Global interconnected and sustainable electricity system

effects of storage, demand response and trading rules

Presented by C1.44 members

Paris – 30 August 2022

16:10 – 18:00

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Antonio ILICETO

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Charlie SMITH

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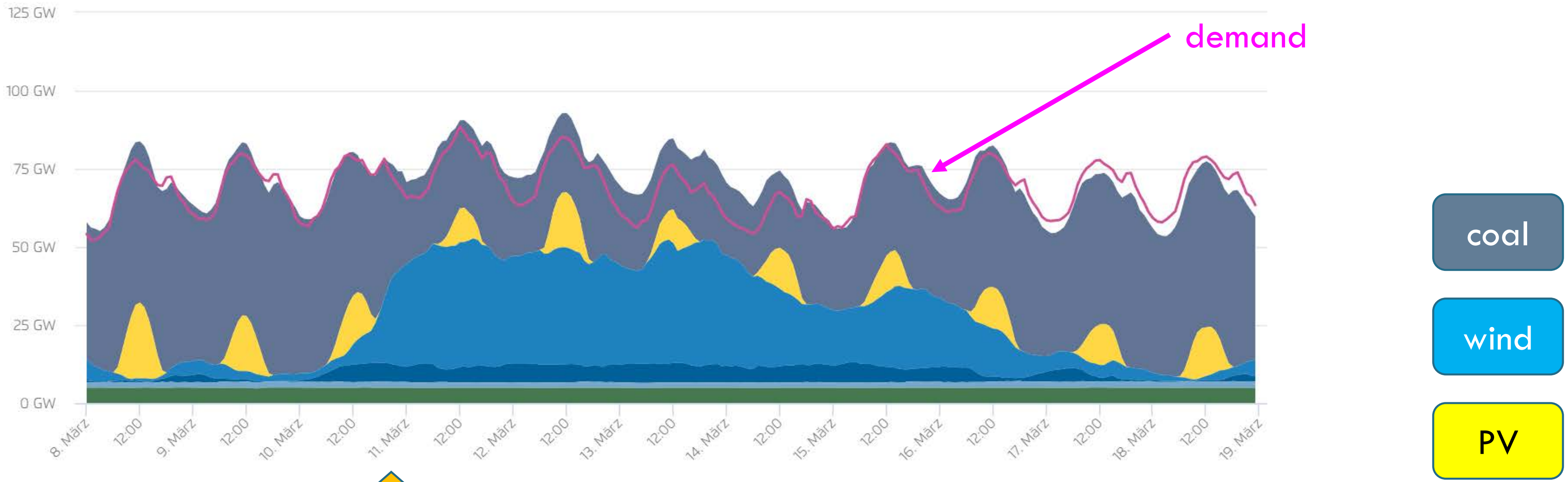
Introduction

Gérald Sanchis

Development of RES for carbon-free energy future

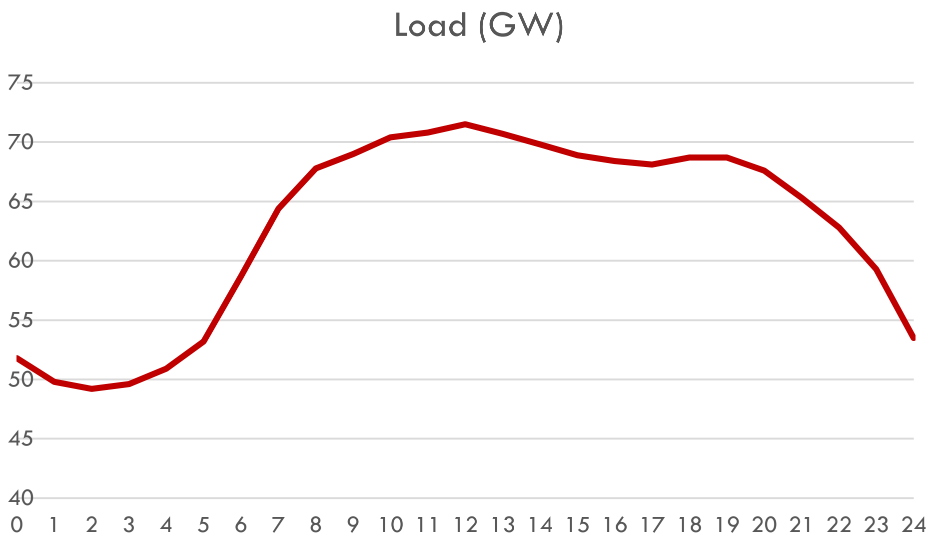
Present situation: Germany case (8 March – 18 March 2021)



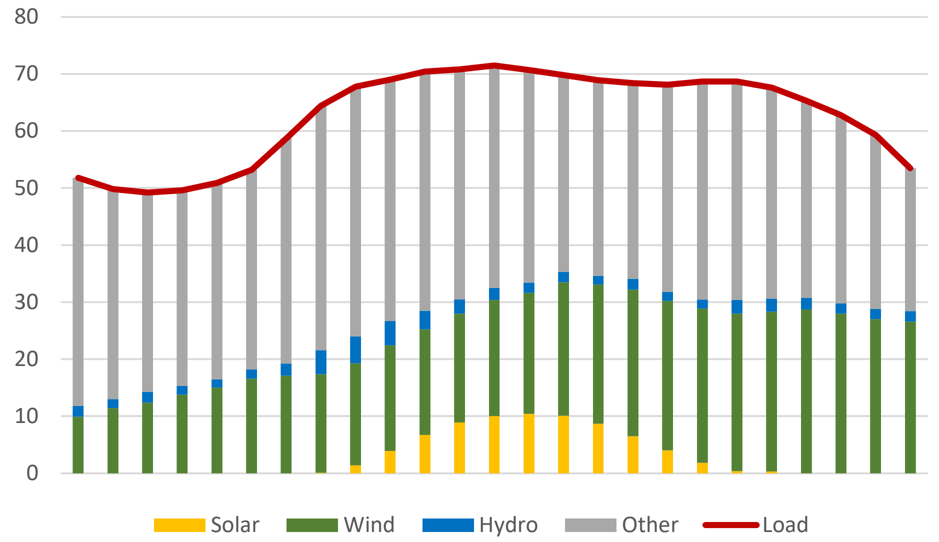
Fast increase of wind from 0 GW to 50 GW

How to balance the load ?

Nowadays



Dayly load (Germany – 31 March 2022)



Nowadays, intermittent sources are supplemented by non-intermittent sources (nuclear, gas, coal, oil,...) to balance the load.

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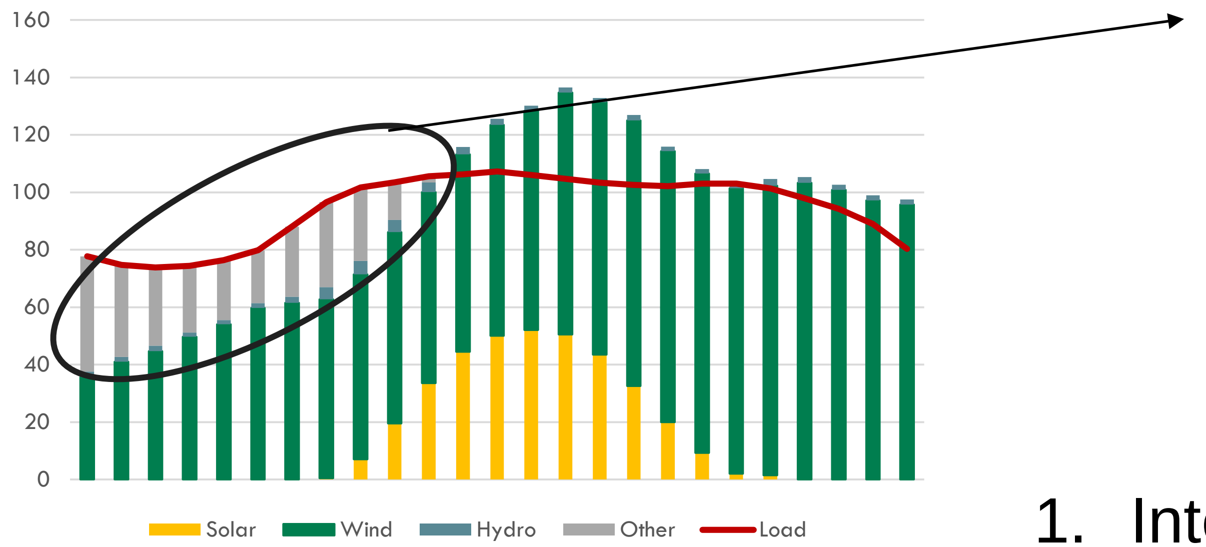
How to balance the load ?

In the future (carbon-free time)



➢How to supplement RES to balance the load with a carbon-free solution?

Main solution

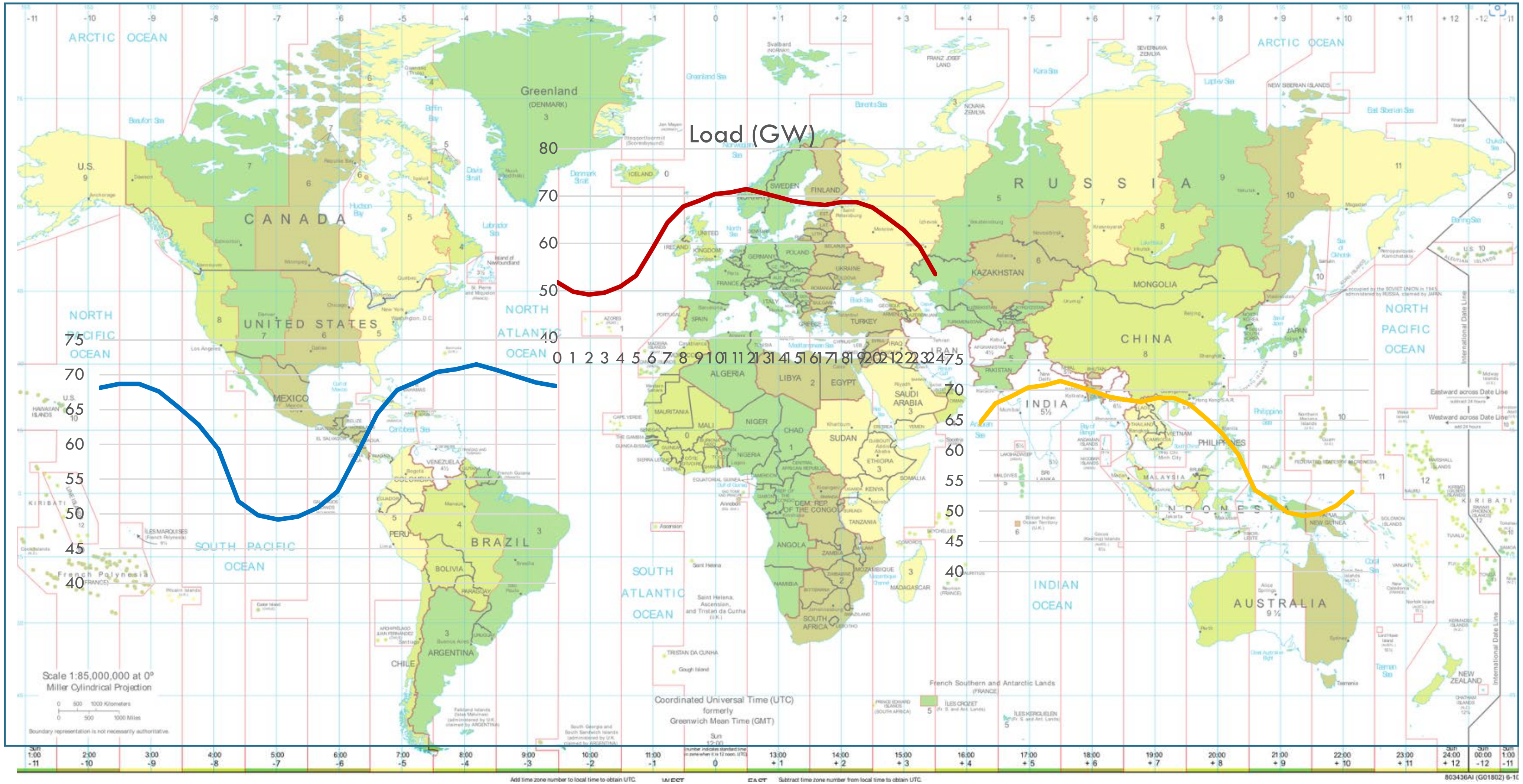
➢Conventional generation (gas with CCS or nuclear).

Alternative Solutions

1. Interconnections
2. Storage
3. Demand Response
4. Combination of all or part

Interconnections - motivation

Time-zone differences



- 7 hours

0

+ 7 hours

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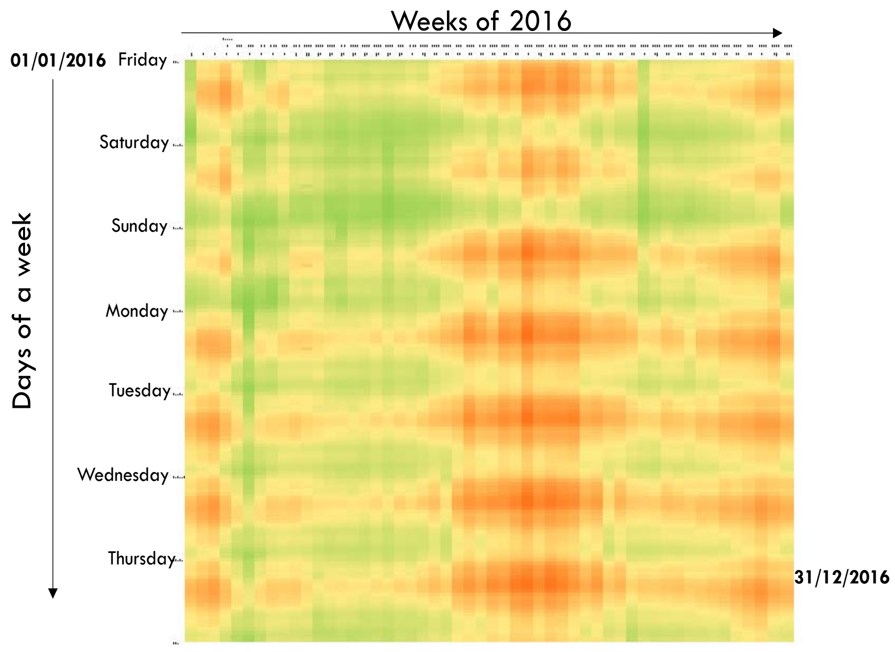
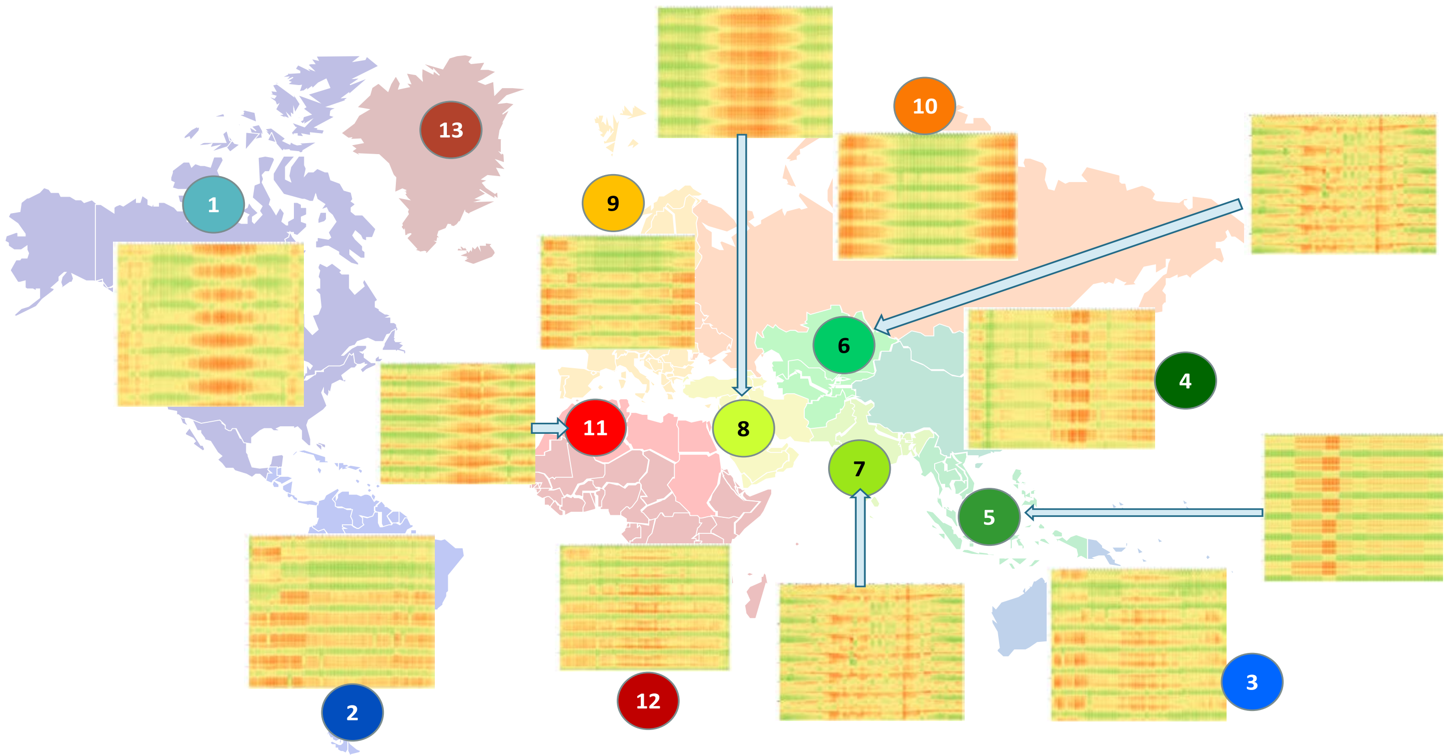
Interconnections - motivation

