Renewable Energy Sources and Energy Storage Systems

Numerical and real applications in different energy contexts

Eng. Alice Mugnini, Ph.D. – Researcher @UNIVPM

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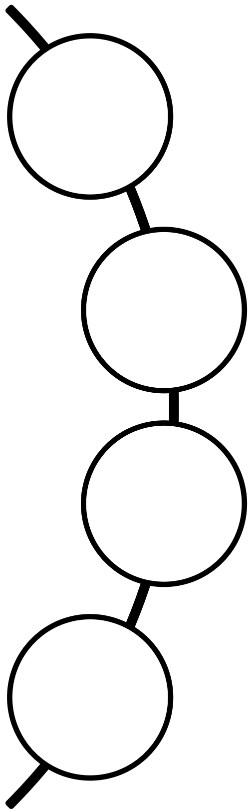
OUTLINE



INTRODUCTION (1/6)

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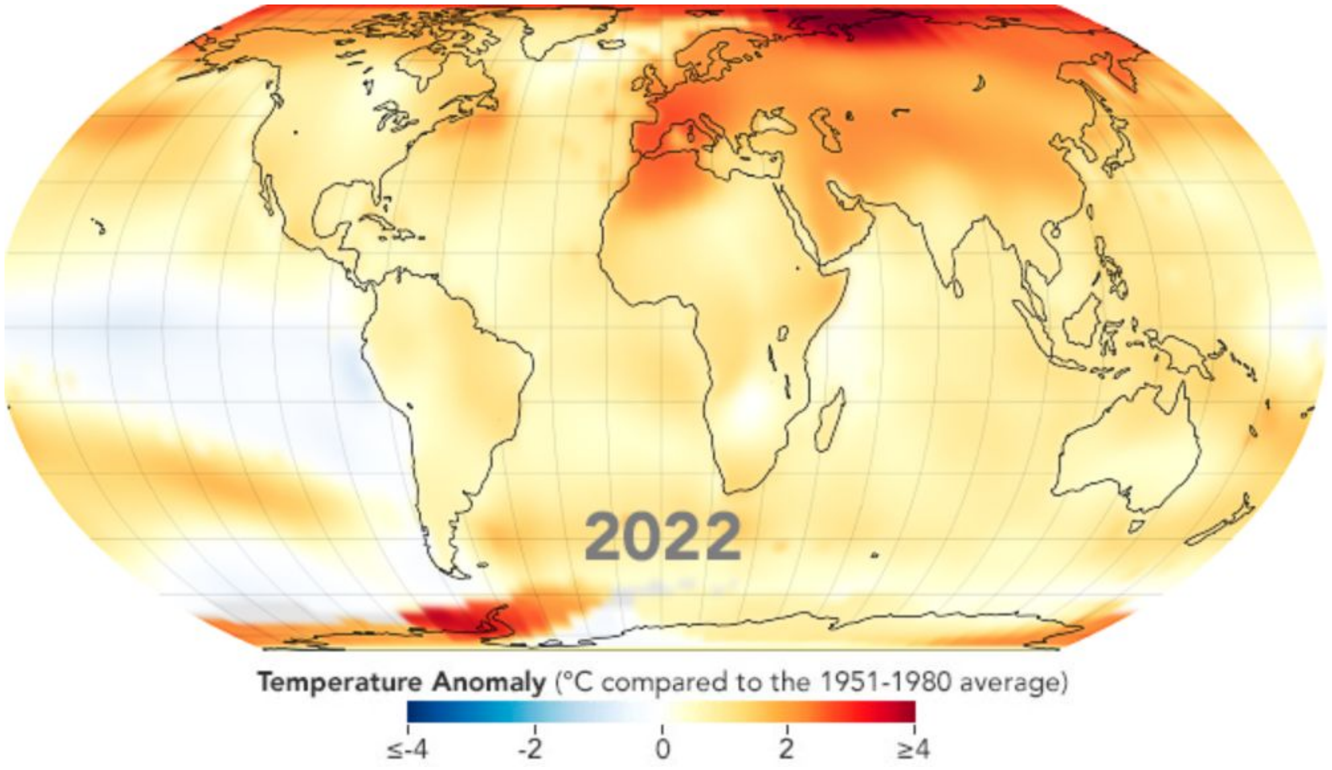
The Paris Agreement

Its overarching goal is to hold "the **increase in the global average** temperature to well **below 2°C** above pre-industrial levels" and pursue efforts "to limit the temperature increase to **1.5°C** above pre-industrial levels."

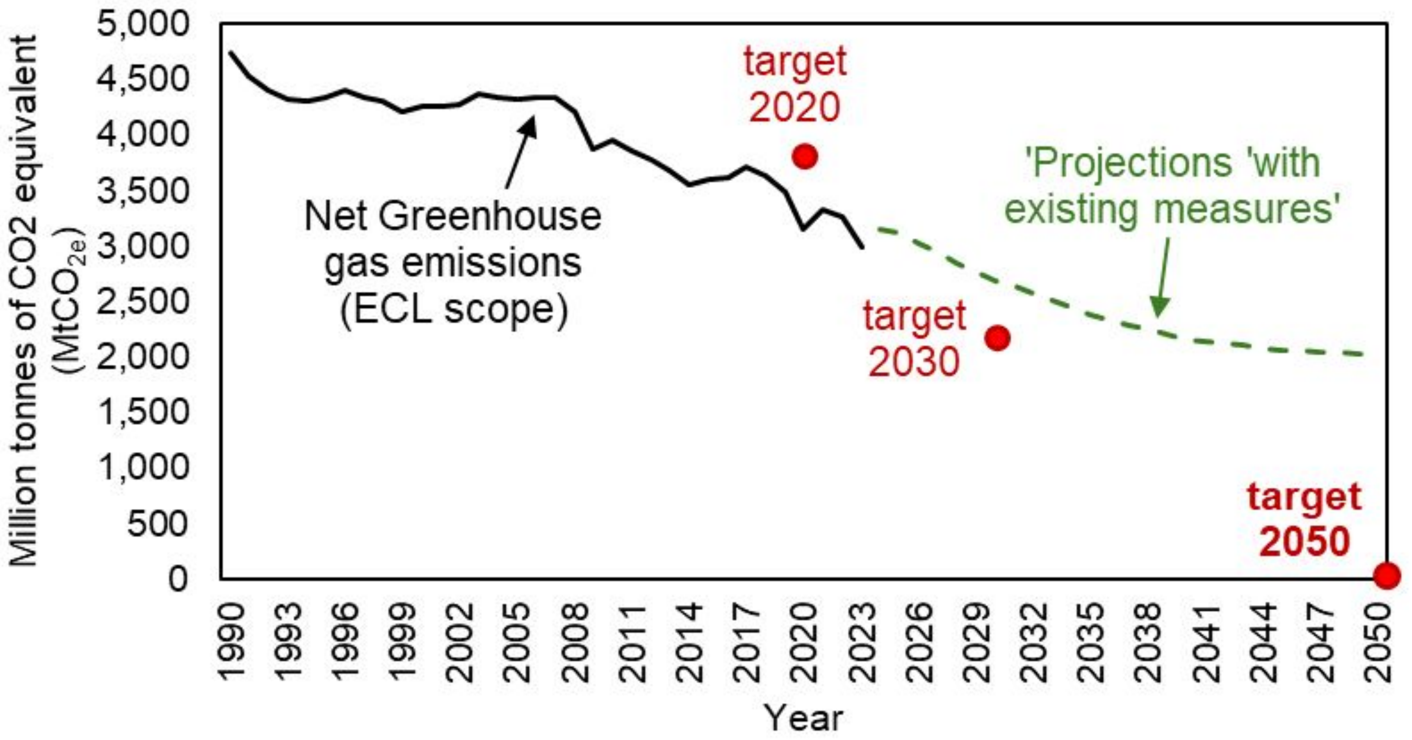


Source: NASA

INTRODUCTION (2/6)

European Goals

The EU aims to be **climate-neutral by 2050** – an economy with net-zero greenhouse gas emissions.

