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**Current and Future Challenges to Energy Security**

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# The impact of distributed power generation on storage and infrastructure in net -zero scenarios

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# Introduction



## Background

- The goal of economy -wide decarbonisation requires the understanding of **scenario options** and **technological interactions**
- **Distributed energy resources** can both **favour** diffusion of renewables and **hinder** operation on **infrastructure**



## Research questions

- How do **distributed energy resources** impact the energy transfer and *vice versa*?
- How can we better track the **infrastructure constraints** in **integrated energy system modelling** (multi-vector, multi-node, multi-sector) at large scale?

# OMNI-ES (Optimisation Model for Network -Integrated Energy Systems )

## Modelling approach



Bottom -up capacity expansion model  
 Central planner perspective  
 Techno -economic optimisation  
 Linear programming (LP) formulation

## Spatial description



Lumped nodal scheme  
 Multi-node resolution

## Model objective



Minimisation of the total annual cost:

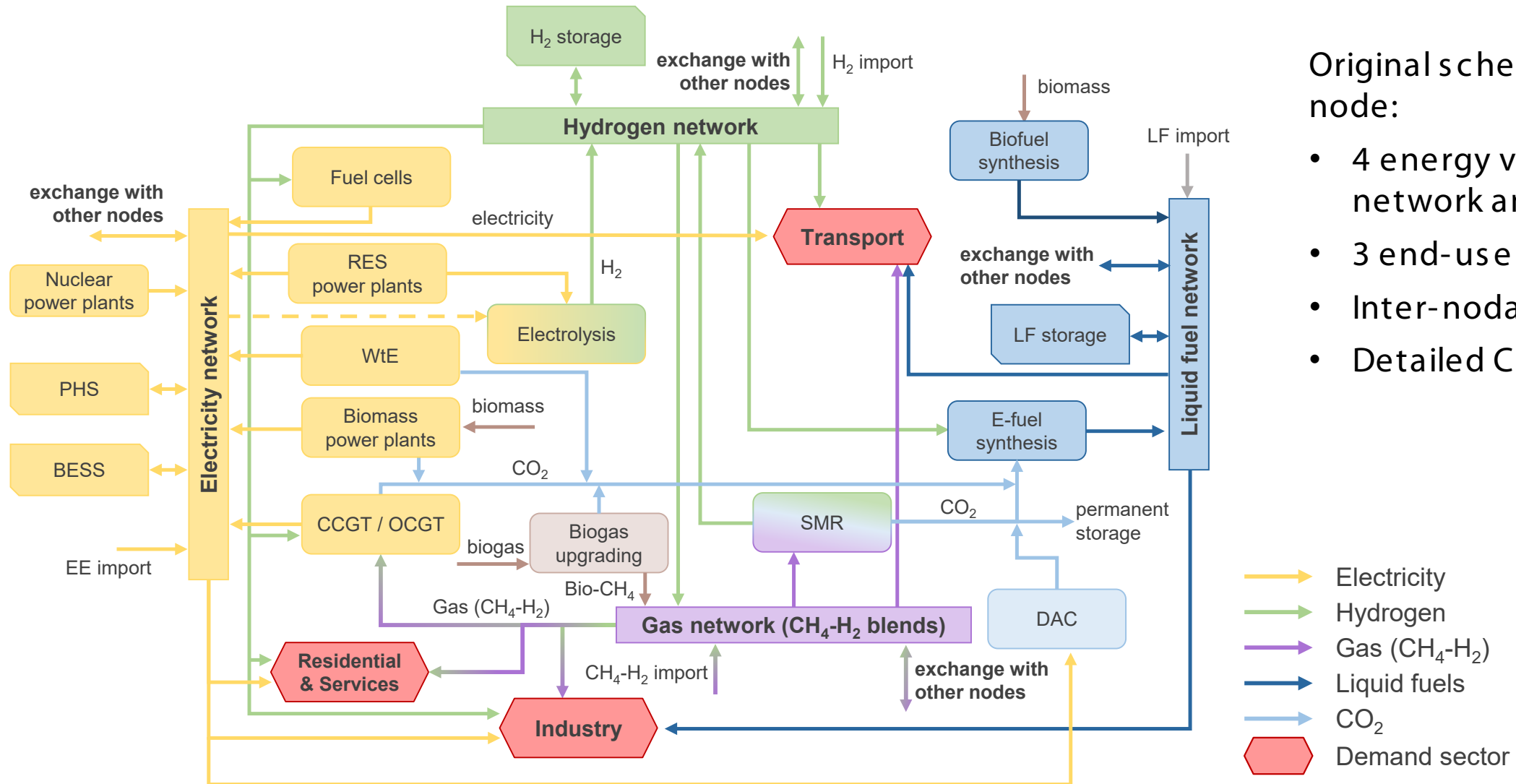
$$TAC = \sum_i CAPEX_i \cdot CRF_i + \sum_i OPEX_i$$

