side-product heat used in DH



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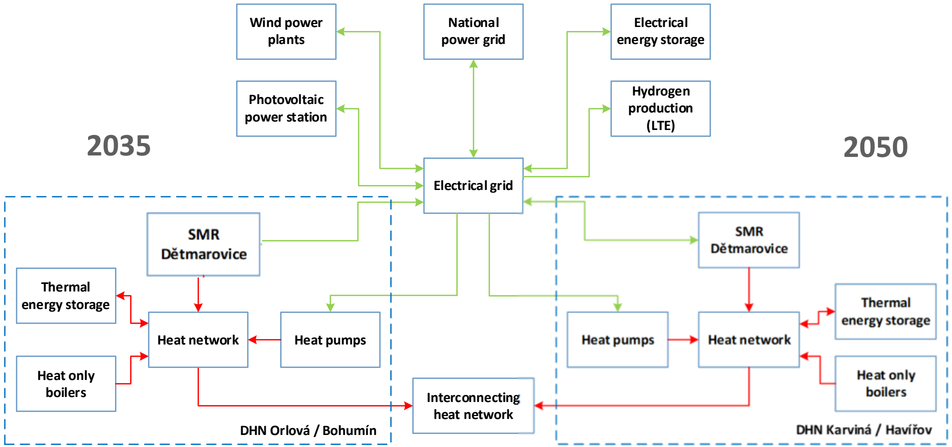
HES-study cases architecture

District heating : national priorities – Central Europe variant

- Czech Republic configuration : replace a part of coal heat sources with low-emission SMR sources in the highly industrialized Moravian-Silesian Region having a large share of CO_2 production
  - Large stationary CO_2 sources
    - Iron and steel works (Třinec, Vítkovice and Ostrava)
    - Power plants (Dětmarovice and Třebovice)
    - Heating plants (Karviná)
  - Interconnected heat networks
    - DHN Bohumín/Orlová
    - DHN Havířov/Karviná
  - Coal fired stations progressively replaced by SMRs in Dětmarovice



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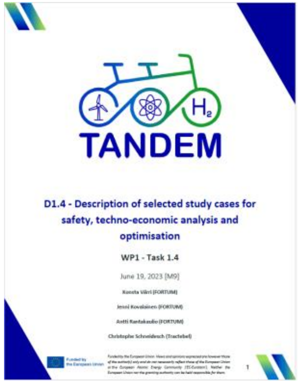
Characterization of the studied hybrid systems

Study cases

- The TANDEM energy study cases are developed as use-cases for the purpose of demonstrating the benefits of Small Modular Reactor (SMR) penetration during the timeframes of 2035 and 2050

- They are correlated with two European energy scenarios, reflecting the most probable and available energy mix projections toward
- The study cases will also demonstrate the relevance and efficacy of the methods and tools developed by the project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D1.4 - Description of selected study cases for safety, techno-economic analysis and optimisation

WP1 - Task 1.4

June 19, 2023 [M9]

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