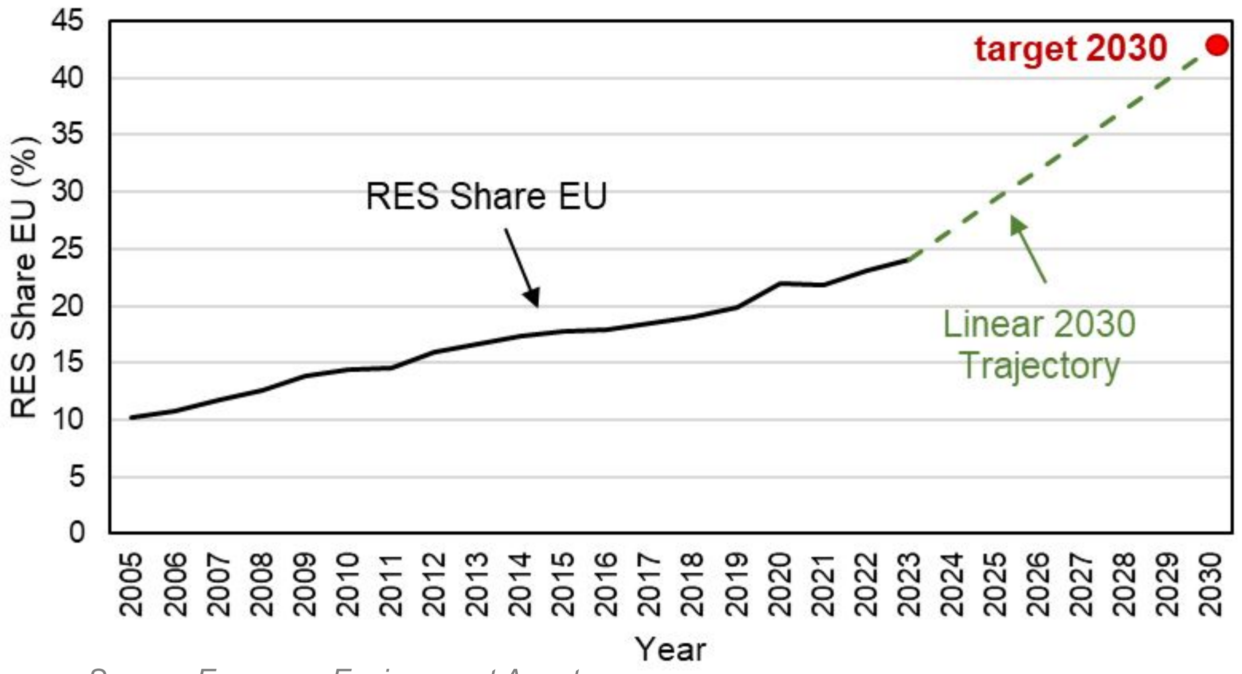


Source: European Environment Agent

INTRODUCTION (3/6)

Renewable energy targets

The revised Renewable Energy Directive, adopted in 2023, raises the EU's binding renewable energy target for 2030 to a **minimum of 42.5%**



Source: European Environment Agent

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INTRODUCTION (4/6)

Renewable energy

Renewable energy sources for the EU include:

- **Wind power** – Both onshore and offshore wind farms generate electricity from wind.
- **Solar power** – Solar panels capture energy from the sun to produce electricity.
- **Hydropower** – Energy generated from flowing water, typically through dams or river systems.
- **Biomass/Biogas**– Organic materials, such as wood or agricultural waste, used to produce energy.
- **Geothermal energy** – Heat energy from beneath the Earth's surface used for heating and electricity generation.
- **Ocean energy** – Energy harnessed from tides and waves, though still emerging.

Article 2

Definitions

For the purposes of this Directive, the definitions in Directive 2003/54/EC apply.

The following definitions also apply:

(a) 'energy from renewable sources' means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases;

Source: Directive 2009/28/EC

INTRODUCTION (5/6)

Renewable energy

Programmable Renewable Energy

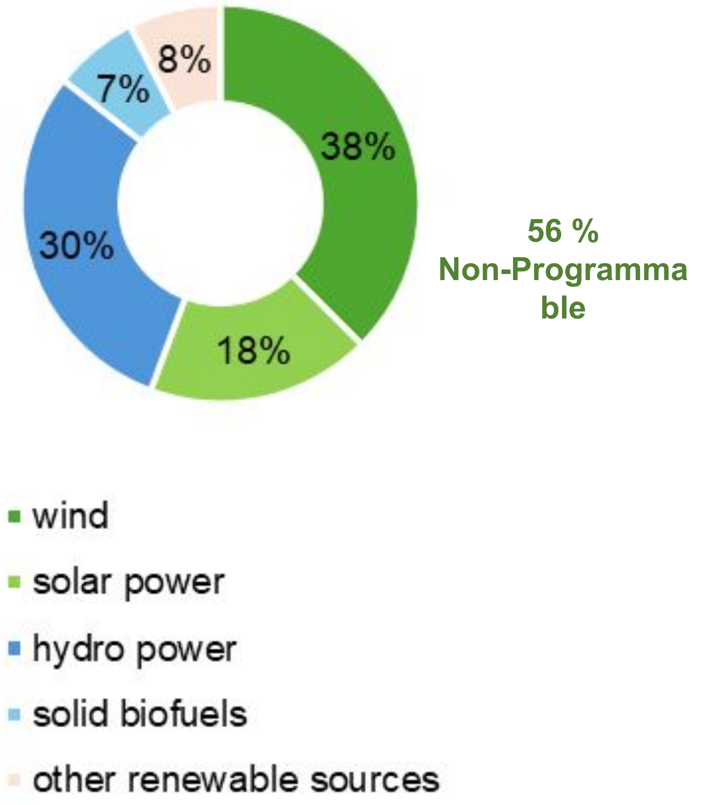
These sources can be controlled or scheduled to generate power when needed

- **Biomass/Biogas**
- **Hydropower**

Non-Programmable Renewable Energy

These sources are variable and cannot be controlled or scheduled, as they depend on natural conditions.

- **Solar Power**: Generation depends on sunlight
- **Wind Power**: Generation depends on wind speed.