Seasonal effect

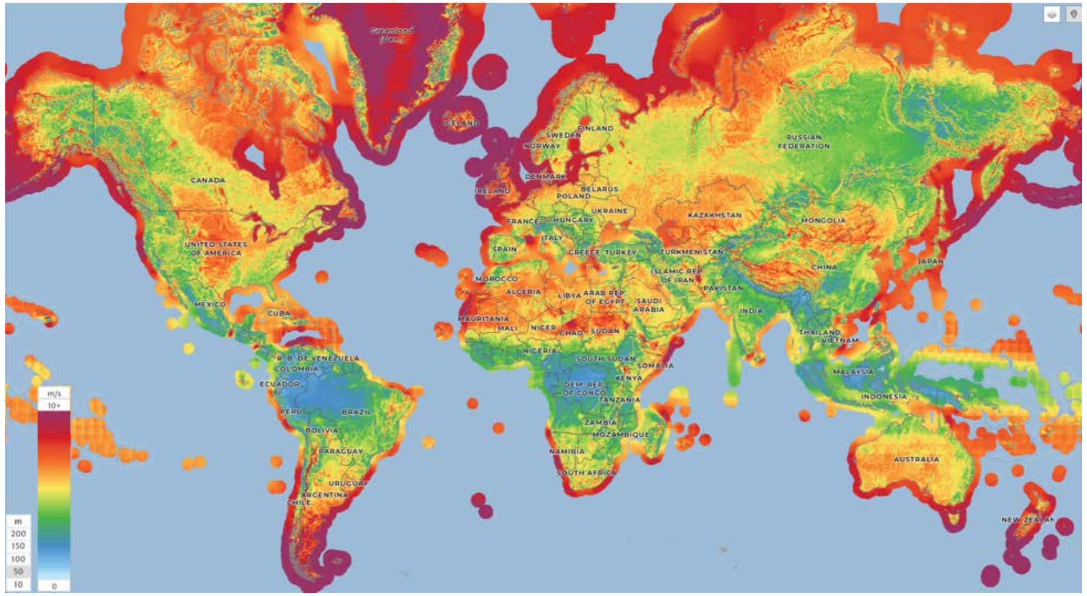


Electricity consumption - all world

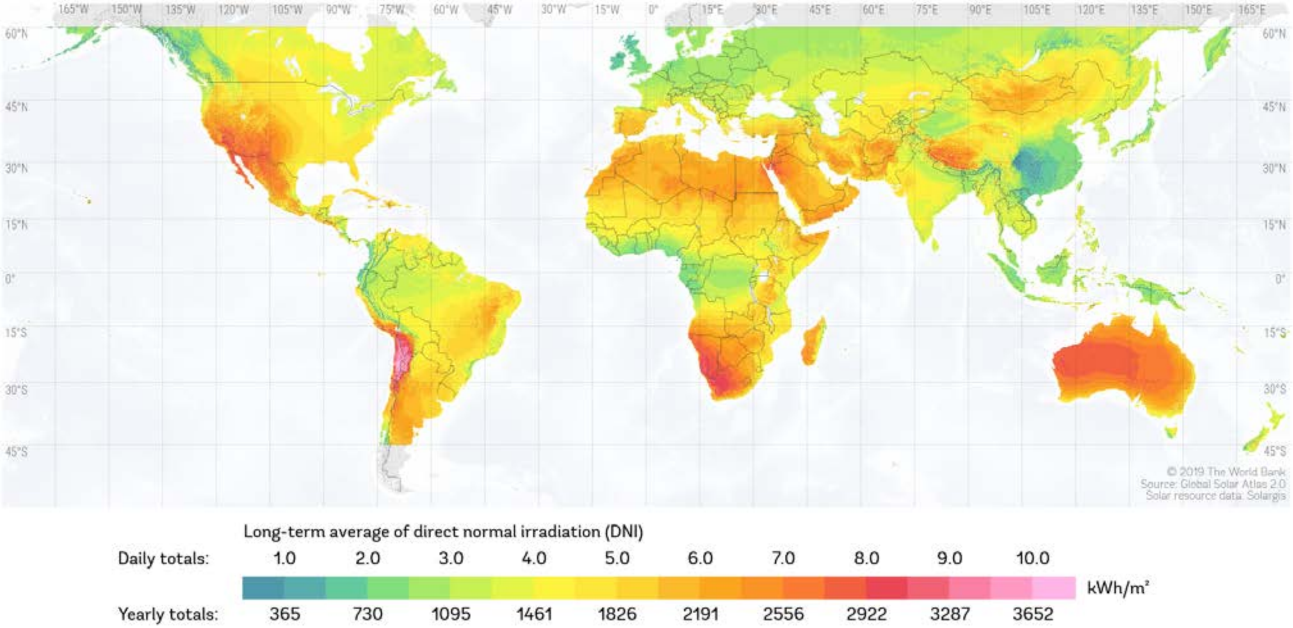


Interconnections - motivation

RES potential



Wind potential



Solar potential

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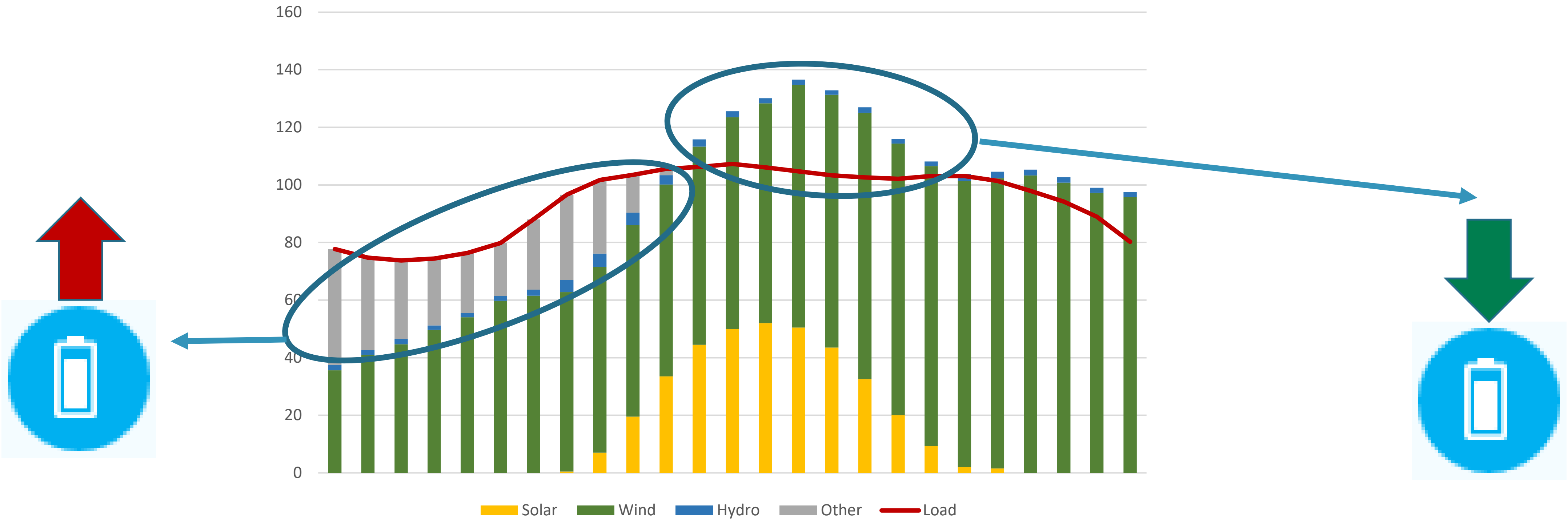
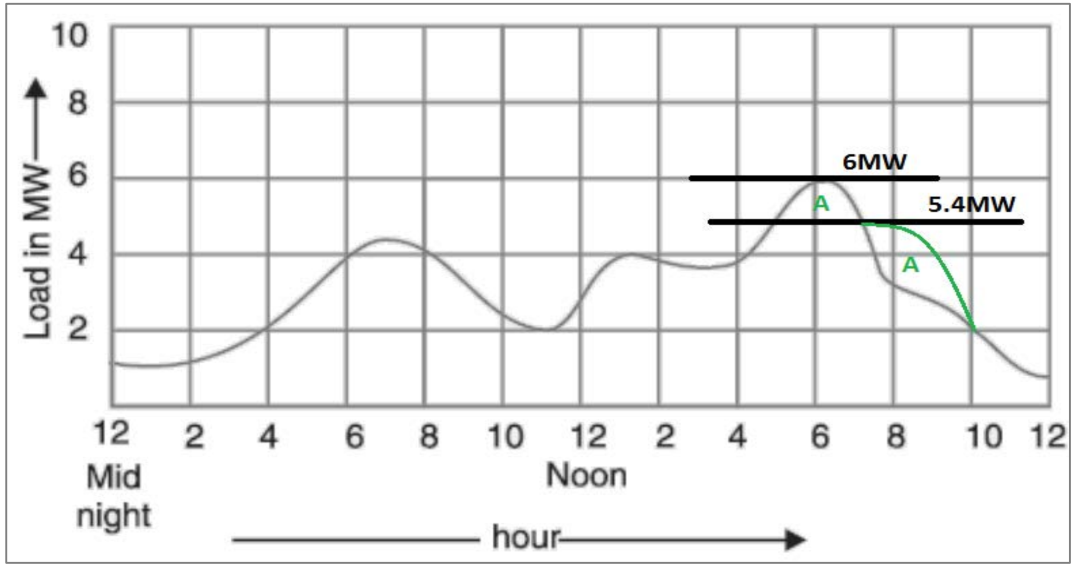
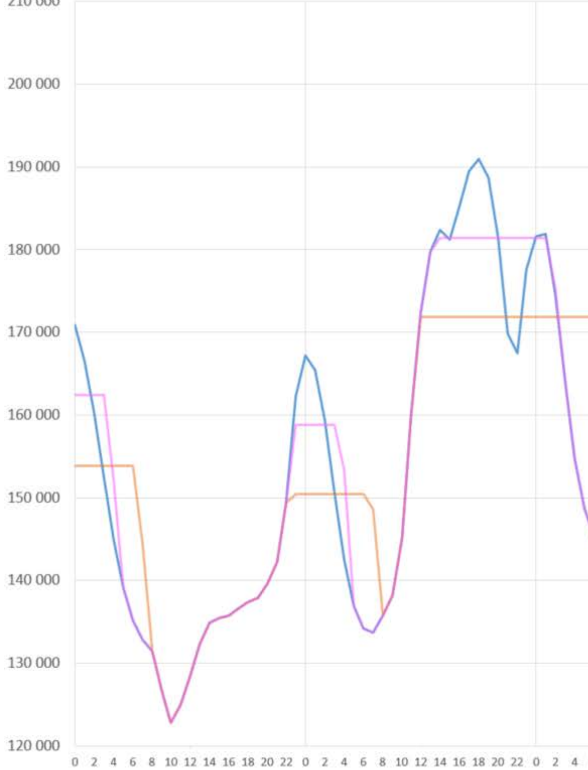
Storage motivation



Demand Response motivation





DR aims at reducing the peak load by moving time-of-use of some electricity consumption.

The threshold of peak load shaving retained is 10%, the same for all regions. The energy used (**A** in the diagram) is shifted to the following hours after the peak.

This solution should reduce the generation investment capacity, requested at peak periods.

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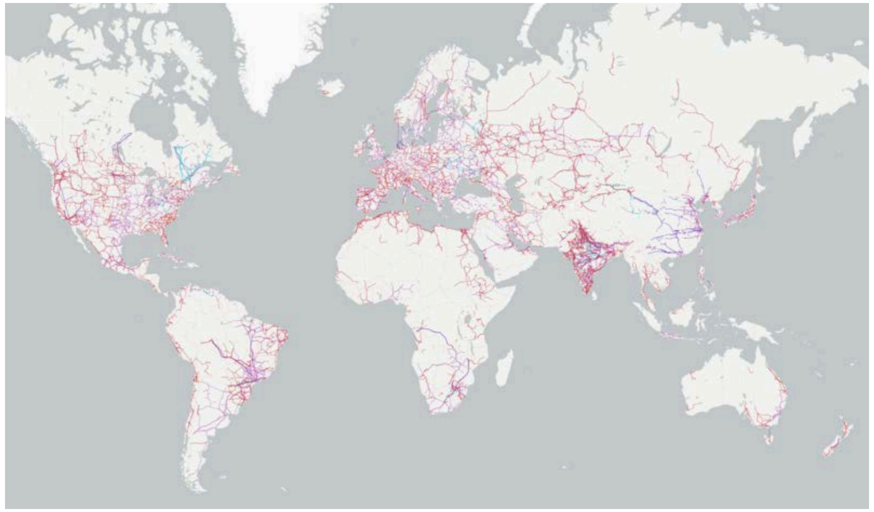
Data collection

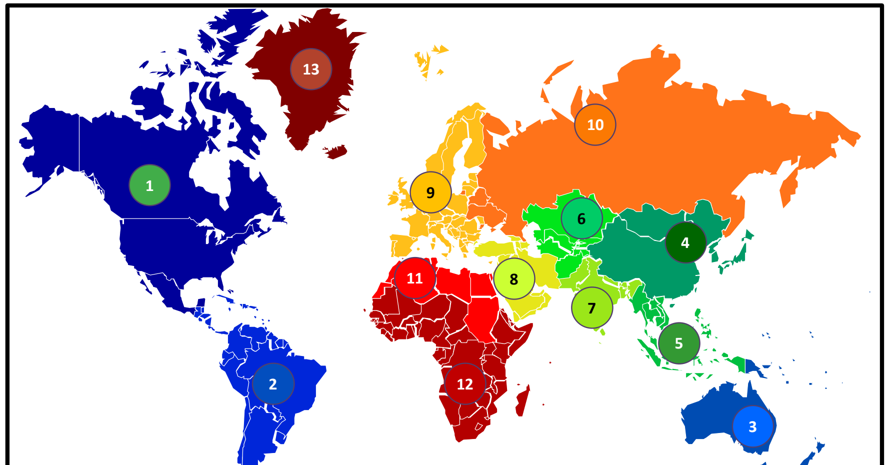
Gérald SANCHIS

Model: Regions

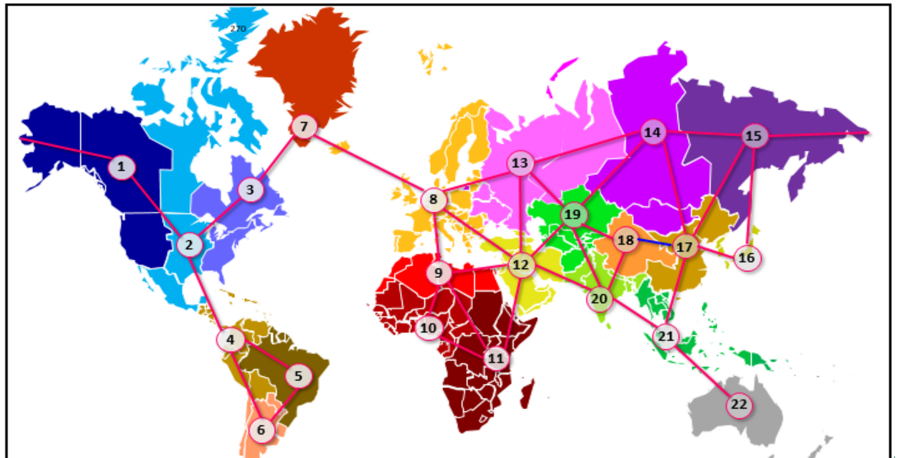
World split according to borders, with balanced area and taking into account the current electrical network.

➔ More consistency in the model with 22 regions (instead of 13).





C1.35



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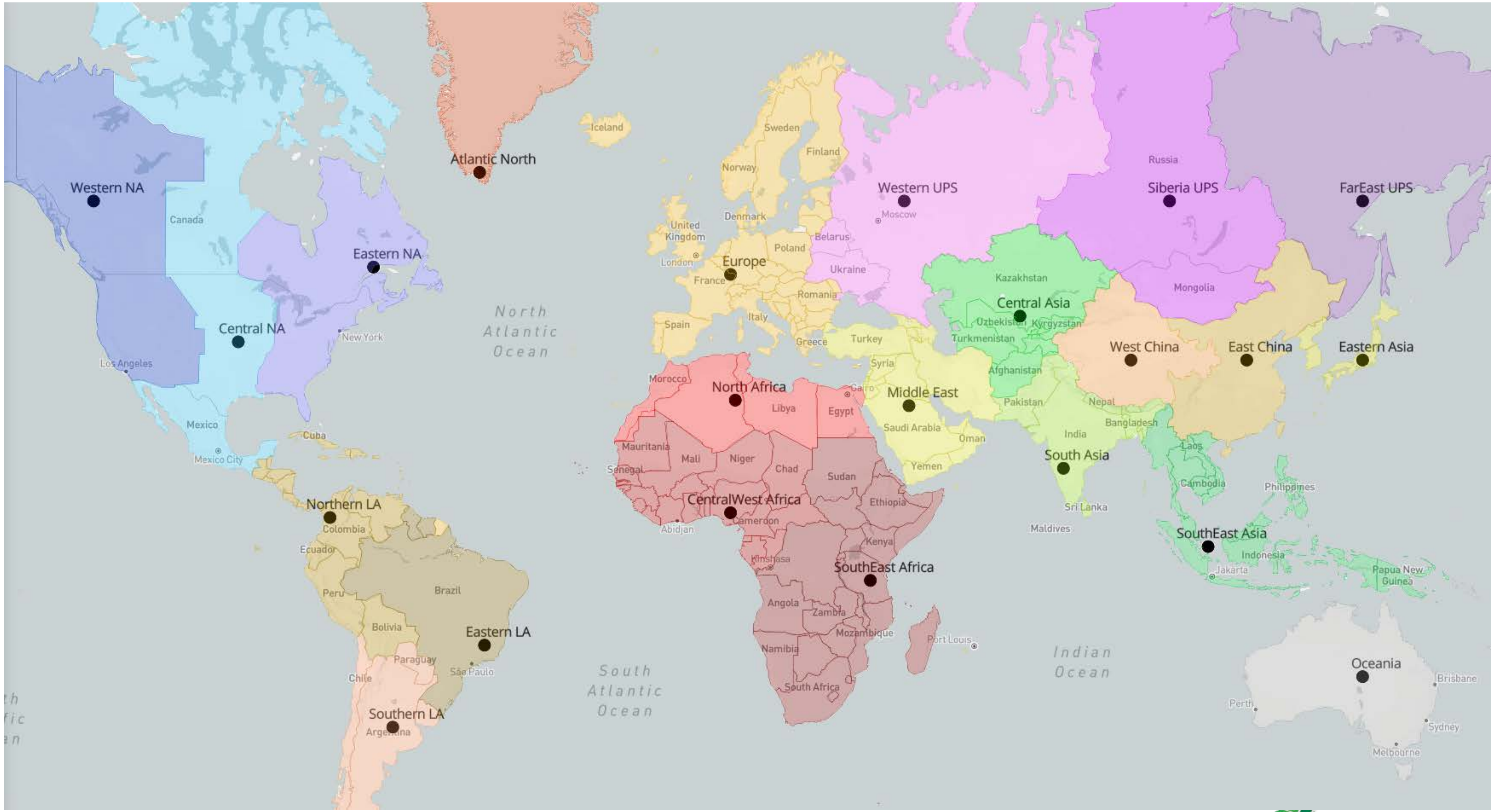
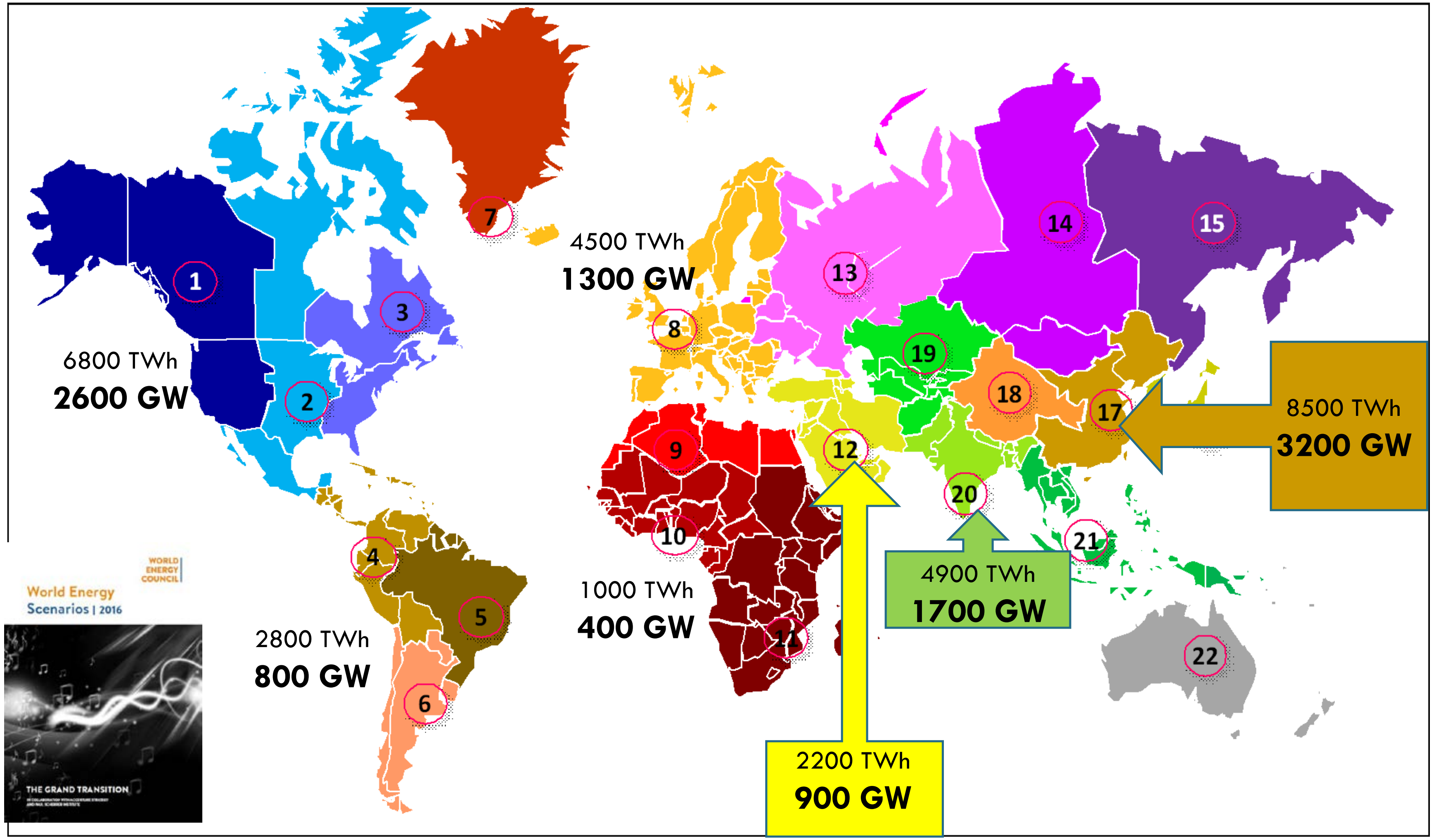
Model: World divided in 22 zones

01 Western North America
02 Central North America
03 Eastern North America
04 Northern Latin America
05 Eastern Latin America
06 Southern Latin America
07 Atlantic North
08 Europe
09 North Africa
10 Central West Africa
11 Southeast Africa
12 Middle East
13 Western UPS
14 Siberia UPS
15 Fareast UPS
16 Eastern Asia
17 East China
18 West China
19 Central Asia
20 South Asia
21 Southeast Asia
22 Oceania



Input data for electricity generation forecast by 2050

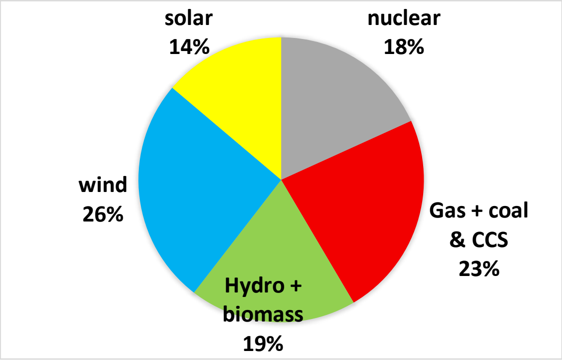
Case #1: 2050, without additional storage, without DR, without interconnection.