## Temporal description



Snapshot approach:  
 → optimisation over a single target year  
 Hourly resolution

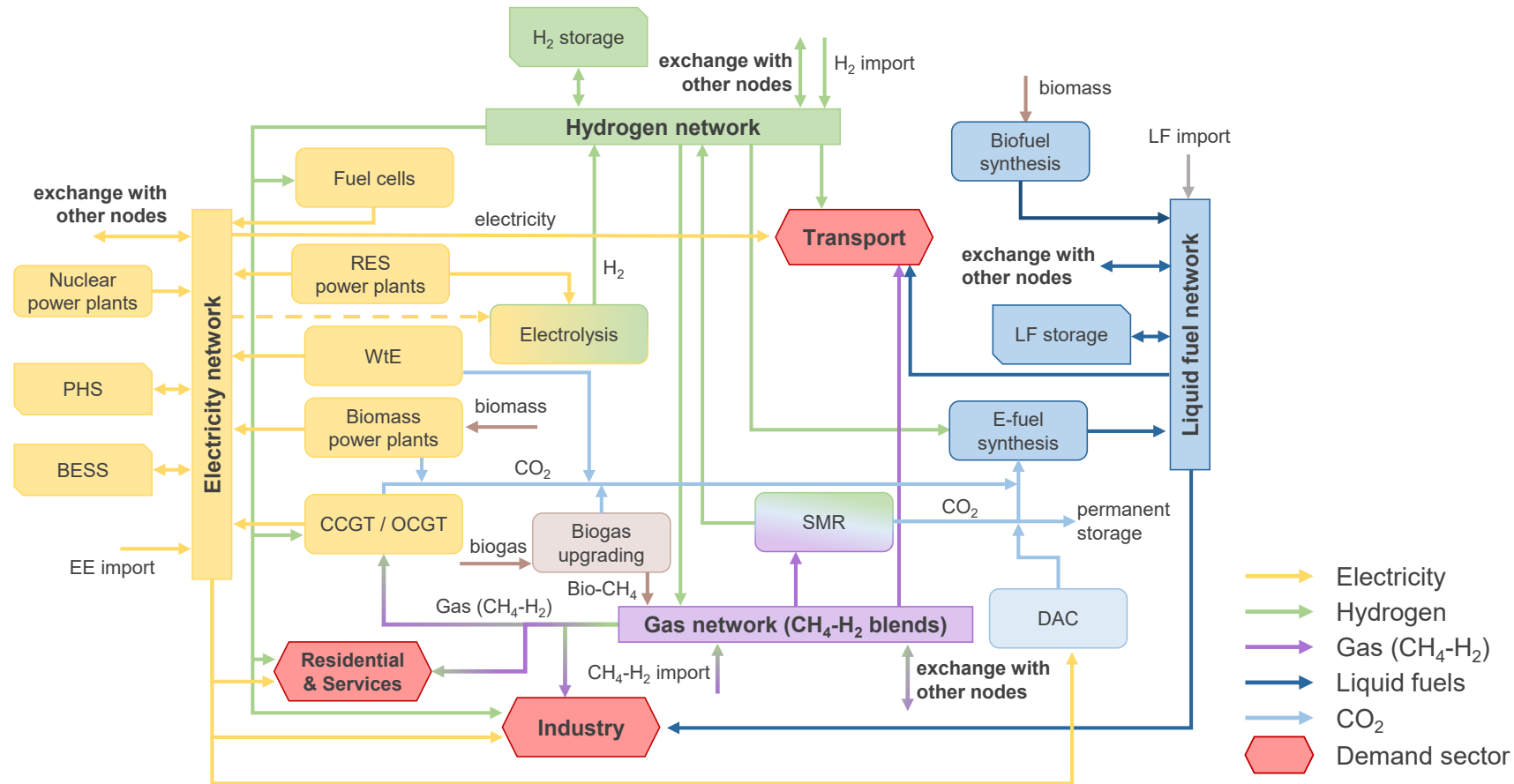
# OMNI-ES - Model structure



Original scheme of a single node:

- 4 energy vectors, with network and storage
- 3 end-use categories
- Inter-nodal exchanges
- Detailed CO<sub>2</sub> balances

# OMNI-ES - Model structure: CO<sub>2</sub> tracking and constraint



CO<sub>2</sub> emissions  
at point of use  
(*e.g.*, combustion)

+

CO<sub>2</sub> emissions  
related to  
supply chains

+

Unavoidable  
CO<sub>2</sub> emissions  
(*e.g.*, agriculture)

