UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dipartimento di Ingegneria e Architettura

Engineering Energy Transition

Production, Transmission and Distribution

Fundamentals of Modern Power Systems

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Importance of Electric Power Systems

- Importance of electric energy to our **social welfare**
- Awareness of the **finite supply of fossil fuels**
- The use of fossil fuels releases **carbon into the atmosphere**
- **Traditional power systems may have to change**
- Also … electric power is being used for a **wider range of applications** as time goes on
- **Reduction in the need of energy** requires **efficiency** and very often this involves the use of electricity
- All this indicates **the need for well-educated, innovative engineers** to build the power systems of the future

Electric Power Systems in developed countries

- Electric utility service is **ubiquitous** in **developed countries**
- Standardized levels of **voltage and frequency** permit a wide range of appliances to be simply plugged in and operated
- **Blackouts** are uncommon
- **We depend on electric power** to keep the lights on, to control heating, cooling, cooking, and refrigeration systems in our homes and businesses

Electric Power Systems in developing countries

- **One billion people have not access to electric power**
- **In many developing countries** there're widespread distribution systems but **generation is insufficient**
- Today the most used **primary resources** are new renewables (photovoltaics and wind), fossil fuels, falling water and heat from nuclear fission
- **Sun and wind** will be soon the most used primary resources

Definitions

- **Energy w** is the quantitative property that is transferred to a body or to a physical system. In the International System of Units, the unit of energy is **joule (J)**. Often energy is measured in **watt-hour (Wh)**
- **Power p** is the amount of energy per unit time
  In the International System of Units, the unit of power is the **watt (W)** corresponding to one joule per second (J/s)

$$p = \frac{\Delta w}{\Delta t} \qquad w(T) = \int_0^T p(t)\,dt$$

1 watt-hour = 1 watt × hour = 3.600 J

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Definitions

- 1 W is also 1 V × 1 A
- The **volt (V)** is a unit of electrical potential
- The **ampere (A)** is a unit of current flow
- Power is expressed in watts, kilowatts, etc…
- **A basic unit of electric energy is the kilowatt-hour (kWh)** corresponding to 3.6×10^6 J
- Electricity is sold at retail by the kilowatt-hour and, usually, at wholesale by the megawatt-hour

Multiple	Prefix	Symbol
10^{15}	peta	**P**
10^{12}	tera	**T**
10^{9}	giga	**G**
10^{6}	mega	**M**
10^{3}	kilo	**k**
10^{-3}	milli	**m**
10^{-6}	micro	**μ**
10^{-9}	nano	**n**
10^{-12}	pico	**p**
10^{-15}	femto	**f**

Application	Current
Integrated circuit	1 nA – 1 µA
Current that a person can feel	1 mA
Mobile phone charger	150 mA – 1 A
Photovoltaic module	5 – 10 A
Residential power plant	1 – 20 A
Industrial power plant	10 – 200 A
HV transmission line	30 – 500 A
Synchronous Generator	10 – a few kA

Application	Voltage
Radio antenna	100 nV – 10 μV
Car battery	12 V
Home plug	230 V
Industrial plug	400 V
Electrical distribution system	0,4 – 150 kV
Electrical transmission system	400 kV

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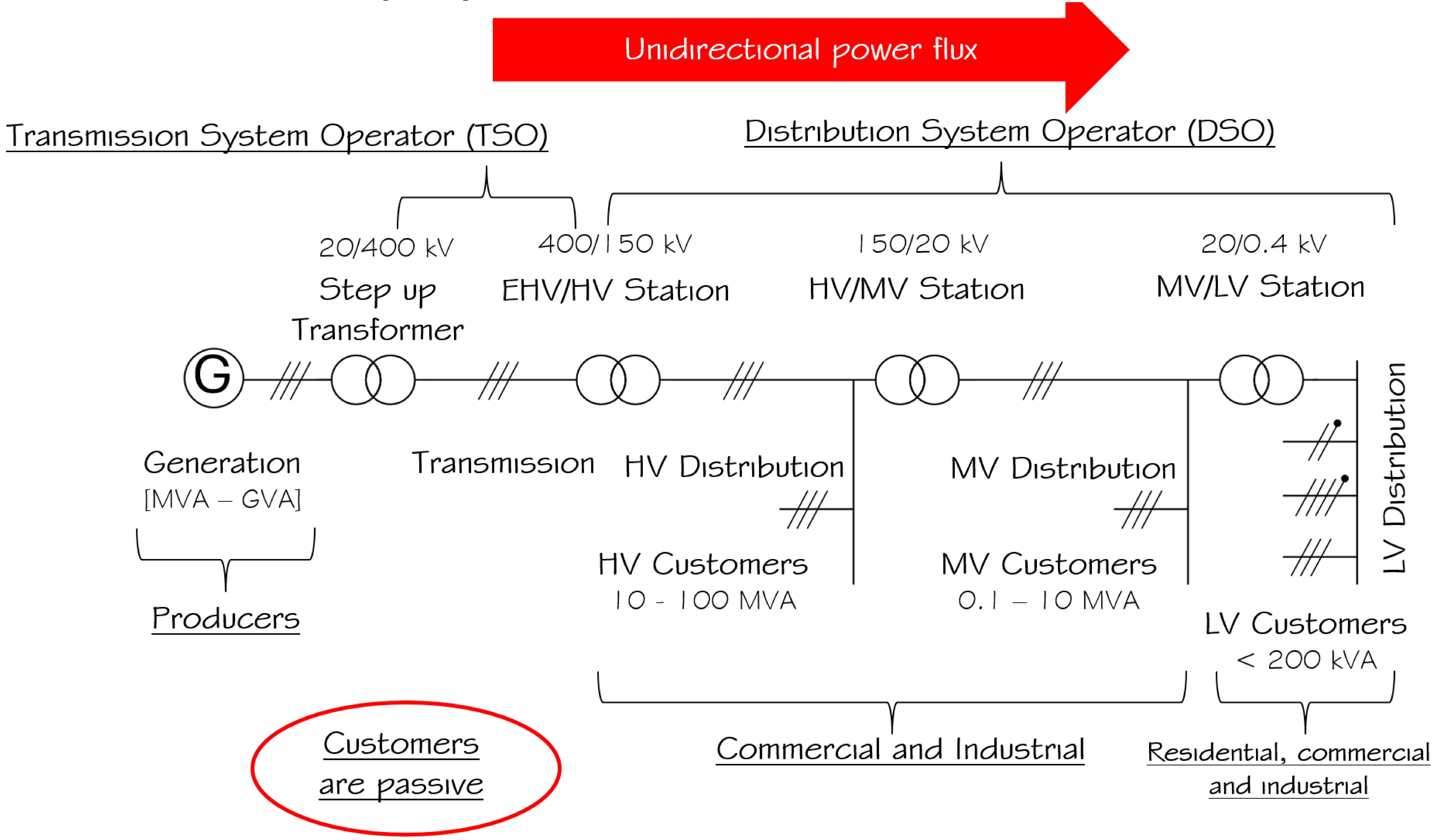
Application	Power
Smartphone receiver	5 pW
Personal Computer	100 W
Dishwasher	1 – 2 kW
Residential power system	3 kW
E-Vehicle charger	3,7 – 22 – 120 kW
Synchrotron	1- 5 MW
Electrical distribution system	0,1- a few MW
Electrical transmission system	100 - a few GW
Power plants	0,01- a few GW

Application	Energy
Smartphone battery	10 Wh
Fridge use annually	150 – 300 kWh
Average energy consumption of a family	2.000 kWh
Car battery capacity	20 – 100 kWh
Photovoltaic plant yield (1 kWp)	1.500 – 5.000 kWh
Power plant yield	0,01 – 10 TWh

Centralized utility systems



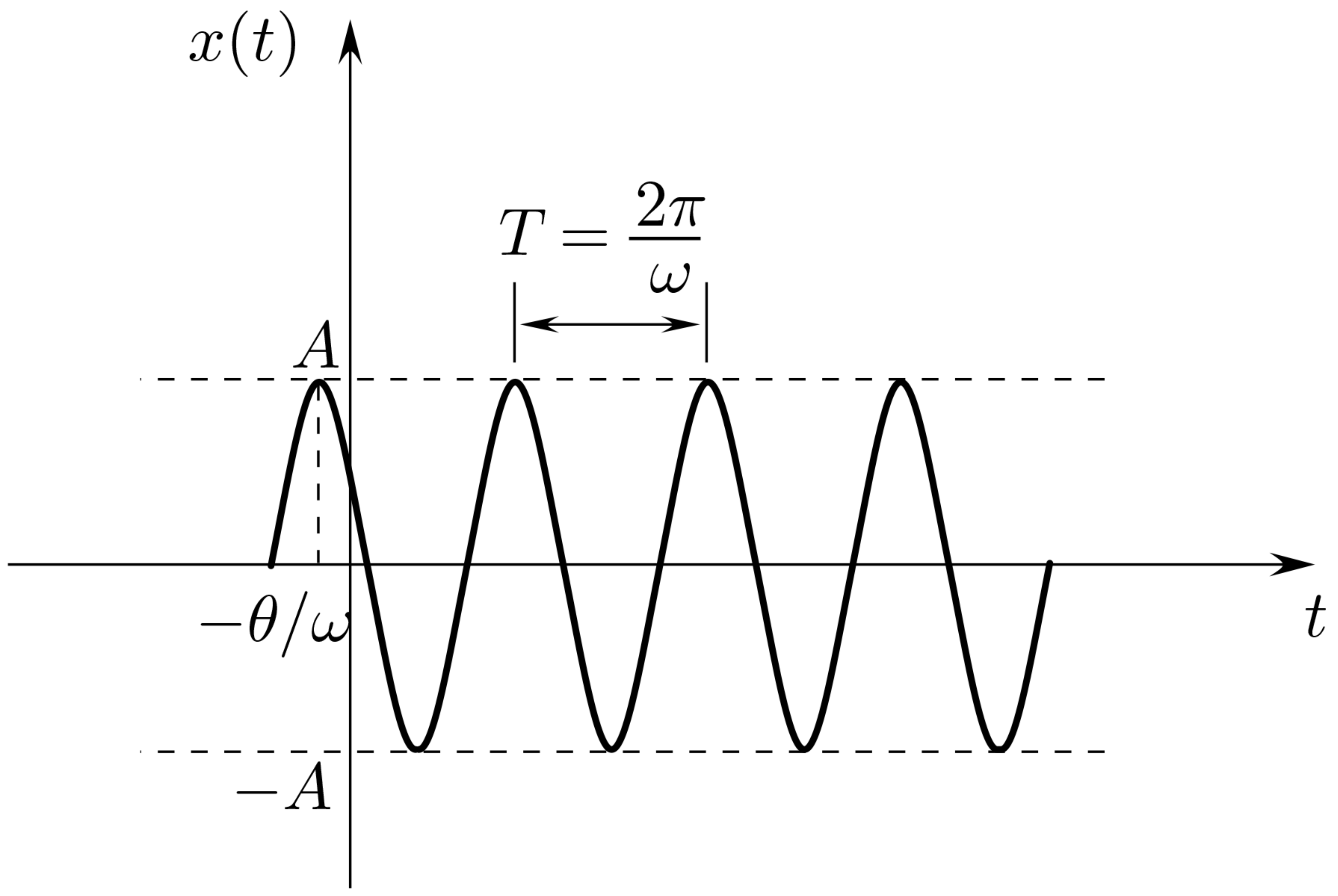
Single line diagrams

Sinusoidal function

$$\omega = 2\pi f$$

$$x(t) = A\cos(\omega t + \theta)$$

$$T = \frac{1}{f}$$



- A – amplitude
- ω – pulsation [rad/s]
- θ – initial phase [°]
- T – period [s]
- f – frequency [Hz]
- rms – root mean square

$$A_{rms} = \sqrt{\frac{1}{T}\int_0^T A^2\, sin^2\, \omega t dt} = \frac{A}{\sqrt{2}} = 0{,}707A$$

$$\boldsymbol{A_{rms} = \frac{A}{\sqrt{2}}}$$

DC - 1ΦAC - 3ΦAC ???

- l [m]– length of an electrical line connecting a generator to a load
- P [W]– active power absorbed by the load
- V [V] – voltage across the load
- ρ [Ω×m] – resistivity of the conductor
- P_{xy} [W] – power losses
- $V_{cond,\ z}$ [m^3] – volume of the conductor

$$P_{DC} = 2\rho \frac{l}{S_{CC}} \left(\frac{P}{V}\right)^2$$

$$P_{1\phi} = 2\rho \frac{l}{S_{1\phi}} \left(\frac{P}{V \cos\varphi}\right)^2$$

$$P_{3\phi} = \rho \frac{l}{S_{3\phi}} \left(\frac{P}{V \cos\varphi}\right)^2$$

$$\frac{V_{cond,1\phi}}{V_{cond,3\phi}} = \frac{4}{3}$$

$$\frac{V_{cond,3\phi}}{V_{cond,cc}} = \frac{3}{4\cos\varphi^2}$$

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Voltage and power levels (Italy)

- **Extra High Voltage** (EHV): > 150kV – typically 230 and 400 kV
- **High Voltage** (HV): > [35 – 150 kV] – typically 132 and 150 kV
- **Medium Voltage** (MV): [1 – 35 kV] – typically 10 and 20 kV
- **Low Voltage** (LV): < 1 kV – typically 400 and 230 V and 20 kV

Power [MW]	Voltage
≤ 0.1	LV
0.1 – 0.2	LV/MV
0.2 – 3 (0.2 – 6)*	MV
3 – 10 (6 – 10)*	MV/HV
> 10	HV

* Producers

Sources of electric power

- **Generators**: prime movers can be **heat engines** (steam and gas turbines, internal combustion engines), or **turbines** converting from water or wind)

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Sources of electric power

More in “Materials and Systems for the Energy Transition”, “Photovoltaic Systems” and “Hydrogen and Fuel Cells”

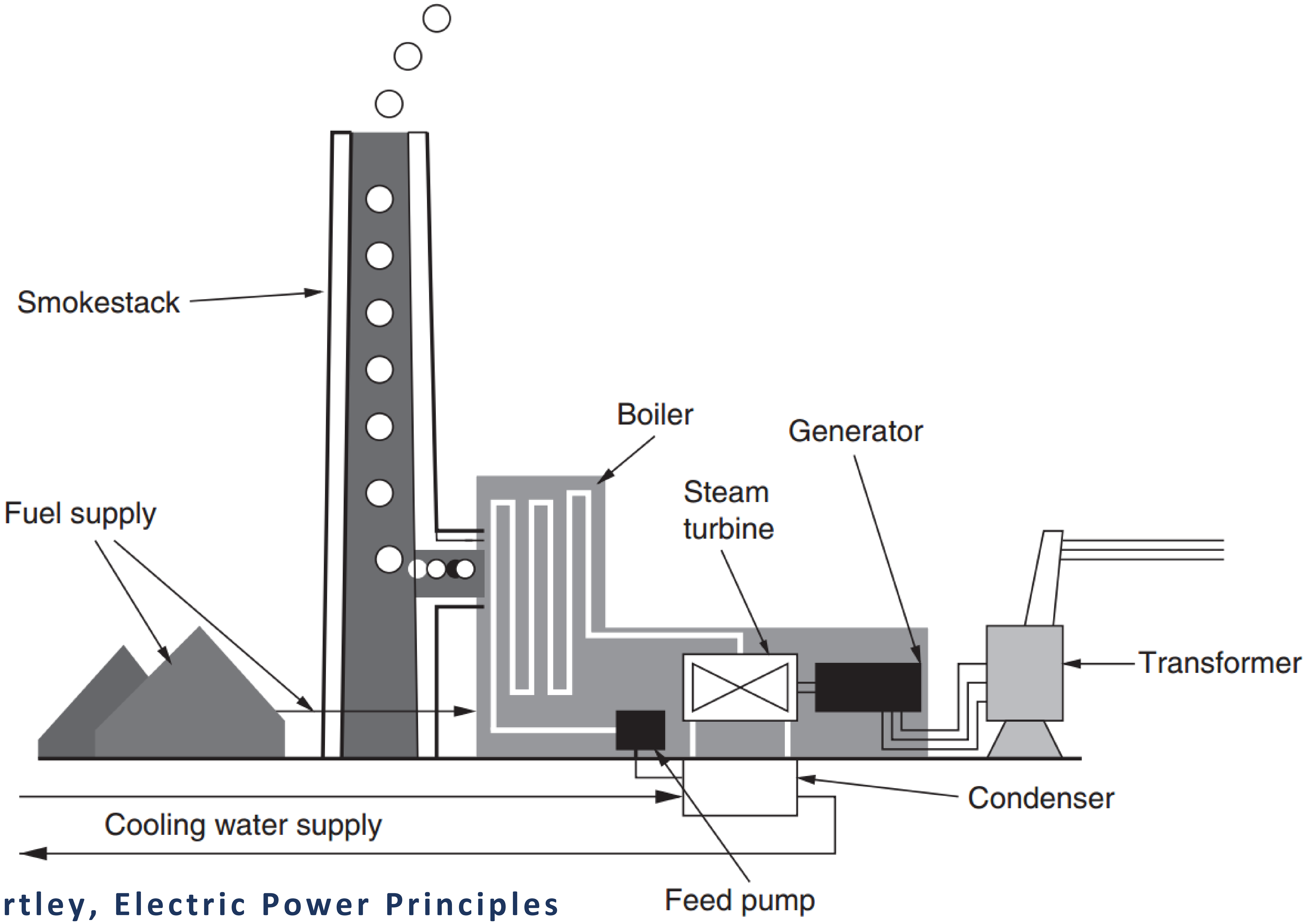
- **Direct conversion**: from chemical energy or sunlight

Power plants

More in "Industrial Energy Management"

And in "Environmental hydraulics"

- Fossil fuels-based
- Production of electricity but of contaminants too: sulfur (**acid rain**), mercury (**food chain**), carbon dioxide (**global warming**)
- Fossil fuel-based energy systems are inefficient and expensive



Kirtley, Electric Power Principles

Nuclear Power plants

More in "Alternative Technologies 2"

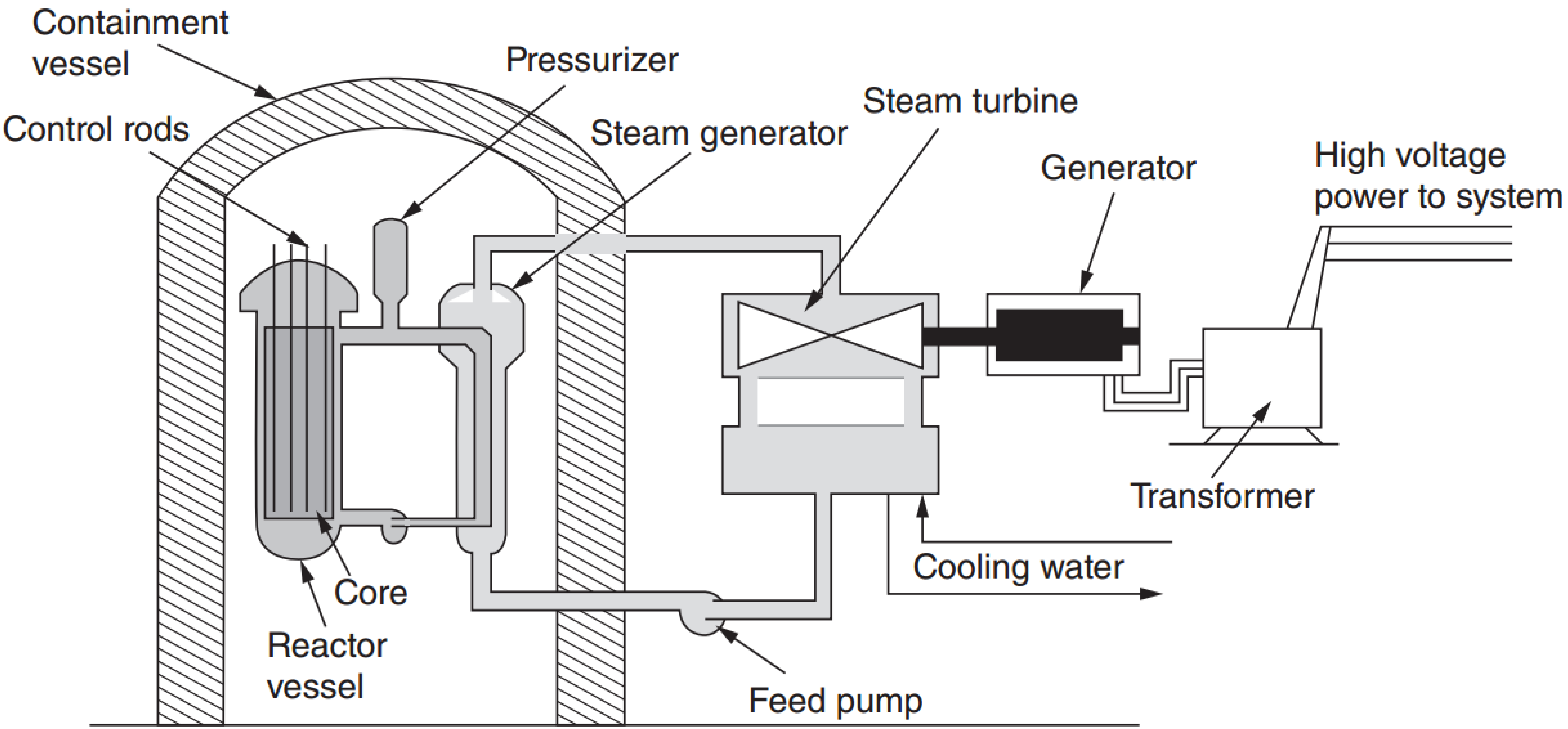


Figure 1.5 Diagram of a nuclear power plant.