2050
40000 TWh
14000 GW

650Mt CO_2/yr

50€/MWh



2020
25000 TWh
6600 GW

13500Mt CO_2/yr

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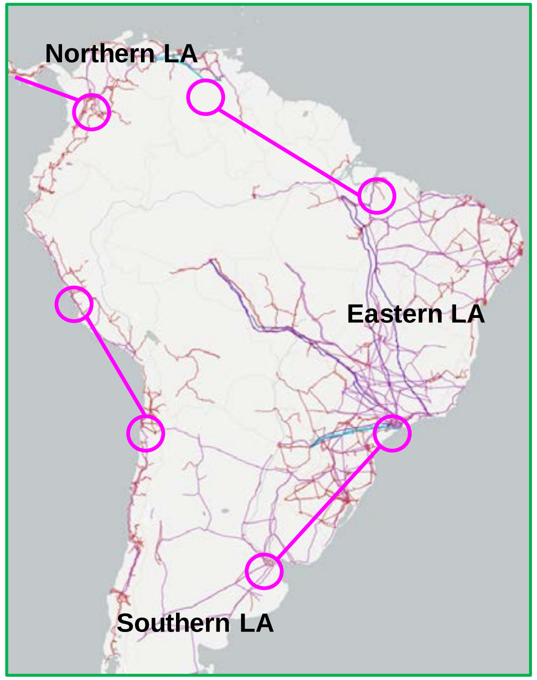
Model: corridors

Methodology:

1. selection of lines according to the current network



2. Identification of the path, the length, and line technology (OHL or cable).

➔ **More robust assessment.**

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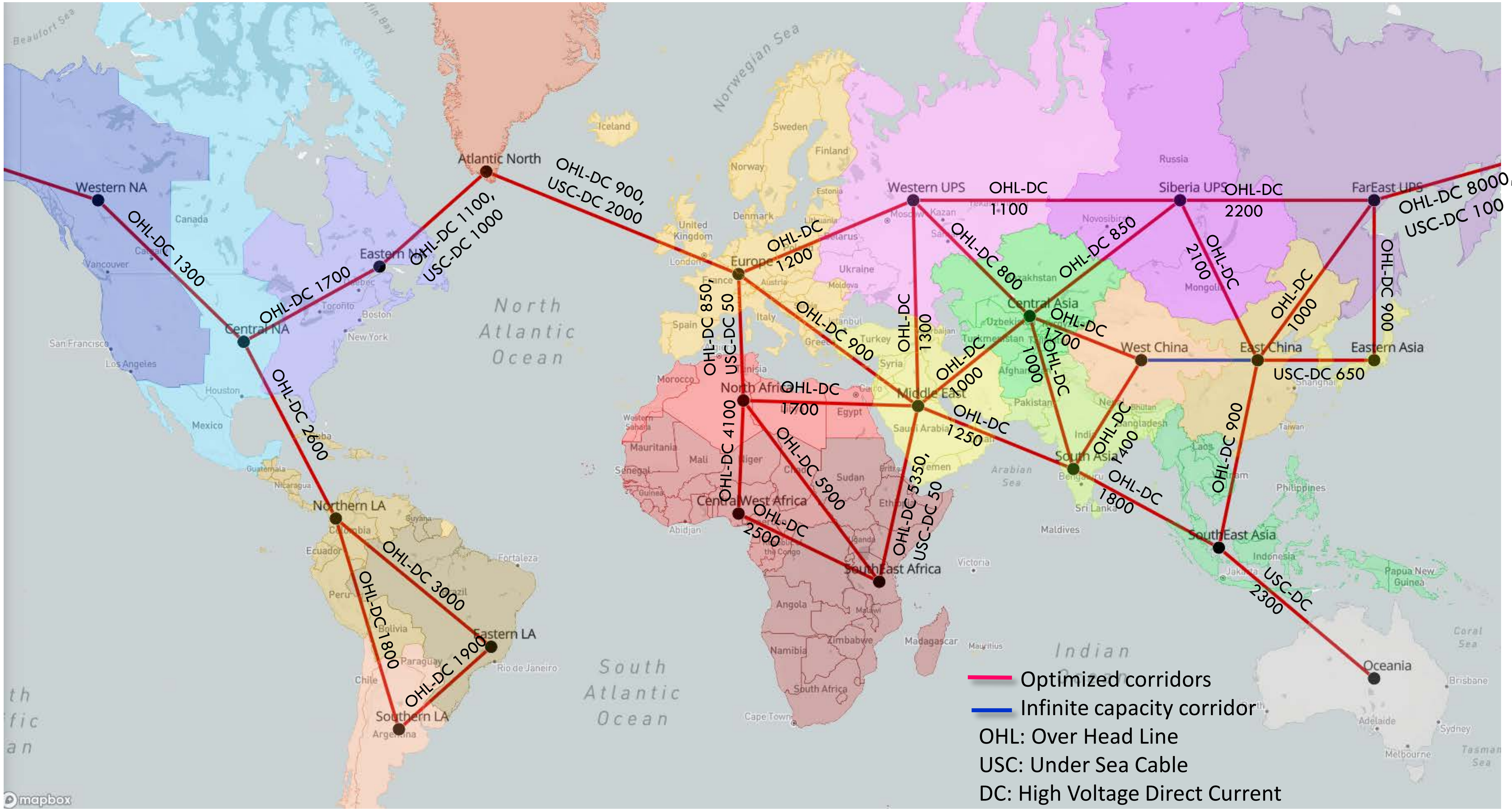
Interconnections selected

35 corridors (OHL HVDC or USC HVDC)

Total corridors length: 70250 km (90% OHL, 10% USC)



	Unit cost
DC OHL	0.26 M€/km/GW
DC USC	1.6 M€/km/GW

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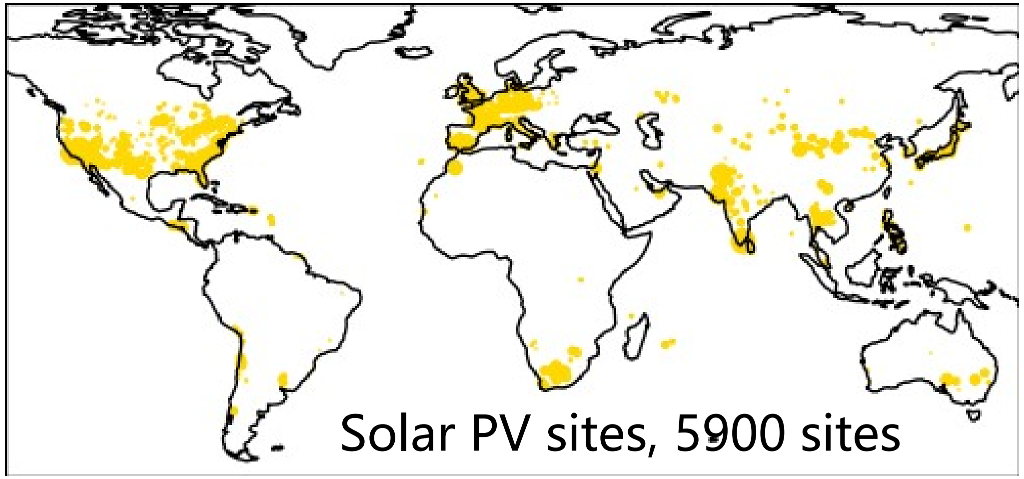
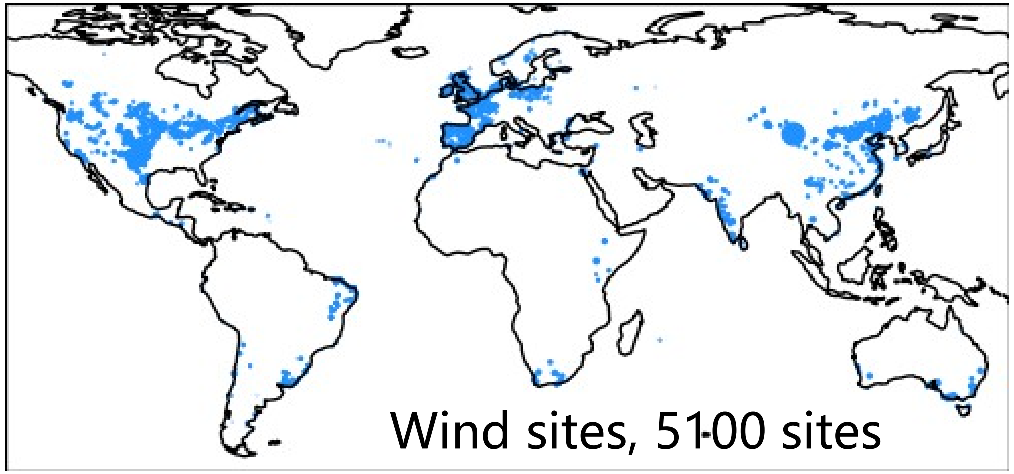
Model: capacity factors

Methodology:

Potential of RES assets are derived from the capacity factors of existing (and planned) plants, validated with the IRENA RES generation dataset.





NB: This leads to a more conservative estimation of RES generation potential, thus avoiding the caveats identified in C1.35 (Central Asia wind). Where data is missing (North Atlantic), reanalysis data is used.

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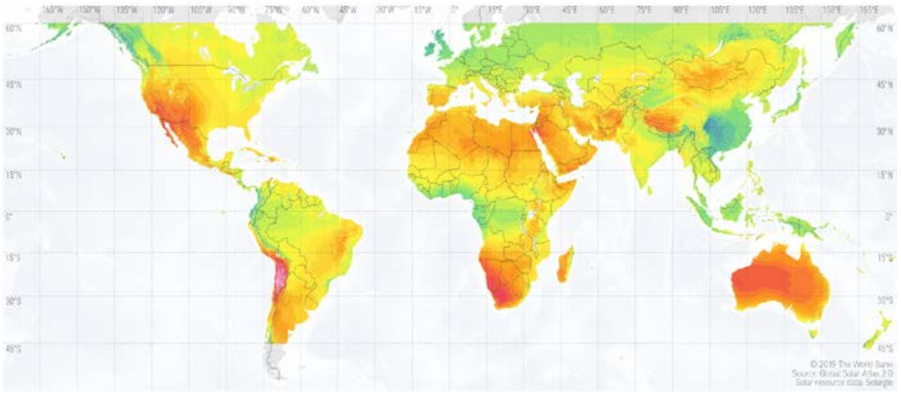
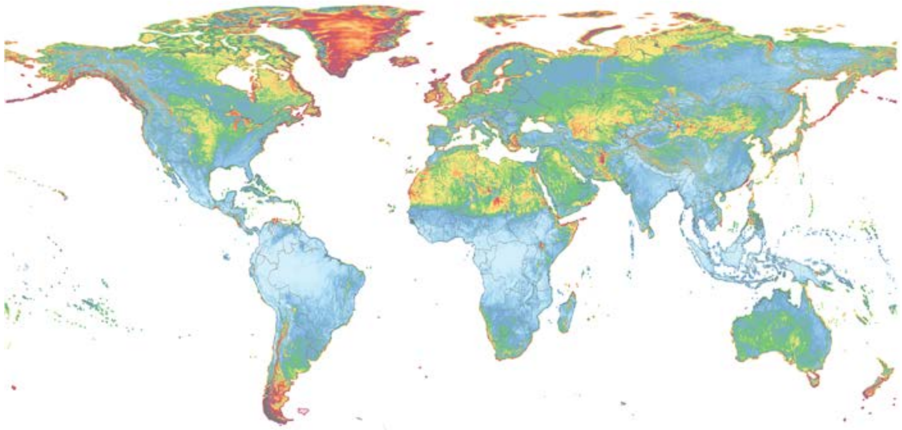
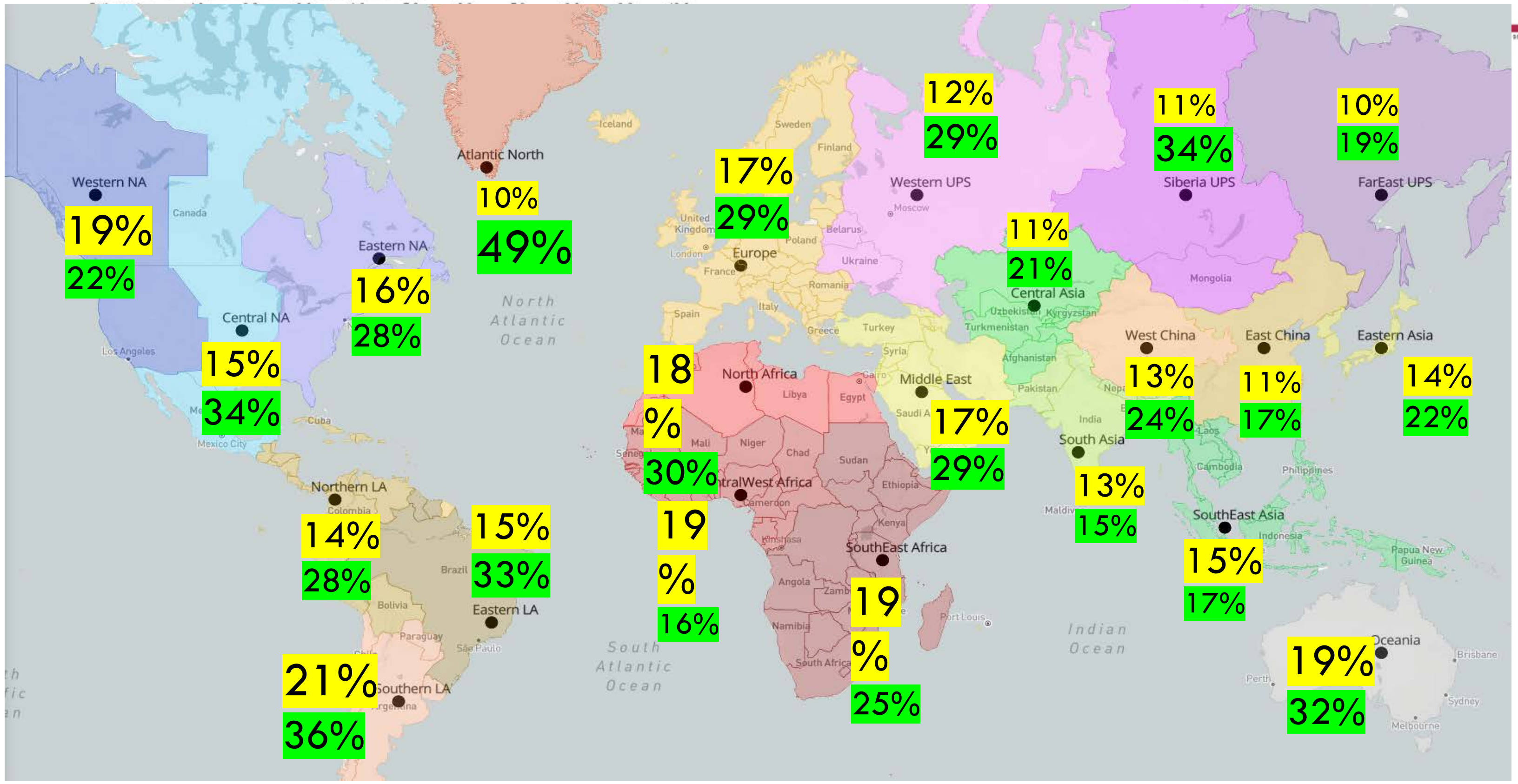
Model: capacity factors



Long-term average of direct normal irradiation (DNI)





Solar PF: from 10 to 21%
Wind PF: from 16 to 49%

For each region, the yearly sun and wind power factor patterns have been shaped through the hourly average values derived from the existing and planned solar/wind power plants validated with the IRENA RES generation dataset.

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RES: Solar PF in a winter day *(North Hemisphere)*

Zones	01 Western NA	02 Central NA	03 Eastern NA	04 Northern LA	05 Eastern LA	06 Southern LA	07 Atlantic North	08 Europe	09 North Africa	10 Central West Africa	11 SouthEast Africa	12 Middle East	13 Western UPS	14 Siberia UPS	15 FarEast UPS	16 Eastern Asia	17 East China	18 West China	19 Central Asia	20 South Asia	21 SouthEast Asia	22 Oceania	World
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25/02/2050 01:00	32	3	0	0	0	0	0	0	0	0	0	0	0	0	12	36	19	7	0	0	23	65	9
25/02/2050 02:00	12	0	0	0	0	0	0	0	0	0	0	0	0	2	21	43	33	22	2	3	40	67	11
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26/02/2050 02:00	11	0	0	0	0	0	0	0	0	0	0	0	0	5	20	32	33	14	3	3	40	63	10

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RES: Solar PF in a summer day *(North Hemisphere)*

Zones	01 Western NA	02 Central NA	03 Eastern NA	04 Northern LA	05 Eastern LA	06 Southern LA	07 Atlantic North	08 Europe	09 North Africa	10 Central West Africa	11 SouthEast Africa	12 Middle East	13 Western UPS	14 Siberia UPS	15 FarEast UPS	16 Eastern Asia	17 East China	18 West China	19 Central Asia	20 South Asia	21 SouthEast Asia	22 Oceania	World
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25/07/2050 22:00	64	37	25	18	0	10	6	0	0	0	0	0	0	0	4	25	0	0	0	0	0	15	9
25/07/2050 23:00	57	28	12	8	0	0	3	0	0	0	0	0	0	1	9	37	3	0	0	0	2	27	9
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26/07/2050 02:00	20	3	0	0	0	0	0	0	0	0	0	0	2	21	25	51	27	25	10	4	25	50	12

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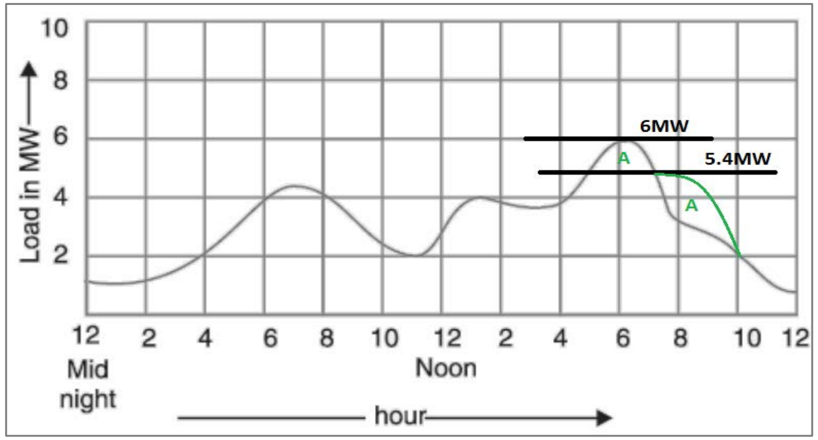
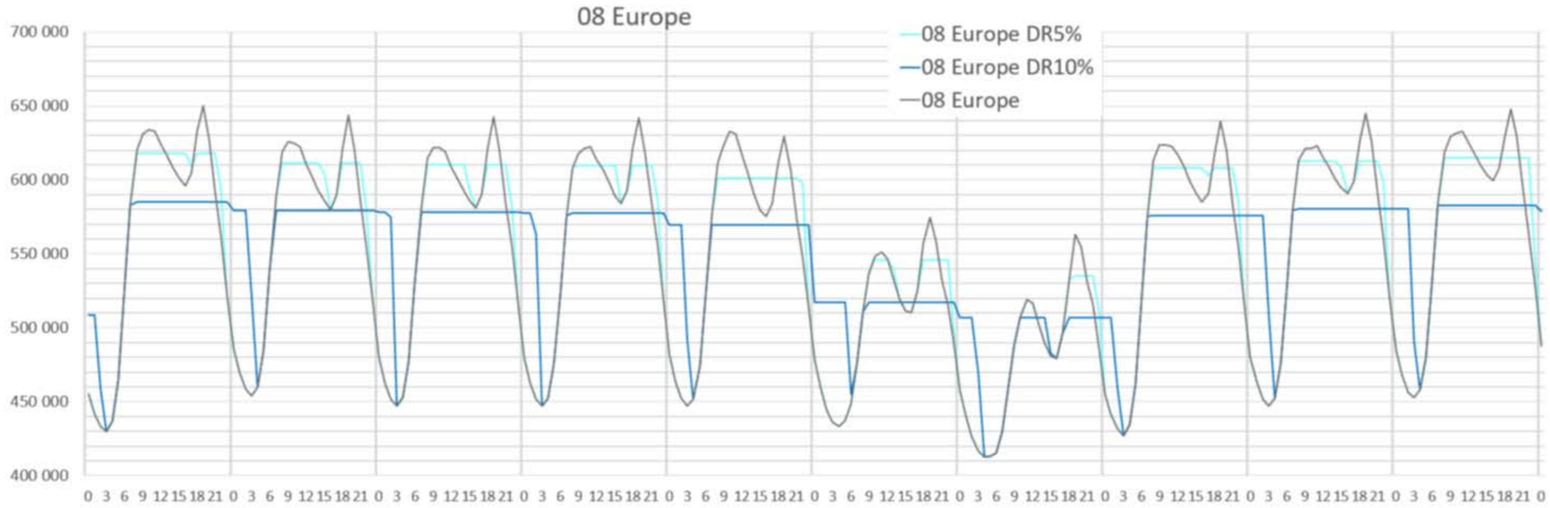
Model: Demand Response





Example for a region (Europe), for a period (week 2050).

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Mid- and short-term pure storage solutions

Storage facilities are modelled in two activation types:

- short-term (4 hours) corresponding to BESS (Battery Energy Storage System)
    - **The development potential was considered to be virtually unconstrained**
- medium-term (48 hours), corresponding to PHS (Pumped Hydro Storage)
    - **Modelling without natural inflows**
    - **Legacy installed capacity derived from IEA 2050 study**
    - **Total of 34TWh of energy storage capacity resulted as legacy**

Some economic features of storage modelling (Source: EIA):

Storage type	Pmax /unit MW	CAPEX $/kW ($/kWh)	Fixed cost $/kW.yr	Fixed $/MWh	Lifetime years
BESS	30	1446 (362)	8	0.3	10
PHS	1000	5088 (106)	15.9	0.0025	80

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Methodology and modeling

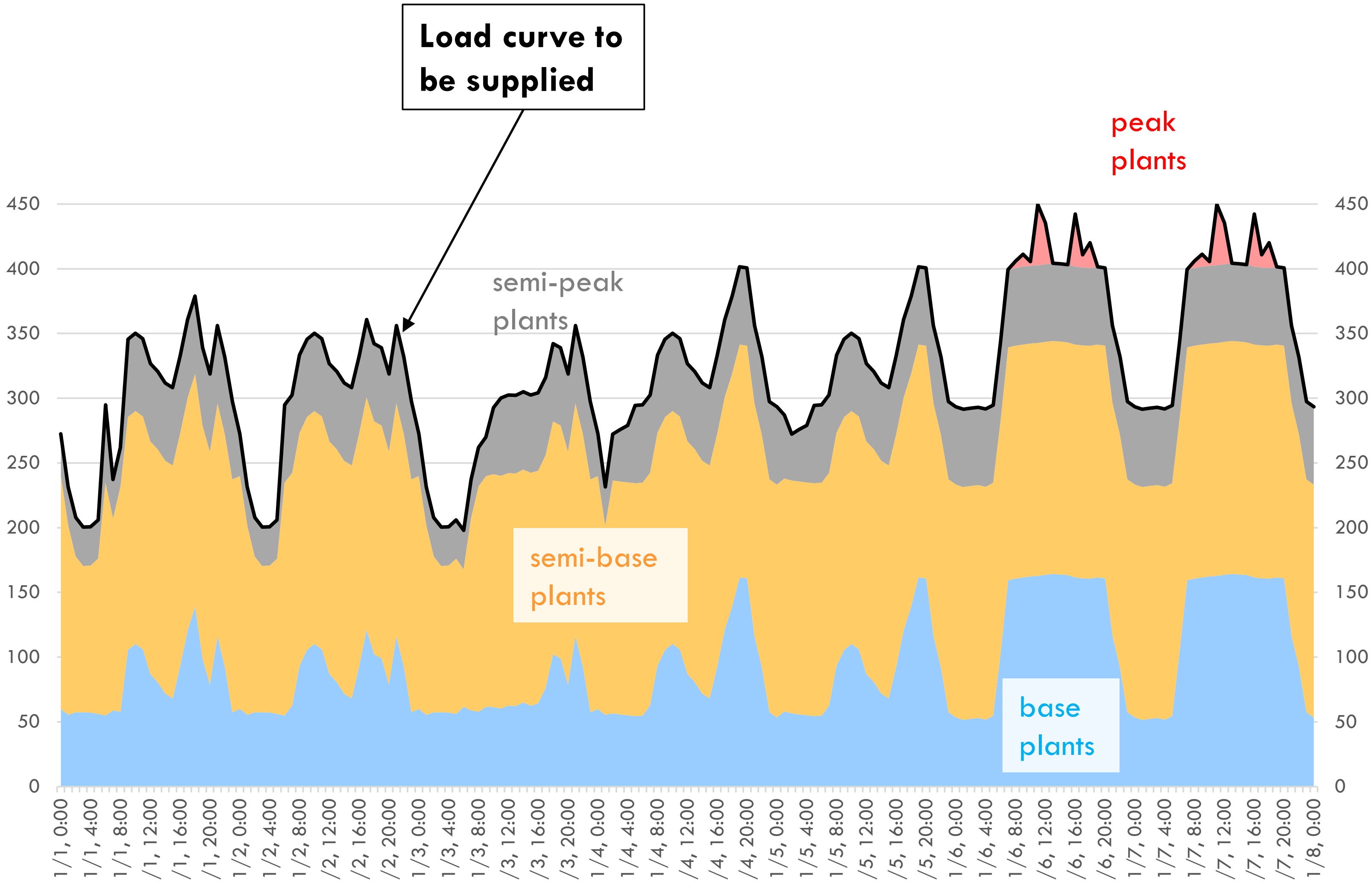
Nicolas Chamollet

Global Interconnected and sustainable electricity system

CIGRE Paris Session 2022 – 30 August 2022

Basis: Basics of power generation mix optimisation

- For a given load curve to be satisfied
- the aim is to find the “optimal” power generation mix
- “Optimal” power generation mix :
  - ✓ **Objective → minimize the cost of generation**
  - ✓ **Constraints → balance production and demand on every time step.**