Source: Eurostat

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INTRODUCTION (6/6)

Issue related to high penetration of non-programmable Renewable Energy Sources (RESs)

High RES penetration in the electricity generation mix

Solutions to guarantee the secure operation of the energy system

Increased electrified sectors

ENERGY FLEXIBILITY

ENERGY STORAGE SYSTEMS

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ENERGY FLEXIBILITY (1/2)

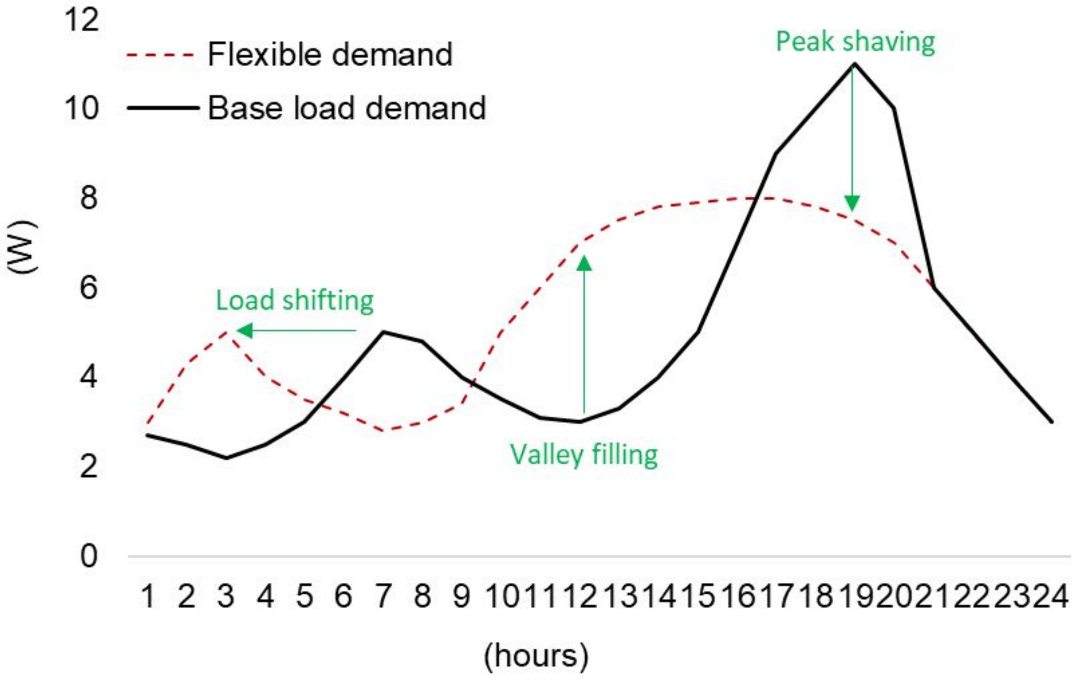
A paradigm shift in the energy system will be necessary…

DEMAND-FOLLOWING **GENERATION-FOLLOWING**

Source: Morabito, Alessandro. (2020). Business Model For Energy Management Enterprises. 10.13140/RG.2.2.15129.54883.

ENERGY FLEXIBILITY (2/2)

An **energy flexible system** is defined as a system *“able to manage its energy demand and generation according to local climate conditions, user needs, and energy network requirements”* (Jensen et al., 2017).



Source: European Environment Agent

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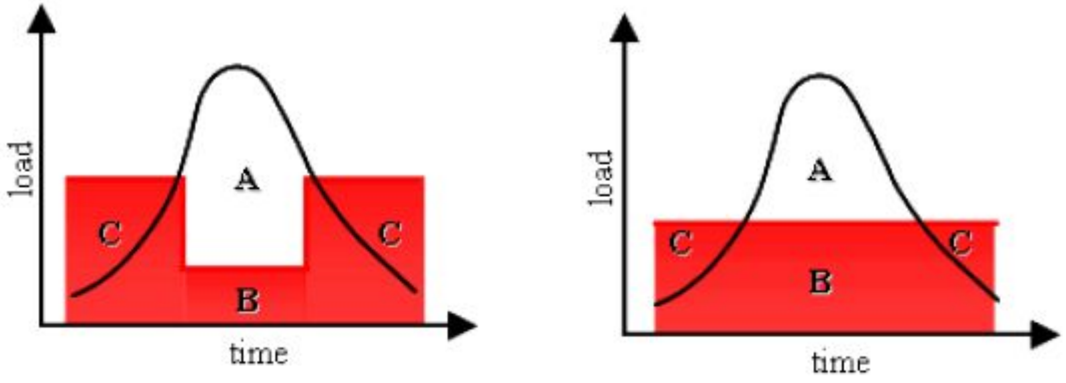
ENERGY STORAGE (1/2)

Energy storage systems play a crucial role in enabling the integration of renewable energy sources.

Energy storage systems **store excess energy generated during periods of high renewable output** (e.g., wind or solar) **and release it when demand exceeds supply or when renewable generation** is low.



A: storage meet demand
B: generation system meet demand
C: generation system charges the storage

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ENERGY STORAGE (2/2)

Energy storage systems that can be applied to renewable energy sources.

Mechanical Storage Systems:

- **Pumped Hydroelectric Storage**: Excess energy pumps water to a higher elevation. When needed, the water is released to generate electricity.
- **Compressed Air Energy Storage**: Excess electricity compresses air in underground caverns. The air is released to drive turbines and generate power when needed
- **Flywheel**: Excess energy is used to spin a flywheel. When energy is needed, the flywheel's motion generates electricity

Electrochemical Storage Systems (Batteries)

- **Lithium-Ion Batteries**: Store energy in chemical form and release it when needed
- **Flow Batteries**: Energy is stored in liquid electrolytes, which flow through the system to produce electricity
- **Sodium-Sulfur (NaS)** Batteries: High-temperature batteries that store energy and release it as needed

Thermal Storage Systems

- **Sensible Heat Storage:** Heat is stored in a material, such as molten salt, and released when needed (Solar thermal, concentrated solar power.
- **Latent Heat Storage (Phase Change Materials):** Stores energy when a material changes its state (e.g., solid to liquid) and releases it during the reverse process.
- **Thermochemical Storage:** Energy is stored through reversible chemical reactions and released during the reverse process.

Hydrogen Storage

Excess electricity is used to produce hydrogen through electrolysis. The hydrogen can later be used in fuel cells to generate electricity.