Kirtley, Electric Power Principles

Hydroelectric power

More in “Renewable Energy Technologies”

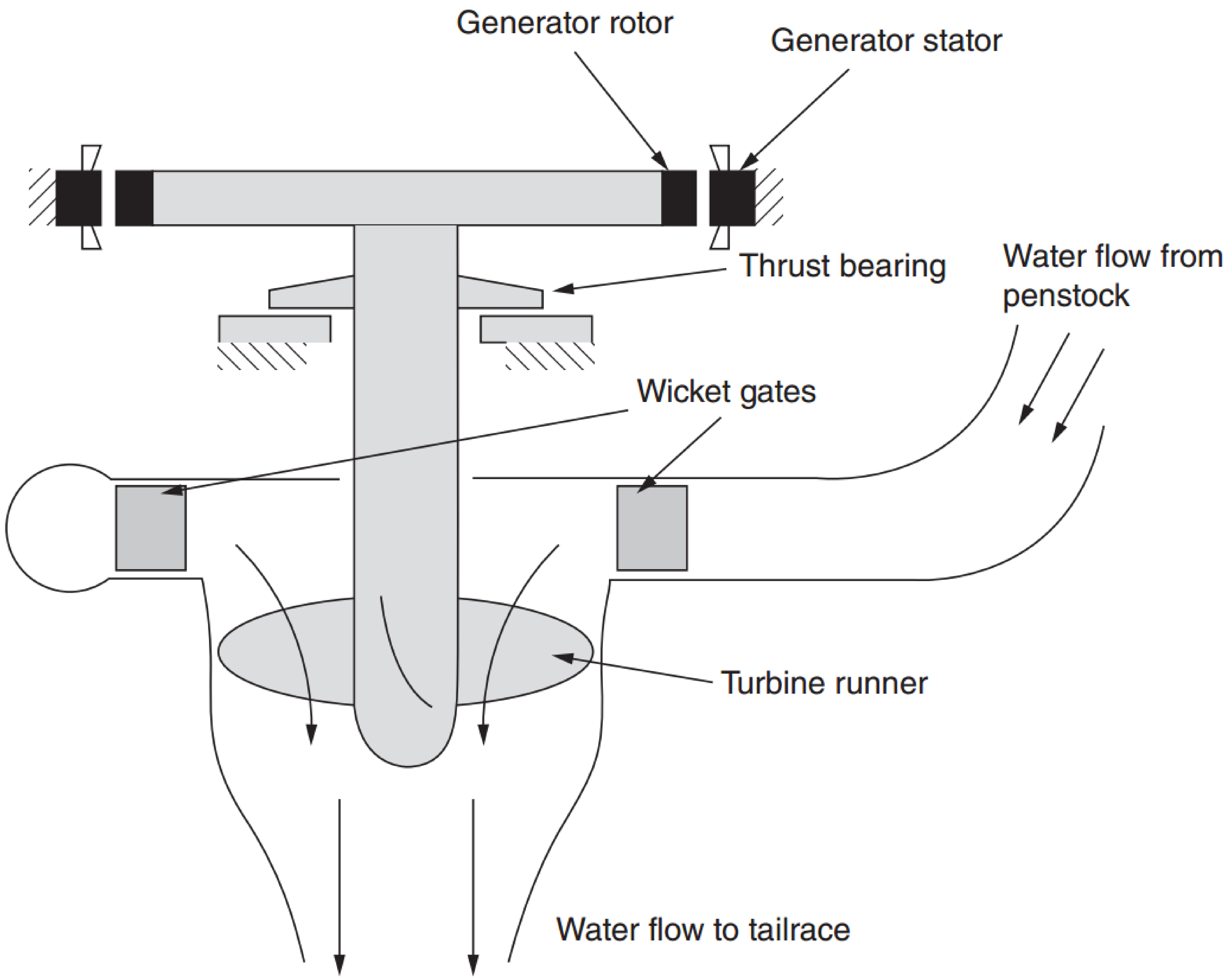


Figure 1.6 Diagram of a hydroelectric generating unit.

Kirtley, Electric Power Principles

Wind turbines

More in “Alternative Technologies 2” and in “Renewable Energy Technologies”

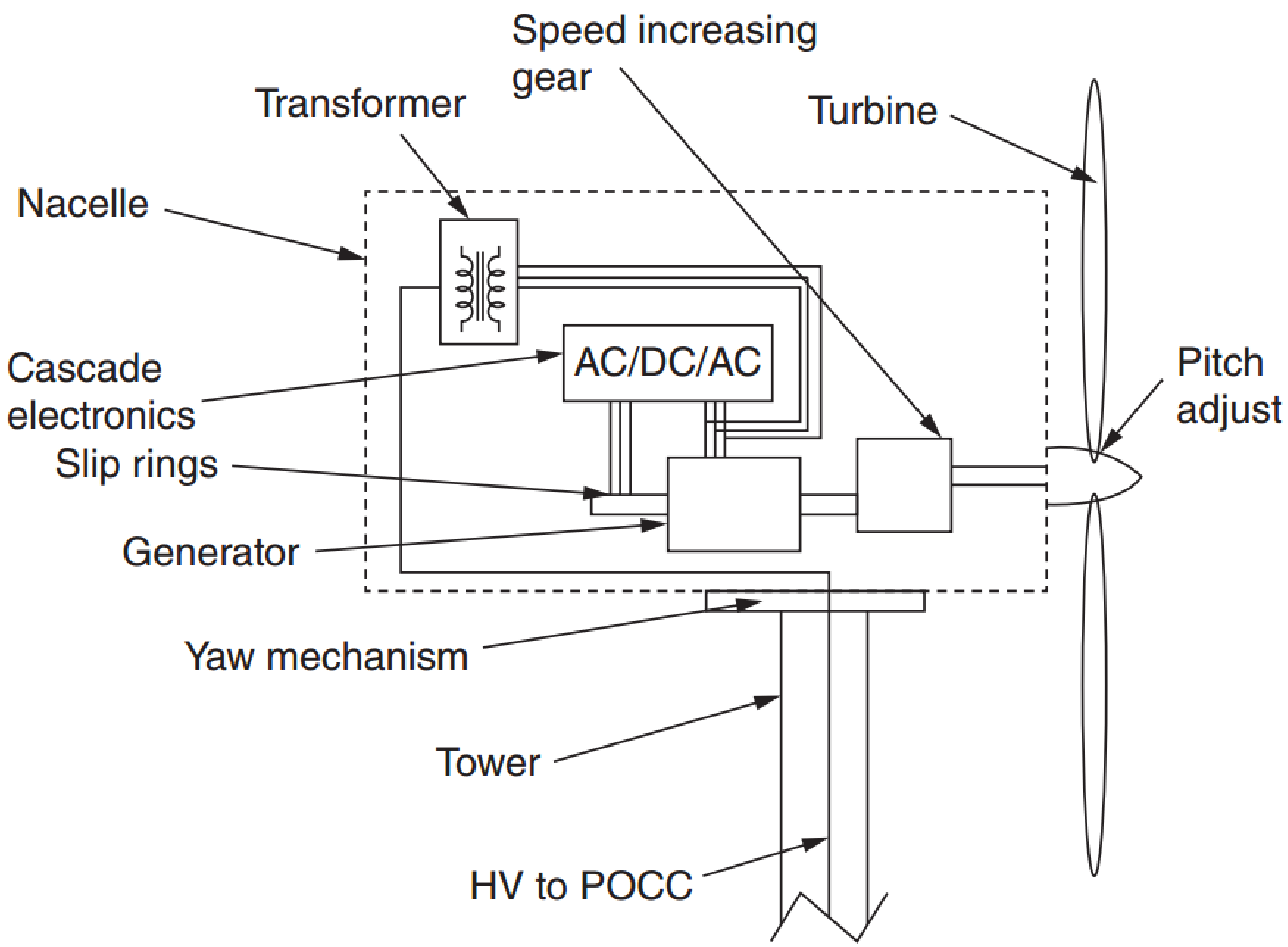


Figure 1.8 Wind turbine components.

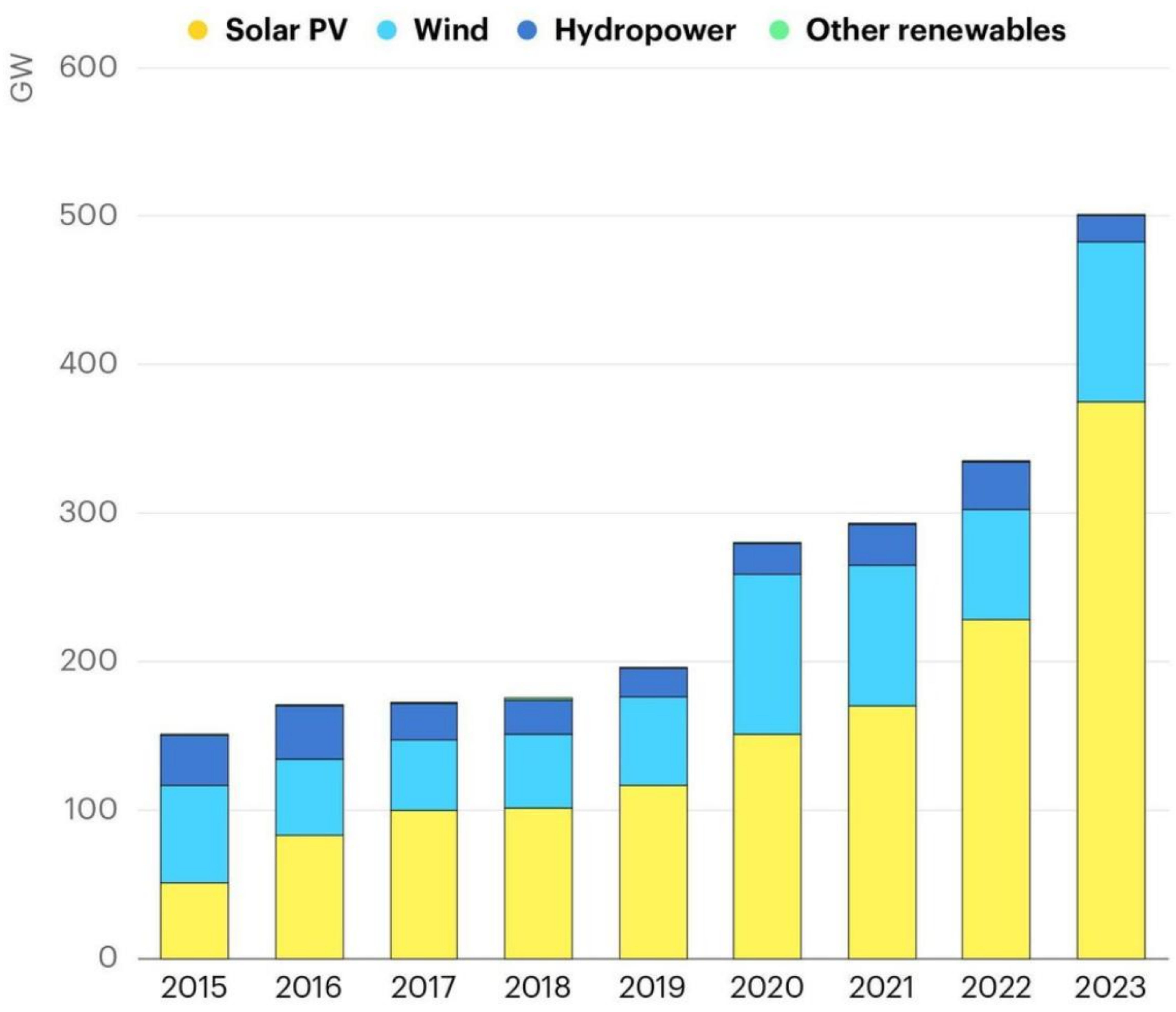
Kirtley, Electric Power Principles

Power plants: global

TECHNOLOGY	2023 [GW]	2022 [GW]	VARIATION [%]
PHOTOVOLTAICS	1600	1200	33.3
WIND	1021	904	12.9
BIOMASS, SOLID BIOFUELS AND WASTE	290	277	4.7
GAS	1926	1895	2.3
HYDROPOWER	1412	1392	1.6
COAL	2190	2142	2.2
NUCLEAR	372	371	0.3

- China 2023: 217GW of PV, 90GW of wind, 1GW of nuclear
- Nuclear in China: 34.4GW during the last 10 years, they have a plan to install other 30GW by 2030 (5 per year)

Power plants: global



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Power generation in Italy

TECHNOLOGY	2005	2020	2022	2023	2024
THERMAL POWER	81%	60%	**67%**	**58%**	**51%**
HYDROPOWER	15%	17%	**9%**	16%	20%
PHOTOVOLTAICS	0%	9%	9%	12%	14%
WIND POWER	1%	6%	7%	9%	9%
BIOMASS	2%	6%	6%	3%	5%
GEOTHERMAL	2%	2%	2%	2%	1%

Comparing technologies

	FF-TE	N-TE	GT	CC	HP	WIND	PV
Power [MVA]	dozens thousands	dozens thousands	1 - 350	1 - 350	1 - hundreds	1 - hundreds	1 - hundreds
OCS [€/kW]	900 – 1.400	???	300	500	1.000 – 2.000	900 – 2.000	600 - 800
η [%]	36 – 50	50	33 - 40	60 – 75	50 – 90	20 – 70	20 - 25
Utilization hours	6.500 – 7.500	8.000	6.500 7.500	6.500 7.500	2.000 4.000	1.700 4.250	1.200 1.700
Speed	low	low	high	high	high	high	high
Load	full	full	variable	variable	variable	variable	variable
Fuel cost	variable	???	high	high	0	0	0
LCOE [€/kWh]	0.12 ↑	???	0.15 ↑	0.10 ↑	0.08 ↑	0.08 ↓	0.04 ↓
EROEI	17 ↓	14 ↓	15 ↓	19 ↓	84	18 ↑	25 ↑
Flexibility	low	low	high	high	high	low/high	low/high

Levelized Cost Of Energy

$$LCOE = VO\&MC + \frac{OCS \times CRF + FO\&MC}{8760 \times CF}$$

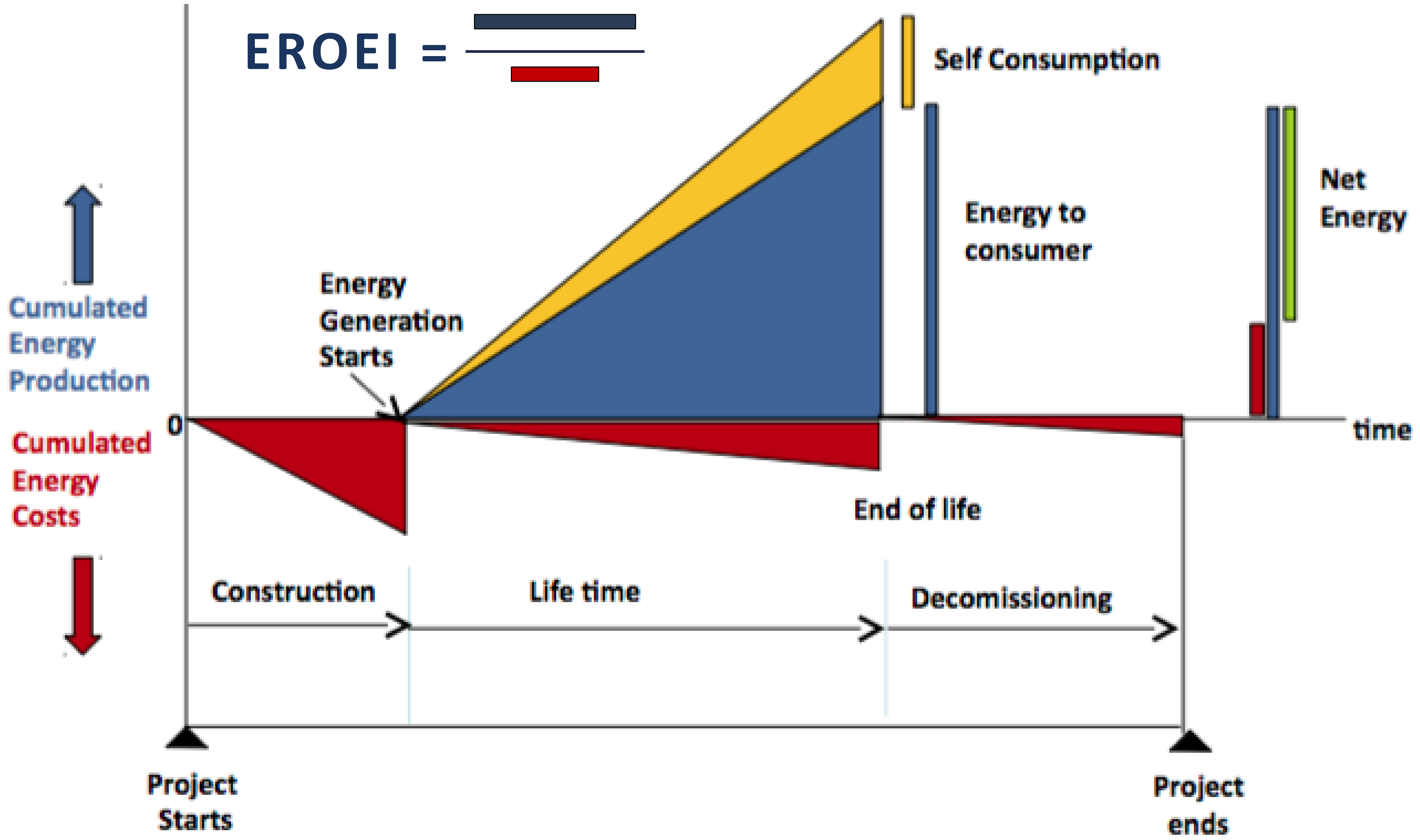
$$CRF = \frac{WACC \times (WACC + 1)^N}{(WACC + 1)^N - 1}$$

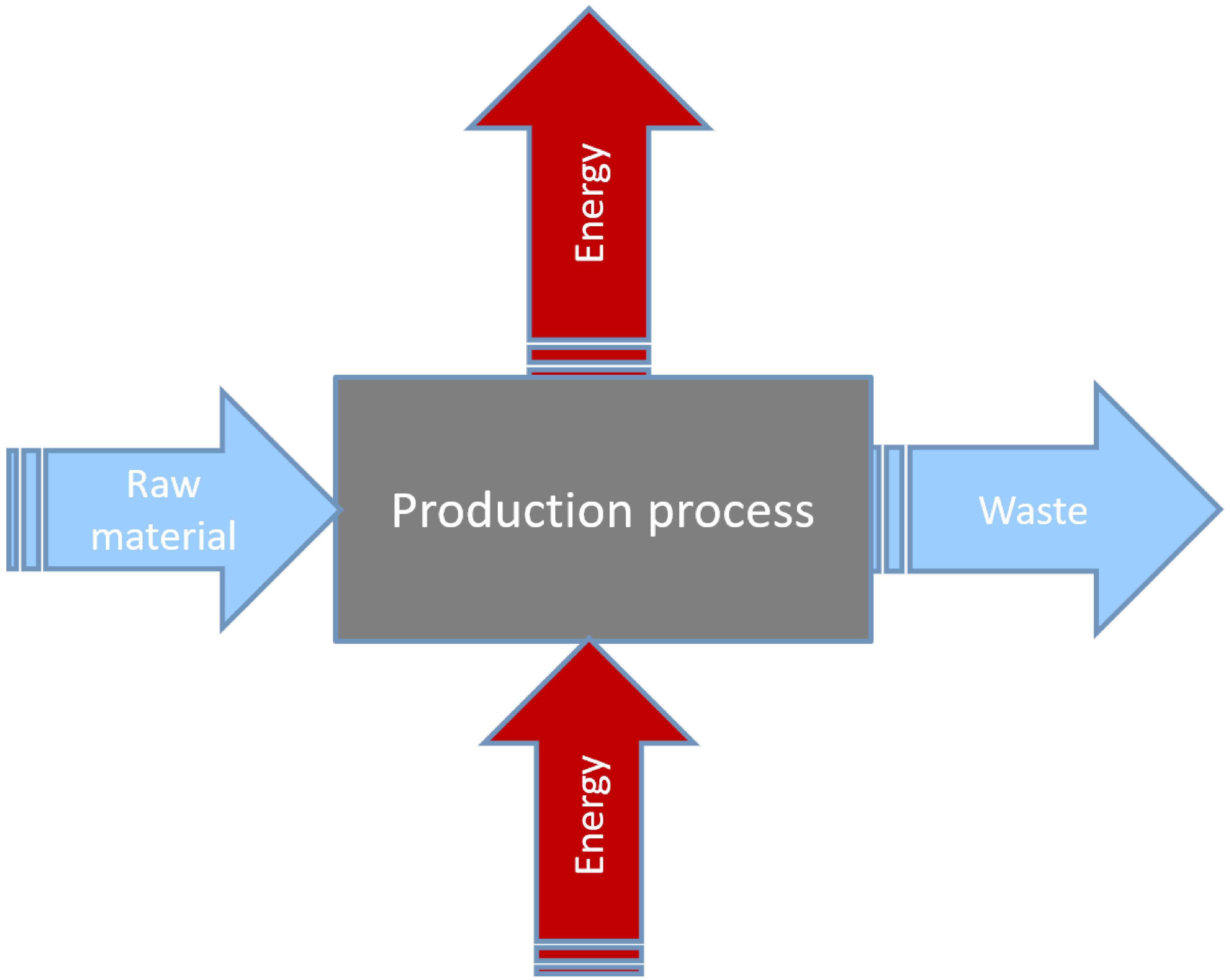
$$WACC = \frac{E}{E + D} \times K_e + \frac{D}{E + D} \times K_d$$