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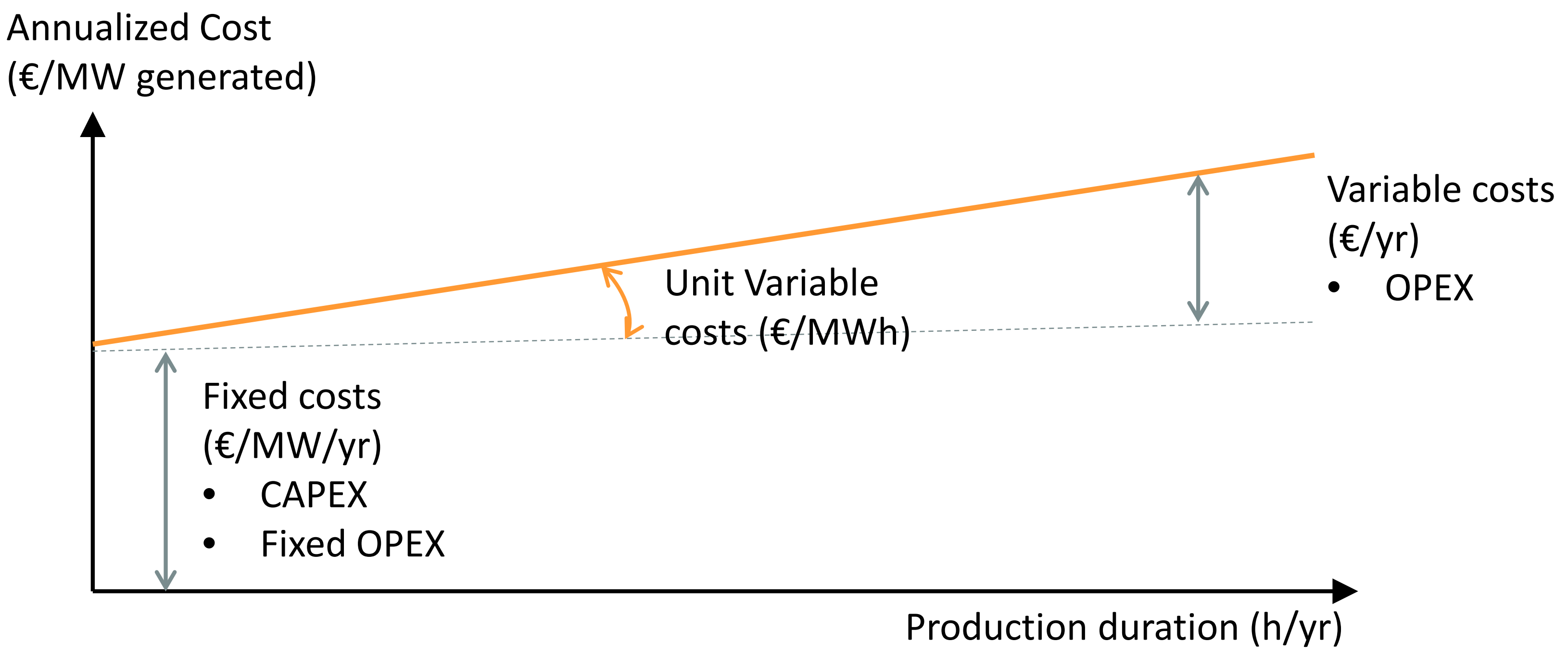
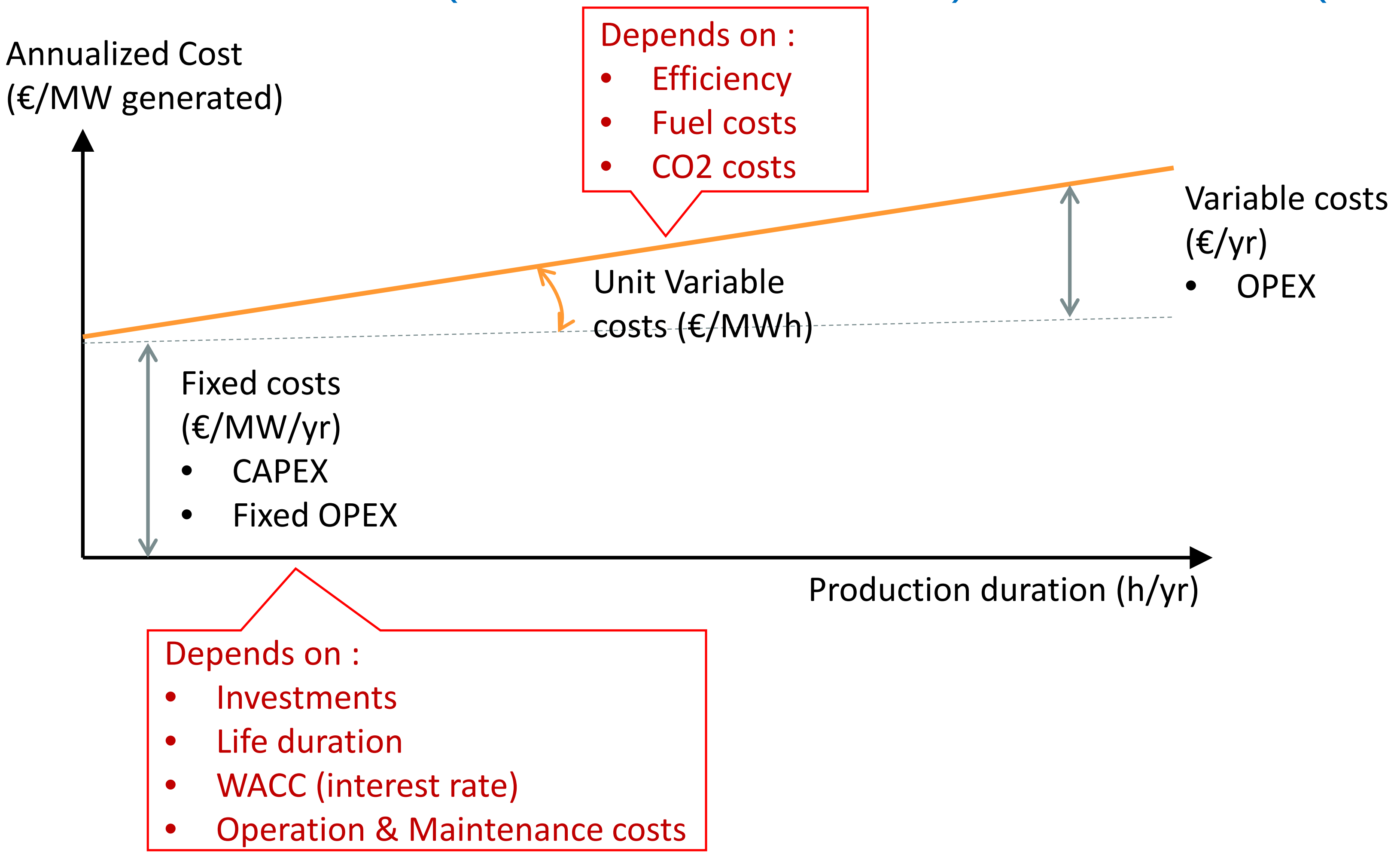
Basis: Breakdown of annualized generation cost

Total generation cost: fixed costs (CAPEX and fixed OPEX) and variable costs (OPEX)



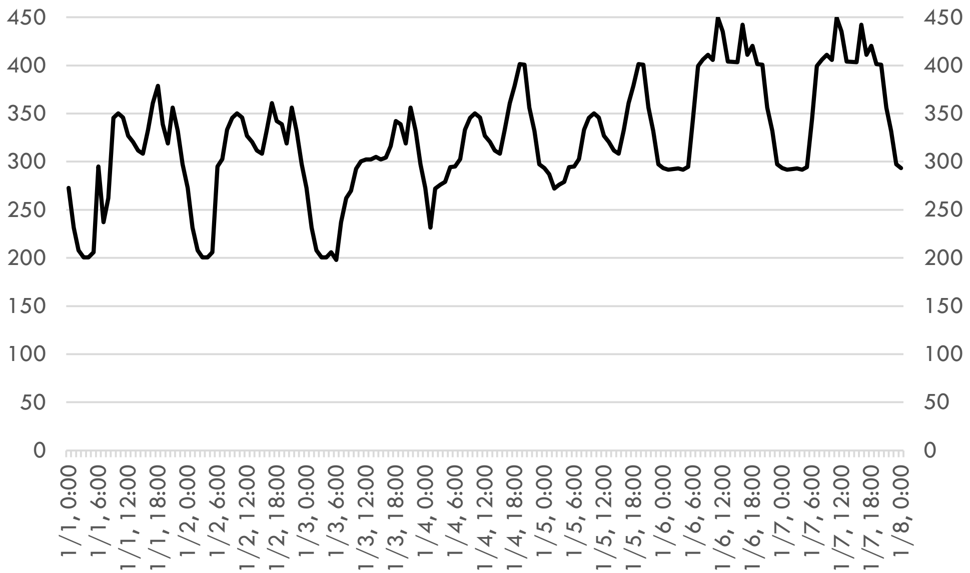
Basis: Breakdown of annualized generation cost

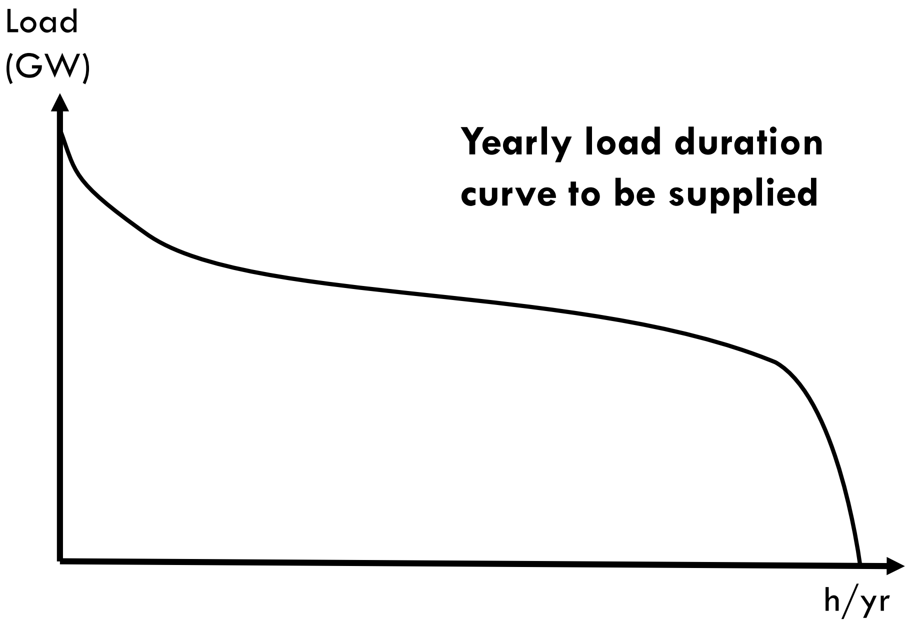
Total generation cost = Fixed costs (CAPEX and fixed OPEX) + variable costs (OPEX)



Finding the trade-off between fixed costs and variable costs

Basis: Optimal power generation mix





- For one power system, the yearly load duration curve is made up from the yealrly load pattern at hourly steps.

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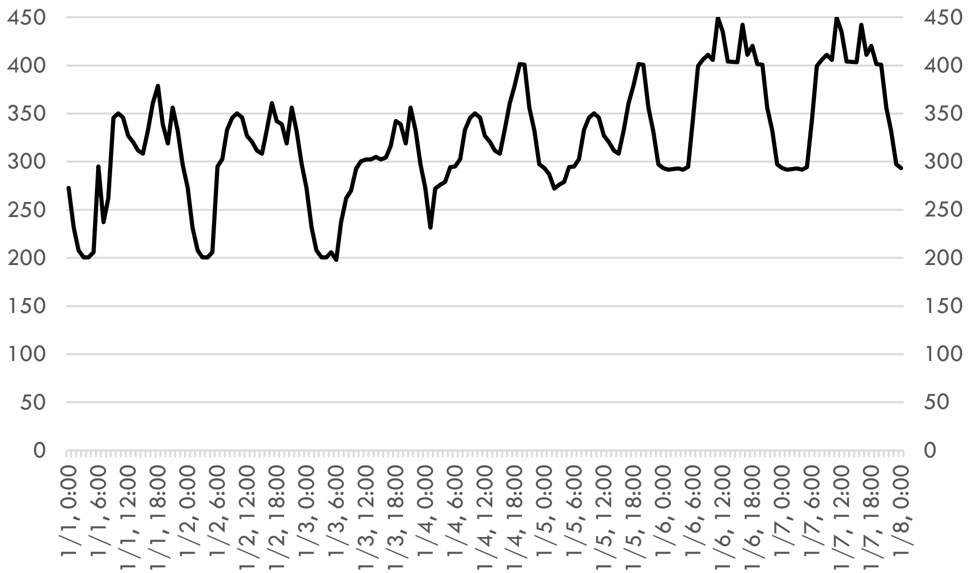
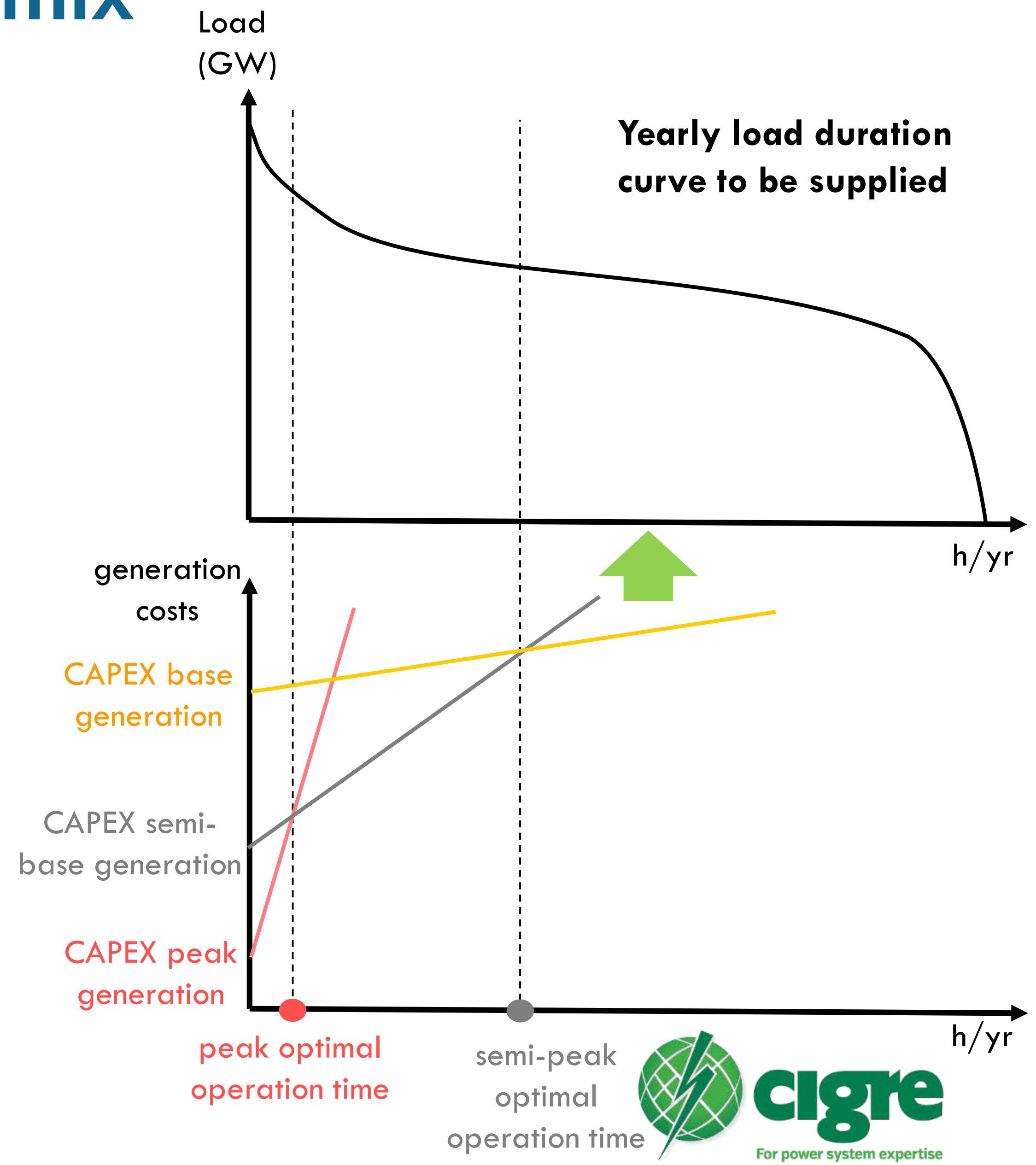
Basis: Optimal power generation mix





- For one power system, the yearly load duration curve is made up from the yealrly load pattern at hourly steps.
- Generation technologies costs to be adjusted to meet the load duration cost at minimal cost

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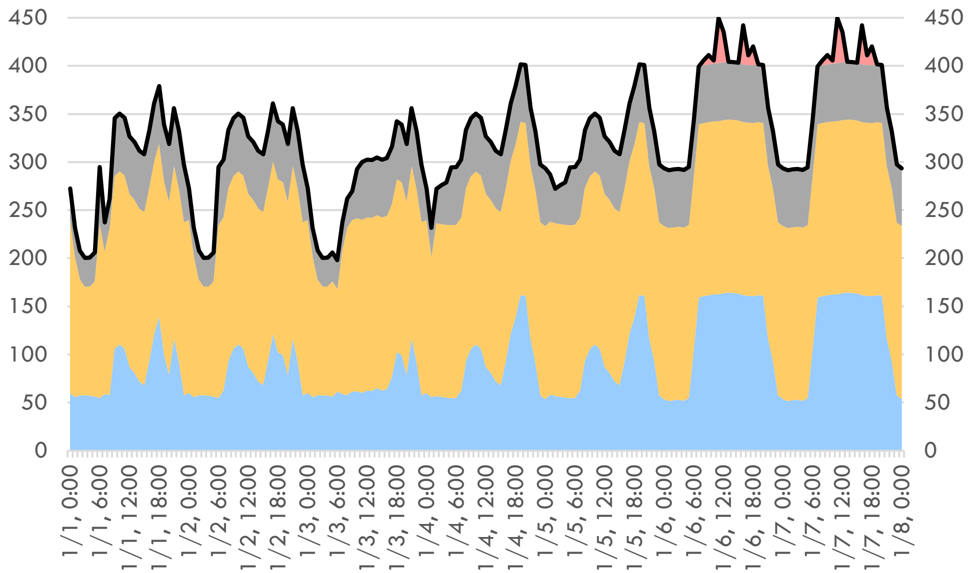
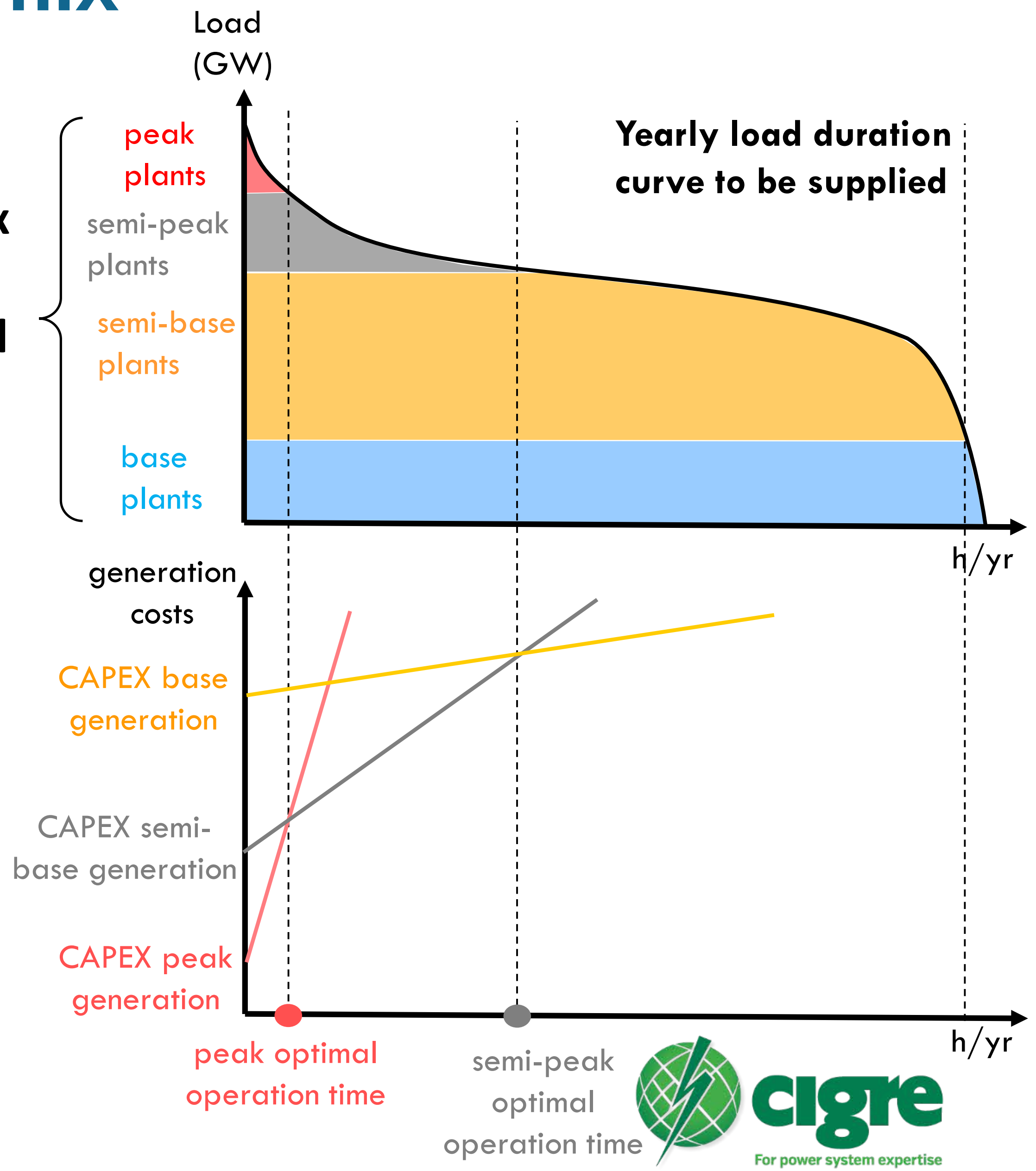
Basis: Optimal power generation mix