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ENERGY STORAGE (2/2)

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Application

Optimized building thermal demand management with energy storage system and heat pump in the presence of non-programmable renewable sources

APPLICATION (1/6)

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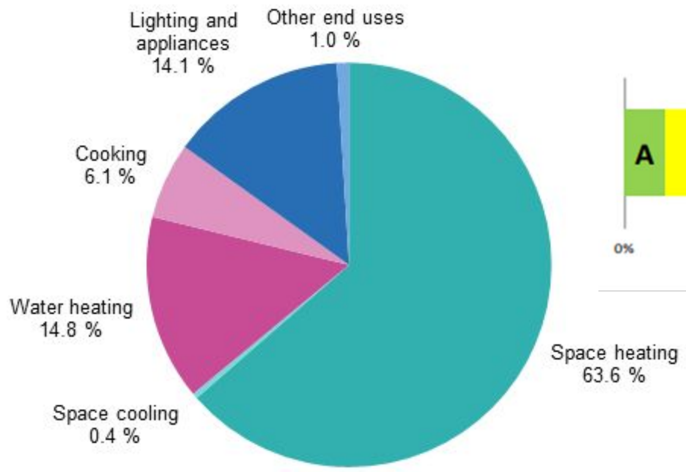
Residential sector represents about **26 %** of final energy consumption in the EU

Final energy consumption in the residential sector by use, EU, 2019

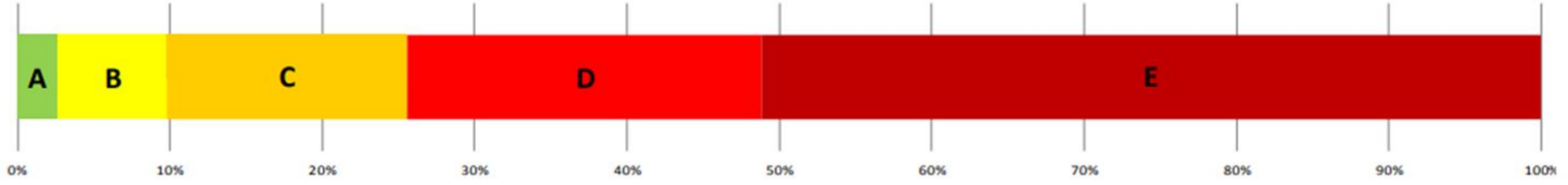


Source: Eurostat (online data code: nrg_bal_c)

eurostat

In most EU countries, **50 % the residential stock** was **built before** the first thermal regulations (built before **1970**)

Distribution of the building stock in the EU per EPC class



Buildings Performance Institute Europe

APPLICATION (2/6)

The coupling of heat pumps to natural gas boilers is one of the solutions for the **retrofit** towards decarbonization of **domestic heating** (SPACE HEATING plus DOMESTIC HOT WATER)

HEAT PUMP

GAS BOILER

HYBRID HEAT PUMP (HHP) SYSTEMS

<u>Control technique</u> is essential to achieve specific performances

APPLICATION (3/6)

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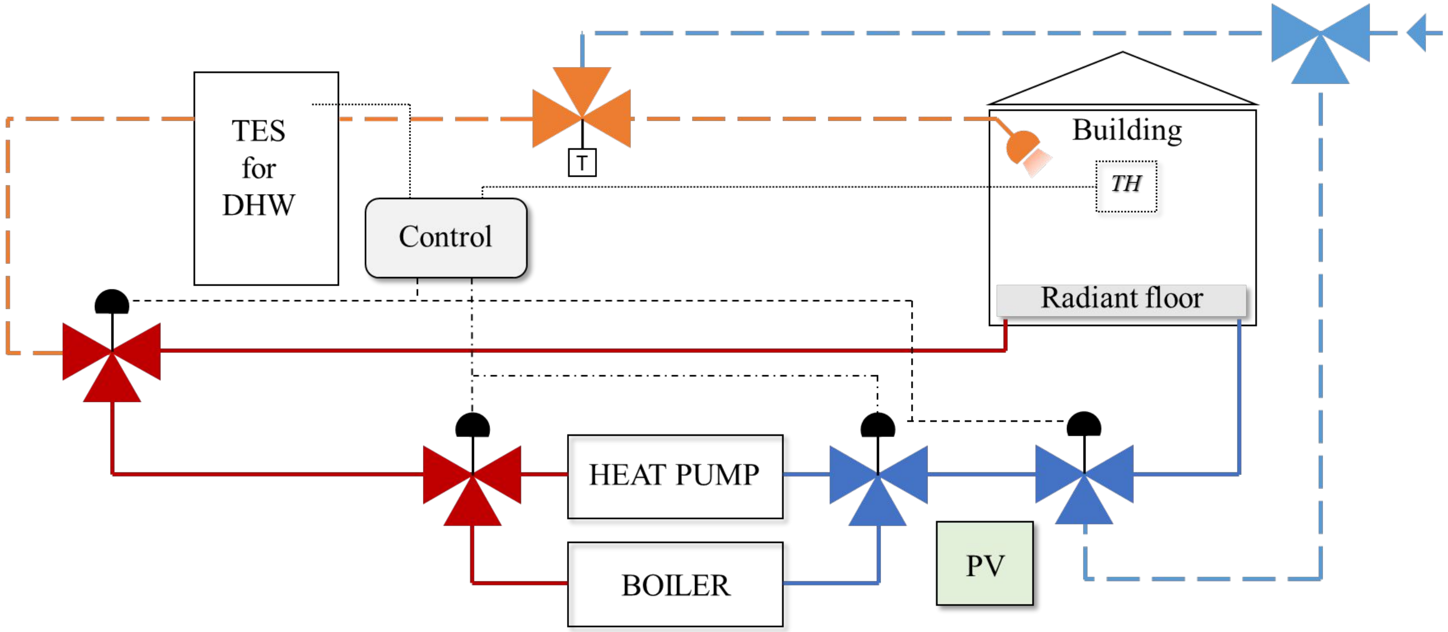
Focus on **<u>control technique</u>** of the HHP system in case of **optimized management** of available resources (**<u>INCLUDING PHOTOVOLTAIC PLANT</u>**) and satisfaction of different heat demands (**Space Heating**, SH, and **Domestic Hot Water**, DHW)



- ❑ Base Rule-Based Control **(BRBC)**
- ❑ Model Predictive Control **(MPC)**

complexity

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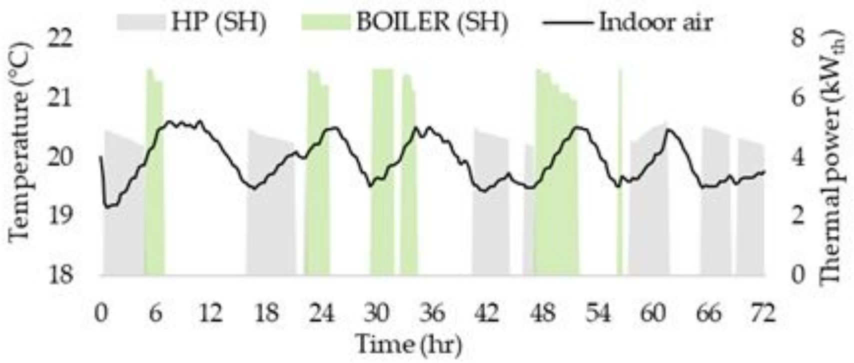
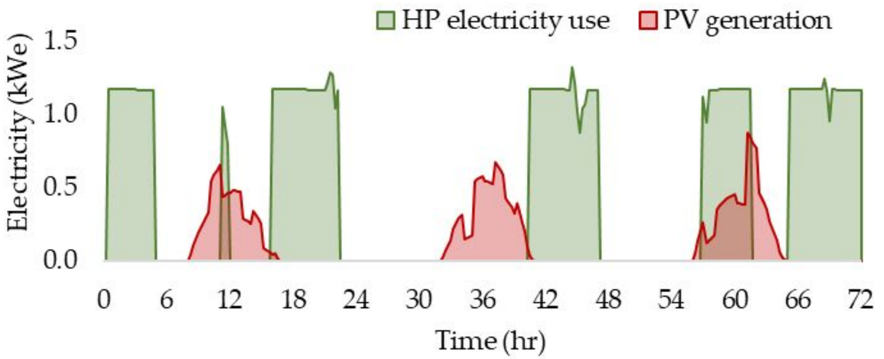
APPLICATION (4/6)