- VO&MC [€/year]: variable operation and maintenance costs
- OCS [€]: overnight capital cost
- CRF [ ]: capital recovery factor
- FO&MC [€/year]: fixed operation and maintenance costs
- CF [ ]: capacity factor

- WACC [%]: weighted average cost of capital
- N [ ]: number of annuities received
- E [%]: equity – D [%]: dept
- Ke [%]: the return of equity – Kd [%]: the cost of dept

Energy Returned on Energy Invested





More in "Design for Sustainability of Processes"

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Some EROEIs

King et al., Nature Energy, 2018

Table 1 | Comparison of mean EROIs for different energy sources

	Energy source		**Optimistic EROI**	**Optimistic net energy percentage**
Coal	Thermal		46:1	98
	Electricity		17:1	94
	Electricity with CCS		13:1	92
Oil	Thermal		19:1	95
	Electricity		7:1	85
Gas	Thermal		19:1	95
	Electricity		8:1	88
	Electricity with CCS		7:1	86
Biofuels & waste	Solids	Thermal	25:1	96
		Electricity	10:1	90
	Gases and liquids	Thermal	5:1	80
		Electricity	2:1	50
Nuclear			14:1	93
Hydroelectric			84:1	99
Geothermal			9:1	89
Wind			18:1	94
Solar PV			25:1	96
Solar thermal			19:1	95

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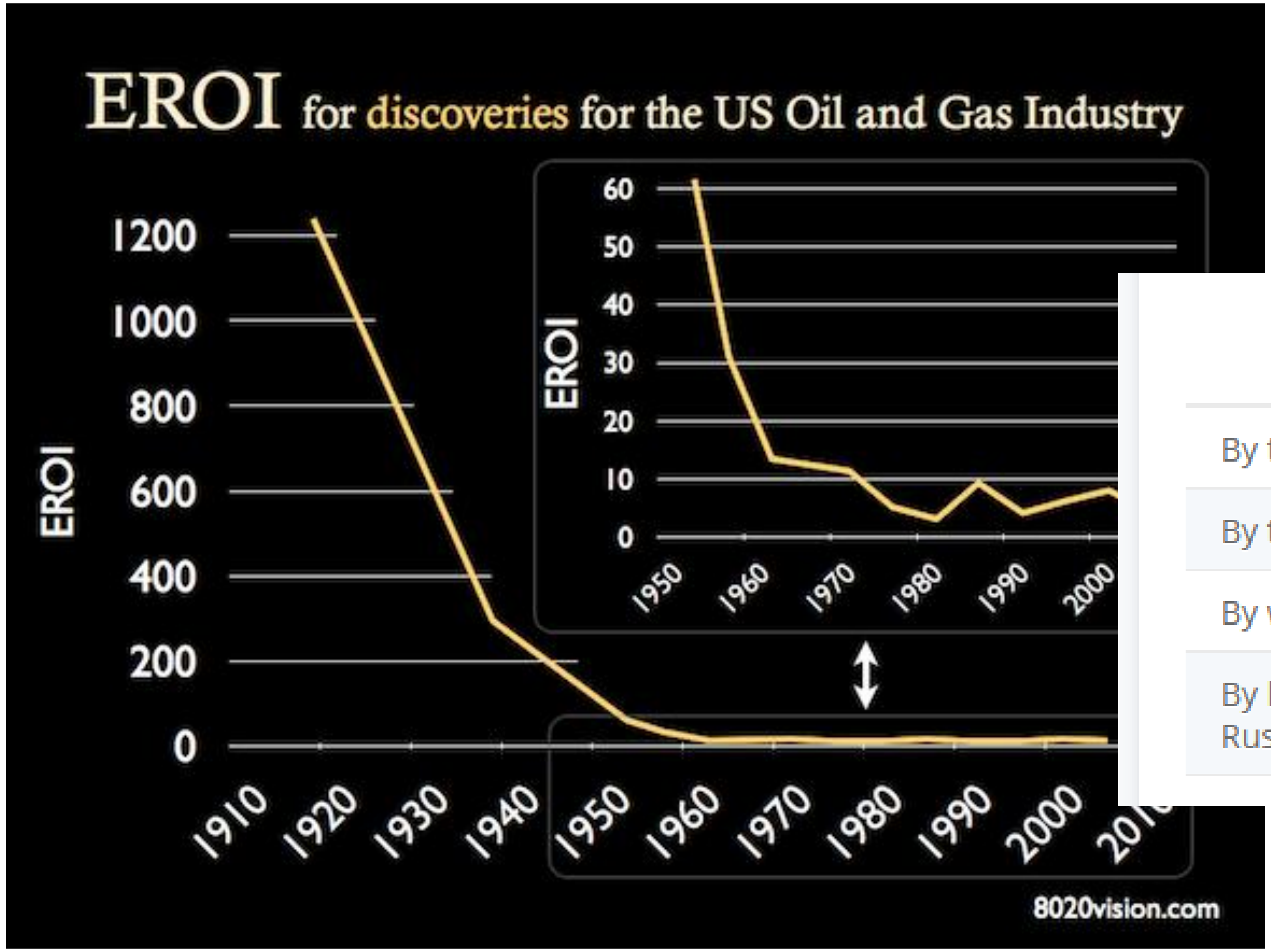
Oil and gas



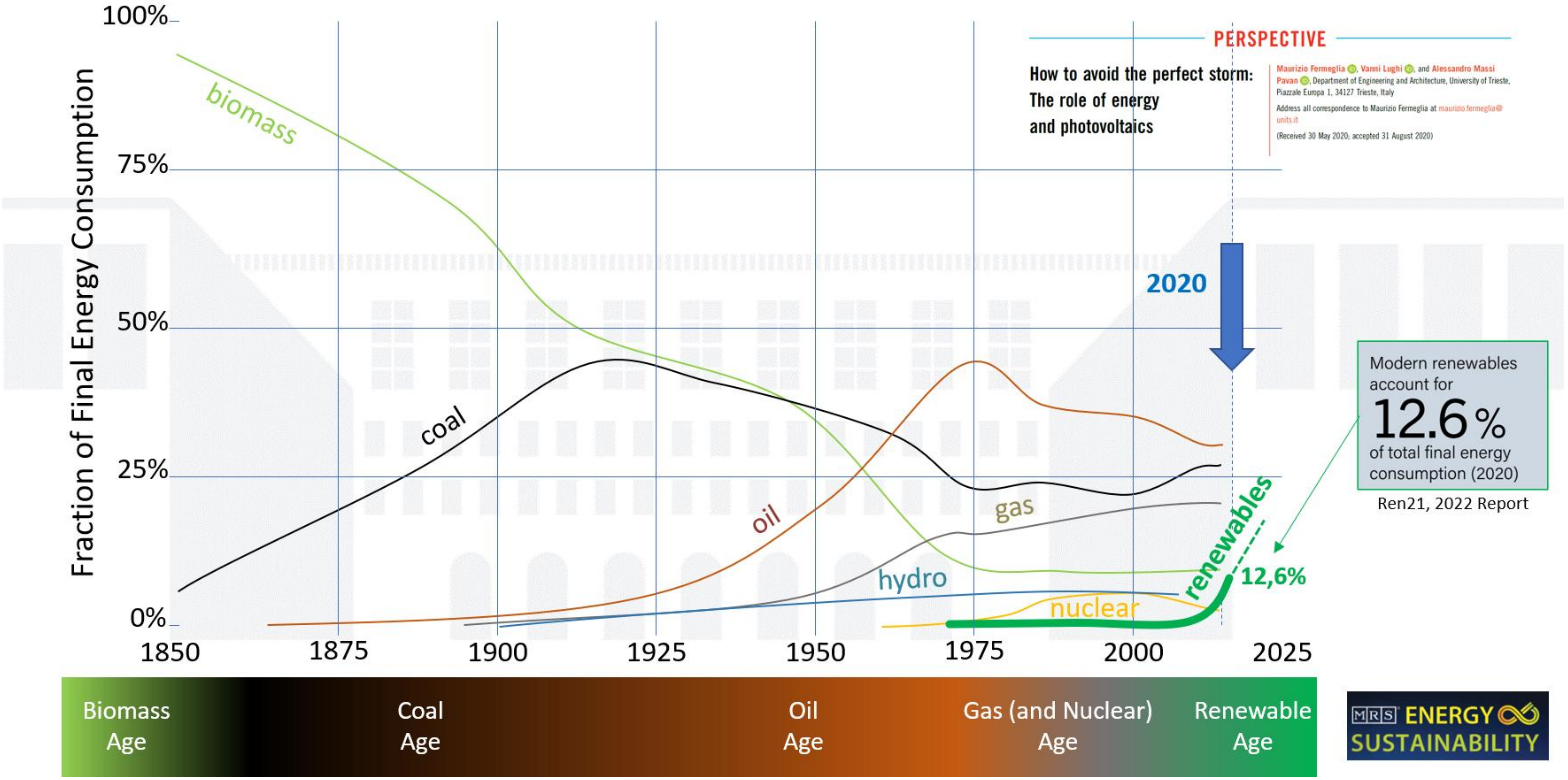
Characteristic	Depth/length in feet
By true vertical depth: Bertha Rogers No. 1 (Anardarko basin, Oklahoma, U.S.)*	31,441
By true vertical depth: BP Deepwater Horizon (Tiber field, Gulf of Mexico, U.S.)	35,000
By water depth: Maersk Drilling Raya-1 (Block 14, Uruguay)	11,156
By length, vertically and directionally drilled: Sakhalin O-14 (Chayvo field, Russia)	49,000

Guilford et al., Sustainability, 2011

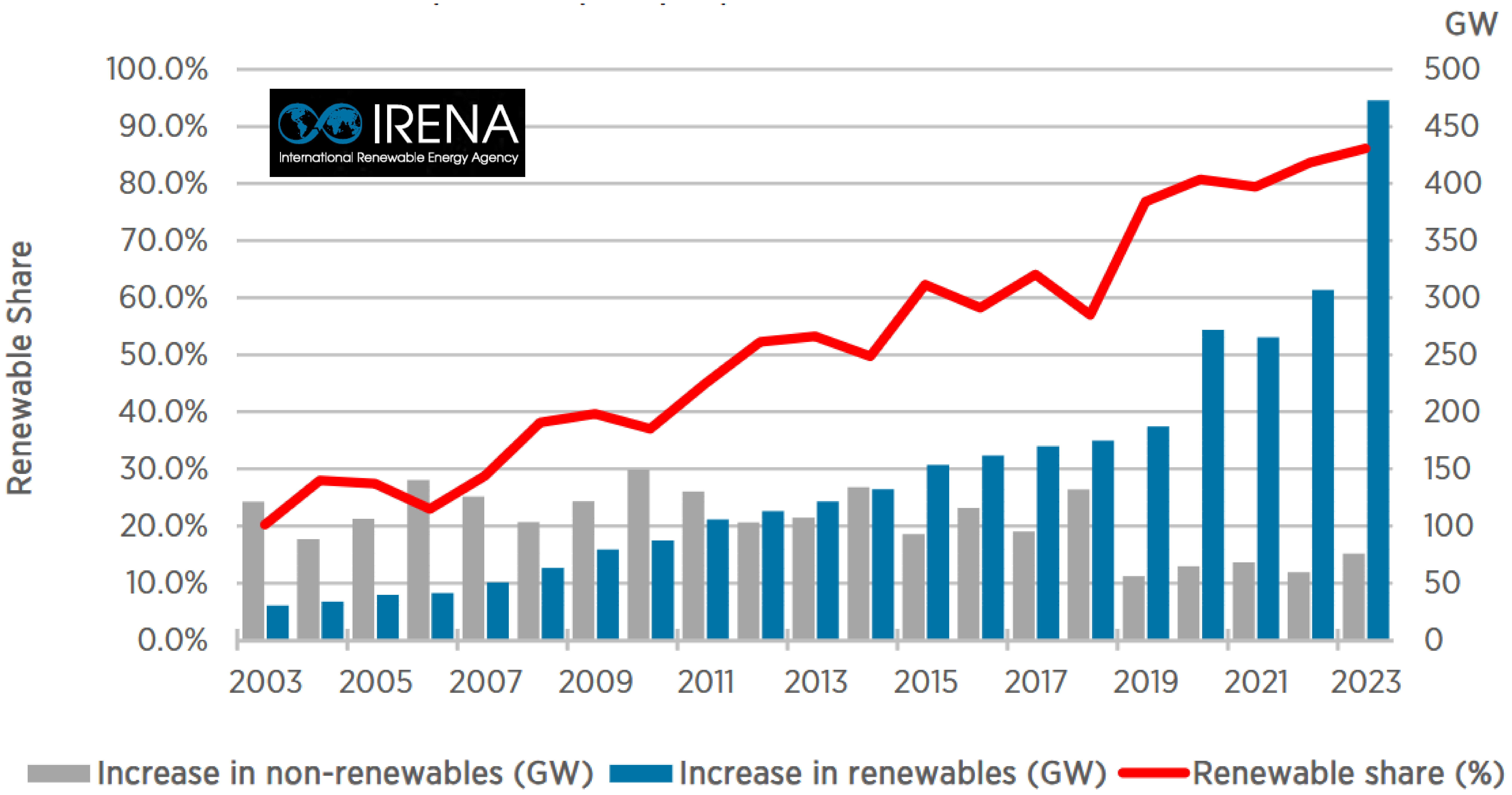
Longest vertically and directionally drilled oil and natural gas wells worldwide as of 2019

Energy transitions

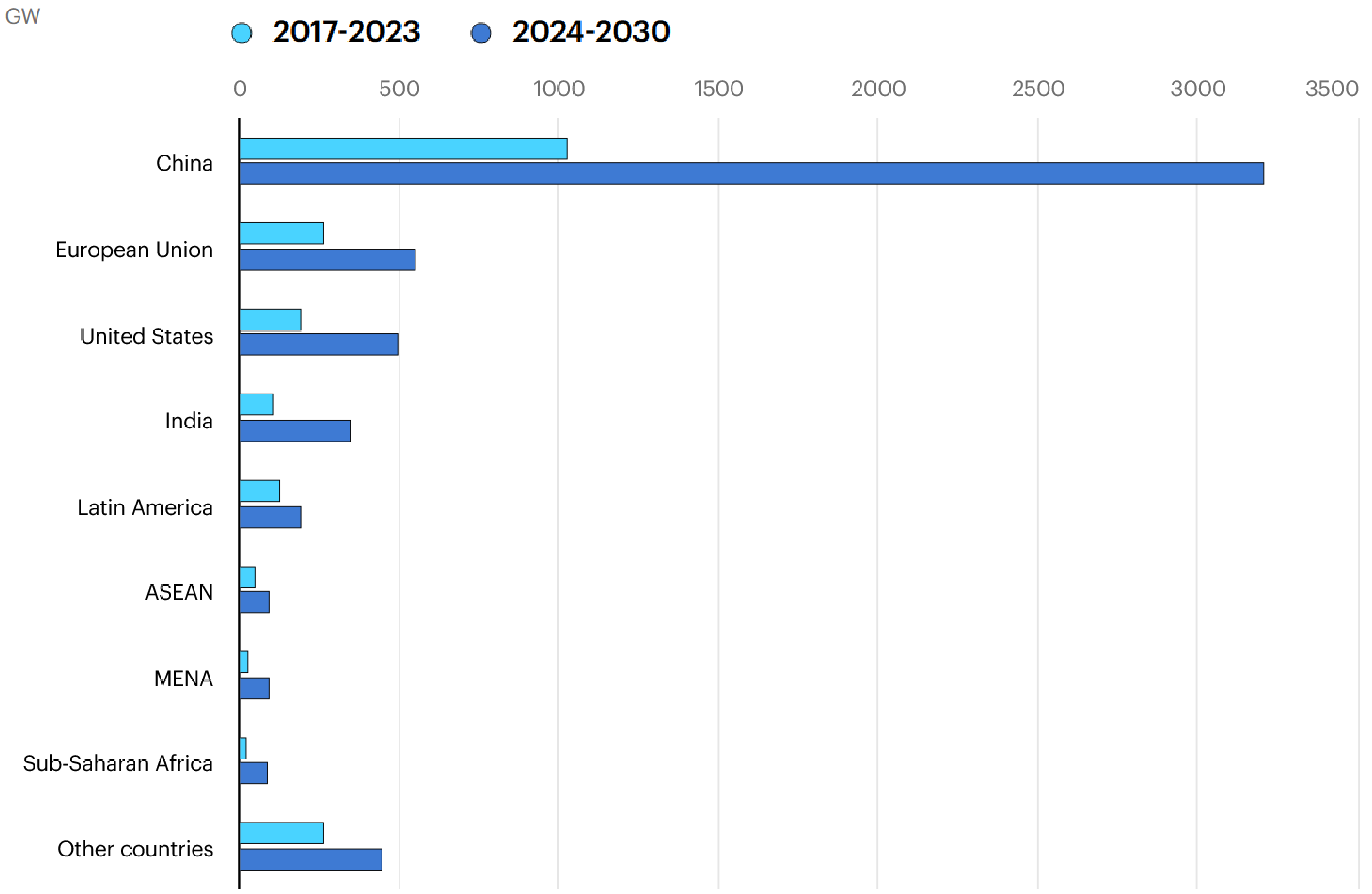
More in “Fundamentals of the Energy Sector”