This power generation mix leads to the minimum total cost for this load curve



- For one power system, the yearly load duration curve is made up from the yealrly load pattern at hourly steps.
- Generation technologies costs to be adjusted to meet the load duration cost at minimal cost
- The choice between base, semi-base or peak generation plants depends on the plant load factor
- The plant load factor depends on the load curve

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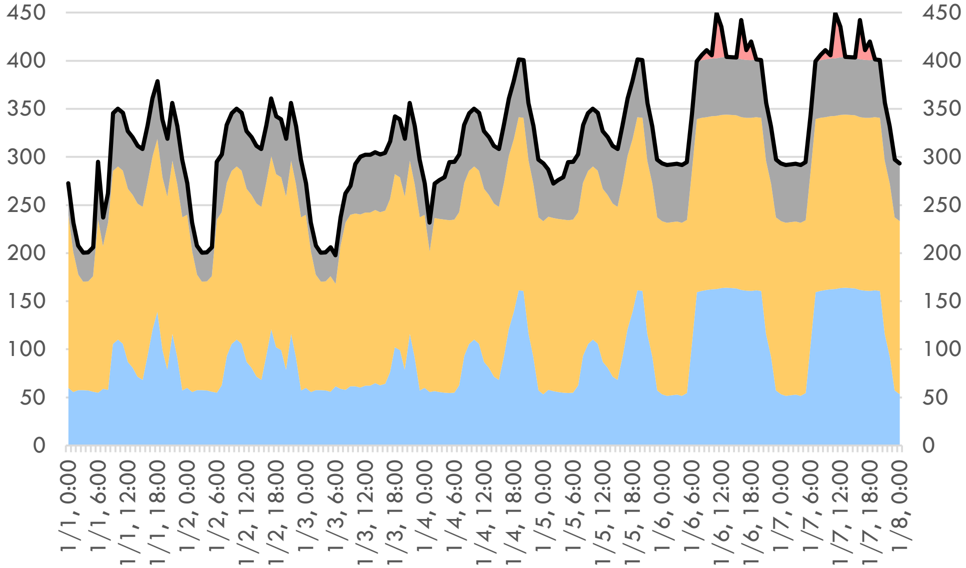
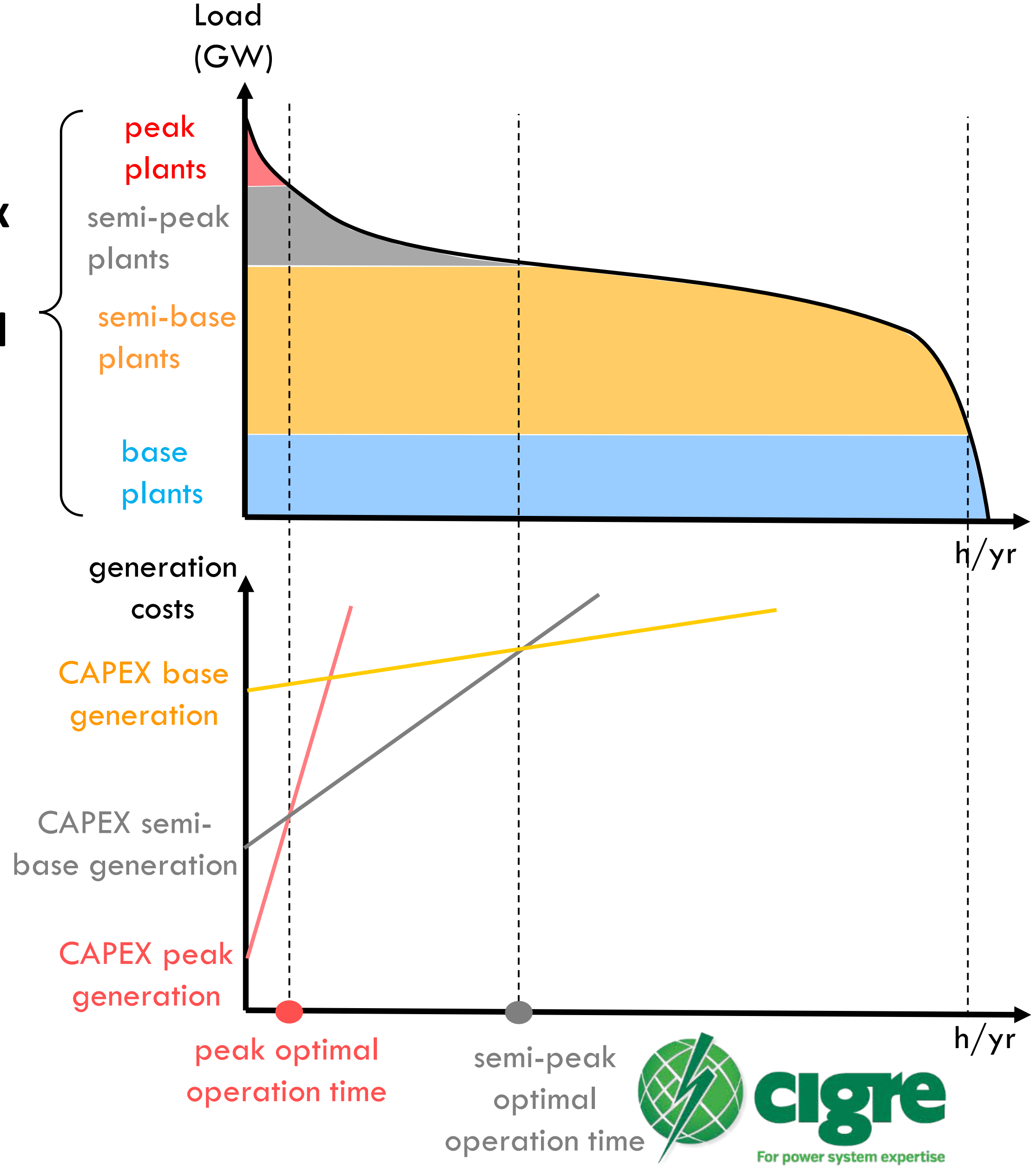
Basis: Optimal power generation mix



This power generation mix leads to the minimum total cost for this load curve



Limits of rough methods: Using load duration curve for dimensioning power generation mix is limited to strong assumptions

- ✓ Dispatchable plants
- ✓ No dynamic constraints
- ✓ Copper-plate grid, ...

If this assumptions are not met, numerical methods are required → PLEXOS tool for instance

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Basis: Cost of Transmission versus Generation

- The value of transmission grids is strongly linked to the economy of power generation mix
- Orders of magnitude :
  - ✓ **Power generation ~ 1 000 M€/GW**
  - ✓ **Transmission line ~ 1 M€/GW/km**

→ **1 GW power generation ~ 1 000 km transmission lines**

- **The most expensive part of electric systems is the power generation**
- **it is worth investing in transmission as much as it helps reducing the generation costs**

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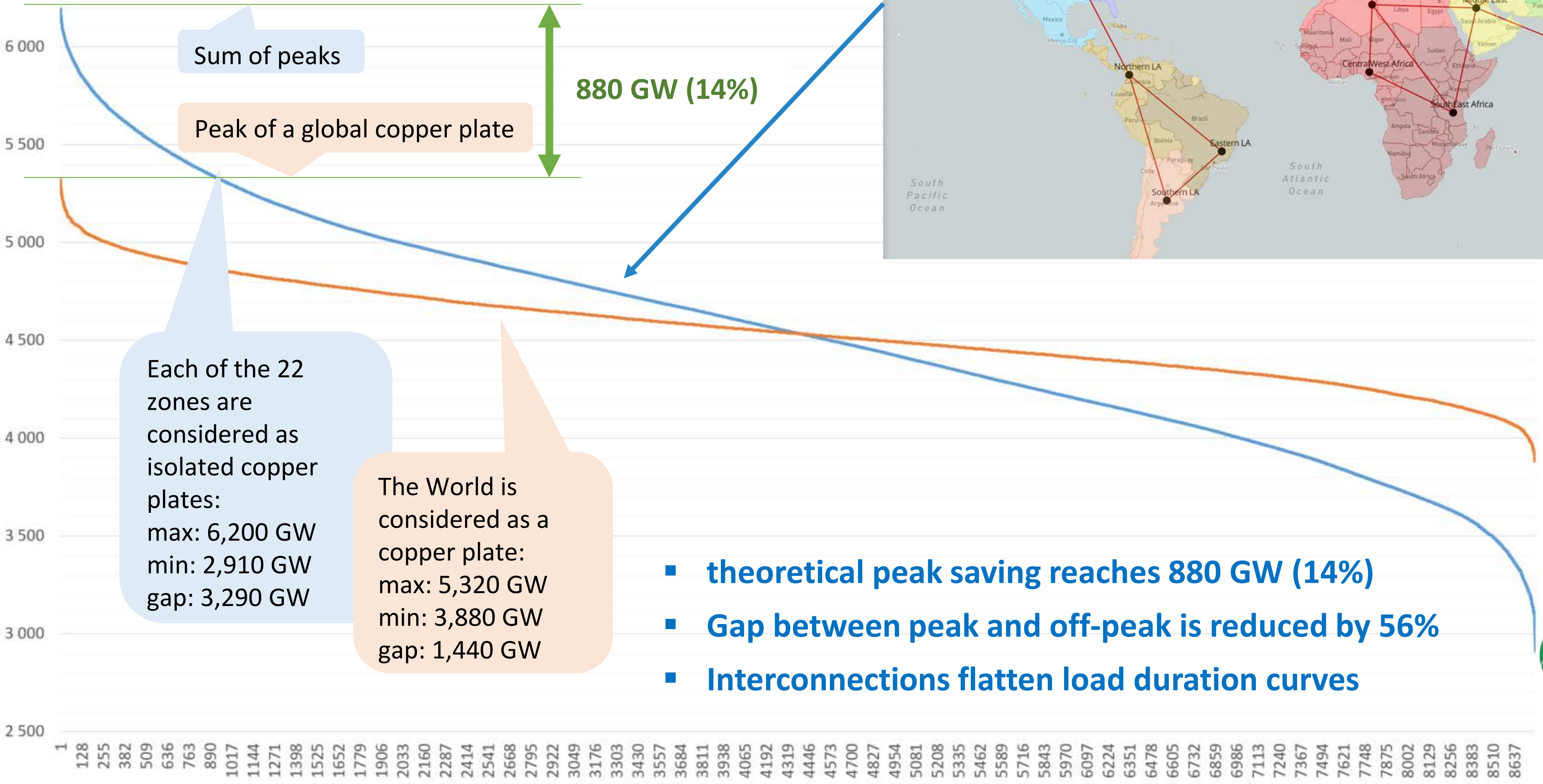
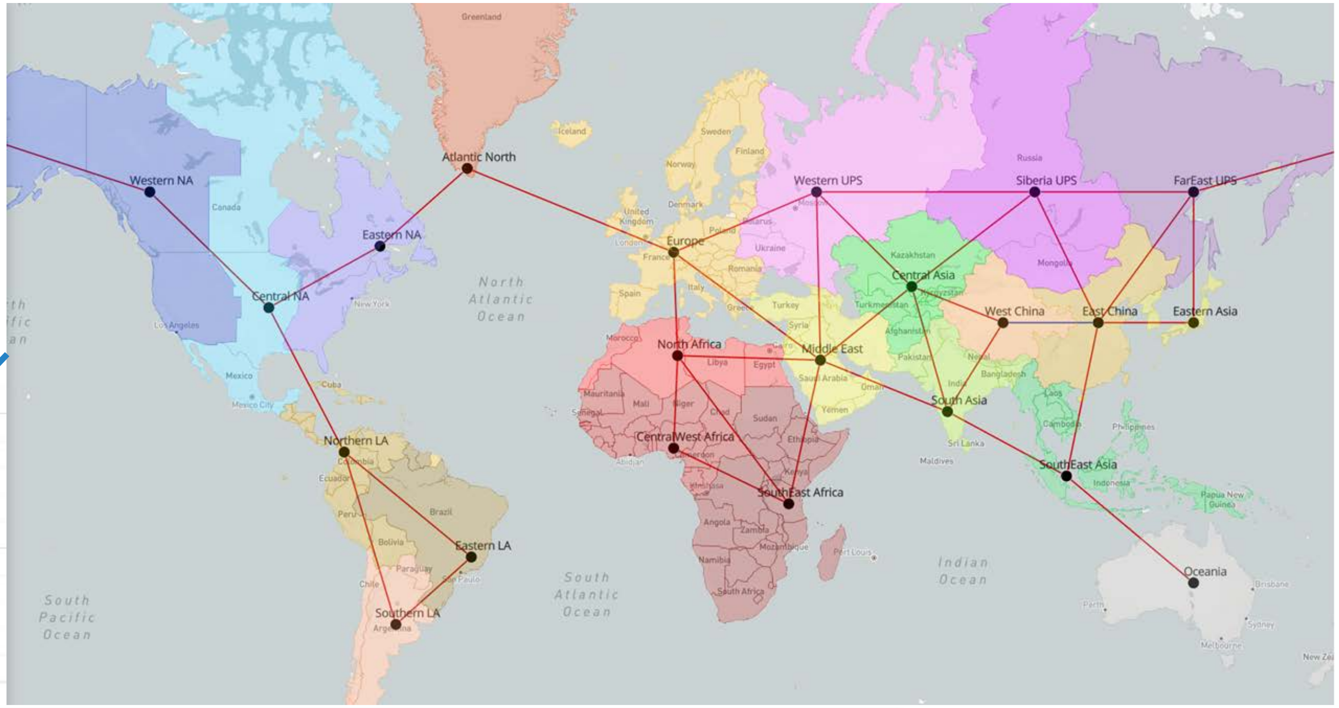
Basis:

Sum of the 22 load duration curves versus the theoritical global load duration curve



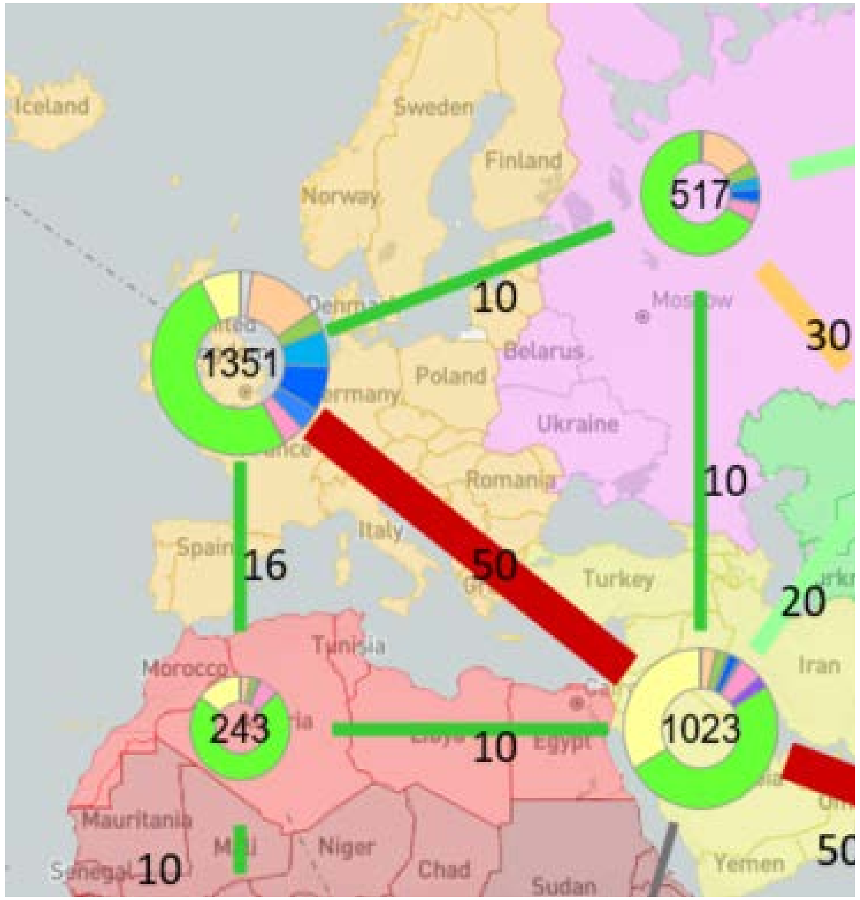


- **theoretical peak saving reaches 880 GW (14%)**
- **Gap between peak and off-peak is reduced by 56%**
- **Interconnections flatten load duration curves**

PLEXOS tool

Energy Exemplar contributed its energy simulation platform PLEXOS to model the optimal combination of production, storage, and interconnections to minimize total system cost.

- Modeling of hourly scenarios of demand, CF for wind, solar, hydro, etc., availability of power plants, …
- Probabilistic software
- Double loops for an "optimal" mix:
  - ✓ **Optimising the capacities** for production, storage and interconnections
  - ✓ **Optimising the unit commitment** for each zone and for each hour: Sum of productions - curtailments + imports + loss of load = demand + exports + losses in exporting interco + losses in storages



Energy Exemplar

https://www.energyexemplar.com/

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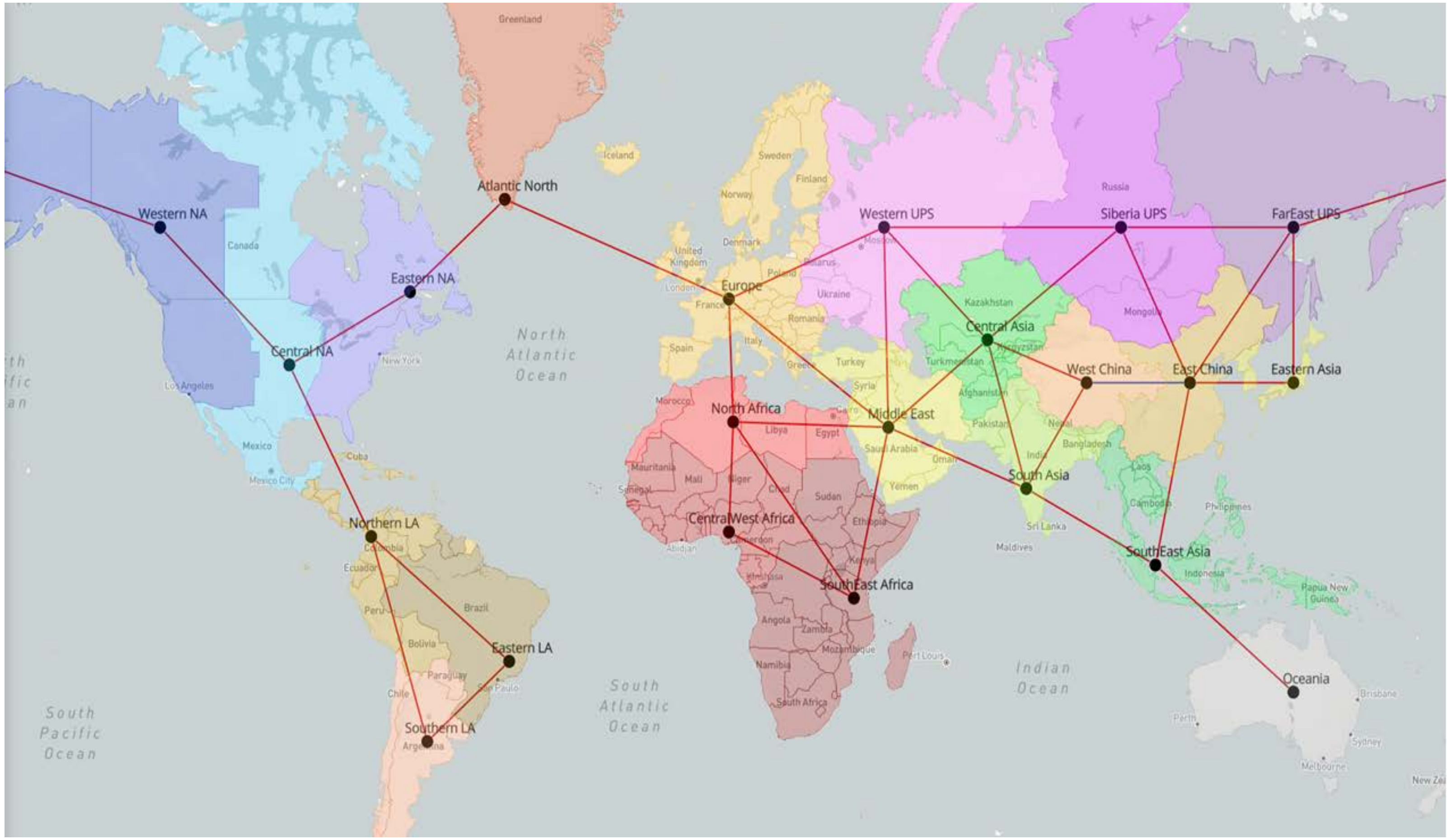
Results of the simulations

Nicolas Chamollet

Recall of major hypothesis

- **The 22 zones are seen internally as “copper-plates”**
- **Production and storage:**
  - unit costs are the same worldwide
  - nuclear, Coal-CCS, hydro and biomass are imposed according to WEC scenario hypothesis
  - Gas technologies (CCGT-CCS, CCGT, OCGT), wind and solar are optimized to minimize the total cost.
- **Interconnection:**
  - 35 potential interconnections
  - Capacity limited to 50GW
  - Expansion cost of the corridors increases while capacity increase:
    - From 0 to 10 GW, the cost of each additional MW respect the assumptions of Grid Cost.
    - From 10 to 30 GW, the cost of each additional MW increased by a factor of 1.5.
    - Above 30 GW the cost of each additional MW increased by a factor of 2.