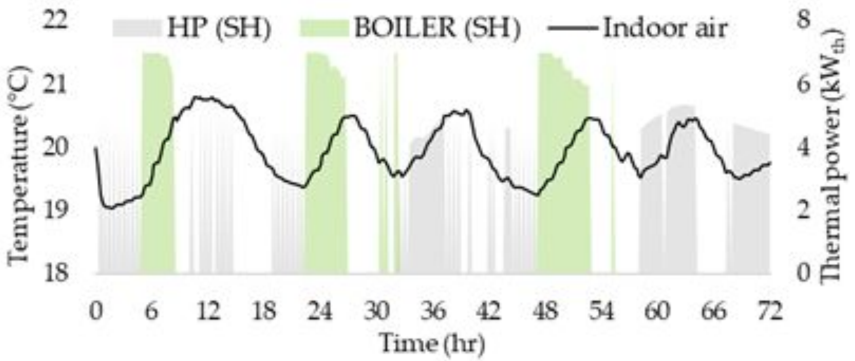
RESULTS

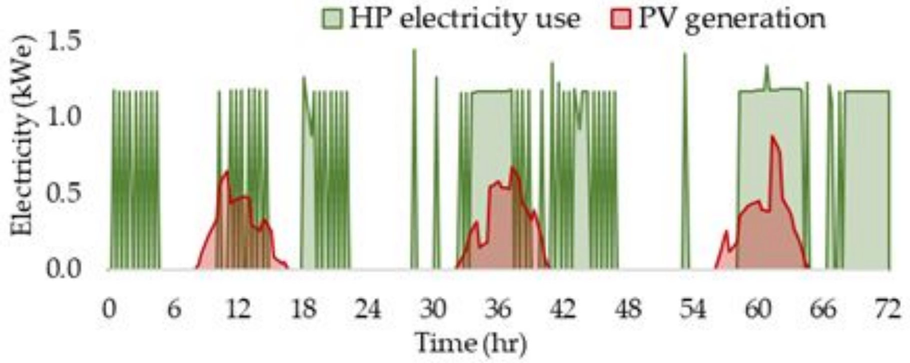
- **Base Rule-Based Control (BRBC)**





- **Model Predictive Control (MPC)**





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APPLICATION (5/6)

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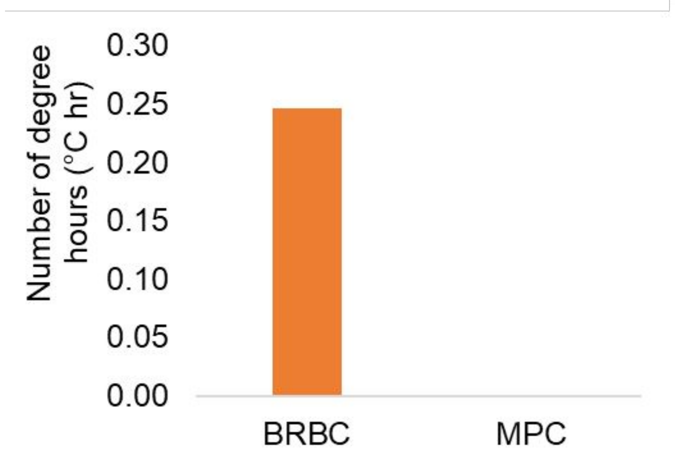
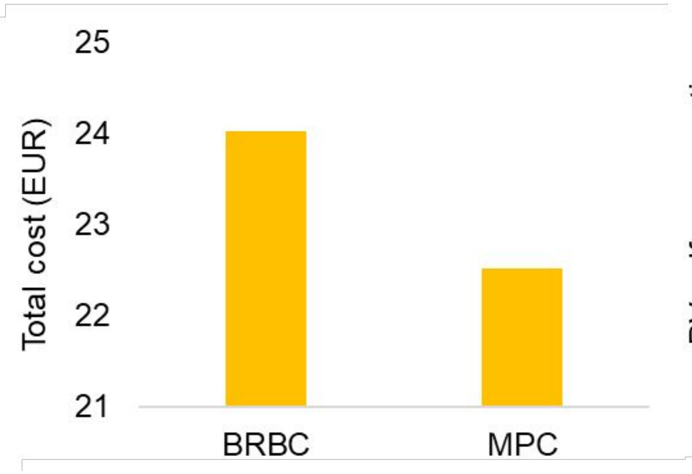
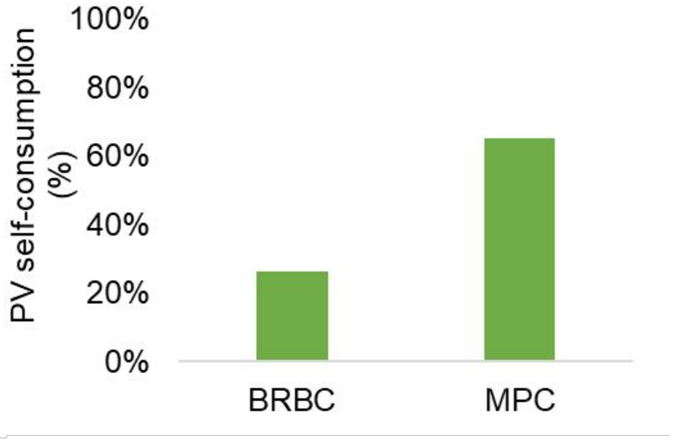
RESULTS

- ❑ Base Rule-Based Control **(BRBC)**
- ❑ Model Predictive Control **(MPC)**

complexity







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APPLICATION (6/6)

CONCLUSIONS

- A **storage system is essential** to decouple demand from generation and thus to have a reserve of flexibility. However, **advanced control logic is required** to activate it.

- **Model Predictive Control (MPC) allows to take into account both performance and comfort**, however the complexity of the implementation is not comparable to the Ruled Based Control (RBC)

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Q&As?

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Renewable Energy
And
Energy Storage Systems