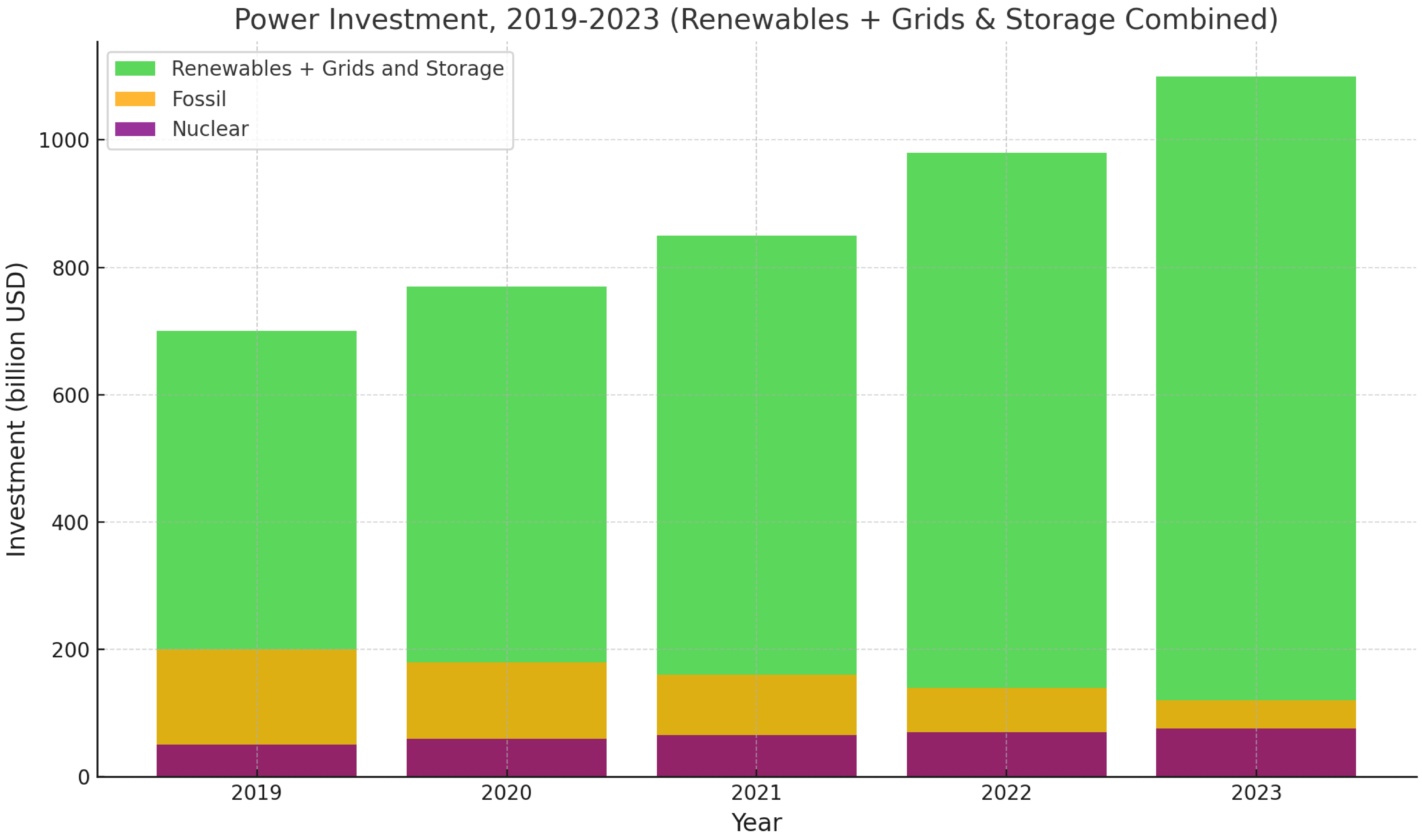
Power capacity growth

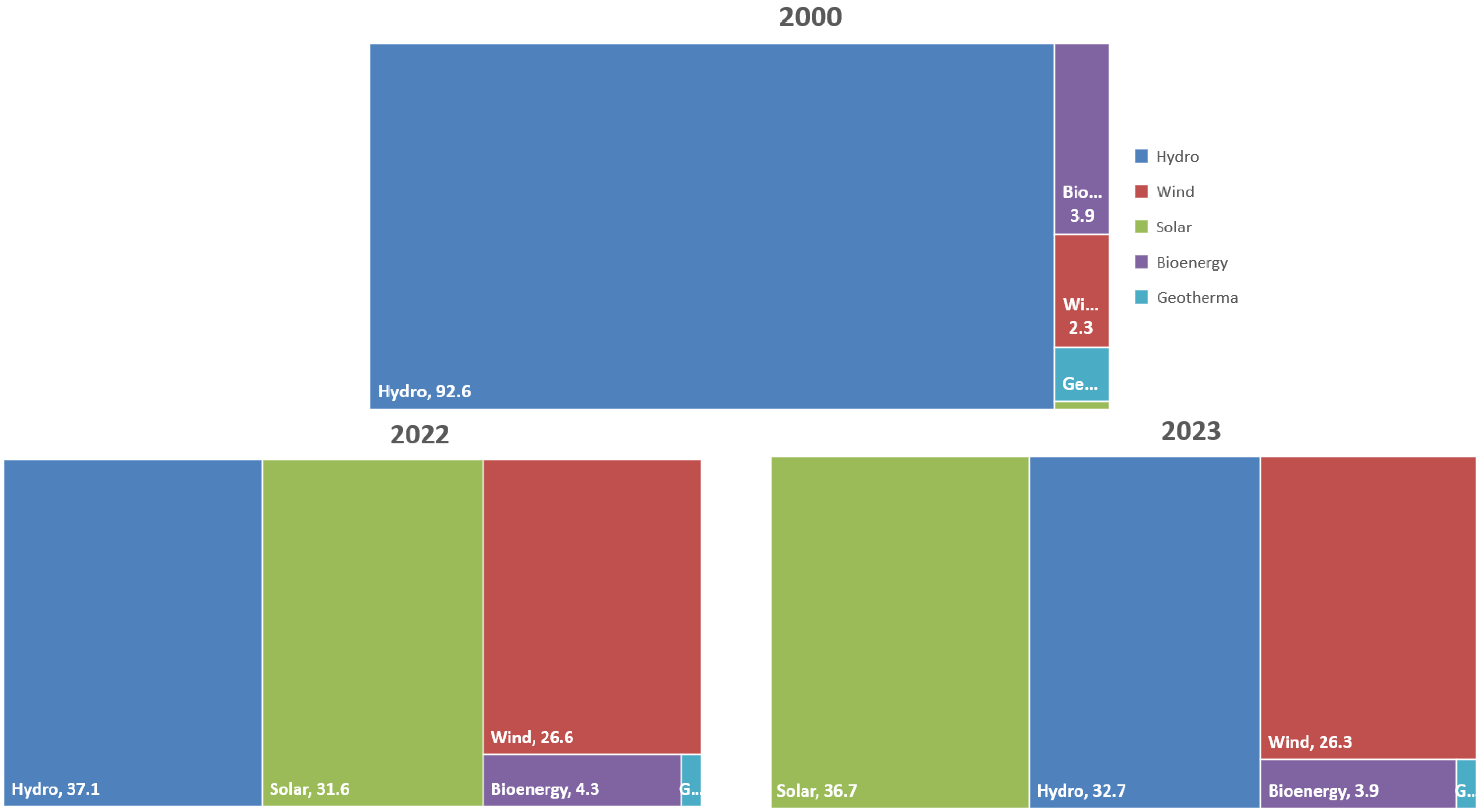


Power capacity growth

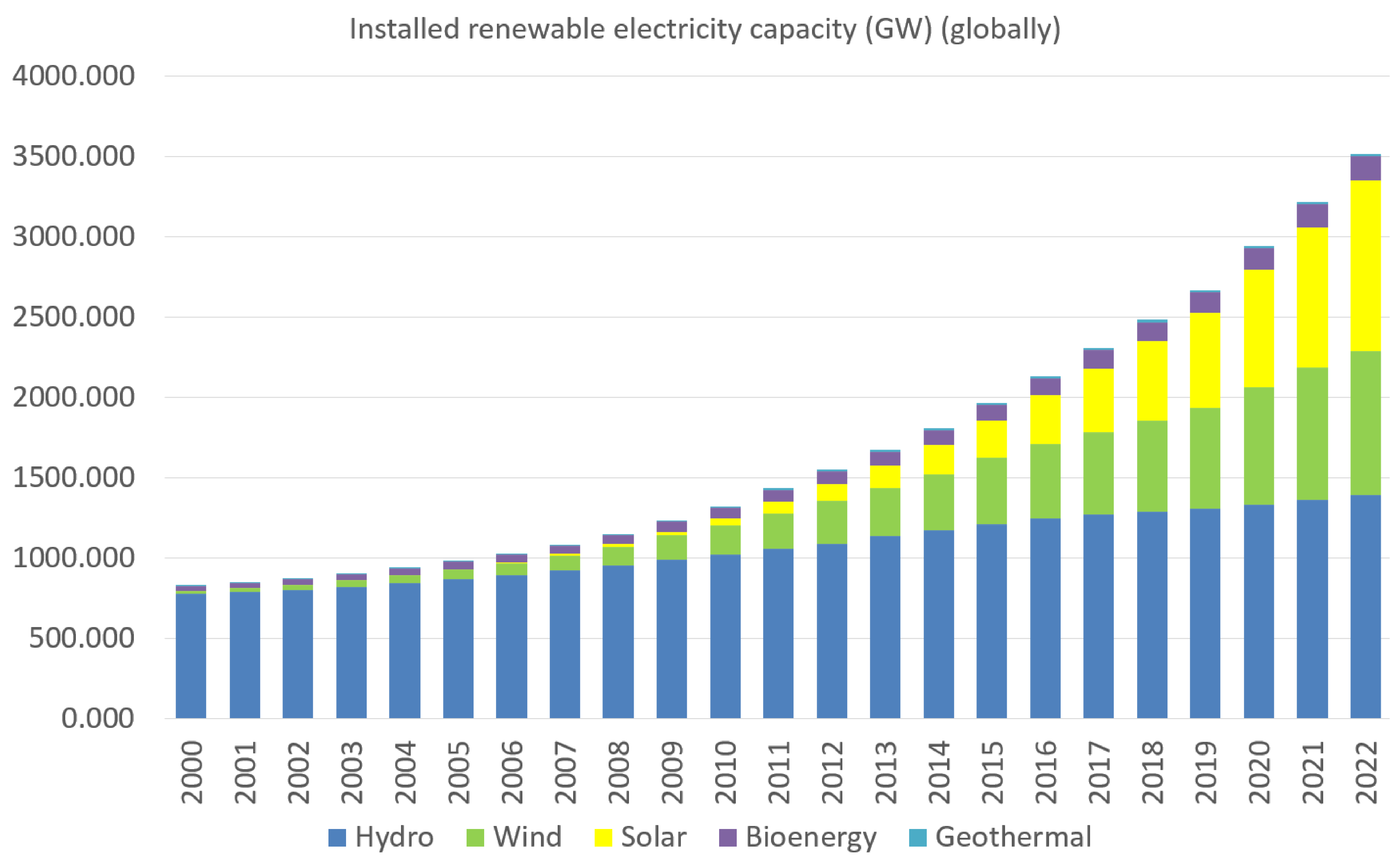


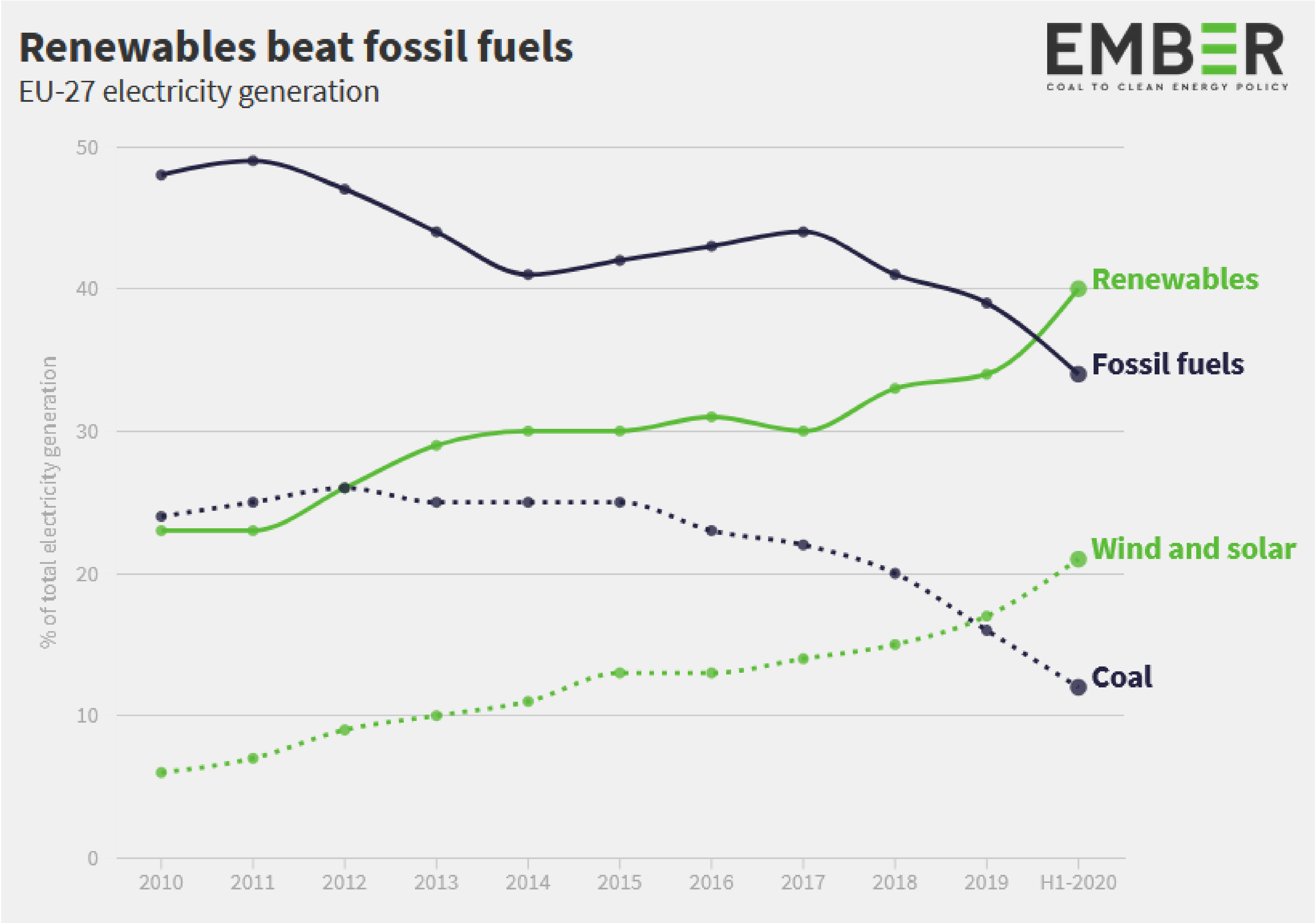
Investments in the power sector




2000
Hydro, 92.6
Bio... 3.9
Wi... 2.3
Ge...
Hydro
Wind
Solar
Bioenergy
Geotherma
2022
Hydro, 37.1
Solar, 31.6
Wind, 26.6
Bioenergy, 4.3
G...
2023
Solar, 36.7
Hydro, 32.7
Wind, 26.3
Bioenergy, 3.9
G...

The rise of renewables





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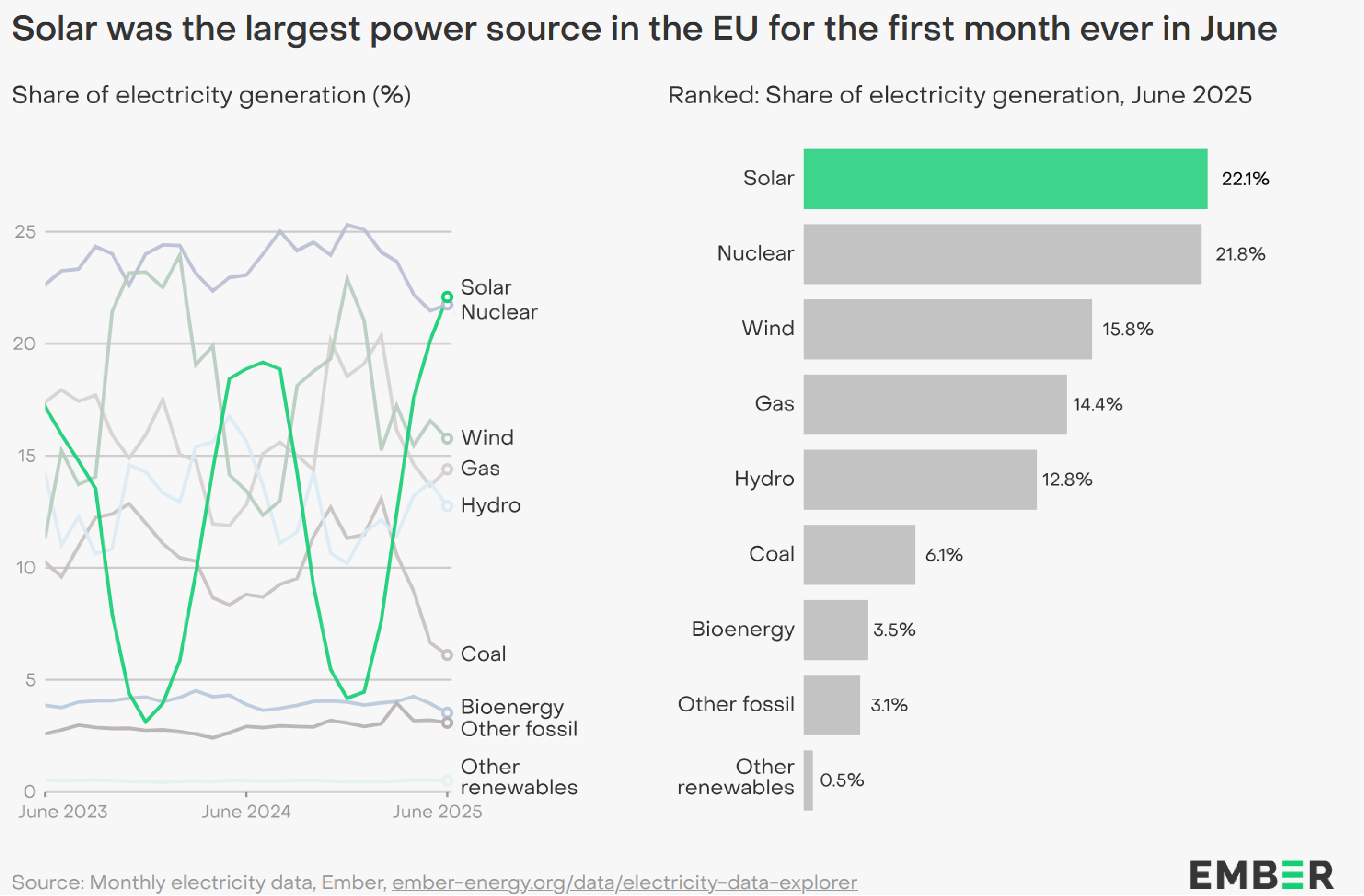
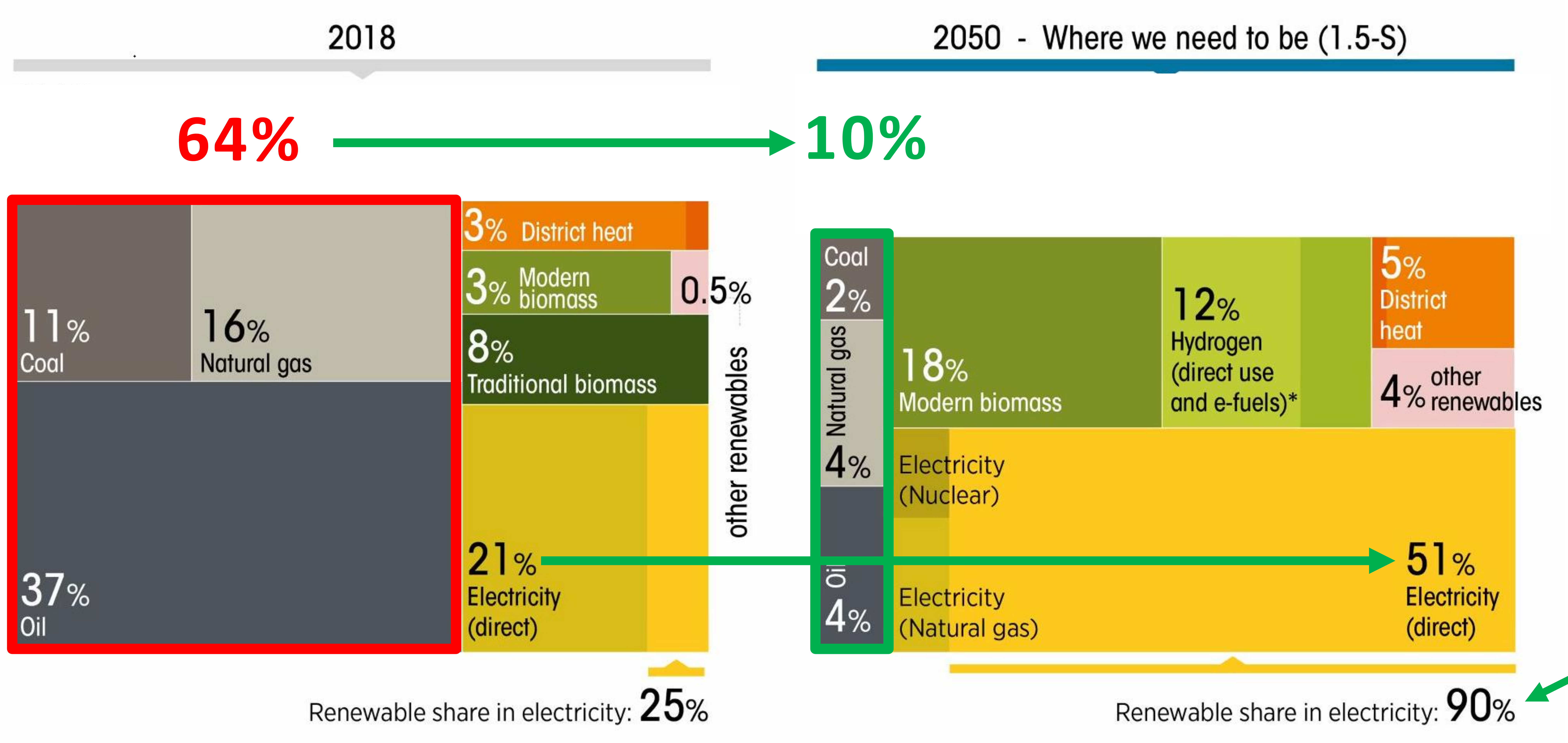
The rise of photovolaics