-

Net natural  
absorption  
(LULUCF)

-

Stored CO<sub>2</sub>  
(CCS)

≅

Zero

# Describing energy networks in energy system models

## Traditional approach

Energy system models traditionally consider a low number of spatial nodes and adopt a **copper -plate assumption within each node** , limiting infrastructure analysis to **energy flow exchanges between nodes (transmission level)**

## Limitations

- No insight on **infra -regional exchanges** , reverse flow, distribution network **congestion**
- Underestimation of **flexibility** needs

## Proposed solution

The OMNI-ES formulation is **upgraded** to represent the energy network with **multiple layers** within each node

### For each node:

- Define **three** levels (representative of HV, MV, LV)
- **Allocate** technologies according to connection options and differentiate investment costs
- Distinguish **losses** for energy flow exchanges between levels and within levels

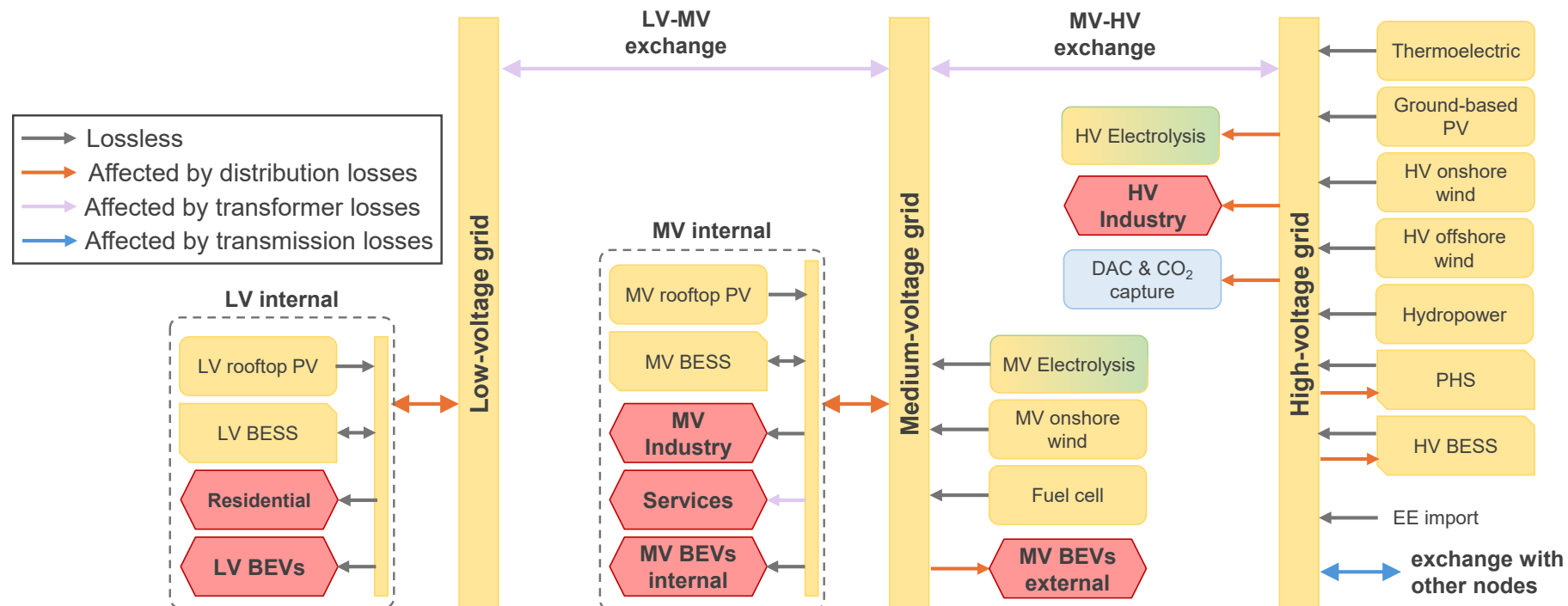
### Expected results:

- Variation of cost -optimal **distribution of resources**
- Impact of **Uplift Cost**
- Impact of network **upgrades**

# Modelling the multi-layer structure of energy networks

The **formulation** in OMNI-ES is extended to improve accuracy in modelling the electricity network (can be adapted to gas grid, hydrogen pipelines, CO<sub>2</sub> transport).