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Objective and constraints

- **Objective:** To find the optimal combination that satisfied the demand at minimal cost
  - ✓ **Generation:** CAPEX, fixed OPEX, variable OPEX 

  - ✓ **Storage (ST):** CAPEX 

  - ✓ **Interconnection (INT):** CAPEX
  - ✓ **Demand Response (DR):** exogenous parameter applied or not on the load curve
- **Constraints** for each hourly step :
  - ✓ Supply demand balance: production meet the demand on every time step
  - ✓ Dispatchable generators: production cannot excess the installed capacity
  - ✓ RES: production cannot exceed the capacity factor
  - ✓ Storage: maximum power and energy balance over a given period considering the losses due to efficiency
  - ✓ Interconnection: flows cannot exceed installed capacities in both direction

Case studies

Main Factors:

- INT: interconnections
- ST: Storage
- DR: Demand Response

CASE STUDIES	INTERCO	STORAGE	DR
Isolated (#1)			
Isolated with STORAGE		✓	
Isolated with DR			✓
Isolated with DR and ST		✓	✓
Interconnected only	✓		
Interconnected with DR and ST	✓	✓	✓

Main KPI:

- Total Annual Cost (€/MWh) and
- CO_2 emission (Mt/yr)

Main results

CASE STUDIES	INTERCO	STORAGE	DR	COST (€/MWh)	CO2 (Mt/yr)	Cost / #1	CO2 / #1	gas GW %	wind GW %	pv GW %	PHS-BESS GW %	GRID GW %
Isolated (#1)				49,0	453			**2 100**	**5 839**	**3 336**	**158**	
Isolated with STORAGE		✓		48,6	316	-1%	-30%	-30%	-6%	+43%	+444%	
Isolated with DR			✓	49,0	457	0,1%	1%	+2%	-3%	-6%	0%	
Isolated with ST and DR		✓	✓	48,7	330	-0,5%	-27%	-28%	-8%	+38%	+426%	
Interconnected only	✓			47,1	309	-4%	-32%	-47%	+24%	-14%	0%	**738**
Interconnected with ST and DR	✓	✓	✓	47,1	239	-4%	-47%	-56%	+16%	+8%	+274%	-8%

Impacts:

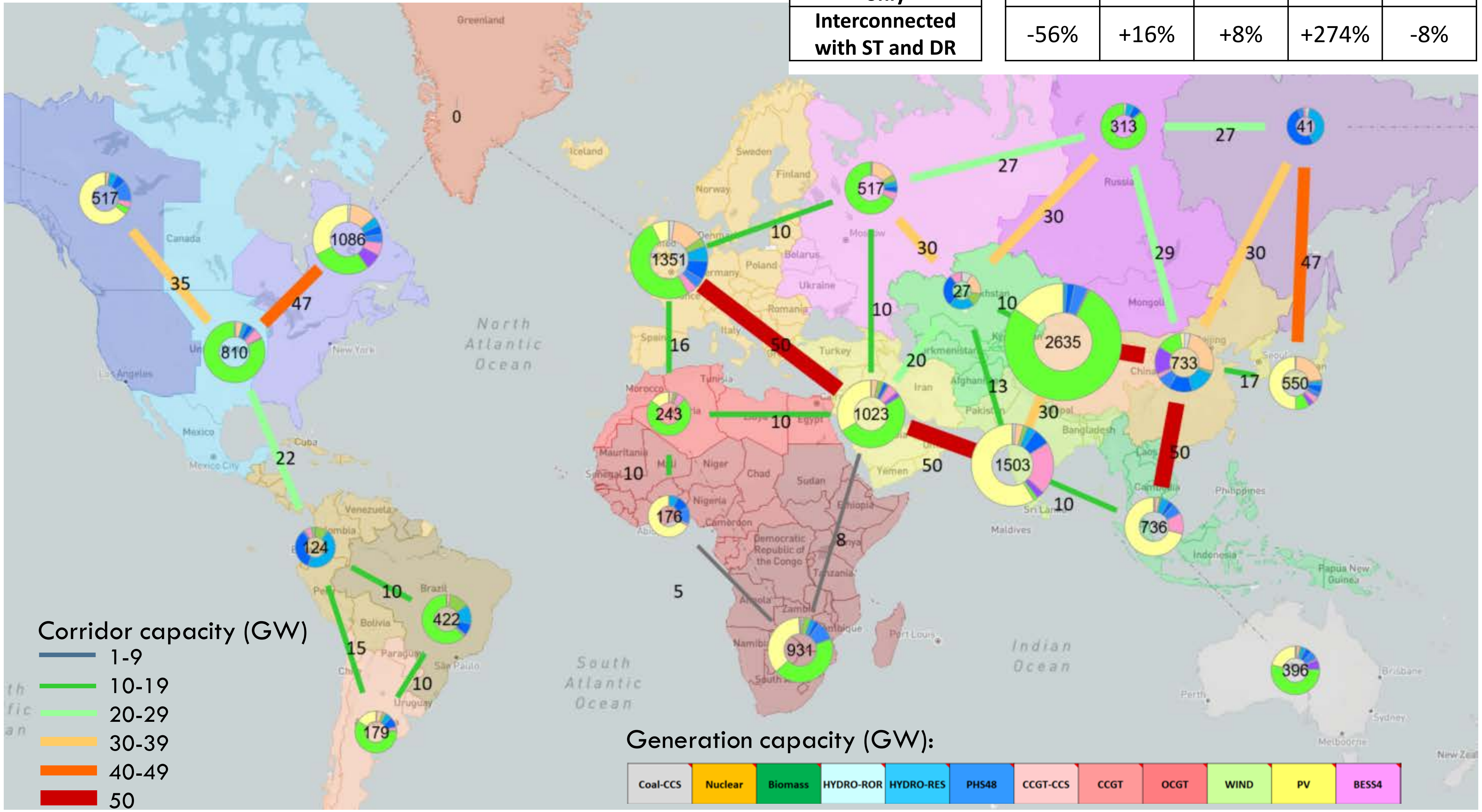
- **on generation mix:** STORAGE foster PV, DR foster GAS..., INTERCONNECTION foster WIND
- **on cost:** INTERCO **decrease the average yearly cost by -4%** while DR and STORAGE have almost no impact
- **on CO2 emission:**
  - With STORAGE or INTERCO, **CO2 emissions fall respectively by -30% and by -32%**
  - With all (INTERCO+STORAGE+DR), **CO2 emissions fall by -47%**

Interconnections + Storage + DR

Optimal grid and generation installed capacities (GW)

CASE STUDIES	gas GW %	wind GW %	pv GW %	PHS-BESS GW %	GRID GW %
Isolated (#1)	2 100	5 839	3 336	158	
Interconnected only	-47%	+24%	-14%	0%	738
Interconnected with ST and DR	-56%	+16%	+8%	+274%	-8%

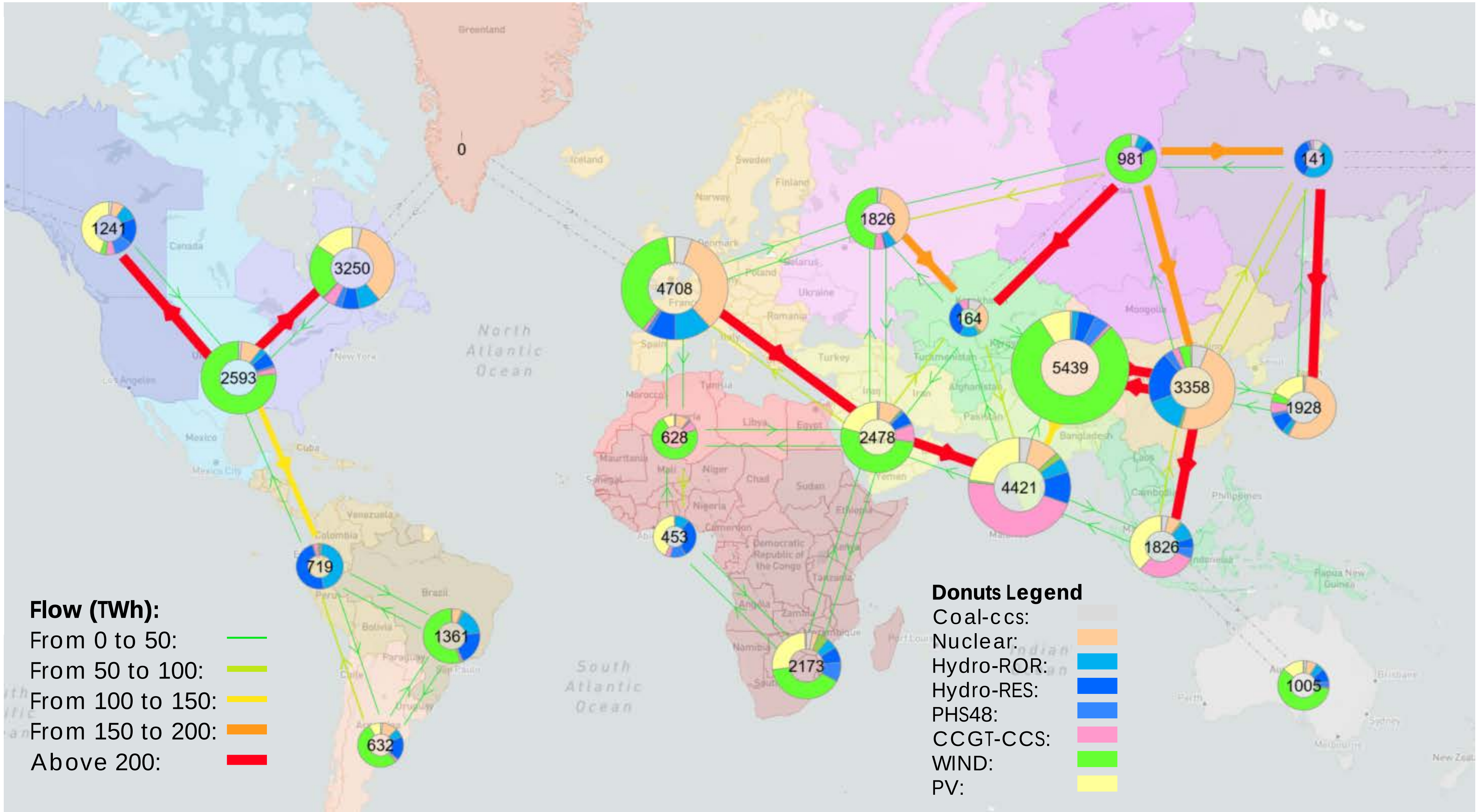
- **Interconnections limited to main lands**
- Main grid backbone:
  - "Europe – ME – S.Asia"
  - North America zones
- Global grid installed capacity: 677 GW (5% of prod capacity)
- Yearly interconnection cost: 32 G€/yr (1,7% of system cost)



Interconnections + Storage + DR

Optimal power volumes (TWh)

- Yearly transfered volume: 4060 TWh/yr (10% of generated power)
- Yearly interconnection cost: 32 G€/yr (1,7% of system cost)
- CO_2 emission: 239 Mt/yr (-23% / Interco only)
- From Isolated to Interco+ST+DR:
  - Cost: -4%
  - CO_2: -47%



Storage foster PV generation over Wind development

DR decrease peak load and thus PV potential installed capacity

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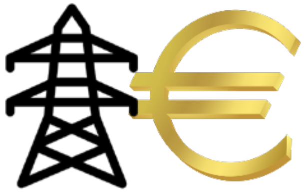
Sensitivity Analysis

- CO2 emission cost (€/ton): 110 €/ton
  - min 80 (-27%) → COST unchanged; CO2 emissions increase: +22% (isolated), +10% (interconnected)
  - max 140 (+27%) → COST unchanged; CO2 emissions decrease: -11% (isolated), -8% (interconnected)



- Transmission cost (€/GW/km):
  - min (-30%) → COST slightly decreases; CO2 emissions decrease: -5%
  - max (+30%) → COST slightly increases; CO2 emissions increase: +5%

- CO2 emission cost has a greater impact on isolated system
- **Grid contributes to reduce CO2 cost impact**
- Grid cost has a limited impact on CO2 emission and system cost

Lessons - summary

With all (INTERCO+STORAGE+DR), cost decreases by -4% and CO_2 emissions fall by -47%:

- INTERCO fosters the pooling of DEMAND and RES power.
- INTERCO eases wind power transfer from far isolated zone to load centers.
- INTERCO decreases the average yearly cost by -4% and CO_2 emission by -32%.
- STORAGE fosters PV and LOAD patterns adequation.
- DR decreases PV investments.

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Trading rules and governance issues

Angelo L'Abbate

Global Interconnected and sustainable electricity system

CIGRE Paris Session 2022 – 30 August 2022

Key issues

- The need and effects of continental-scale electricity trading rules and governance issues
  - ✓ impact of **continental-scale electricity trading rules** on global grid developments
  - ✓ impact of **continental-scale governance issues** on global grid developments

- Potential effects of the status of transmission system development within a continent on the costs and benefits of a global grid

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Focus on trading and governance impact

A combined approach has been elaborated:

- **Bottom-up** -> collection of background experiences concerning power system structure, cross-border regulation and trading rules

  - ✓ The case of European (EU, UK) region systems
  - ✓ The case of African regions systems
  - ✓ The case of Russian regions system
  - ✓ The case of Chinese regions system
  - ✓ The case of Indian region systems
  - ✓ The case of North American regions systems
  - ✓ The case of South American regions systems

- **Top-down** -> best practices from mature and under development markets

Background: African regions

Source: UNEP, Atlas of Africa Energy Resources, 2017

Overview of African Power Pools

- **North African Power Pool (NAPP)/COMELEC** since 1975
  - Best infrastructure in Africa
  - Highly depending on fossil fuels
  - Low imports and exports
- **Southern African Power Pool (SAPP)** since 1995
  - Most advanced power pool
  - Implemented Day-Ahead- and Intra-Day-Market
  - Lack of generation and interconnection capacity preventing further development
- **Eastern Africa Power Pool (EAPP)** since 2005
  - Plans to have a centralized trading market in place between 2020 and 2025
  - Resigning of Egypt in 2016
- **West African Power Pool (WAPP)** since 2001
  - Small compared to other pools
  - Weakly developed connections between the members
- **Central African Power Pool (CAPP)** since 2005
  - Small compared to other pools
  - Demands are expected to increase in future
  - More hydro-generation compared to other pools

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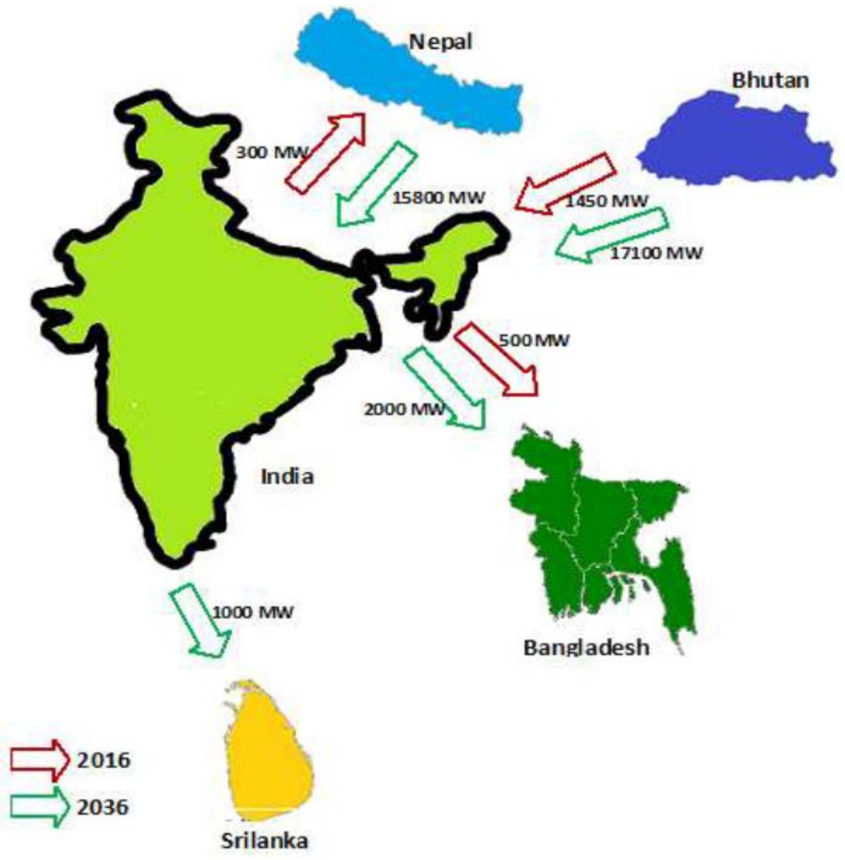
Background: Indian region

Cross-border trading in Indian subcontinent

- As of 2019, **only 3000 MW of power** is traded in south Asia
- Seven countries: India, Bhutan, Bangladesh, Myanmar and Nepal (existing trading), Sri Lanka and Pakistan (possibility for future trading)
- India – largest power system in the region, centrally located for cross-border trading
- Two possibilities for cross-border trading:
  - ✓ **Traditional** – bilateral agreements between Indian entities and entities of India's neighbours
  - ✓ **Liberalized** – competitive bidding over the Day-Ahead Market of the Indian Energy Exchange (IEX) and Power Exchange India Limited (PXIL), since 2019-20

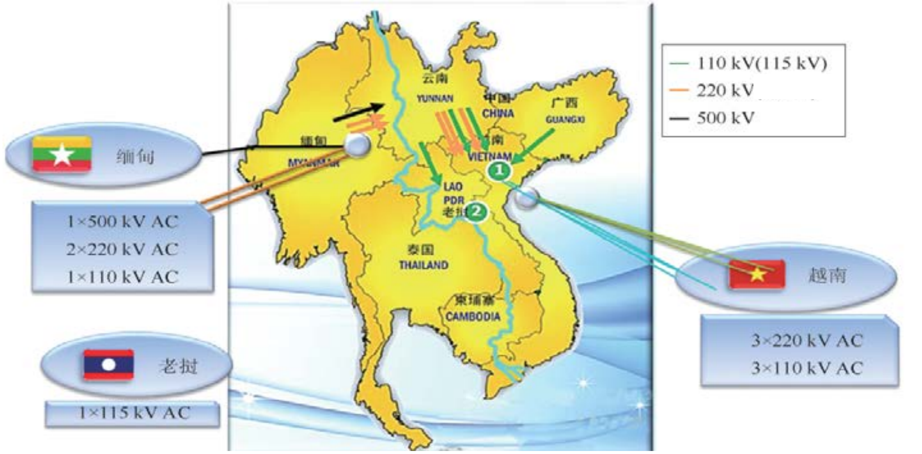


Source: CERC, India

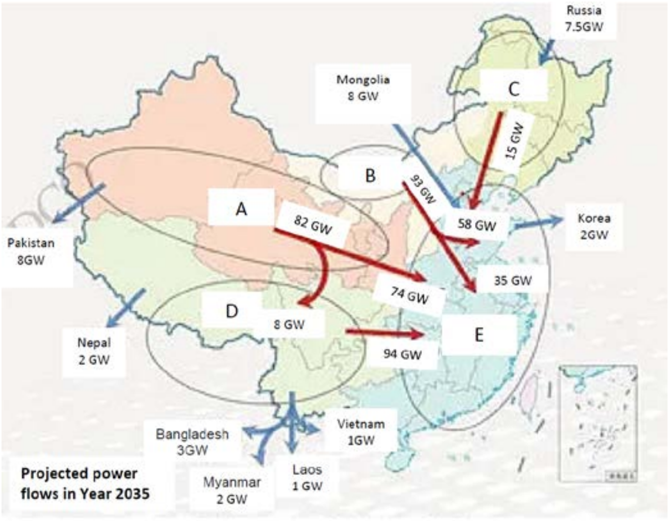
Background: Chinese region

Cross-border trading in Chinese region – with southern neighbours

- Current contracts with neighboring southern countries are based on a single electricity price, to be confirmed every year when determining the level, comprehensively considering the local supply and demand conditions in the involved countries/regions
- At present, China exports electricity unidirectionally to Vietnam and Laos, with no import from them. On the other hand, Myanmar relies on two hydropower stations, and conducts two-way power trading with China



Source: CSG



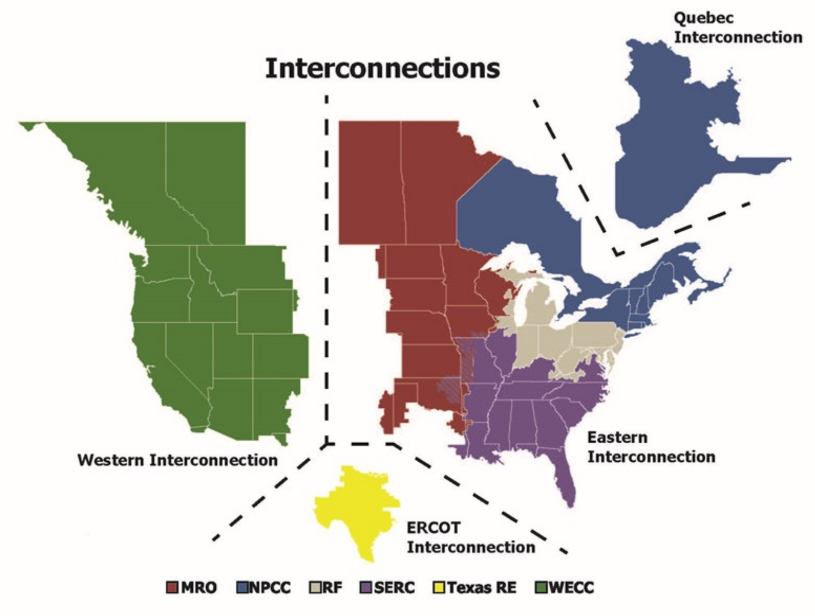
Cross-border interconnections (planning/study) in Chinese region in 2035

Source: GEIDCO (2020)

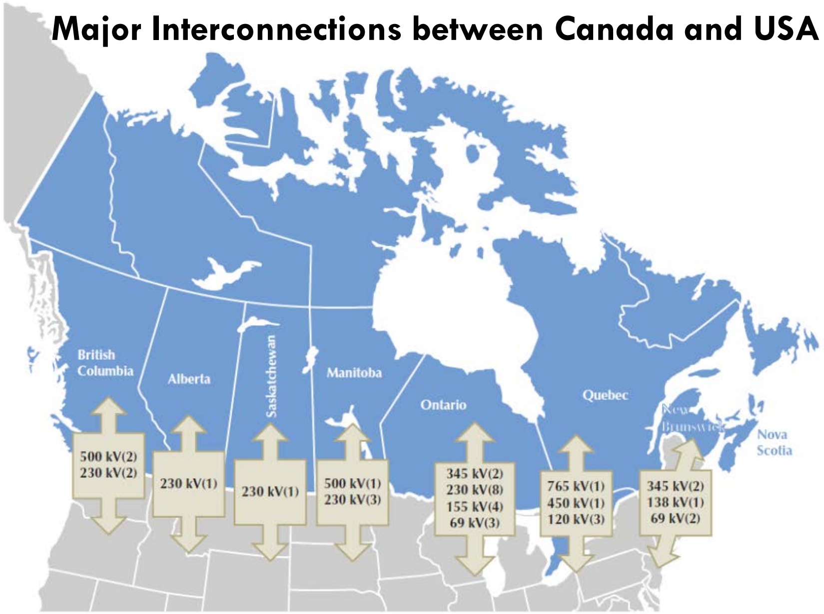
A: North-western Region
B: Inner-Mongolia West/Shanxi Region
C: North-eastern Region
D: South-western Region
E: Eastern Region