Renewables and electricity



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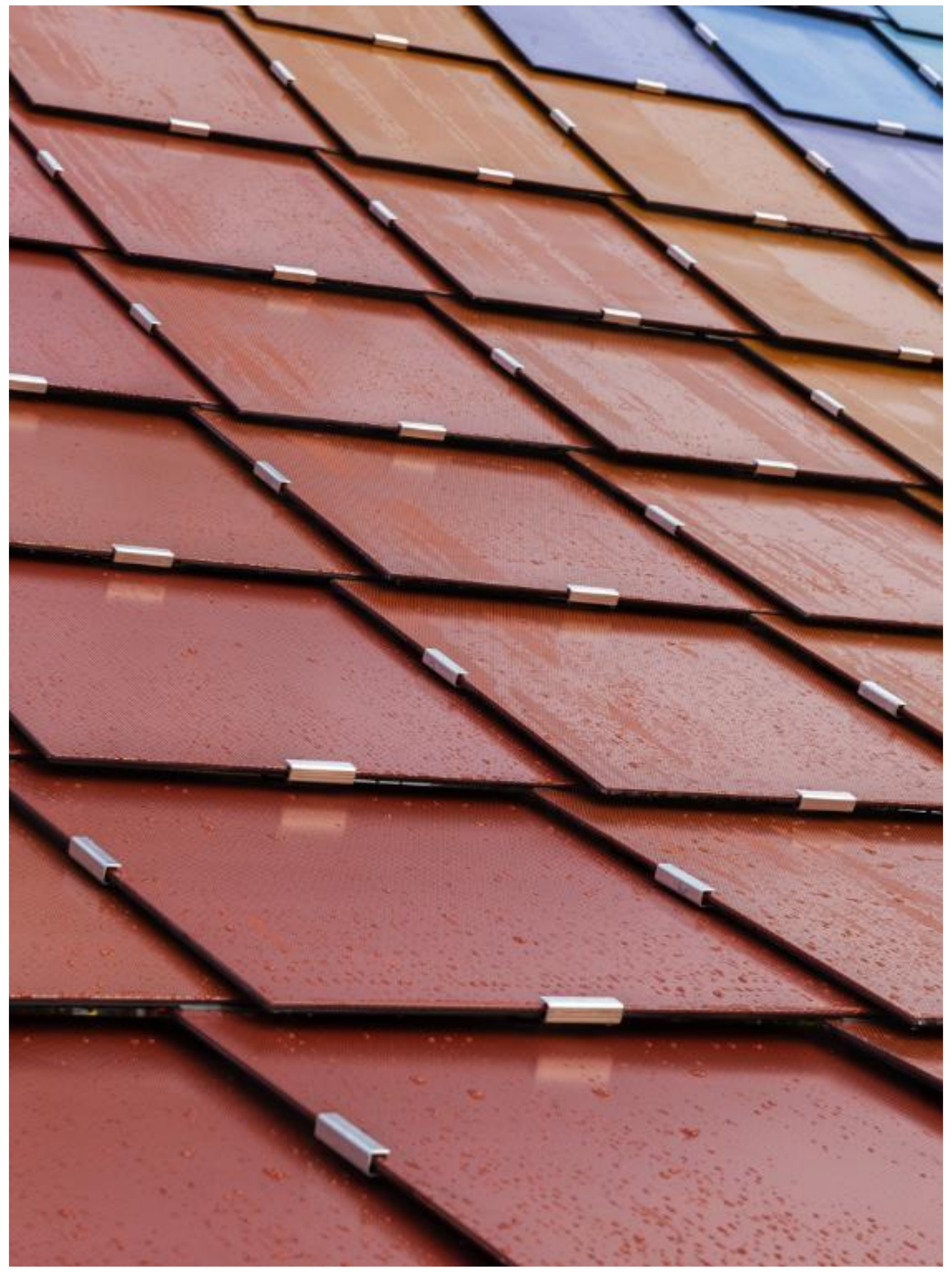
Why electricity?

- The most efficient carrier
- Easy to use
- Zero impact
- Easy to transport long distances
- New distributed generators



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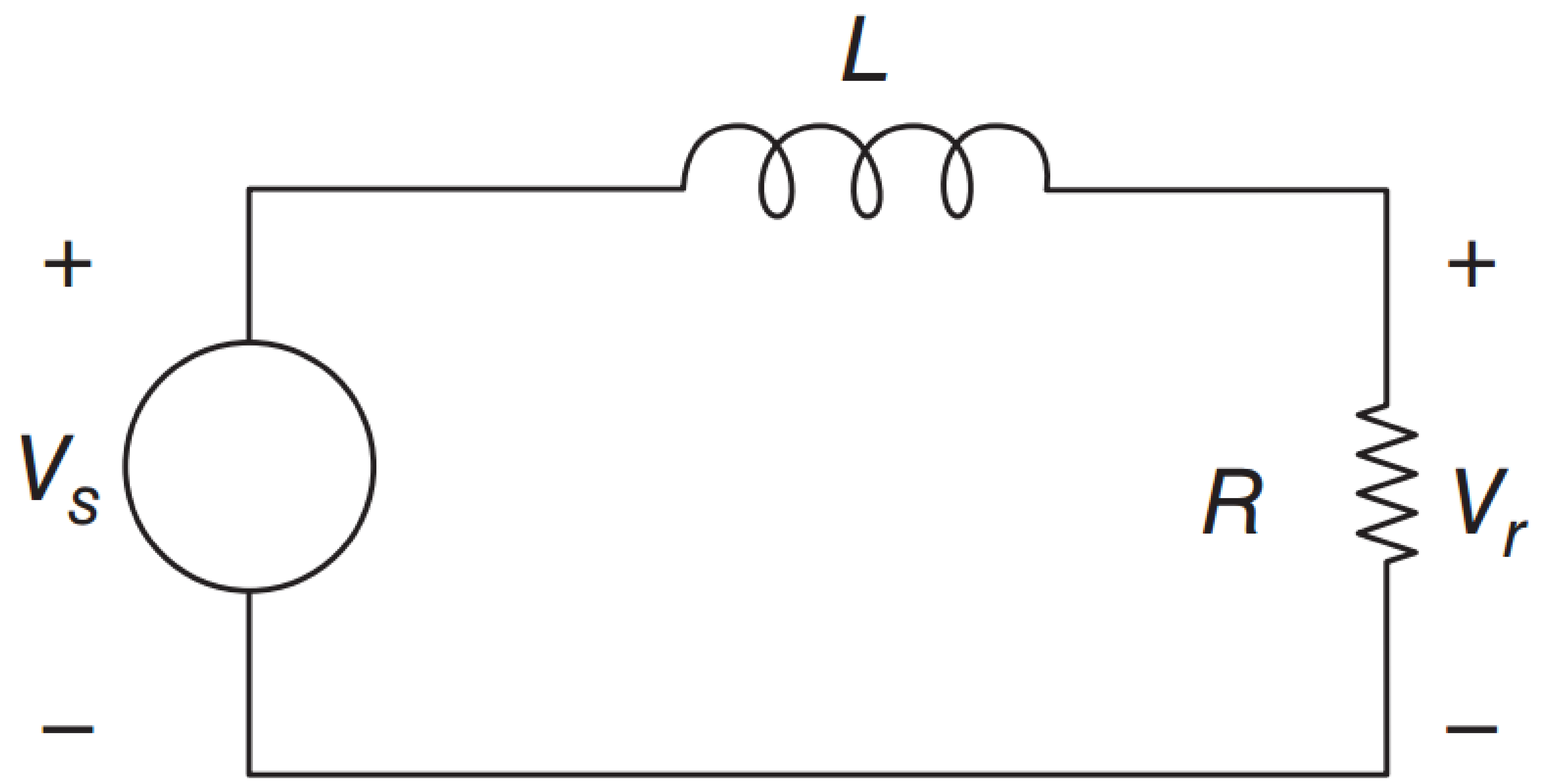
Why electricity?

- New stationary applications: induction cooking and heat pumps

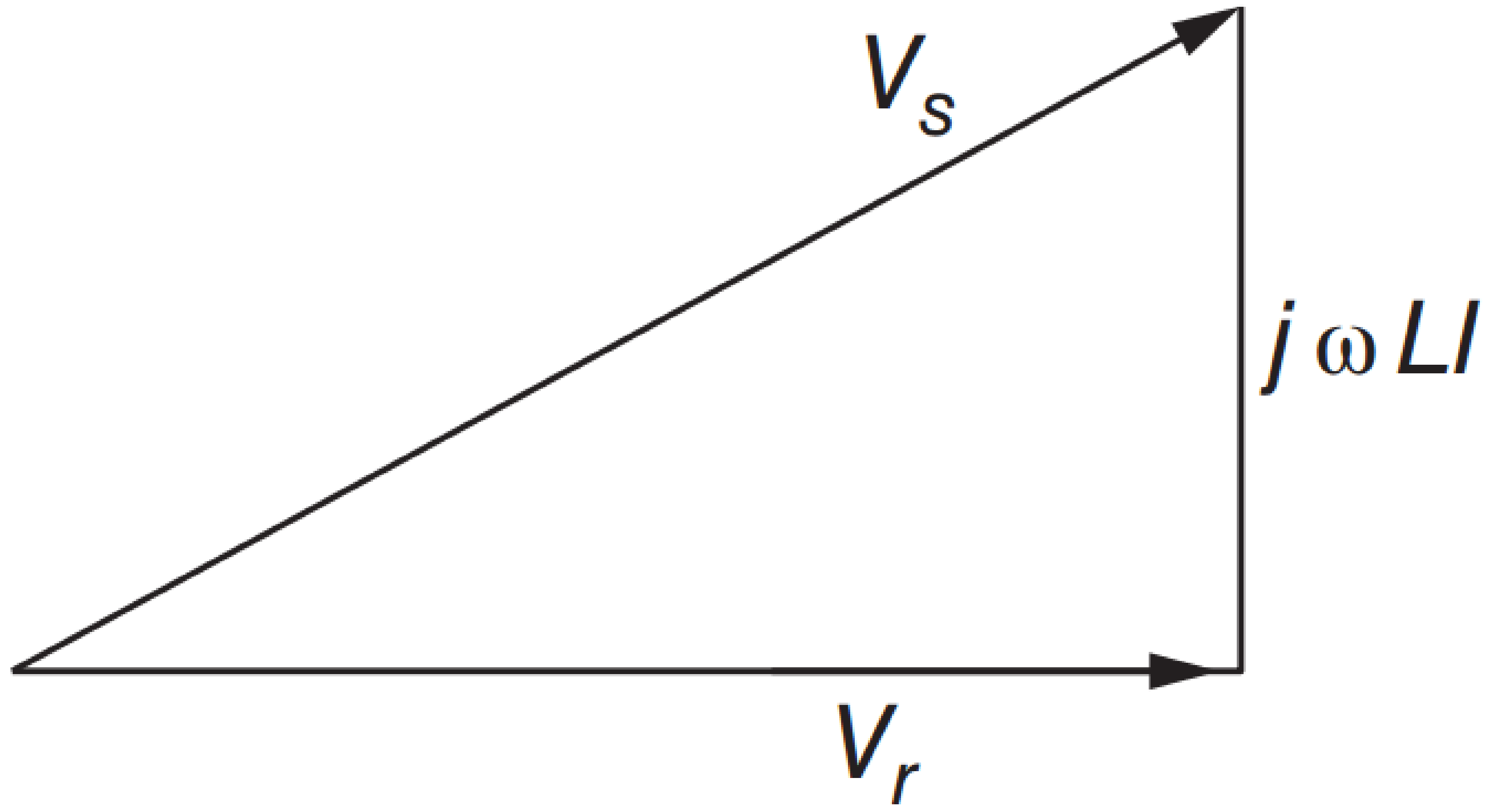
Why electricity?

- New applications: light electric vehicles

Reactive power and voltage



$$V_r = V_s \times \frac{R}{R + j\omega L}$$

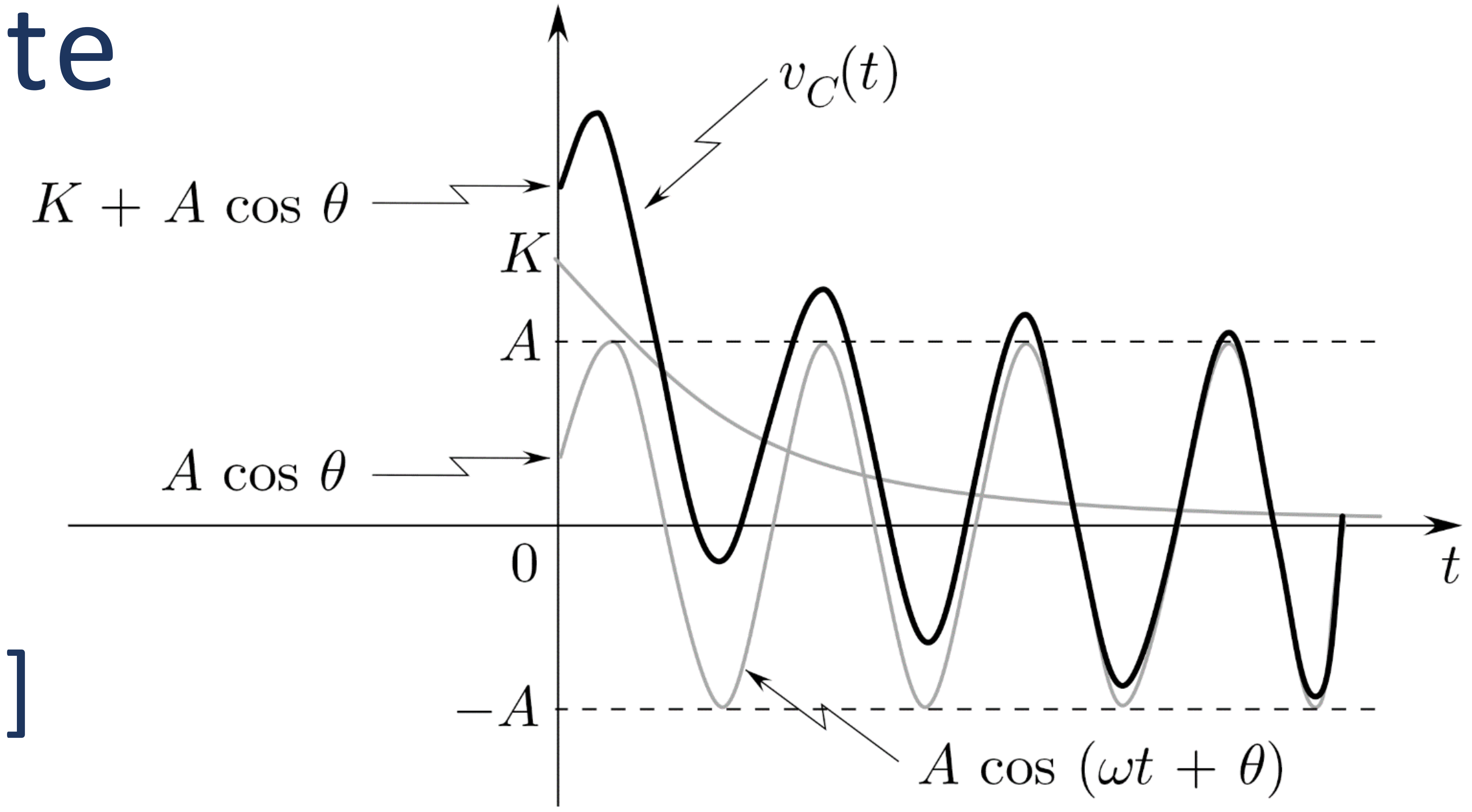


- The receiving voltage is less than the source voltage
- The receiving voltage decreases with the load

Power in the sinusoidal steady-state

$$\bar{S} = \frac{1}{2}\bar{V}\bar{I}^*$$

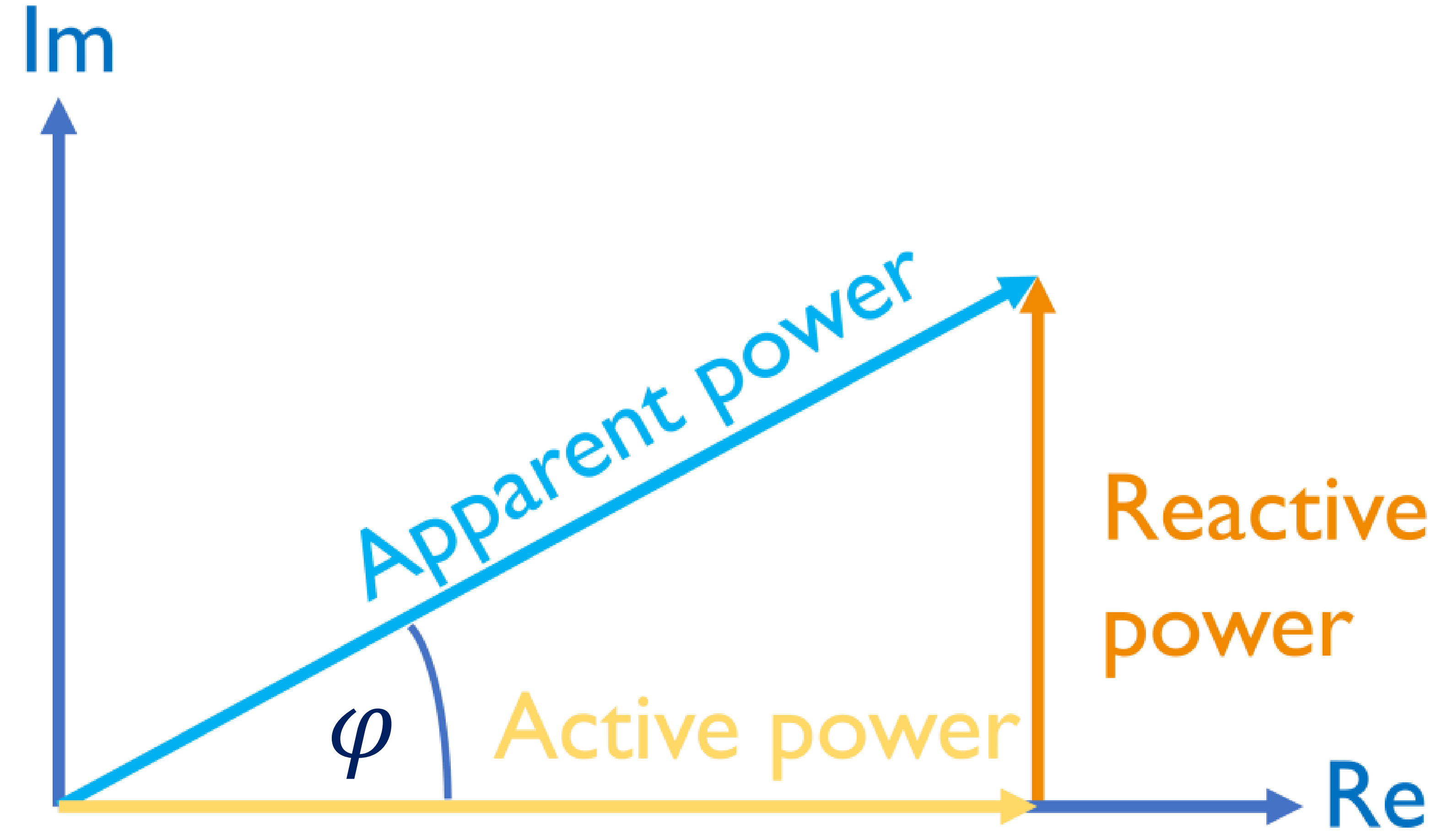
- $\bar{S}$ – complex power [VA]
- S – apparent power [VA]
- P – active power [W]
- Q – reactive power [VAR]
- $\cos\varphi$ - power factor



$$\angle S = \theta_v - \theta_i = \varphi$$

$$S = |\bar{S}| = \frac{1}{2}V_m I_m = V_{eff} I_{eff}$$

$$\bar{S} = \frac{1}{2}V_m I_m \cos\varphi + j\frac{1}{2}V_m I_m \sin\varphi = P + jQ$$