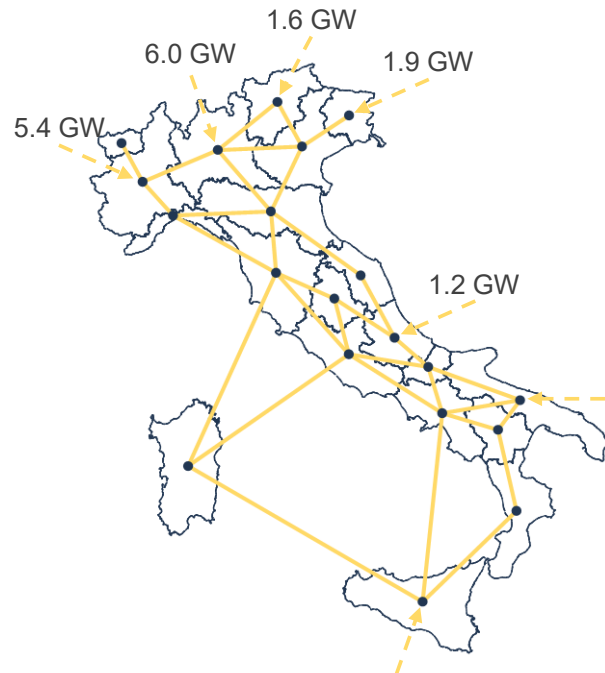
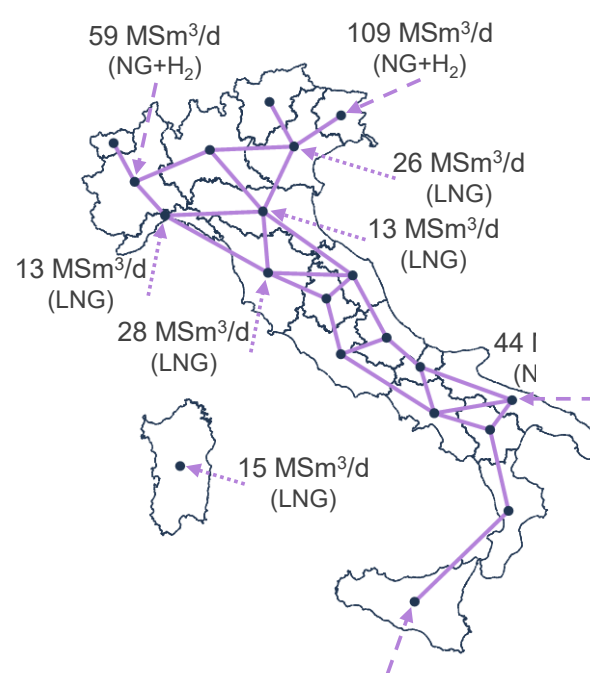
- *Method*: introduce **three layers in cascade** for the electricity network, reflecting the voltage levels of real-world grids (high, medium, low voltage – HV, MV, LV)
- *Goal*: assess, with a relatively simple model applied on a complex integrated energy system, the system behaviour in terms of **upward and downward energy flows** as well as changes in **installed capacities**



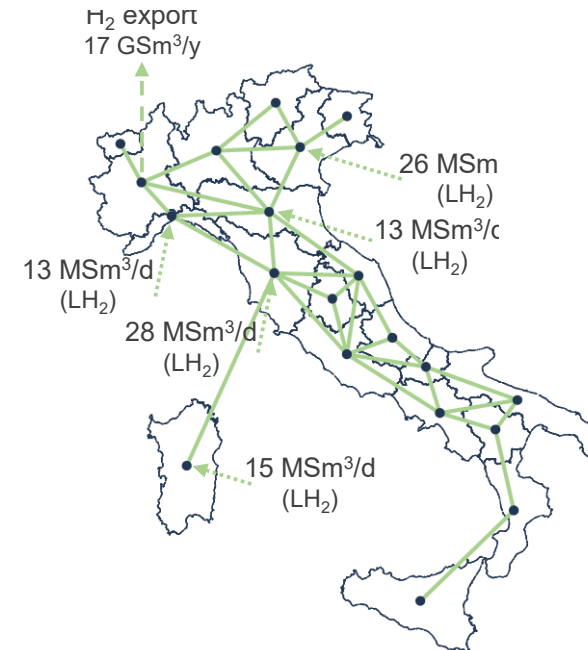
# Case study: Italy, Net -zero emissions (2050)

- Spatial dimension : **Italy** - Spatial resolution: administrative **regions** (NUTS-2)
- Environmental dimension: Economy-wide **net -zero** GHG emissions → target year 2050
- **Supply** side (optimised capacity): **Renewable** power generation (potential based on land, resource, technical constraints)
- **Flexibility** side (optimised capacity): BESS, Electrolysis + H<sub>2</sub> storage
- **Demand** side (assigned): electricity, hydrogen, gas (CH<sub>4</sub>-H<sub>2</sub> blend), liquid fuels in industrial, transport, residential&services