Background: North American region

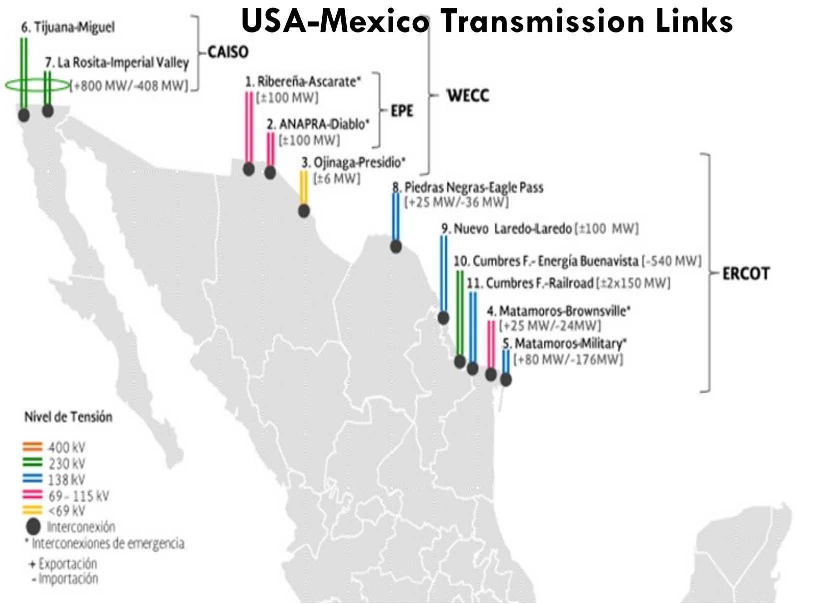
North American power transmission and market overview



Source: NERC



Source: CER



Source: CFE

Background: South American region

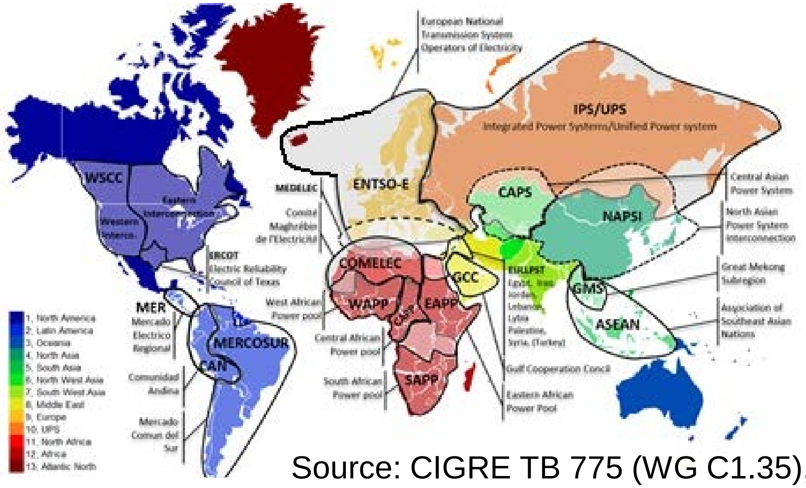
Cross-border trading regulation in South American region – success stories

- **Colombia** and **Ecuador** have been electrically interconnected since 2003. The main **financial agreement** between Colombia and Ecuador is established in the form of **splitting the congestion rents produced in the cross-border line**
- **Bi-national Itaipu agreements** between **Paraguay** and **Brazil** and between **Paraguay** and **Argentina** were established **to make efficient use of the available hydro capacity**. They establish the financial bases on the exploitation of the hydro power plant. These agreements will be reviewed by 2030.
- Some countries have implemented **intermediate solutions** with **direct subsidies or price controls** (that operate as indirect subsidies) to protect local markets. E.g., the agreement **between Chile and Argentina** states that **the exchange of power is based on an interruptible interconnection agreement with a price control rule**, where only generation units that are not dispatched to meet the domestic demand are able to export power.

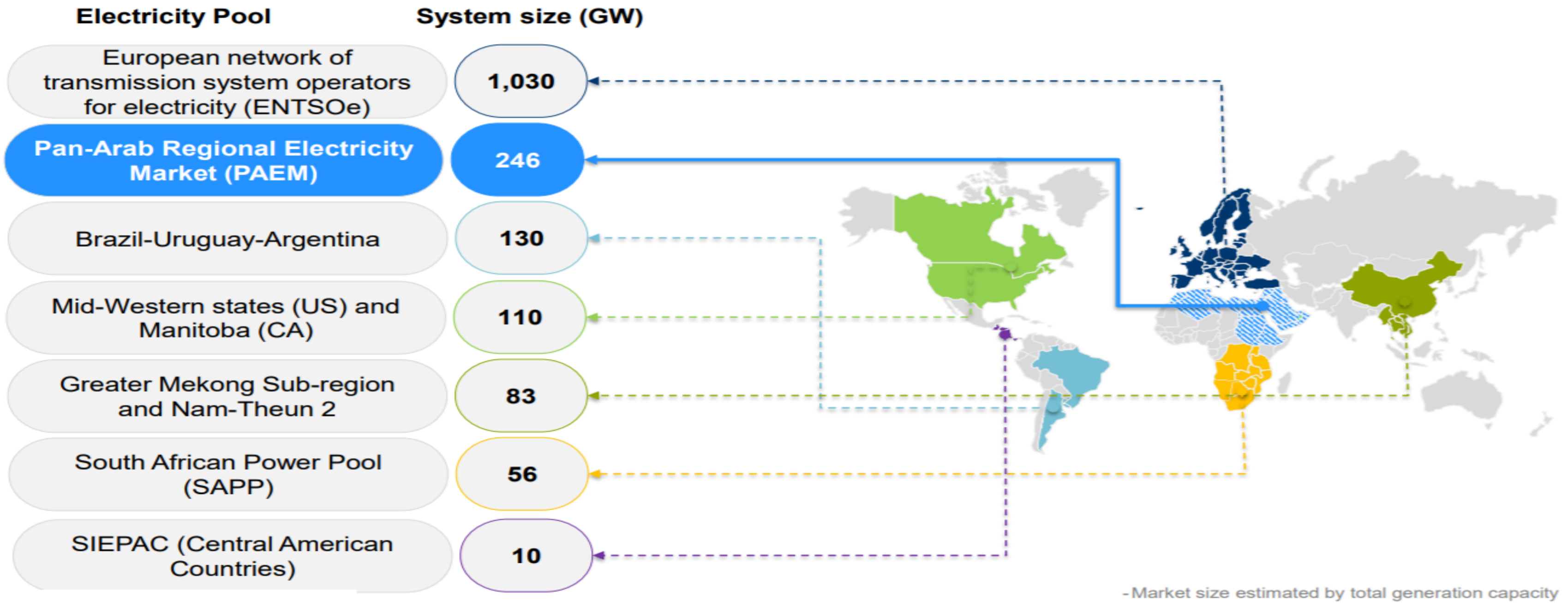
Source: CIER

Granularity of trading arrangements

- **Multilateral trading arrangements** can take place among countries or among established organisations spanning across several countries
- In view of global grid, it seems **natural to leverage on existing/upcoming power sector supranational organisations**, especially if trading rules are already in place inside them
- This occurs in case **a wider framework is in place**, beyond trading rules, including network codes, connection rules, commercial standards, legal/regulatory framework, operational agreements for interconnectors, etc.



Source: CIGRE TB 775 (WG C1.35), 2019

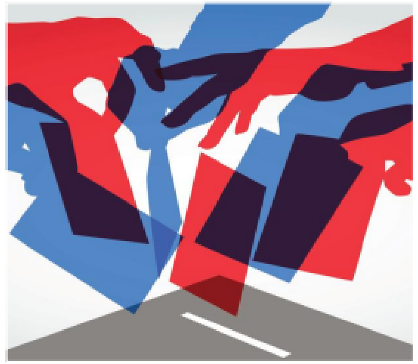


Source: Middle East – PAEM initiative, 2020

- Market size estimated by total generation capacity installed or peak demand
- Map is for illustration of regional power pools and does not reflect geographical borders

Enablers for accelerating Cross-Border Electricity Trading (CBET)

Political



- Regional Outlook/Vision
- Political Consensus
- Intergovernmental agreement(s)
- Implementation Mechanism
- Power Market Reform

Regulatory

- Permissibility to use intermediary transmission network under open access
- Rules for identification of transmission capabilities & congestion
- Rules for measurement of imbalance and settlements
- A conducive & friendly ecosystem for investors

Technical and Commercial

- Harmonisation of grid codes & standards, Grid Connectivity
- Transmission pricing & transit charge
- Co-ordinated Regional Transmission Grid Planning
- Settlement & payment mechanism
- Dispute resolution mechanism

Institutional

- Institutional arrangements
- Regional Coordination Forums are desirable
- Will foster long term sustainability

Cross Border Electricity Trade in SAARC Region: Webinar on "Cross Border Electricity Trade in SAARC Countries-11.30 AM (IST), Tuesday, 11th August 2020" by Rajiv Ratna Panda, Technical-Head /SARI/EI/IRADE

Source: SAARC Region CBET, 2020

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Set-up of common frameworks

Cross-border electricity trading regulation: local peculiarities and general issues

- Bilateral, multilateral, regional, continental trading patterns
- Is it necessary a common market set-up or trading agreement can suffice as a start, especially for point-to-point interconnections?
- Is it necessary to include trading/utilisation patterns in the interconnection realisation agreement?
- Business models for interconnector utilisation: merchant, national public grid, special status, reserved use
  - ✓ **Merchant: transport fee, wheeling charge, etc. -> users are energy sellers/buyers in the interconnected jurisdictions**
  - ✓ **Public grid in open market: utilisation embedded in advanced spot/future market mechanisms**
  - ✓ **Public interconnector without open market: reserved use, monopolists suppliers/purchasers -> coordination of rules across the different jurisdictions**
- Utilisation scheme of the interconnections: capacity allocation, congestion management, inter-TSO compensation mechanisms (if any), etc.
- Main reasons and barriers for cross-border electricity trading
  - ✓ **Different legislative set-up: institutions, decision bodies, regulators -> map of decisional path in all jurisdictions involved**
  - ✓ **Different regulation and market**
  - ✓ **Technical issues**
  - ✓ **Economic issues**
  - ✓ **Environmental issues**
- Private commercial agreements or public common rules? Role/need of governmental back-up
- Evolution to a regional/multiregional common market (example of Europe with ENTSO-E)

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Key recommendations

- **A gradual approach – from bilateral to multilateral, regional, continental up to global level trading – is necessary** and should be followed given different conditions and local constraints
- **Political support is needed** for realisation of interconnectors, but also for backing-up general trading arrangements and individual commercial transactions
- **Legal risk and investment protections** considering the **huge upfront investment effort** in transmission assets and new power plants and a **stable legal framework** at macro-regional level **are essential** to attract private investors and cross-border trade
- **Bilateral energy trading** — **The market model** for energy trading and using transmission capacity **should be as simple as possible**, especially **in the early stages of interconnected operations**. Therefore, the starting point could be based on the use of **bilateral contracts in the form of PPA** between generators and buyers, plus relevant arrangements for transfer capacity
- **Regional market model** — The regional market model **in a mature restructured power system** would see the **coexistence of bilateral energy trading and short-term energy transactions on a spot market** where the various market agents (sellers, purchasers, traders) operate

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Key recommendations

- **Access to the transmission grid** — The transmission system should be open to connection of IPPs. Remuneration for using the grid should be transparent, non-discriminatory and, as far as possible, stable over the time. Transmission fees should reflect costs
- **Regional institutions should be promoted and created**, in the form of Regional Energy Committee, with tight operational links with the involved TSOs and utilities
- **Regulatory harmonisation** — While some national reforms may well be needed, regional rules should minimise interference with domestic policies. This will allow the intercontinental/interregional interconnection to be developed more quickly, and this will continue to give national governments freedom to set domestic policy

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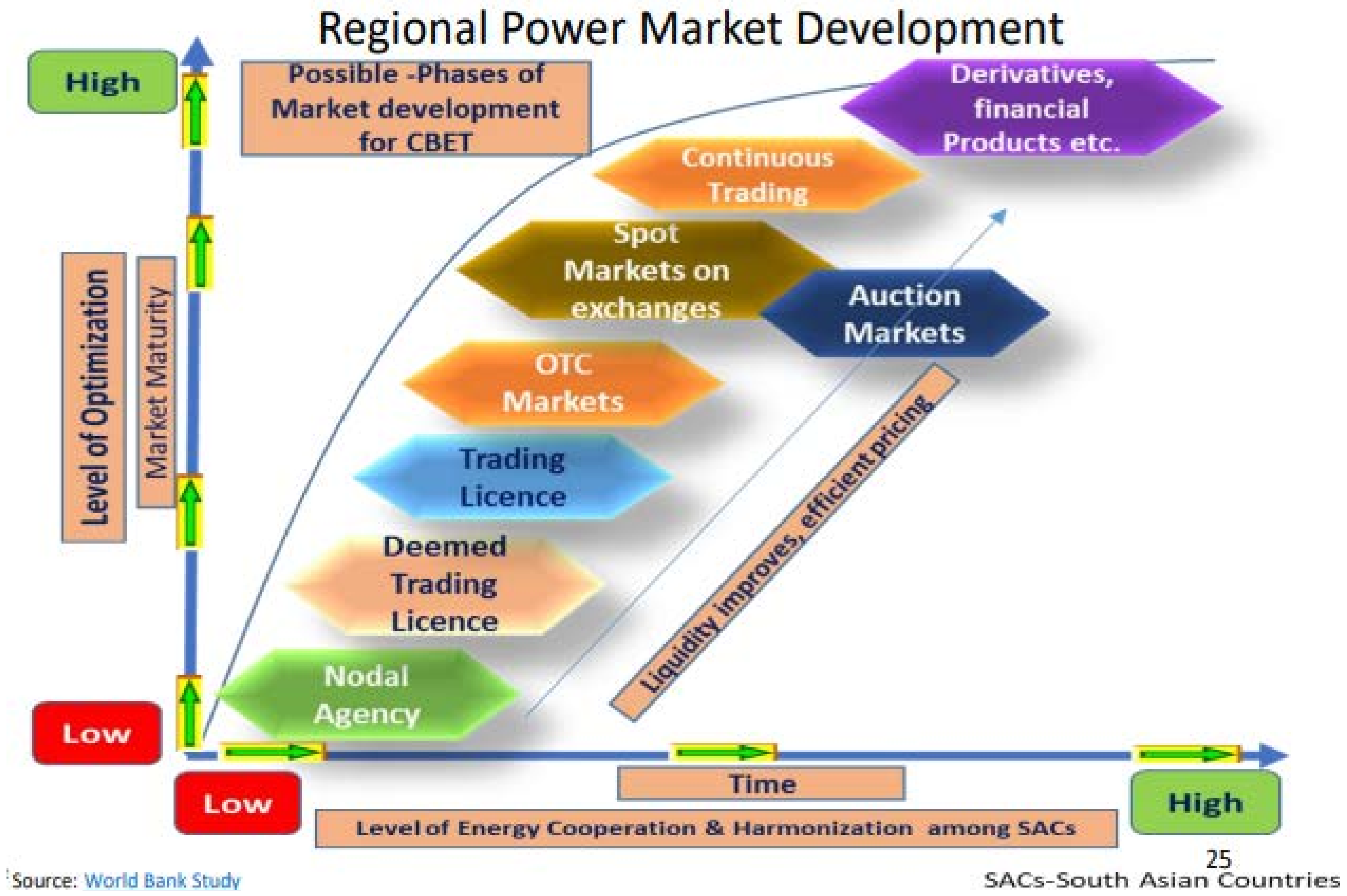
Gradual development of a common electricity trade framework



Disclaimer, recommendations and conclusion

Antonio ILICETO

Global Interconnected and sustainable electricity system

CIGRE Paris Session 2022 – 30 August 2022

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Main conclusions

Future decarbonised and DER system needs combination of all flexibility means			
Storage	Demand Response	Sector Coupling	Interconnections
Proper combination of all means, depending also on local conditions			

Grids flexibility as indispensable component

Main conclusions

Future decarbonised and DER system needs combination of all flexibility means			
Storage	Demand Response	Sector Coupling	Interconnections
Proper combination of all means, depending also on local conditions			

Grids flexibility as indispensable component

Economic viability of intercontinental connections, shown by WG C1.35, is clearly confirmed			
Complementarity of load & generation profiles	Storage (shift in time) vs interconn. (shift in location)	Demand Response decreases investments in PV	Further benefits of interc. on system stability and security
Storage increases PV while decreasing global interconnections by only 10%; DR is less impactful			

Main outcome, strenghtening the advocay for interconnections even in energy transition

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Main conclusions

Future decarbonised and DER system needs combination of all flexibility means			
Storage	Demand Response	Sector Coupling	Interconnections
Proper combination of all means, depending also on local conditions			

Grids flexibility as indispensable component

Economic viability of intercontinental connections, shown by WG C1.35, is clearly confirmed			
Complementarity of load & generation profiles	Storage (shift in time) vs interconn. (shift in location)	Demand Response decreases investments in PV	Further benefits of interc. on system stability and security
Storage increases PV while decreasing global interconnections by only 10%; DR is less impactful			

Main outcome, strenghtening the advocay for interconnections even in energy transition

Optimised system comprises around 700 GW interconnections, corresponding to only 5% of generation capacity and to 2% of electricity cost			
Main flows are in the axis Europe, Middle East, Asia	High flows also within Asia and within North America	Americas and Oceania weakly or not interconnected	High decarbonis. in all cases, also with different CO_2 prices
Even with high level of storage and demand response, level of interconnections remains high			

Interconnections are used bidirectionally, depending on season; inter-regions flows can be more impacted

Interconnections remain a fundamental component of an optimal configuration

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Disclaimers and considerations on assumptions

Regions granularity well consistent with depth of study → Corridors and terminal points identified comprehensively → N.B. Ukraine considered in UPS at time of modelling

No further fine tuning needed

Load data not very recent for worldwide consistency → Reflecting forthcoming elec-trification and geographical trends → Very important by-product is the world global load profiling

Future updating can be useful, but not a game changer

Disclaimers and considerations on assumptions

Regions granularity well consistent with depth of study →	Corridors and terminal points identified comprehensively →	N.B. Ukraine considered in UPS at time of modelling	No further fine tuning needed
Load data not very recent for worldwide consistency →	Reflecting forthcoming elec-trification and geographical trends →	Very important by-product is the world global load profiling	Future updating can be useful, but not a game changer
Forecast of generation mix is evolving (e.g. CCS) →	Capacity factors solar&wind deeply checked and revised, as one of main drivers for simulations →	Capacity Factors of progressive real projects could differ from average	Monitor if need of updating
Technologies and costs at edge state-of-art →	Proven technology and prudential costs assumed →	Grids realisation hurdles considered as growing cost per GW built	Future updating suggested, can be a game changer

The set of assumptions is deemed sufficiently detailed and robust for the scope of a prefeasibility study

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Disclaimers and considerations on methodologies

Storage → Short and mid term modelled, not long term (sector coupling) → Molecules (Power-to-Hydrogen) and thermal / mechanical storage can compete with interconnections

Future work recommended

Demand Response → Simple modelling, more sophisticated possible but not impacting the scope → Demand response reduces Capex in generation and in grids

DR impacts more grid operation than grid architecture

Disclaimers and considerations on methodologies

Storage	Short and mid term modelled, not long term (sector coupling)	Molecules (Power-to-Hydrogen) and thermal / mechanical storage can compete with interconnections	Future work recommended
Demand Response	Simple modelling, more sophisticated possible but not impacting the scope	Demand response reduces Capex in generation and in grids	DR impacts more grid operation than grid architecture
Optimisation model very complete	Hourly resolution, full year horizon, unit committment, pragmatic constraints	Co-optimisation of generation, storage and transmission	Model robust for sensitivities and assumptions changes
Corridors simulations	Only DC adopted, no AC (different from C1.35)	OHL allow viability of most interconnections, cables only few	Marine links should be assessed vs transport of molecules (H2 and derivatives)

Modelling and simulations have identified the most important drivers; utilised simplifications seem acceptable

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Non-technical issues and further work

Out-of-scope in this prefeasibility study →	Dynamics and grid behaviour beyond basic load flow →	Electric topology inside copper-plate regions & individual lines in corridors →	Corridors one-by-one assessment or priority
Trading rules and governance →	Gradual approach from bilateral to multi lateral, regional, up to global →	Political support and risk protections; start with PPA + capacity use →	Business models for financiability

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Introducing sector coupling and hydrogen in the trade-off equation → Hydrogen rôle as long term storage AND as long range energy vector → Energy transition prospect: other sector coupling: thermal, transport, etc.