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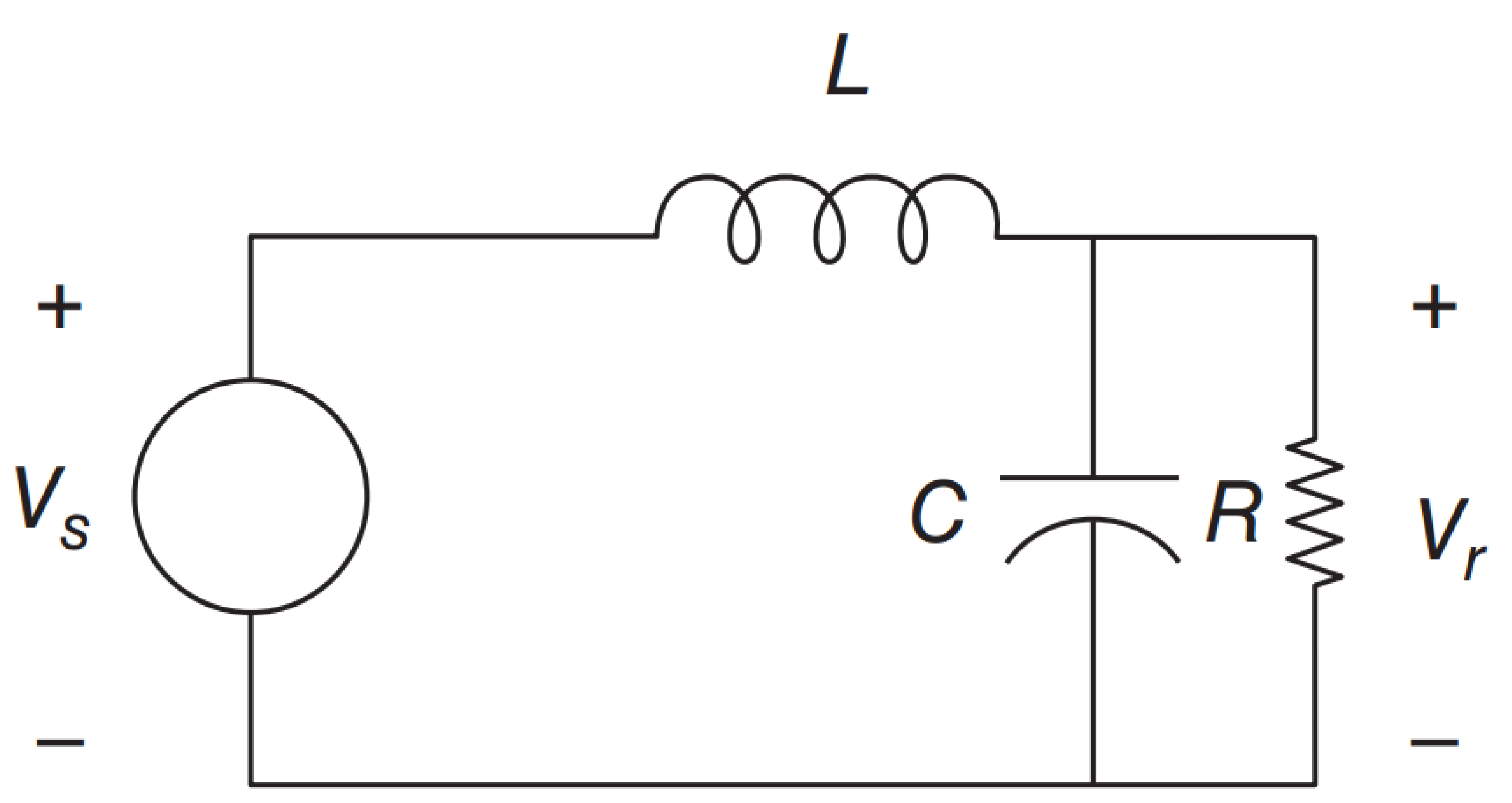
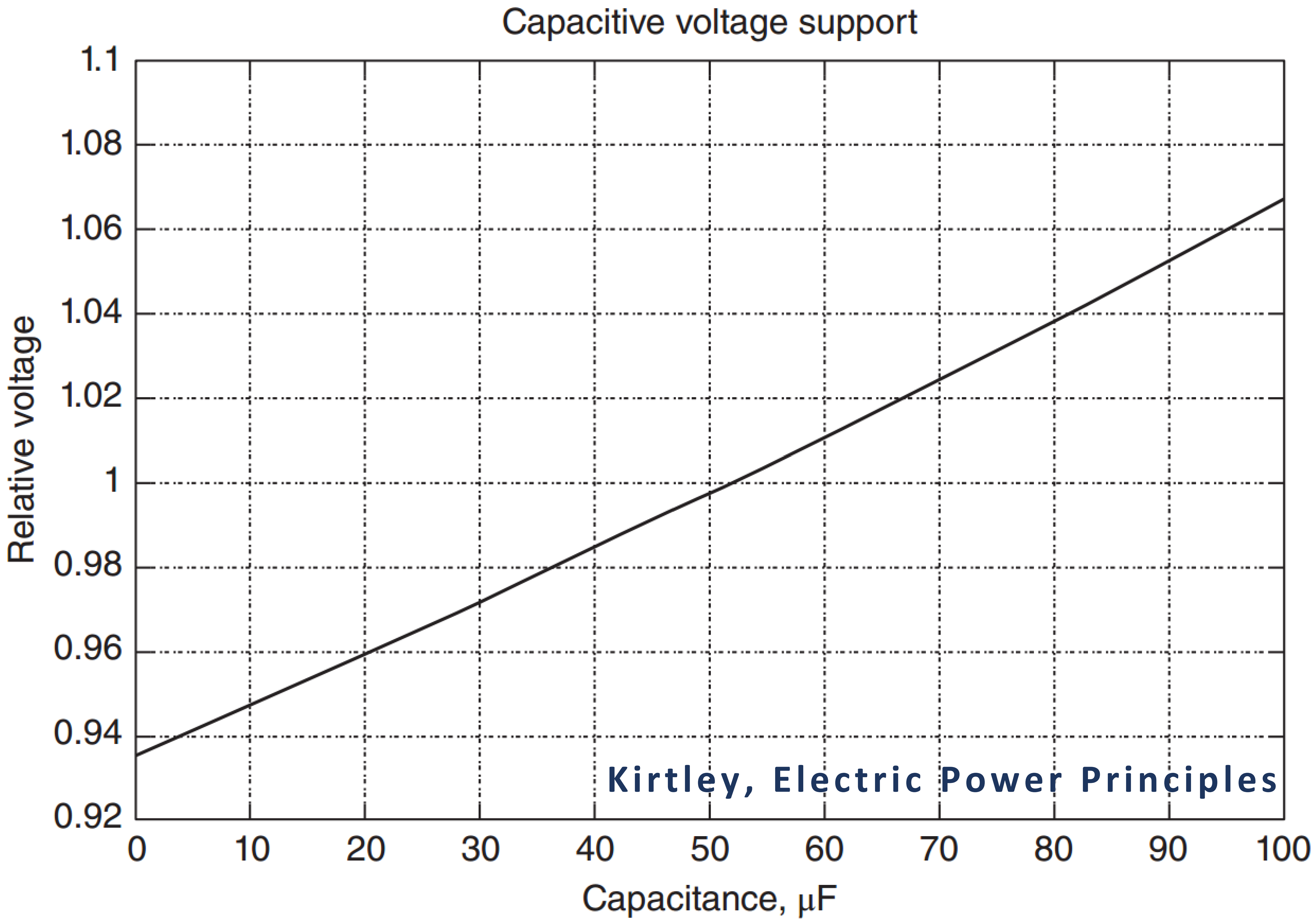
Reactive power and voltage

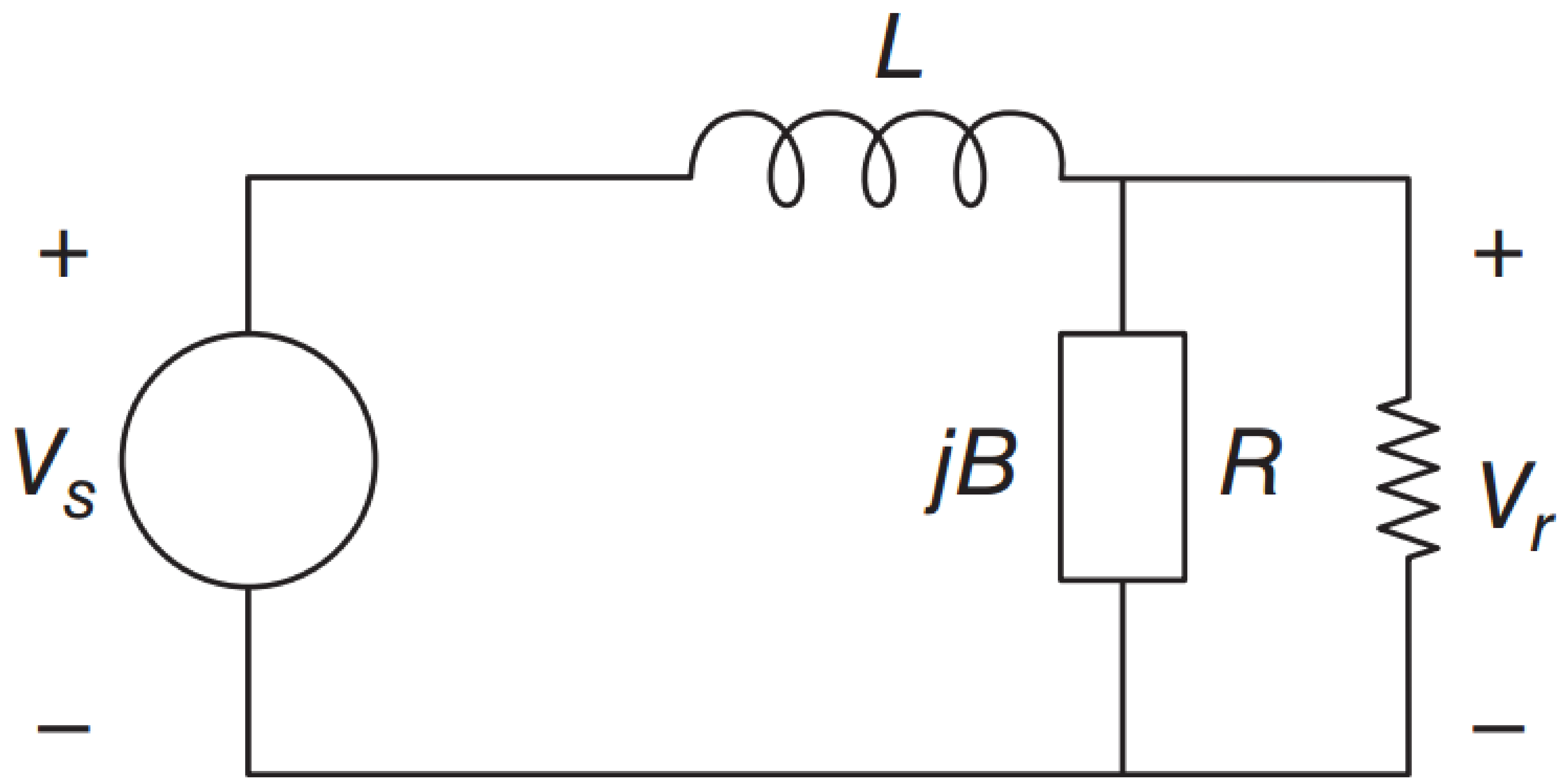


$$V_r = V_s \times \frac{1}{(1-\omega^2 LC) + \frac{j\omega L}{R}}$$

- The capacitor provides (positive) reactive power and thus provides some amount of voltage control

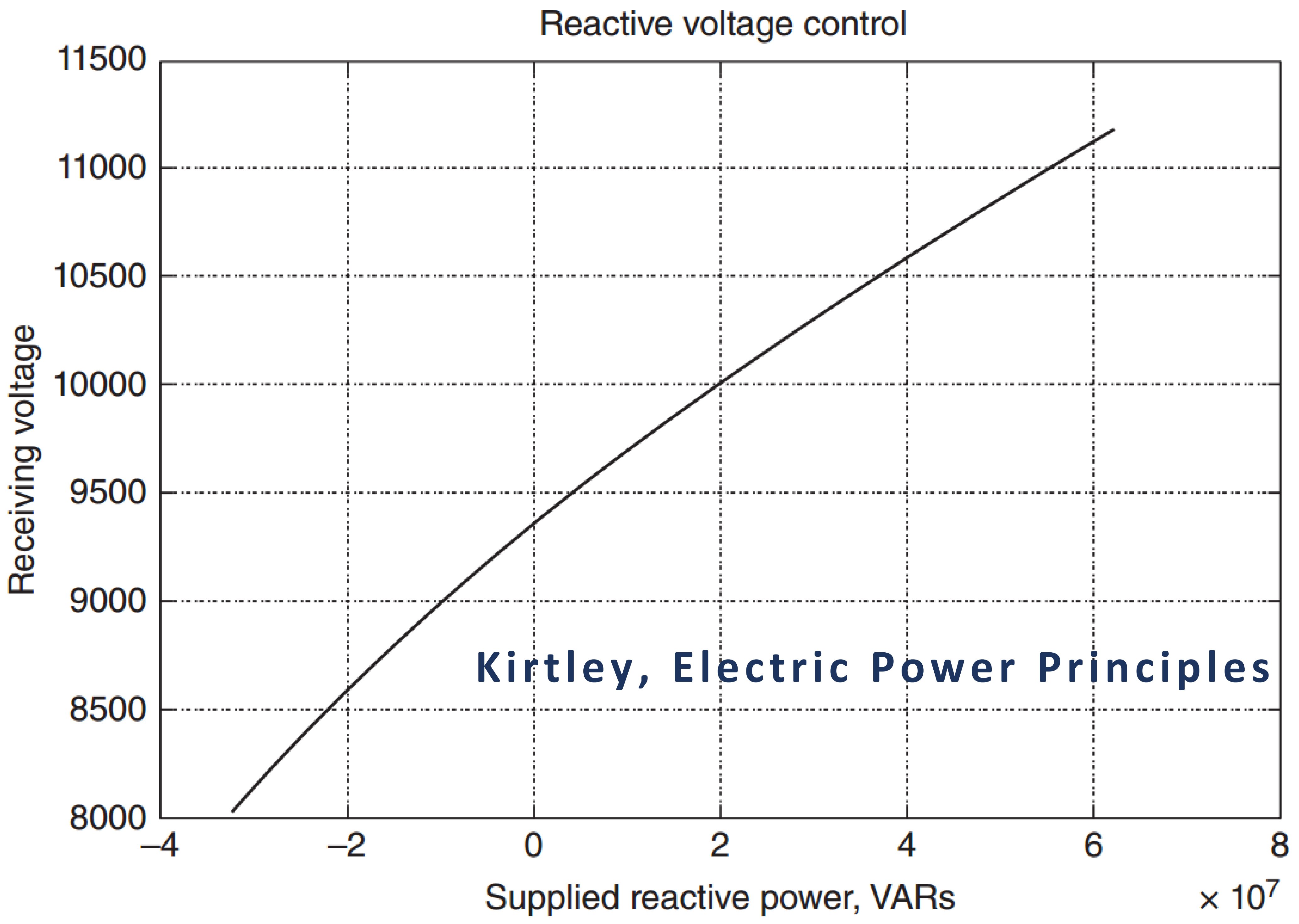


Reactive power and voltage



$$V_r = V_s \times \frac{R}{R \times (1 - X_s B) + jX_s}$$

$$Q = -|V_r|^2 \times B$$



- The capacitor is replaced by a general reactive admittance defined by: $\bar{I} = jB\bar{V}$

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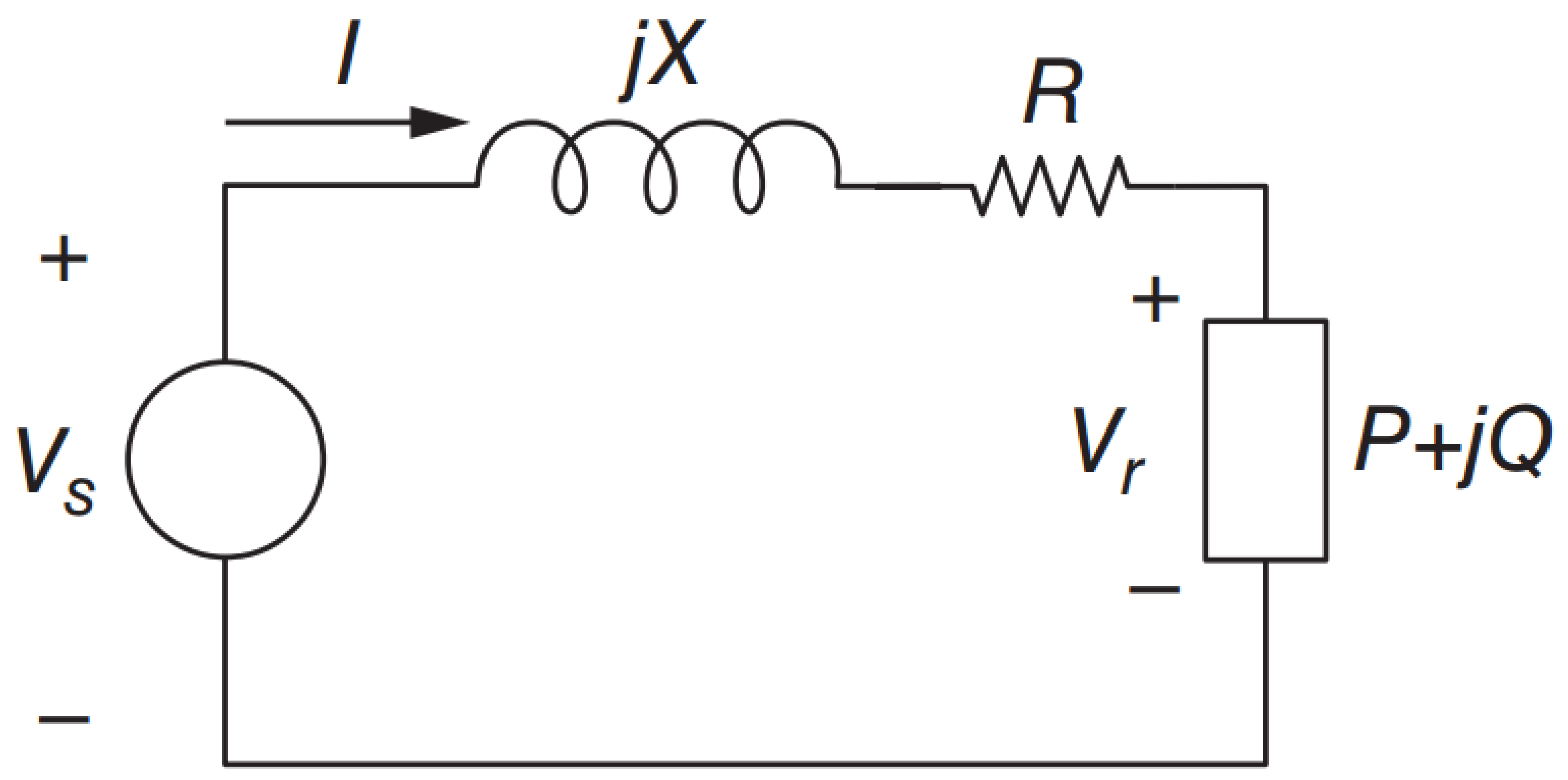
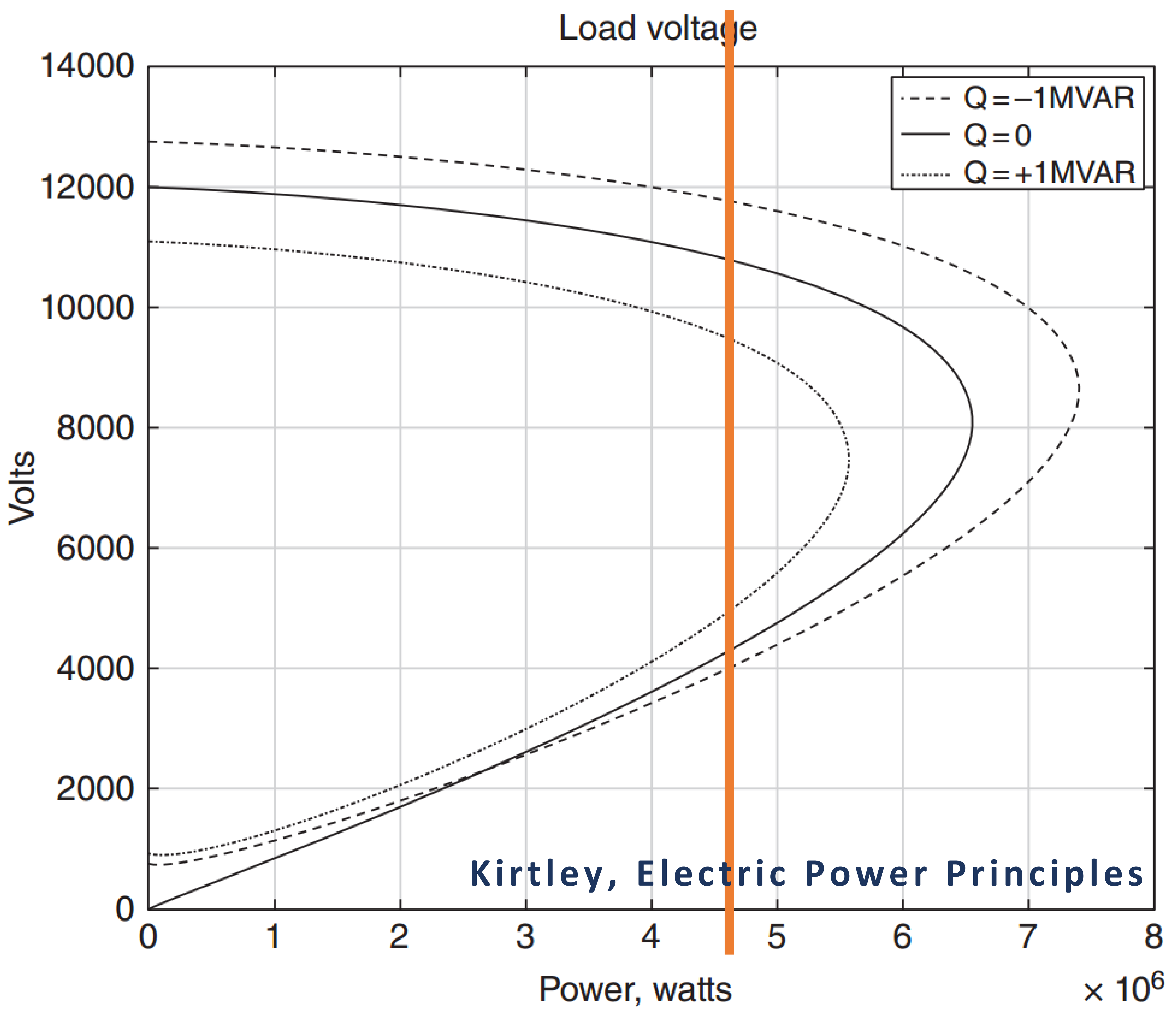