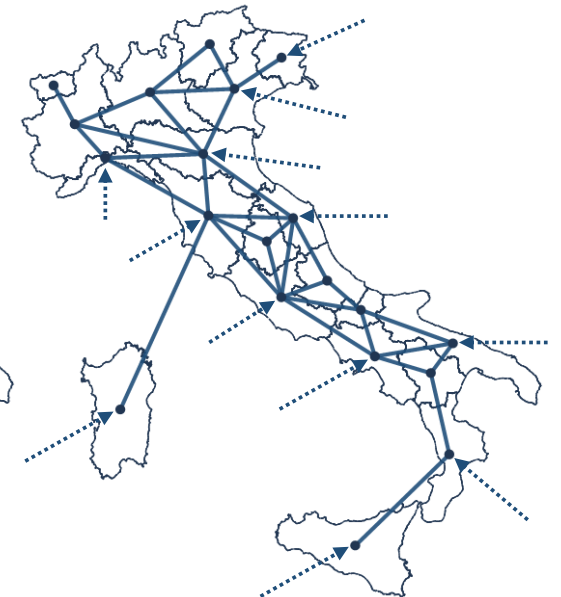
a) Electricity

b) Gas (CH<sub>4</sub>-H<sub>2</sub>)

c) Hydrogen

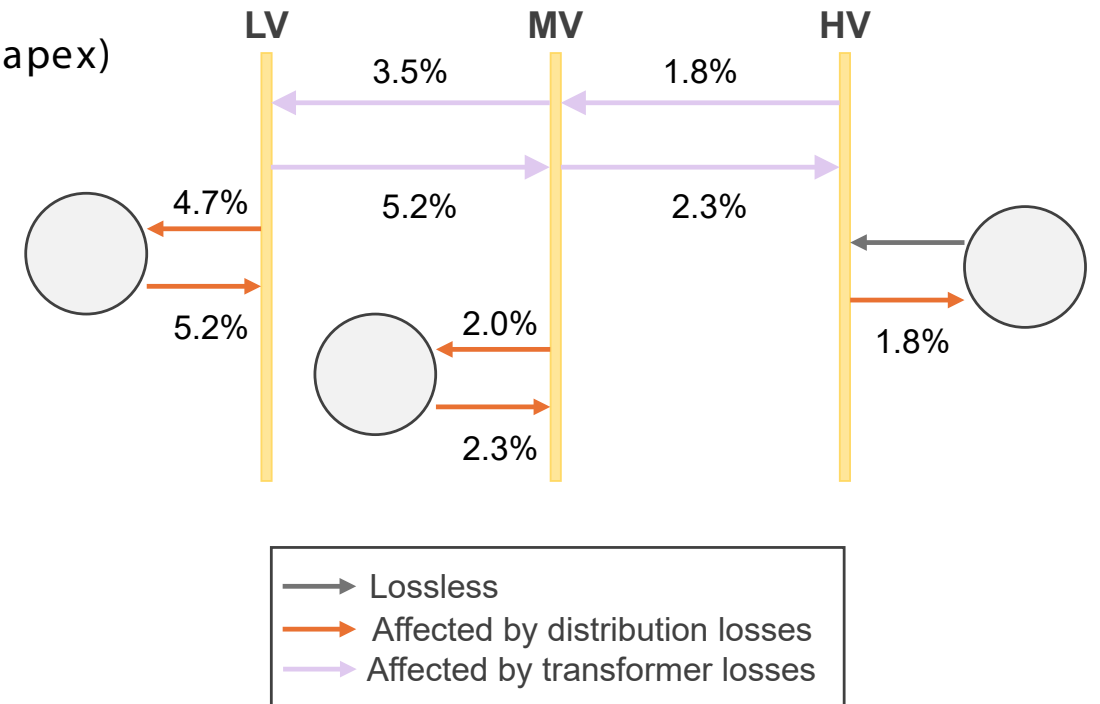


d) Liquid fuels

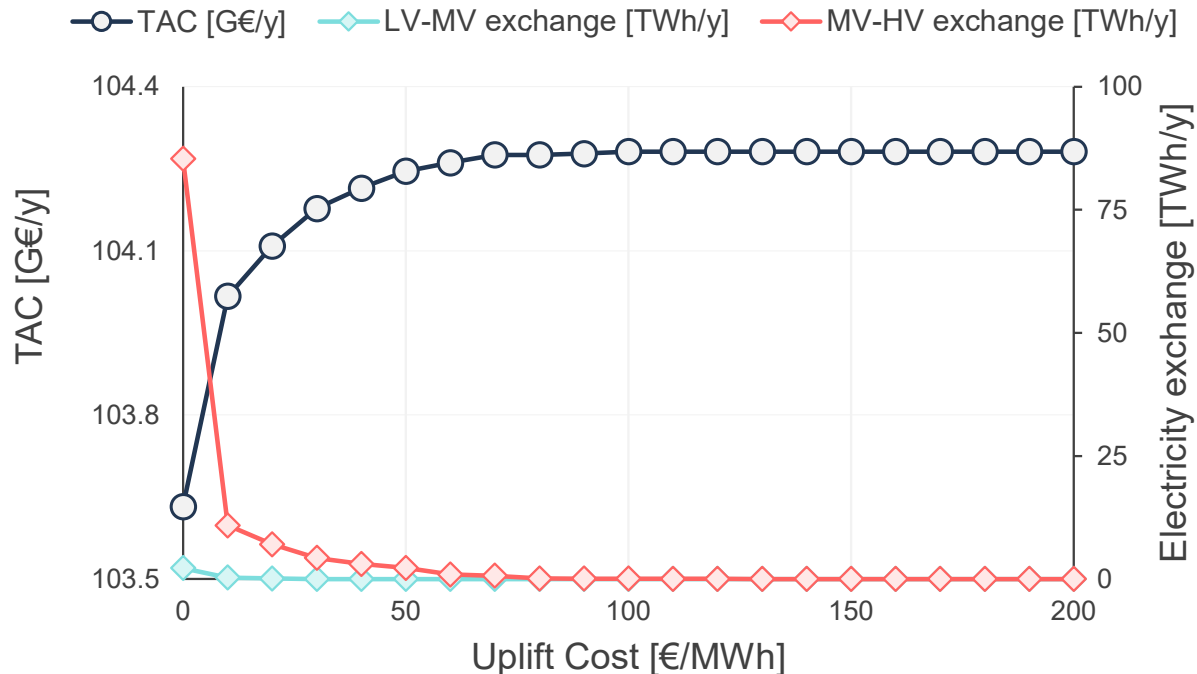


# Case study: Assumptions and data

- Generation, storage, and consumption may occur at the **different levels** .
- Medium- and low-voltage levels feature an **“internal ” sub-node**
  - Represents the **aggregate** of subsystems that may benefit from self-consumption of renewable electricity