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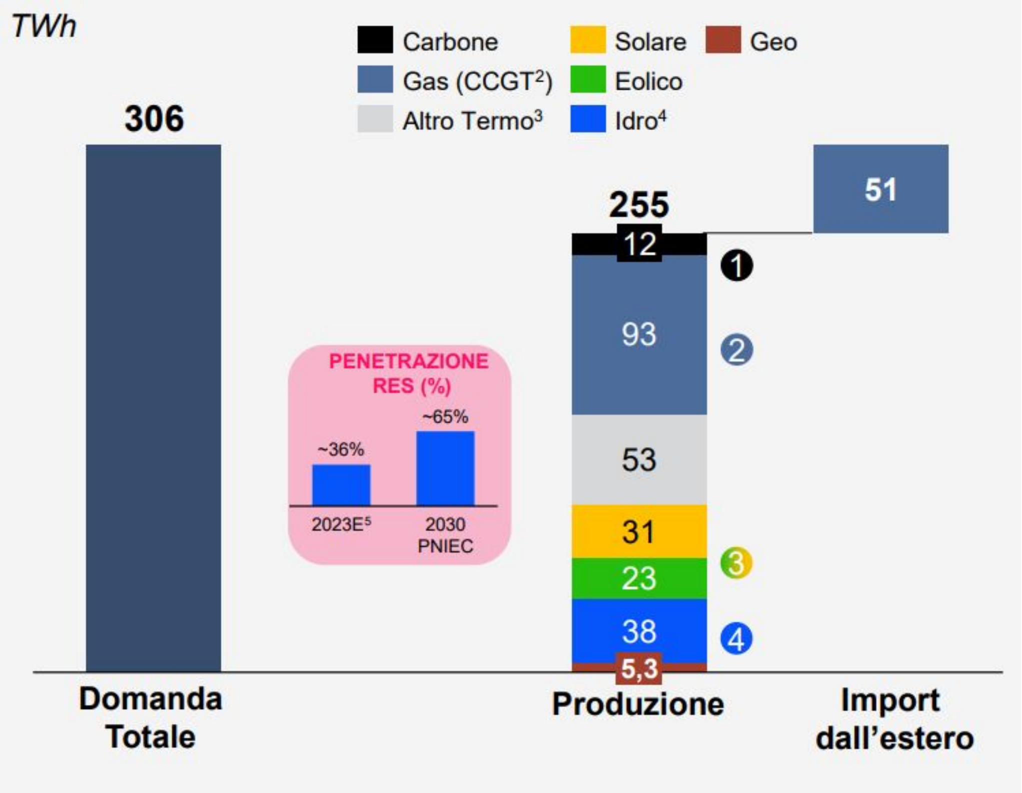
Content

- Renewable Energy Sources (RESs).
- Energy Storage Systems (ESSs).

Renewable Energy Sources (RESs)

- Increase in RESs due to an additional **5.7 GW in 2023**, mainly due to small-scale grid-connected photovoltaics.
- Grid development and simplification of required permitting to reach the Renewable Energy Directive (RED) III targets.
- Natural gas made a significant contribution to meeting both electricity and heat demands, but the aim is to reduce its use.

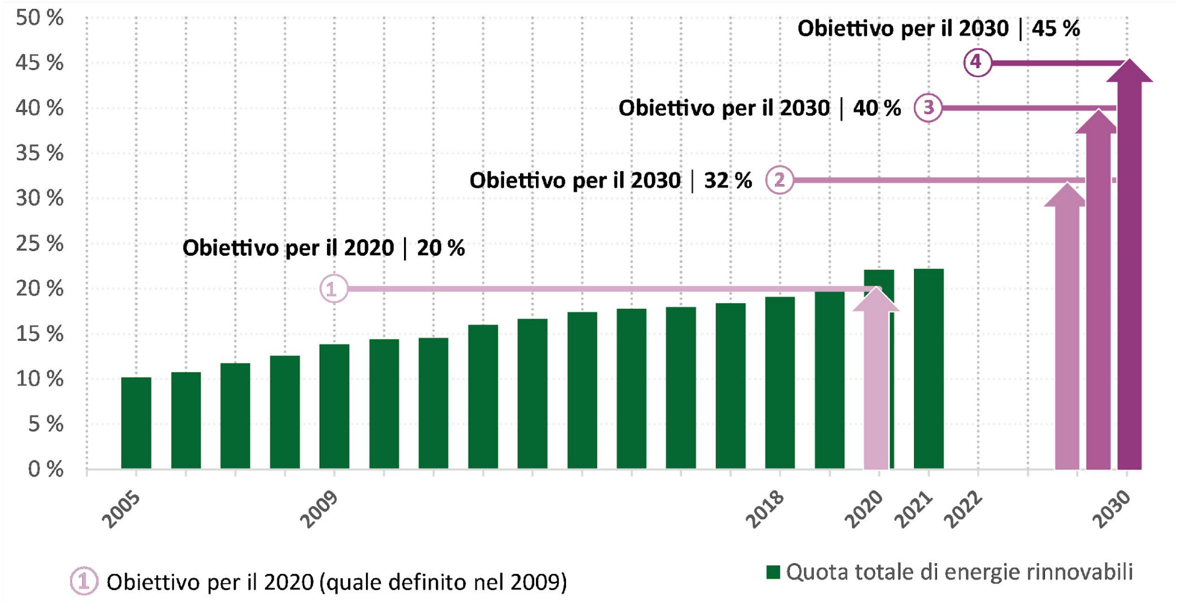


RESs

In 2023, RESs had a significant increase in the share of the European Union's energy production compared to 2022. Here are the highlights for the power, heating/cooling, and transport sectors:

- Power Sector:
  - Renewables accounted for **44.7% of the EU's electricity production in 2023**, moving from 42% in 2022. This represents a **12.4% increase in renewable electricity generation**, reaching 1.21 Million GWh. Solar and wind power drove this growth, while electricity from fossil fuels fell by nearly 20%.
  - **Renewable capacity grew by about 50 GW in 2023**, with solar power dominating new installations. The EU remains on track for significant expansion in renewable capacity by 2028.
- Heating and Cooling:
  - **In 2023, about 25% of the energy used for heating and cooling came from renewables**, continuing a steady increase over recent years. The growth was supported by the use of heat pumps and renewable energy in industrial, residential, and other sectors.
- Transport Sector:
  - The share of renewable energy in the transport sector rose slightly, but challenges remain to meet the 2030 targets of 29% renewable energy in this sector. Biofuels, green electricity, and hydrogen are the key contributors.

RESs



2 Obiettivo per il 2030 (quale definito nel 2018)

3 Obiettivo per il 2030 – Pronti per il 55 % (proposta COM 2021)

4 Obiettivo per il 2030 – REPowerEU (proposta COM 2022)

Solar energy

Two main applications of Solar Energy:

- Photovoltaic (PV): Converts sunlight into electricity using solar panels.

  Installed Capacity in Europe (2020): **143 GW.**

- Solar Thermal: Uses sunlight to generate heat for residential and industrial purposes.

- Installed Capacity in Europe (2020): **120 GW.**

Both technologies play a critical role in achieving Europe's renewable energy targets and reducing dependency on fossil fuels.

PVs

- At the end of 2020, Europe solidified its position as a global leader in PV energy. Across the continent, there were approximately **143 GW of installed PV capacity**, making Europe a key player in the transition to renewable energy.

- By 2022, the self-consumption of solar energy had become a significant trend in Europe. **The total self-consumed energy reached an estimated value of 85 TWh, representing 25% of the net production of all photovoltaic plants across Europe** and nearly 50% of the net production from facilities that engage in self-consumption.

- This growing trend highlights Europe's focus on decentralized energy systems and the increasing role of households, businesses, and industries in driving the renewable energy agenda forward.

Solar thermal energy

- Solar thermal energy uses the sun to heat water for heating and/or for cooking and bathing.

- A solar thermal system can be installed to produce:
  - Domestic hot water.
  - Heat rooms in your house or flat.
  - Heat sports facilities such as swimming pools and gyms.
  - Slow temperature industrial applications.

Wind energy

- At the end of 2020, Europe had a well-established wind energy sector, with approximately **236 GW of installed wind power capacity**. A significant portion of wind installations consisted of small-scale units, although large-scale wind farms dominated overall capacity.