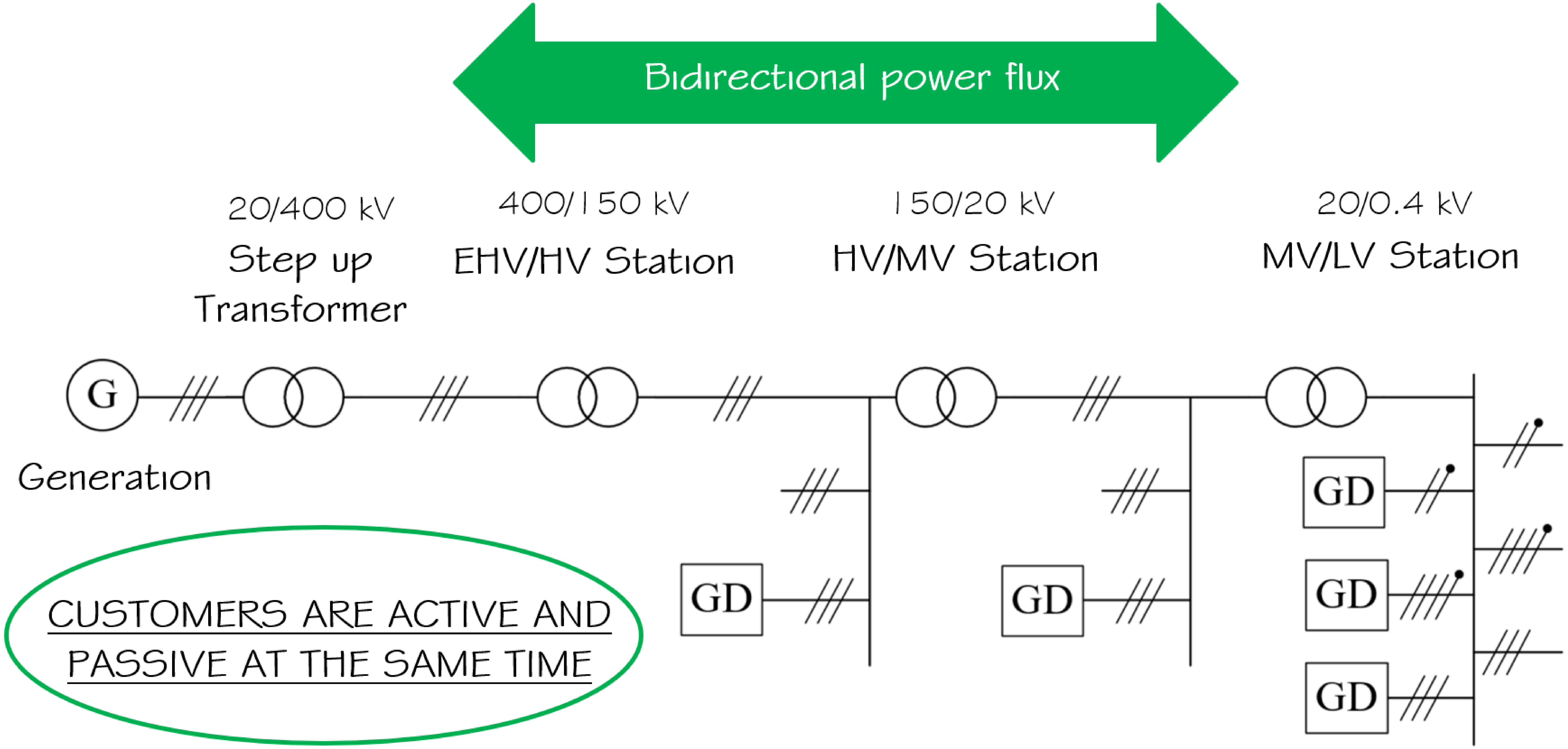
$$P + jQ = \frac{1}{2}\bar{V}_r\bar{I}^*$$

- Inductive reactive power reduces voltage and maximum power transfer
- If Q is constant: ↑P ↓V
- If P is constant: ↑Q ↓V



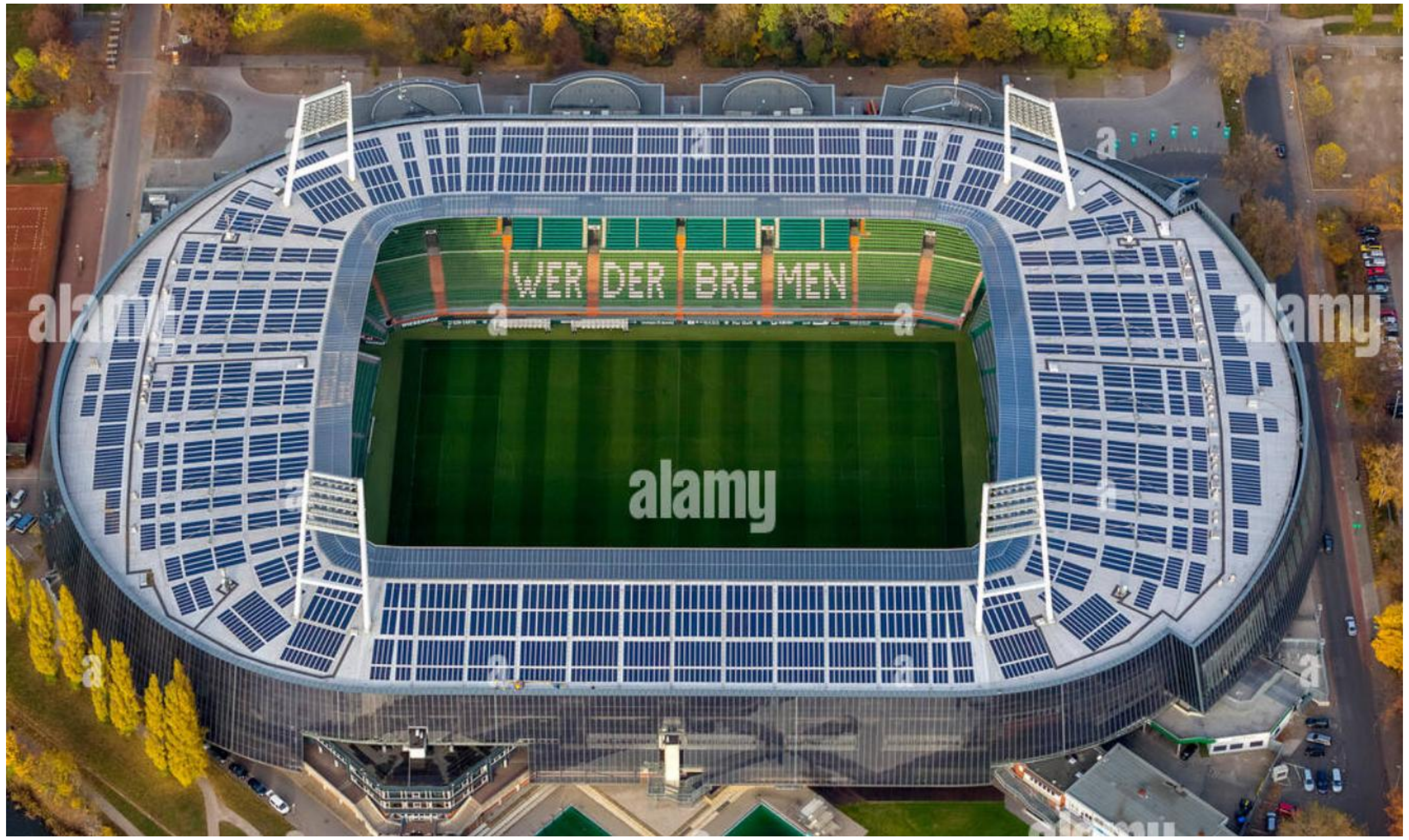
$$V_r^2 = \frac{1}{2}(V_s^2 - 2XQ - 2RP) \pm \sqrt{\left(\frac{1}{2}(V_s^2 - 2XQ - 2RP)\right)^2 - |Z|(P^2 + Q^2)}$$

Hybrid utility systems



In the hybrid system, customers become active/passive (prosumers) because of their distributed generators (GD)

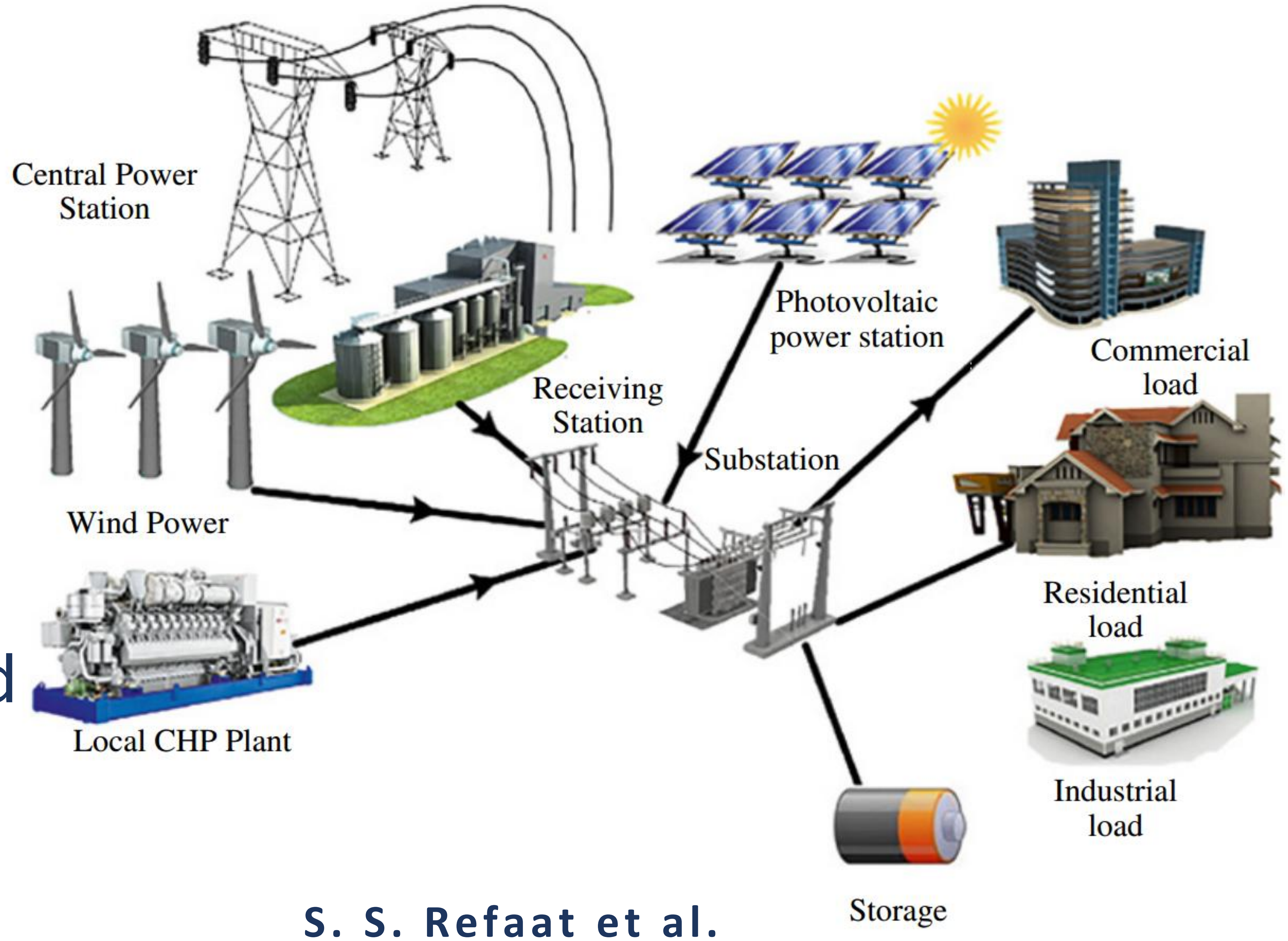
Distributed generators



Distributed generators

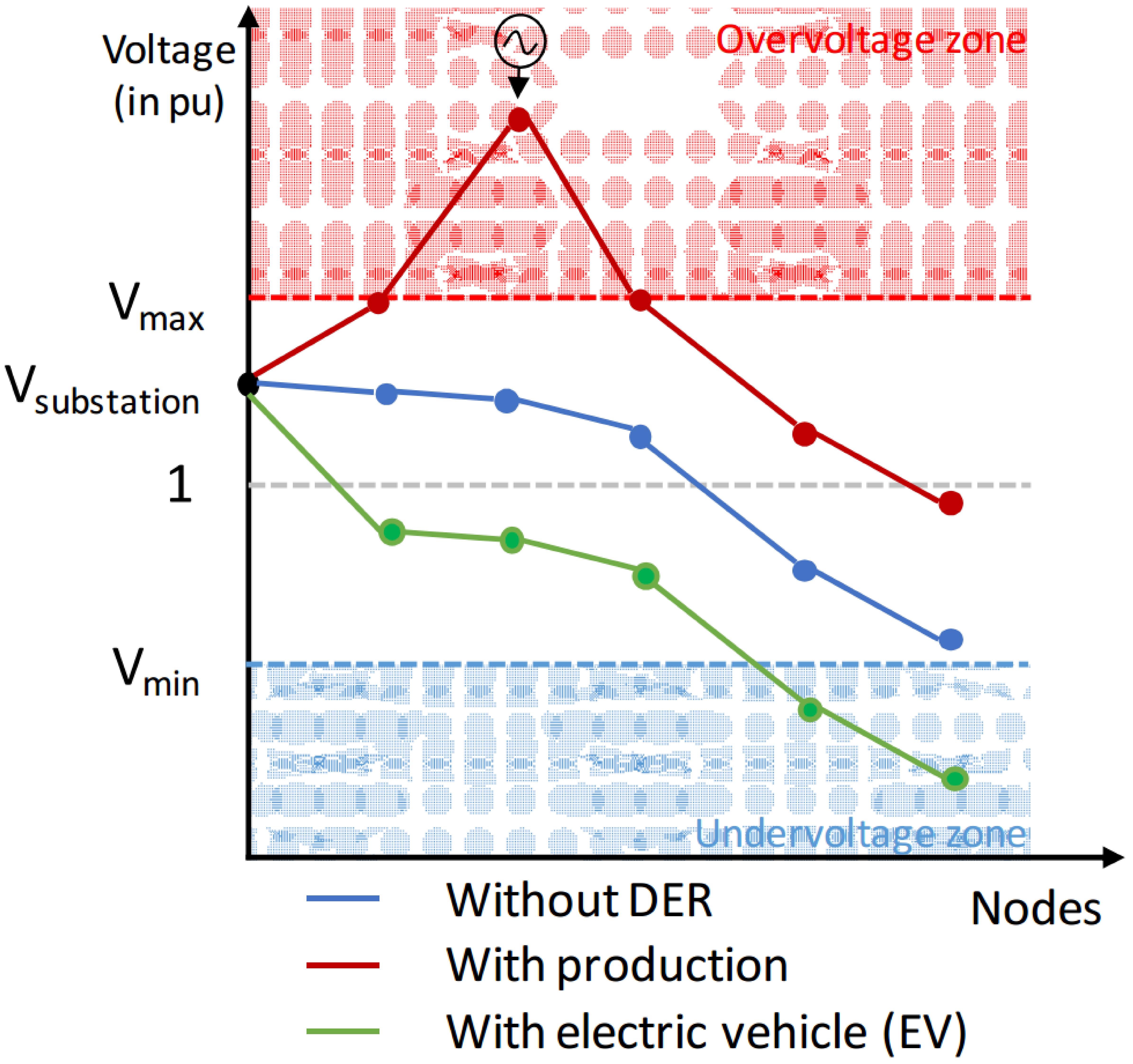
Small-scale decentralized power generators

- Modular, flexible, usually closed to the load
- Mostly RES-based
- Can be controlled and coordinated within a smart grid
- Make the grid bidirectional
- Offer benefits to the grid
- May be part of an isolated grid, of a microgrid or grid-connected
- Support in reducing losses and delivering RS
- Increase the complexity