  - Allows to properly **allocate losses** and favour **self-consumption**
- **PV**: rooftop on LV (higher capex), ground on MV and HV (lower capex)
- **Wind** : on MV or HV
- **BESS**: bound to PV on LV and MV, at grid level on HV
- **Electrolysis** : on MV or HV
- Loss values from current TSO data

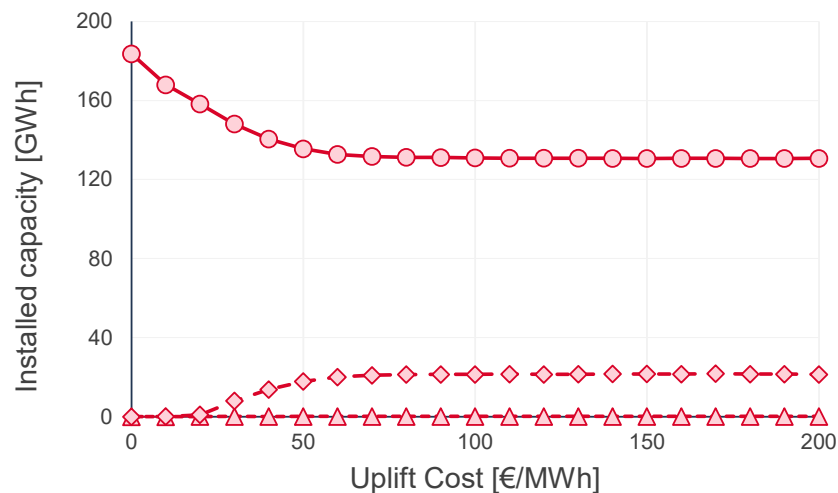
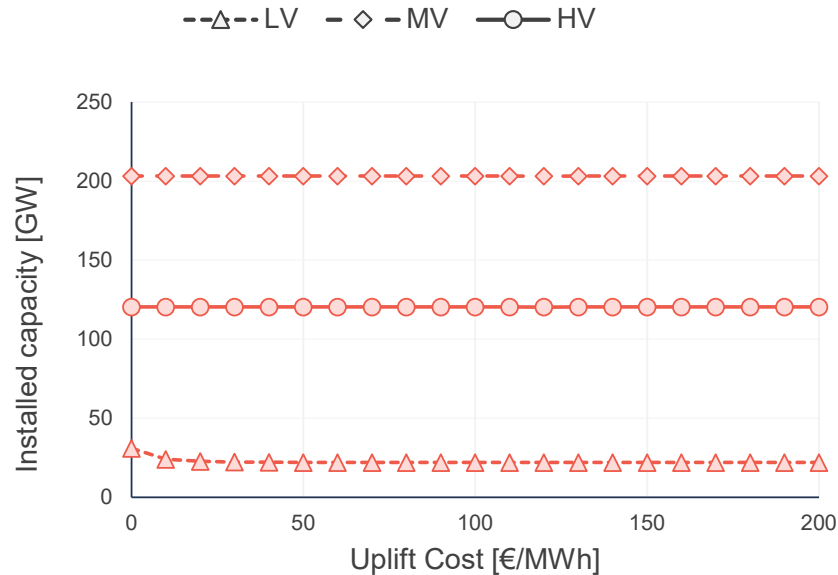
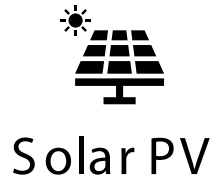