New WG proposed

Challenging also the adopted scenario → whole energy mix to be optimised, not only Gas+Wind+Solar

Which interconnection could start the process? Assess political-social acceptance, to identify more probable game-starters

Most important conditions are robust cooperation mood, mutual trust, strong socio-political support

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Thank you for your attention

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Now Question & Answer

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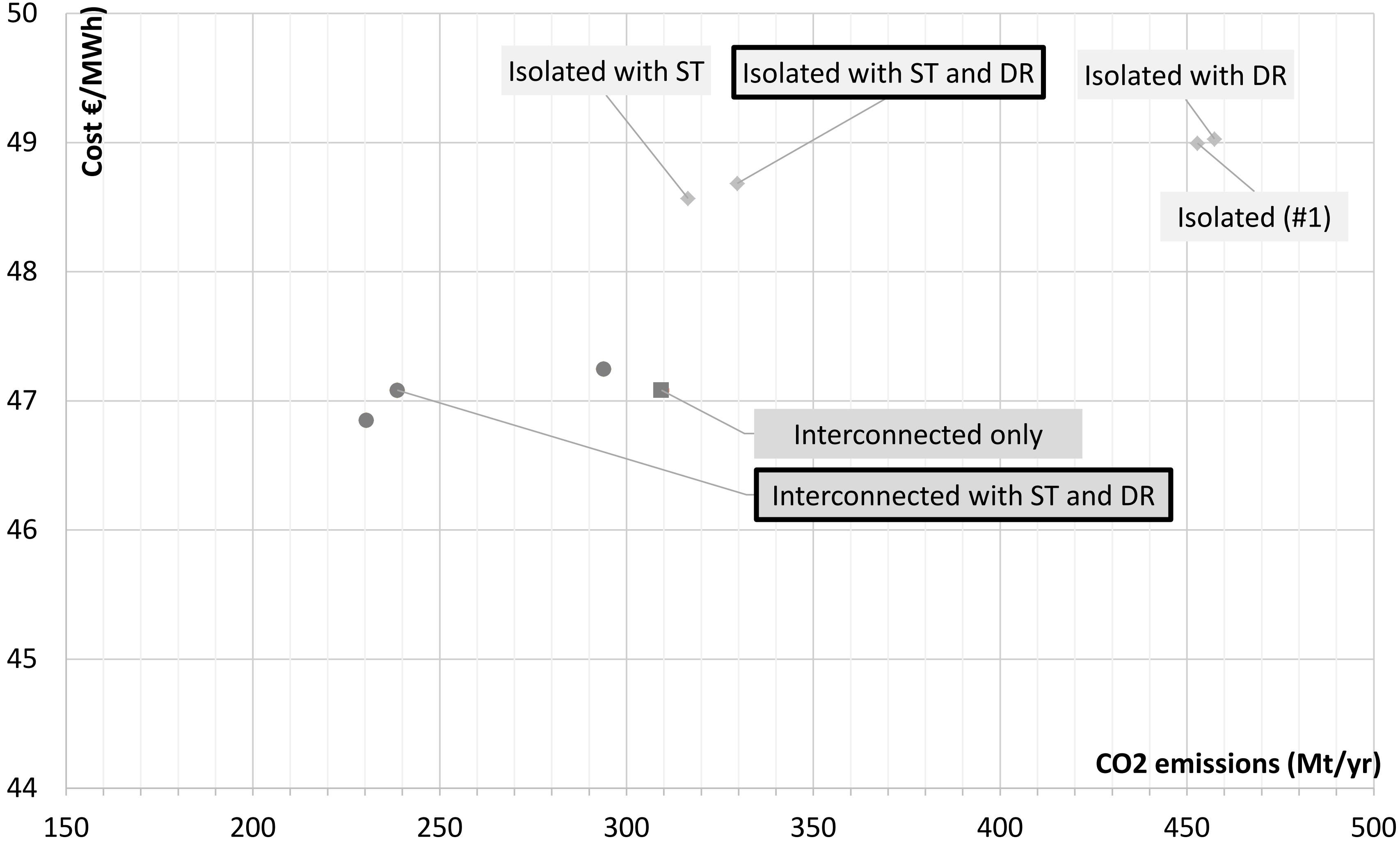
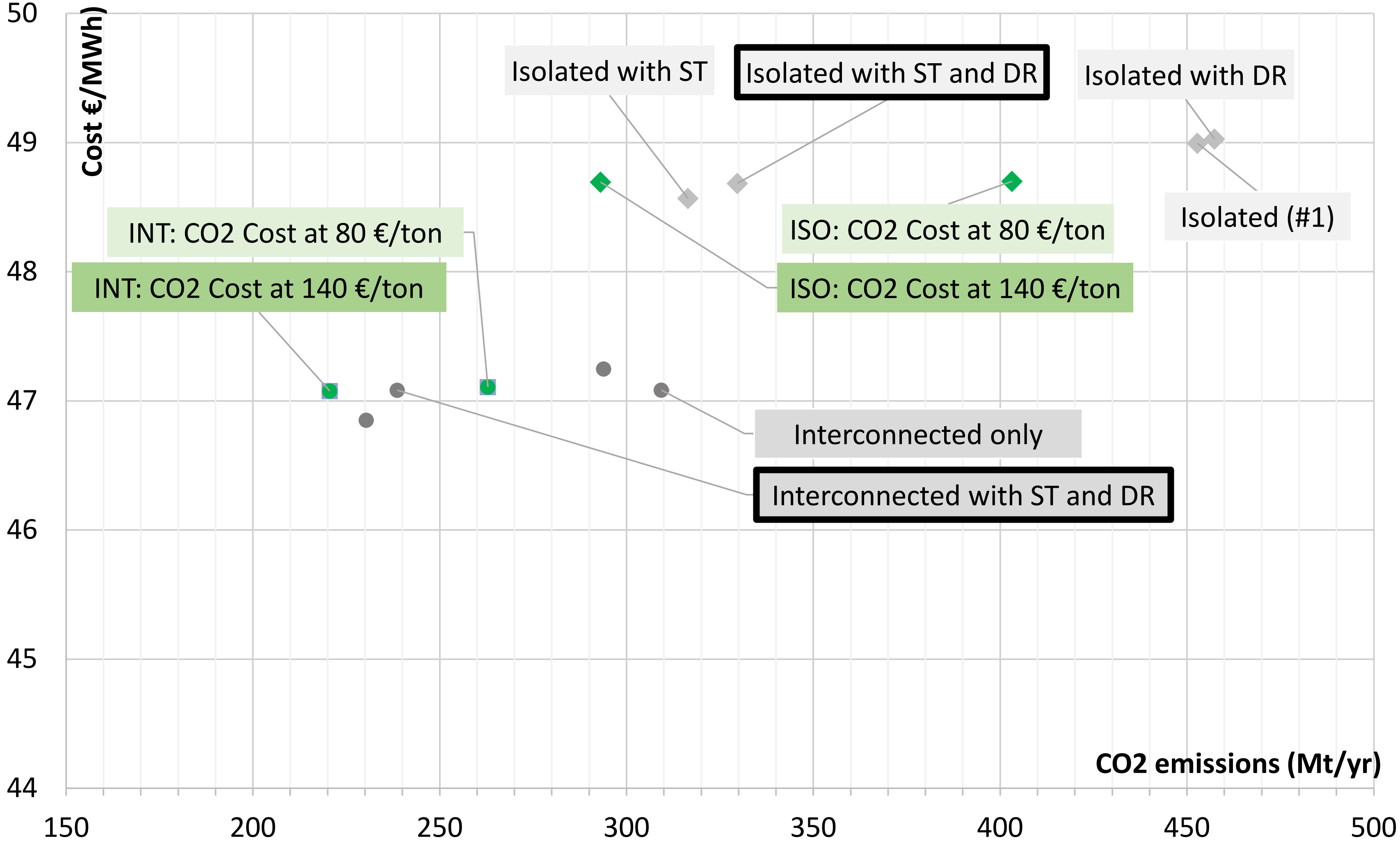
Sensitivity studies: impact of CO2



Sensivility studies: impact of CO2 cost

Case Studies	COST (€/MWh)	CO2 (Mt/yr)
Isolated with ST & DR CO2 cost = 110 €/ton	48,7	330
CO2 cost = 80 €/ton	48,7 (0%)	403 (+22%)
CO2 cost = 130 €/ton	48,7 (0%)	293 (-11%)
Interconnected with ST & DR CO2 cost = 110 €/ton	47,1	239
CO2 cost = 80 €/ton	47,1	263 (+10%)
CO2 cost = 130 €/ton	47,1	221 (-8%)



CO2 cost has a greater impact on isolated system

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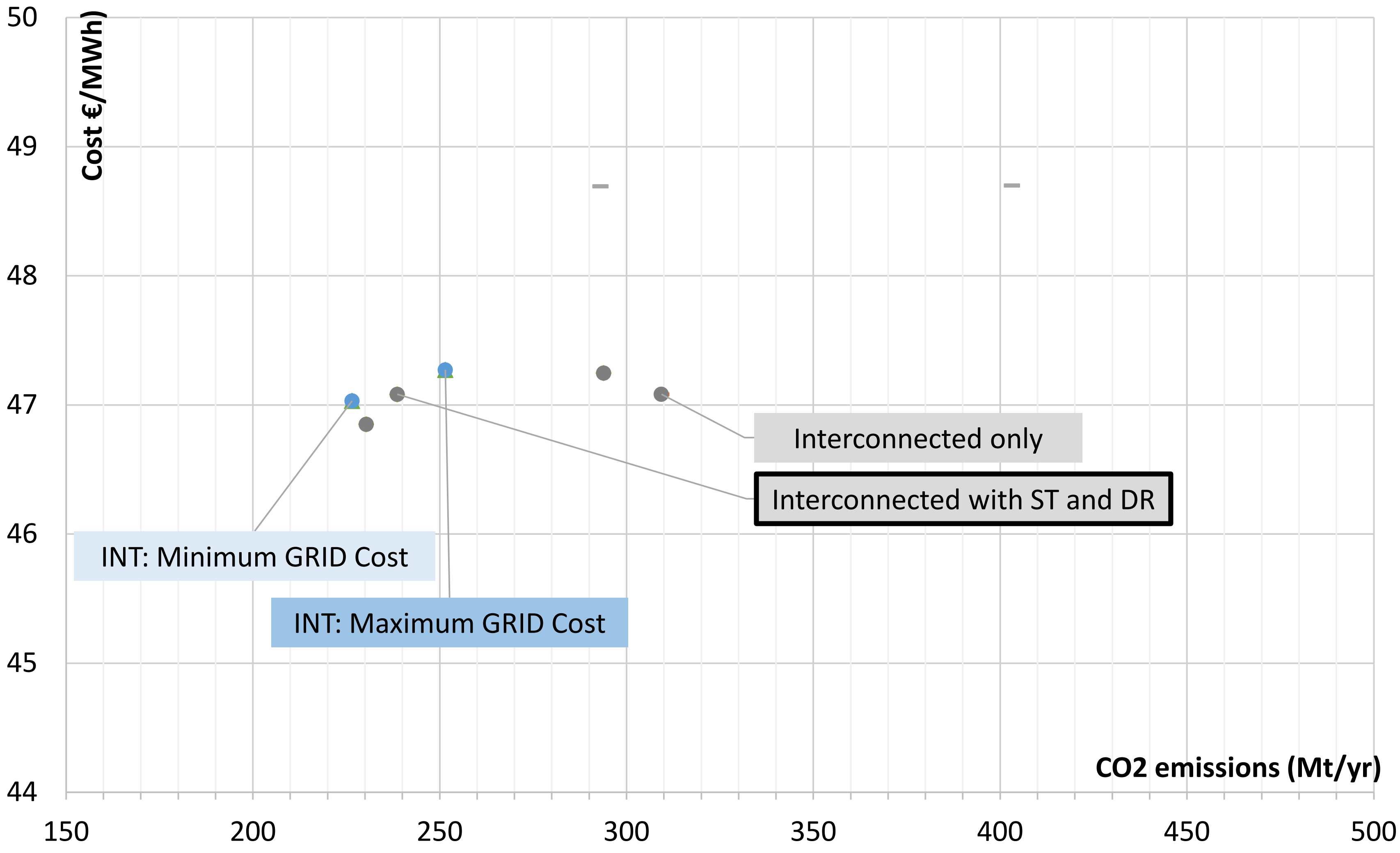
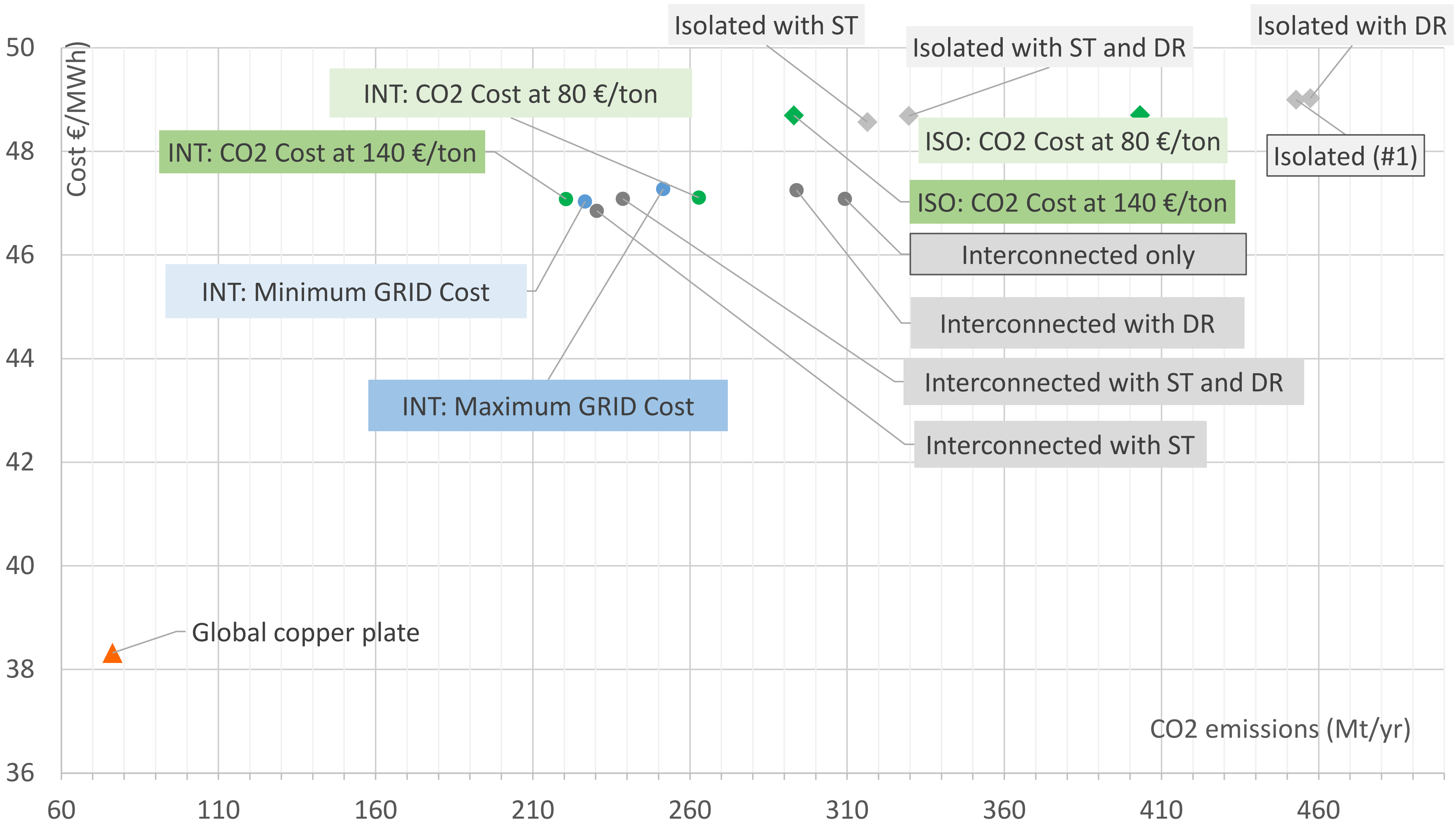
Sensibility studies: impact of Grid Cost

Case Studies	COST €/MWh	CO2 Mt/yr
Interconnected with ST & DR DC-OHL cost = 0,26 M€/km/GW	47,1	239
DC-OHL cost = 0,18 M€/km/GW	47,0	227
DC-OHL cost = 0,33 M€/km/GW	47,3	252



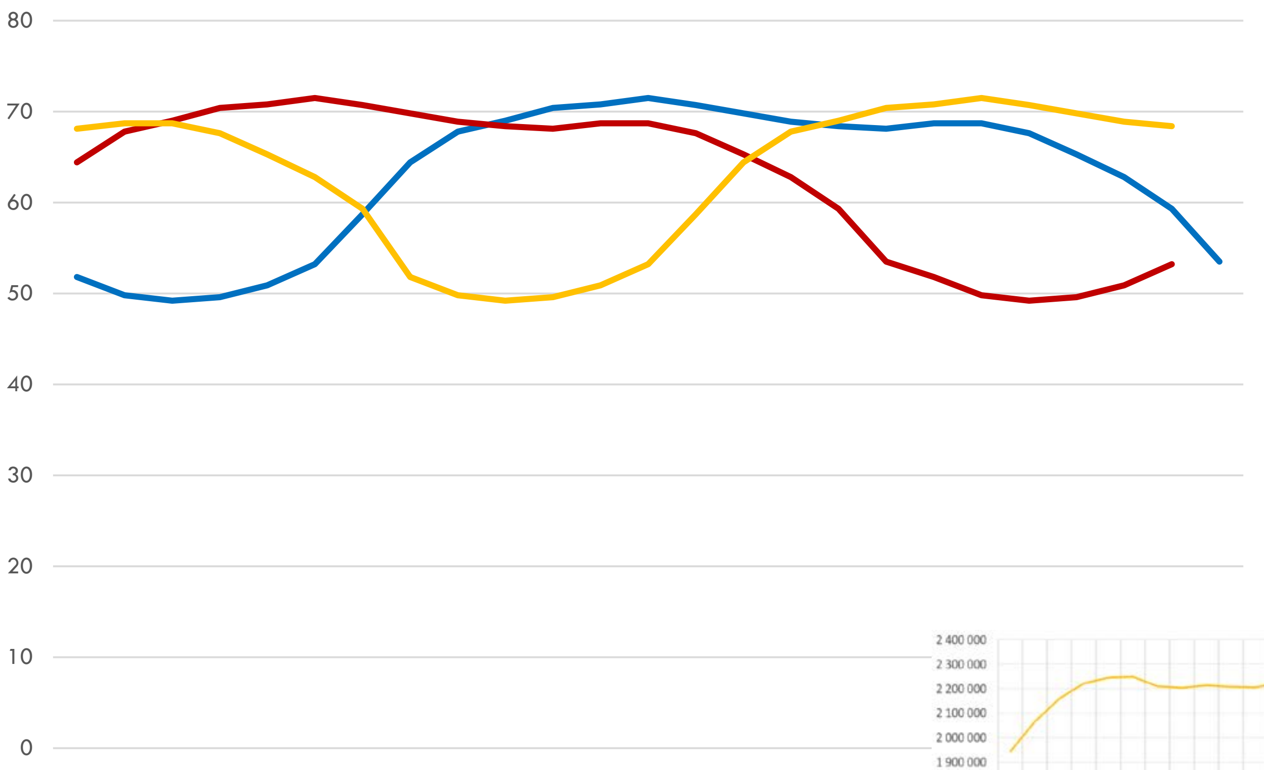
Grid cost as a limited impact on CO2 emission and global system Cost

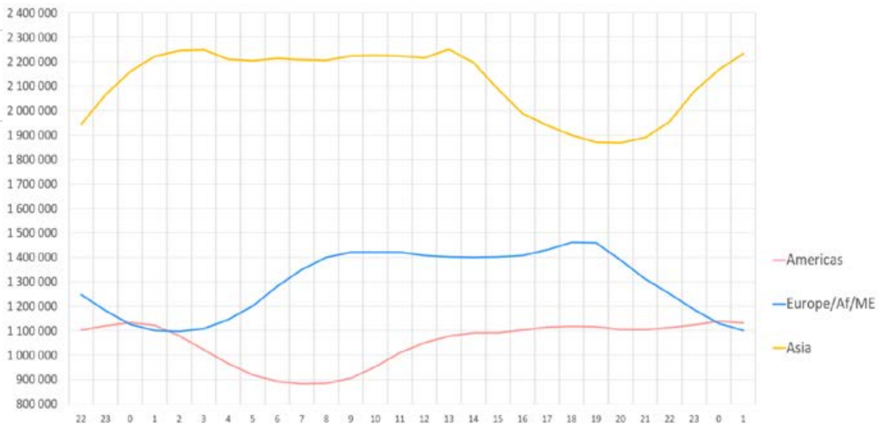
Sensibility studies: wrap-up



Interconnections - motivation

Time-zone differences





Americas	Europe/Af/ME	Asia	WORLD
1 056 312	1 080 297	2 175 647	4 312 255
1 058 538	1 055 242	2 210 105	4 323 886
1 030 823	1 051 593	2 230 799	4 313 215
986 933	1 065 578	2 236 285	4 288 796
941 790	1 104 638	2 196 533	4 242 961
904 264	1 165 894	2 187 596	4 257 754
880 044	1 254 659	2 193 860	4 328 563
874 691	1 329 492	2 186 248	4 390 430
880 010	1 386 090	2 186 079	4 452 178
906 048	1 408 580	2 213 307	4 527 935
957 228	1 409 356	2 212 757	4 579 340
1 019 614	1 410 417	2 215 722	4 645 753
1 065 265	1 398 994	2 206 377	4 670 636
1 090 964	1 394 098	2 246 022	4 731 083
1 103 758	1 394 447	2 190 297	4 688 502
1 103 588	1 399 576	2 079 529	4 582 692
1 113 680	1 405 936	1 975 326	4 494 941
1 116 181	1 429 754	1 923 908	4 469 842
1 112 341	1 462 971	1 877 990	4 453 301
1 106 588	1 456 313	1 853 046	4 415 948
1 093 212	1 384 910	1 851 498	4 329 620
1 090 476	1 306 217	1 878 225	4 274 919
1 102 174	1 248 273	1 944 655	4 295 102
1 119 102	1 181 921	2 065 751	4 366 774
1 133 031	1 125 474	2 159 129	4 417 634
1 122 385	1 101 151	2 221 429	4 444 965
1 079 481	1 097 269	2 243 867	4 420 617
1 020 815	1 108 471	2 249 162	4 378 448
964 916	1 144 370	2 210 769	4 320 055
920 276	1 201 937	2 204 050	4 326 263
893 263	1 282 660	2 214 760	4 390 683
882 150	1 350 144	2 207 844	4 440 139
884 589	1 400 298	2 205 386	4 490 273
905 662	1 420 033	2 224 120	4 549 815
952 809	1 420 019	2 224 880	4 597 708
1 009 088	1 421 128	2 223 453	4 653 669
1 051 500	1 406 989	2 215 259	4 673 748
1 077 040	1 401 589	2 251 137	4 729 766
1 090 321	1 398 808	2 197 318	4 686 447
1 092 031	1 402 516	2 086 844	4 581 391
1 103 031	1 407 780	1 989 086	4 499 896
1 113 595	1 430 244	1 940 739	4 484 578
1 117 905	1 461 598	1 898 494	4 477 997
1 115 713	1 459 261	1 871 432	4 446 405
1 105 231	1 388 127	1 868 623	4 361 981
1 103 659	1 310 163	1 889 926	4 303 747
1 112 058	1 250 388	1 956 043	4 318 488
1 124 611	1 185 861	2 078 284	4 388 756

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Interconnections selected: Expansion Cost (M€/GW)