- **Wind energy accounted for** roughly **36% of the total RES capacity** across Europe, showcasing its critical role in the continent's renewable energy mix. During **2020**, the production of **electricity from wind sources reached** approximately **459 TWh**, representing about **15% of Europe's total electricity production** and a substantial share of the renewable energy output.

- These figures underline Europe's leadership in wind energy development and its commitment to expanding both onshore and offshore wind installations as part of its energy transition goals.

Solar and wind energy

Pros

- Renewable and sustainable energy sources.
- Free energy raw material.
- No direct greenhouse gas emissions.
- Contribute to the decarbonisation process.
- Promote energy self production.

Cons

- Discontinuity of electricity production.
- Environmental impact due to their presence.
- Visual and aesthetic landscape impact.

Biomasses

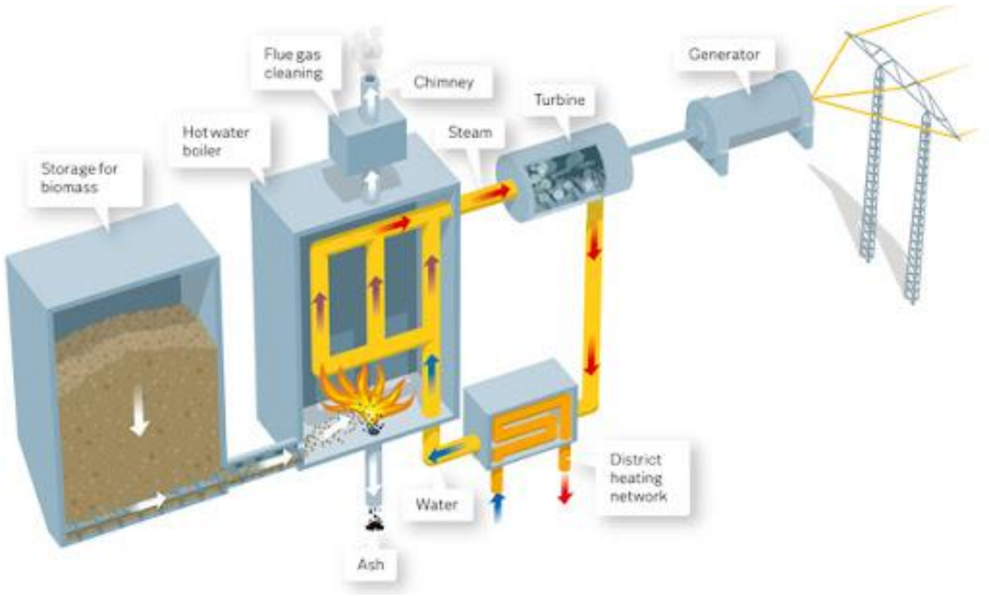
Biodegradable fraction of products, wastes, and residues of biological origin from agriculture, forestry, and related industries:

- **Biomass plant**: this is the most widely used biomass that comes from waste from agriculture, gardening, and grounds maintenance activities.
- **Animal biomass**: it comes from livestock farming (the most commonly used type is manure).
- **Microbial biomass**: comes from the soil and is available from soil elements such as sulphur, nitrogen, fungi, bacteria, microbes, etc.

Possible uses of biomasses

- Production of electricity (industrial) and thermal energy (industrial or domestic).

- Production of biofuels (bioethanol, biodiesel, biomethane, biohydrogen) to be used again for electricity and heat production.



In Europe, there are over **18,000 biogas and biomass plants** actively contributing to the energy mix. Together, these facilities produce approximately **167 TWh** of energy annually, covering **around 5.5%** of the continent's total energy consumption.

Hydropower

- Hydropower is the RES with the longest tradition in Europe.

- As of June 2022, Europe had **over 22,000 hydropower plants**, with the majority of them concentrated in countries with mountainous regions such as Norway, Austria, and Switzerland.

- The total installed capacity reached **around 160 GW**, producing approximately **400 TWh per year**, which accounts for roughly **30% of Europe's total renewable energy** production.

- This highlights the significant role that hydropower plays in Europe’s energy mix, providing a reliable and sustainable source of electricity while supporting the continent's transition to cleaner energy.

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Energy Storage Systems (ESSs)

- The storage of electricity from RESs (especially wind and photovoltaics) plays a key role in allowing these sources to be deployed in a concrete and consistent manner, ensuring a stable and reliable energy supply despite their intermittent nature.

- The main systems include:
  - Pumped Hydro.
  - Batteries.
  - Hydrogen.

- In addition, **thermal energy storage** is increasingly important. This technology involves storing excess energy as heat, which can then be released to generate electricity or provide heating when needed.

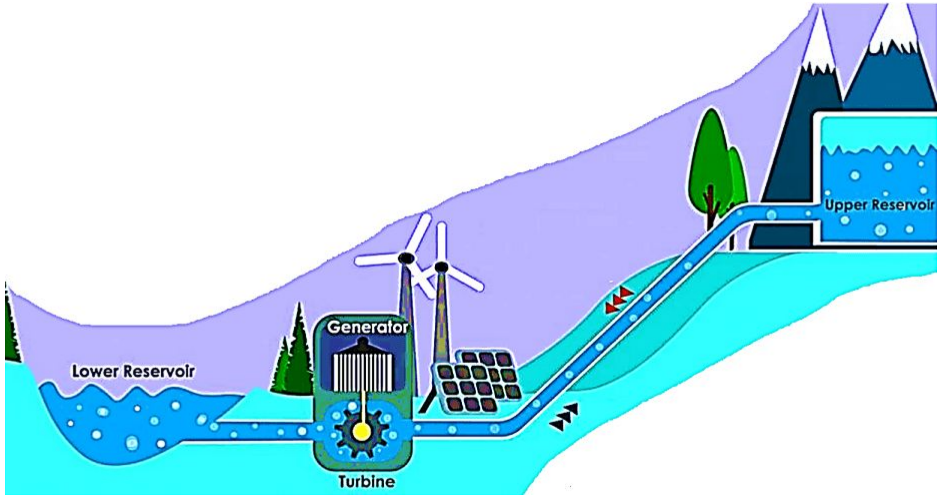
Pumped Hydro

- Electricity (cheap, purchased at night) is used to pump water from the low reservoir to the high reservoir using reversible turbines (or possibly separate pump systems).

- Then, during peak demand periods, energy is produced by flowing the water stored in the high reservoir downwards and driving the turbines.

- In Europe, the exploitation of hydroelectric power has declined in recent years due to economic factors. However, its potential remains significant. **With over 22,000 hydropower plants and a total installed capacity of 160 GW, hydropower generates around 400 TWh per year, accounting for 30% of Europe's renewable energy.**

- In the future, the increasing the use of existing hydroelectric resources will be crucial to enhance energy storage capacity, especially through **pumped hydro**, helping to balance intermittent renewable sources like wind and solar. This will strengthen Europe's energy security and support its transition to a sustainable energy system.



Batteries

- Constant energy supply.
- Reduction of CO_2 emissions.
- Security during blackouts.
- Power grid support.
- Maximisation of self-consumption.