# Results: Impact of Uplift Cost



- Electricity upwards exchanges from MV to HV are more relevant than from LV to MV
  - *Consistent with larger share of electric loads in MV layer and lower installation costs*
- The upward flows rapidly decrease as soon as an uplift cost is introduced (drop from 10% to 1-2% of total electricity consumption)
  - *Average transport fee in 2023: 8.5 €/MWh<sub>e</sub>*
- A **plateau** for ULC above 70 €/MWh<sub>e</sub>, removing all upwards exchanges and stabilizing the system configuration (invariant TAC).
- **Impact** of upward flow constraints on **TAC** is **minimal**: 1% increase from null UPL to plateau

# Results: Impact of Uplift Cost



- No significant changes in total capacities
- Variations in capacity distribution mainly for flexibility systems
  - 30-50% reduction of battery and electrolysis capacities in HV layers, balanced by growth in MV layers
- Slight reduction of PV in LV layers, balanced by an increased presence of wind plants in the HV layer, redirecting the system towards conventional downward operation
- Impact on curtailment and import is minimal

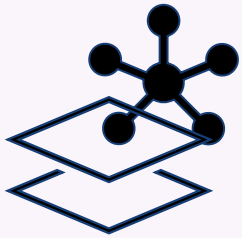
# Results: Impact of upgraded network

- The analysis considered current grid losses, which may **improve** in coming years
- A **second round of runs** is performed with **lower losses** (1.8% on each transfer direction, called “upgraded grid”):
  - **minor overall impact** (-6% BESS capacity, adopted only in HV; -2% TAC)
  - **invariant trend** in the structure of **flows** (conventional up-down, with low uplift)

	Parameter	Single -layer	Multi -layer *	
		Baseline	Standard grid	Upgraded grid
Energy vector total consumption	Electricity [ TWh <sub>e</sub> /y]	684	717	710
	Hydrogen [ TWh <sub>LHV</sub> /y]	177	217	213
	Methane [ TWh <sub>LHV</sub> /y]	107	98	98
	Liquid fuels [ TWh <sub>LHV</sub> /y]	130	130	130
Power generation capacity	<b>Photovoltaic [ GW<sub>e</sub>]</b>	<b>288</b>	<b>347</b>	<b>339</b>
	Wind (onshore)[ GW <sub>e</sub> ]	100	144	142
	<b>Thermal [ GW<sub>e</sub>]</b>	<b>11</b>	<b>20</b>	<b>19</b>
H <sub>2</sub> production	Electrolysis [GW <sub>LHV,H2</sub> ]	49	60	58
Storage capacity	<b>BESS [GWh<sub>e</sub>]</b>	<b>90</b>	<b>168</b>	<b>158</b>
	Hydrogen [ GWh <sub>LHV</sub> ]	4420	5427	5106
Economics	<b>Total Annual Cost [b €/y]</b>	<b>87</b>	<b>104.0</b>	<b>102.4</b>

\* Uplift Cost: 10 €/MWh<sub>e</sub>

# Conclusions



## Tracking multi-layer structure of energy networks

- Impact on configuration and technology choices
- Changes in **flow trends**, with minor impact of loss values
- Low **UpLift Cost** shifts flexibility elements to lower level, if at higher capex



## Insights to decision making

- **Infrastructure** can be a bottleneck
- Distributed generation calls for **distributed flexibility enablers**
- Cost structure of regulated network may affect investment choices



## Broader context (to investigate?)

- Multiplicity of stakeholders (prosumers, industrial investors, network management, ...)
- Possible **extension** to other networks (gas grid, hydrogen, ...)