- Europe is still lagging behind with this technology as it accounts for only 7% of the world market for lithium-ion batteries, while China is the world leader and accounts for 78%.
- To date, batteries are the most promising technology together with hydro-pumping (the latter, however, is limited by the availability of potential sites to be exploited).

Batteries

- **Stand-alone batteries** are used to provide services to the network (TSO) by guaranteeing flexibility services.

- **Utility-scale batteries** are primarily used to provide grid support functions, but can also be combined directly with a renewable generation source to provide more controllable business generation.

- **Behind-the-meter batteries** are located at, or near, the site of energy use and downstream of the point of connection between the utility and the customer; usually applied in homes and workplaces enabling “residential distributed storage”.

Batteries

- As of December 31, 2022, Europe had installed **227,477 energy storage systems** with a total capacity of **1,530 MW** and a maximum storage capacity of **2,752 MWh**. In addition, **Terna** systems contributed an additional **60 MW** and **250 MWh**.

- The most common storage technology is **lithium-based** (99% of the total), followed by **lead-based** systems (0.6%), with a smaller number of **221 flywheel batteries** and **198 supercapacitors**.
- **99.9%** of these storage systems are paired with **photovoltaic installations**, with **99.6%** of them being residential-scale systems.

- Regarding the goals set in the **2020 National Energy and Climate Plan (NECP)**, Europe is still far from achieving the targets. For **centralized electrochemical storage** (400 MW by 2023), only **4 MW** have been installed (1% of the target), and for **pumped storage** (700 MW by 2023), **0 MW** have been reached (0% of the target).

- However, progress has been made in the **distributed storage** segment, with **1,526 MW** installed, representing **38% of the target** set for **4,000 MW by 2030**.

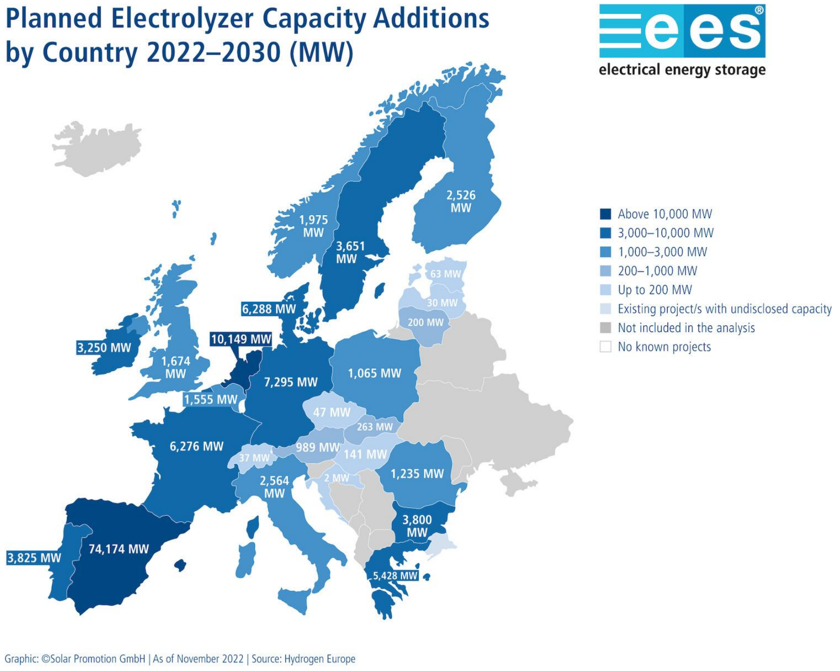
Hydrogen

- The hydrogen carrier plays a key role in the energy transition, particularly in the energy storage landscape.

- Through ‘Power-to-Power’, hydrogen production can support the random and non-predictable nature of renewables:
  - Hydrogen production by electrolysers uses excess energy from RESs plants that cannot be fed into the grid.
  - Temporary or prolonged (seasonal) storage of the hydrogen produced.
  - Conversion of hydrogen to electricity via fuel cells, possibly reversible, when renewables have a low output.

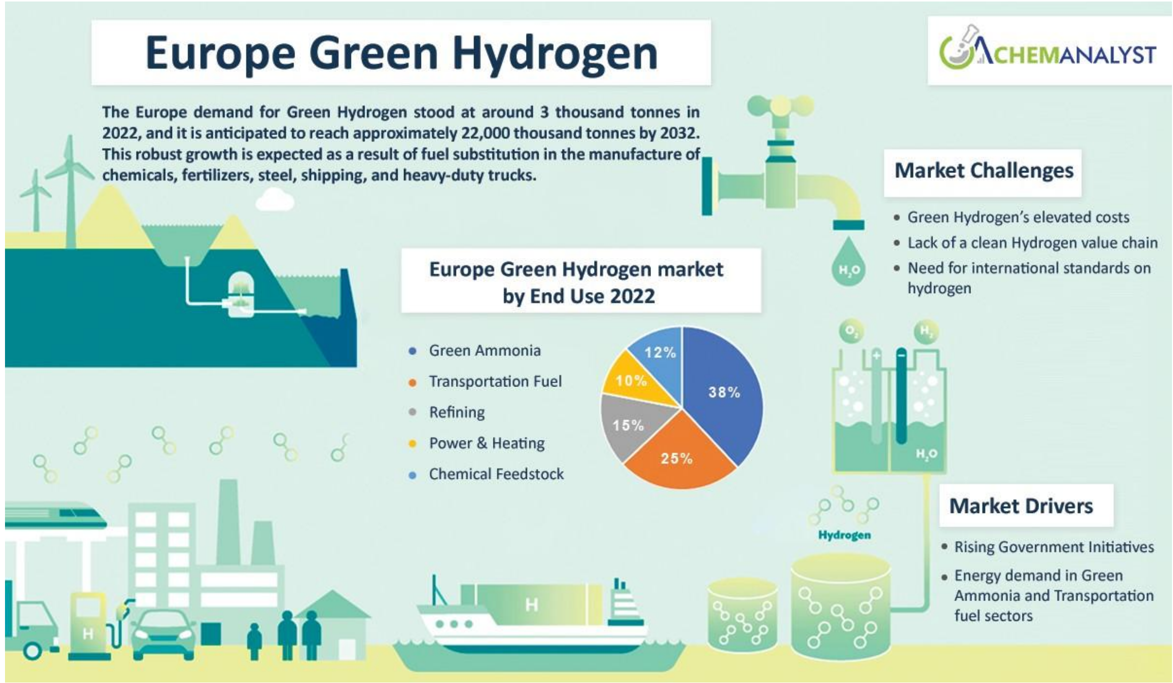
Hydrogen

- A radical expansion of the electrolyser market is required for hydrogen deployment



Hydrogen

- Future hydrogen market



Thermal Energy Storage (TES)

- Stores excess energy as heat in materials like water, molten salts, or phase-change materials, which can then be used for heating or electricity generation.
- Thermal storage can help balance supply and demand, especially in applications where direct electricity storage is less efficient.
- **As of 2022**, thermal energy storage in Europe is still in the early stages of development, with a total installed capacity of around **6 GWth**
- **By 2030**, Europe aims to substantially expand thermal storage capacity, with estimates suggesting it could reach over **20 GW**. This growth will be driven by the increasing use of **solar thermal**, **molten salt storage**, and **phase change materials.**

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