**Thank you for your attention!**

# Data: Techno -economic assumptions

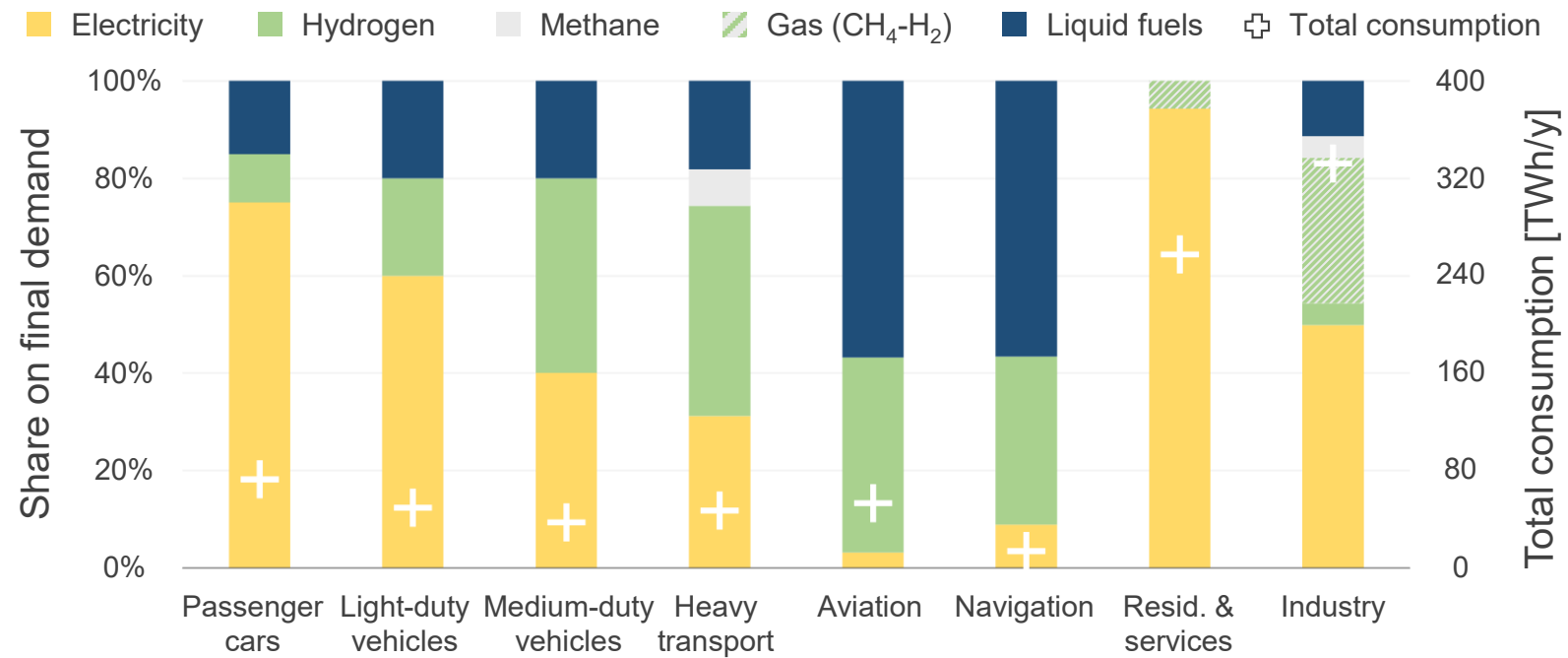
PV technology	Voltage level	CAPEX [€/kW <sub>p</sub> ]	Fixed OPEX [€/kW <sub>p</sub> /y]	Lifetime [y]
Residential rooftop	Low voltage	640	8.9	25
Service and industry rooftop	Medium voltage	410	7.5	25
Ground -based utility scale	High voltage	290	7.4	25

Wind technology	Voltage level	CAPEX [€/kW <sub>e</sub> ]	Fixed OPEX [€/kW <sub>e</sub> /y]	Lifetime [y]
MV onshore wind	Medium voltage	950	42	30
HV onshore wind	High voltage	790	35	30

BESS technology	Voltage level	CAPEX [€/kWh <sub>e</sub> ]	Fixed OPEX [%of CAPEX/y]	Lifetime [y]	Energy -to -power ratio [h]
Dedicated BESS - LV	Low voltage	300	2.5%	15	4
Dedicated BESS - MV	Medium voltage	200	2.5%	15	4
Utility -scale BESS - HV	High voltage	160	2.5%	15	4

Electrolysis technology	Voltage level	CAPEX [€/kW <sub>e</sub> ]	Fixed OPEX [% of CAPEX/y]	Lifetime [y]	Efficiency [ -]
Medium -voltage electrolysis	Low voltage	240	2	20	0.65
High -voltage electrolysis	High voltage	200	2	20	0.65

# Case study: Energy vectors demand



# Impact on capacities