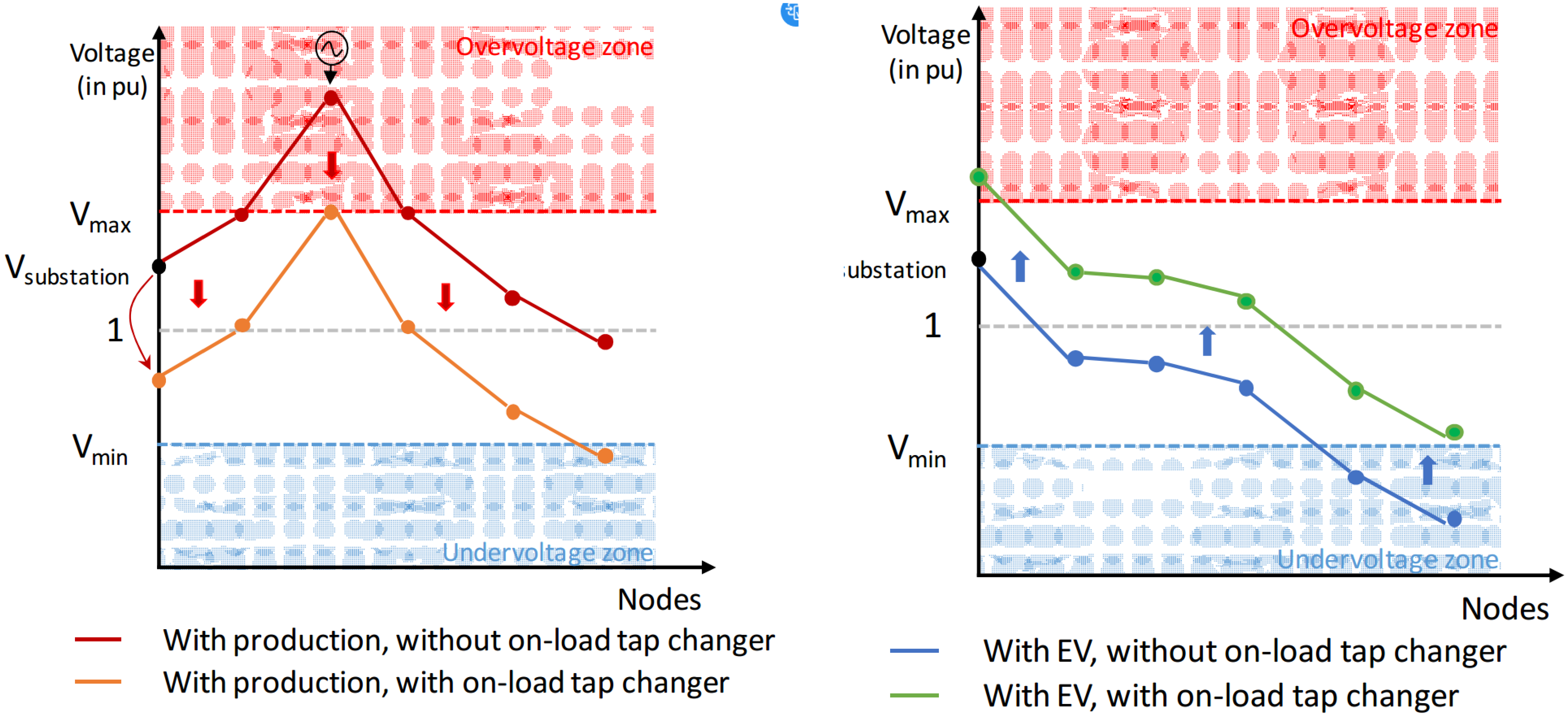


S. S. Refaat et al.
Smart grid and enabling technologies

Integration of distributed generators & e-vehicles



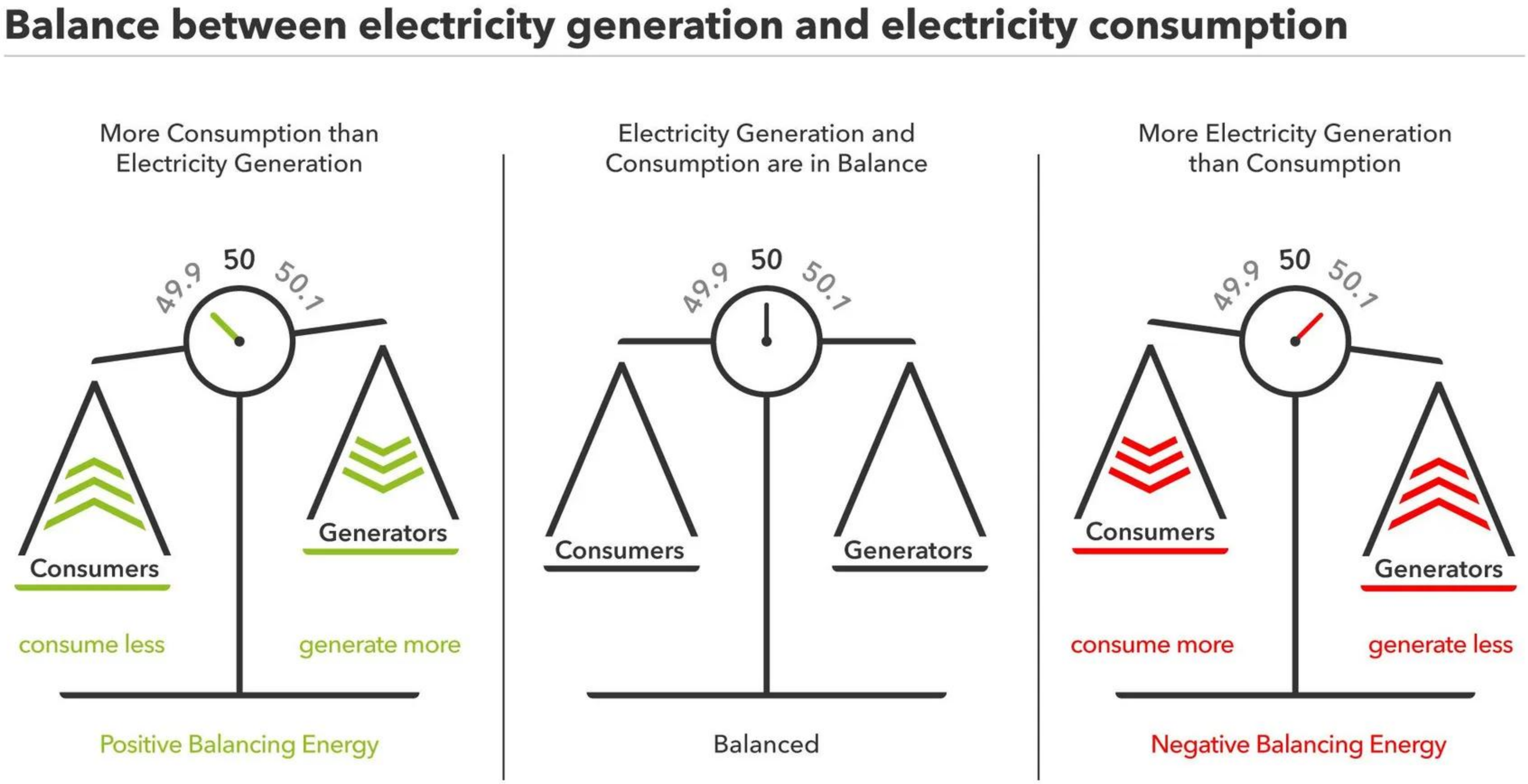
Effect of on-load tap changer



Inertia of the electric power system (load-frequency relationship)

- One generator and a limited set of loads: controlling the frequency means controlling the speed of the generator shaft
- Grid frequency is a measure of the balance between supply and demand

https://www.next-kraftwerke.com/



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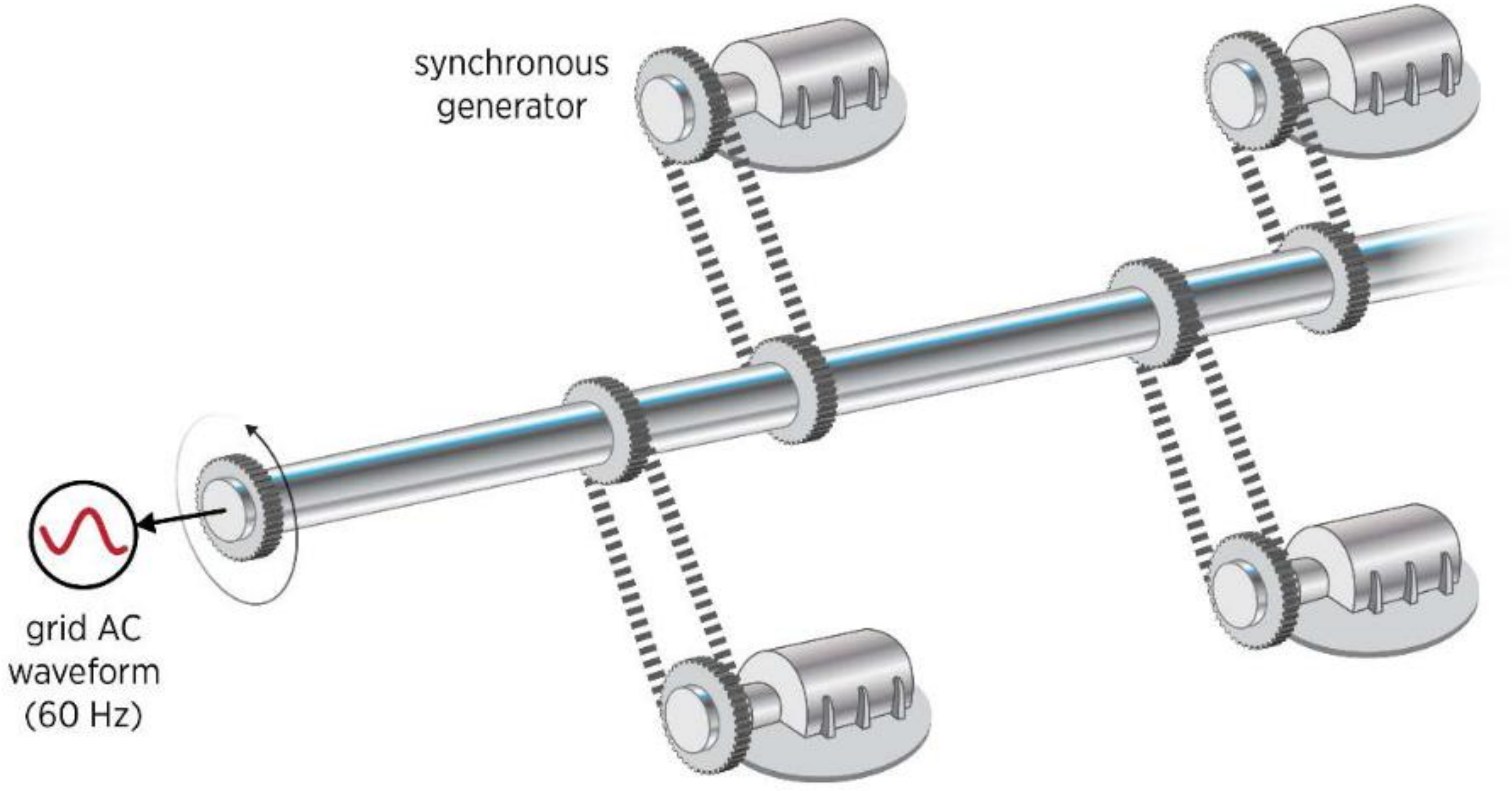
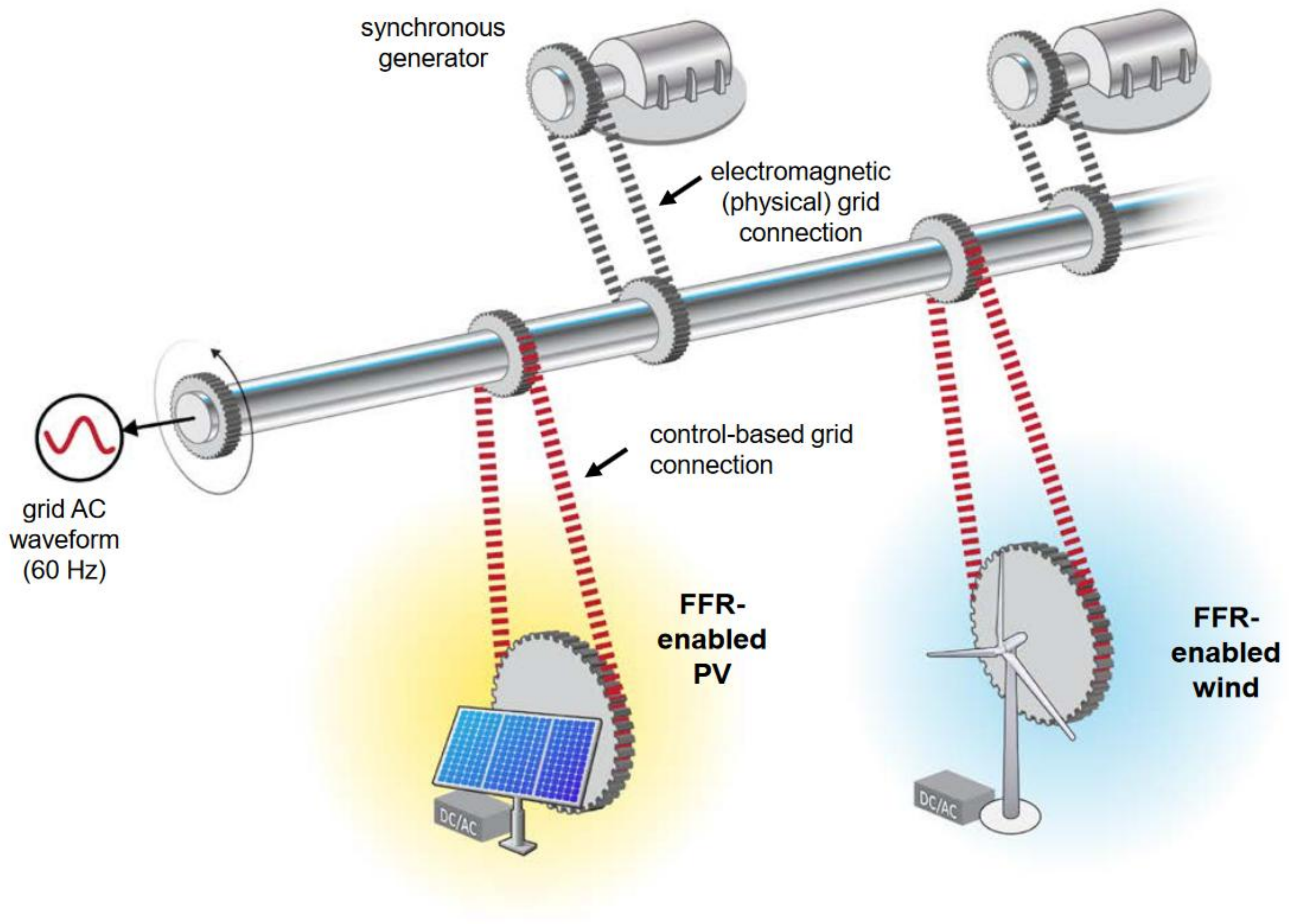
Inertia of the electric power system



Inertia and the Power Grid: A Guide Without the Spin - NREL

- Inertia refers to energy stored in rotating generators
- This energy is valuable when large power plants fail (temporary response – a few seconds)
- Historically inertia was abundant
- With the evolution of the grid (inverter-based sources) questions have emerged (and solution have been found!)

Inertia of the electric power system – Virtual inertia

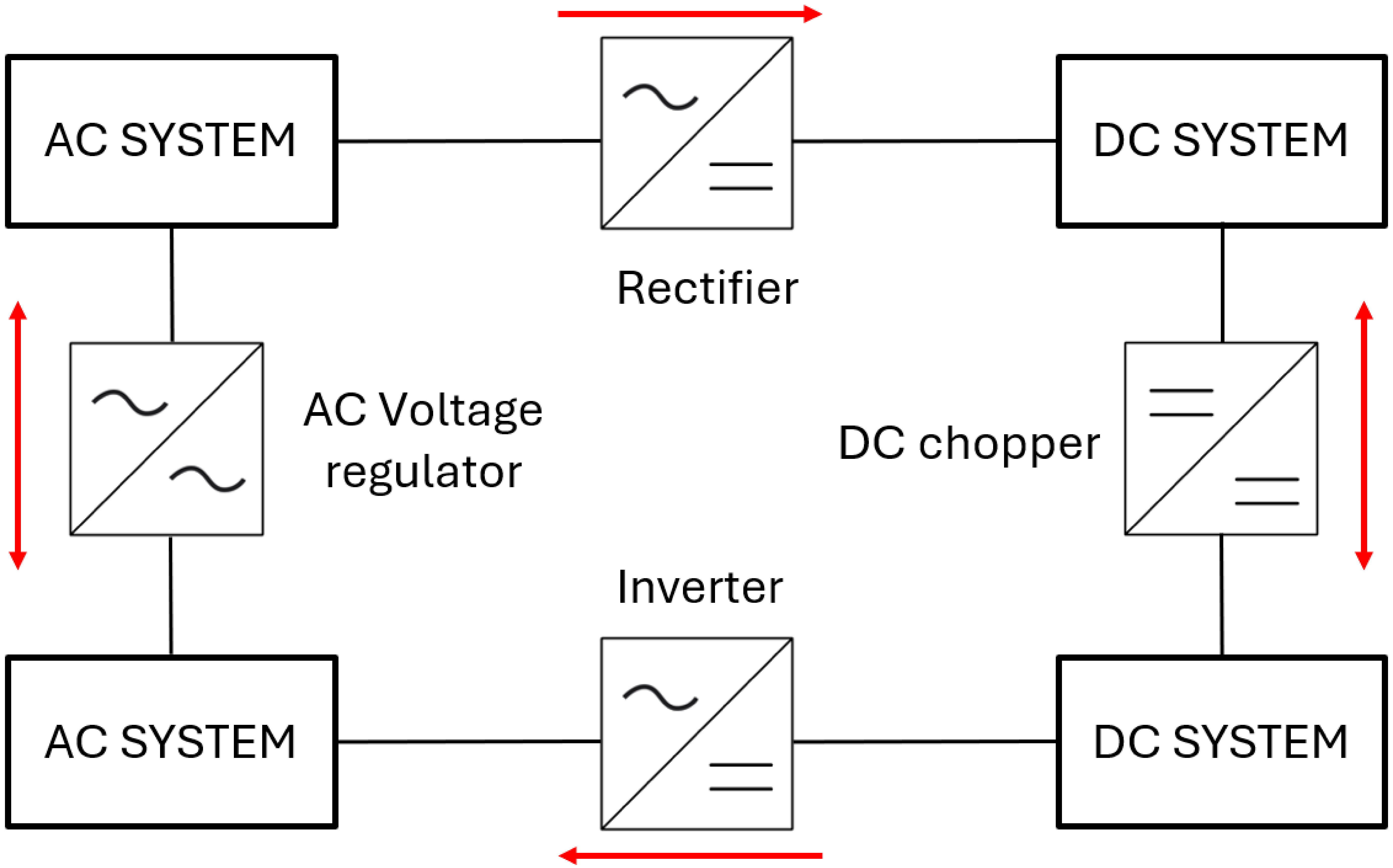


Inertia and the Power Grid: A Guide Without the Spin - NREL

- Wind, solar and storage can provide frequency-responsive services through inverters
- Using sensors and software that control the response (**virtual inertia**)
- Inverter-based resources including photovoltaic, wind and storage can quickly detect frequency deviations and respond to system imbalances
- The response is much faster than traditional mechanical response

Engineering Energy Transition

Power electronics

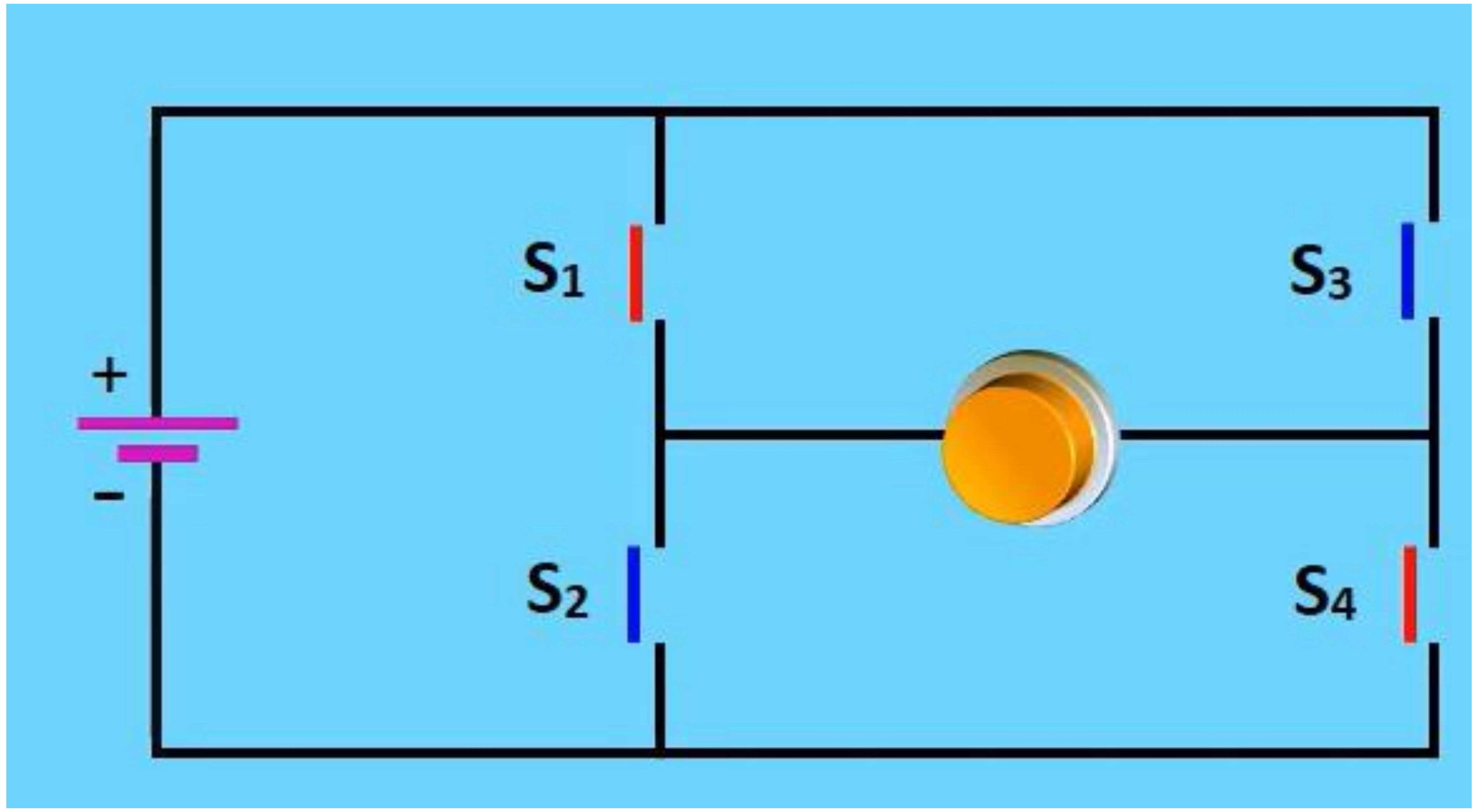


More in “Power Converters”

- An enabling technology for large utilization of RES
- Photovoltaics, wind, storage, …
- Distributed generation

Inverter

More in "Power Converters"

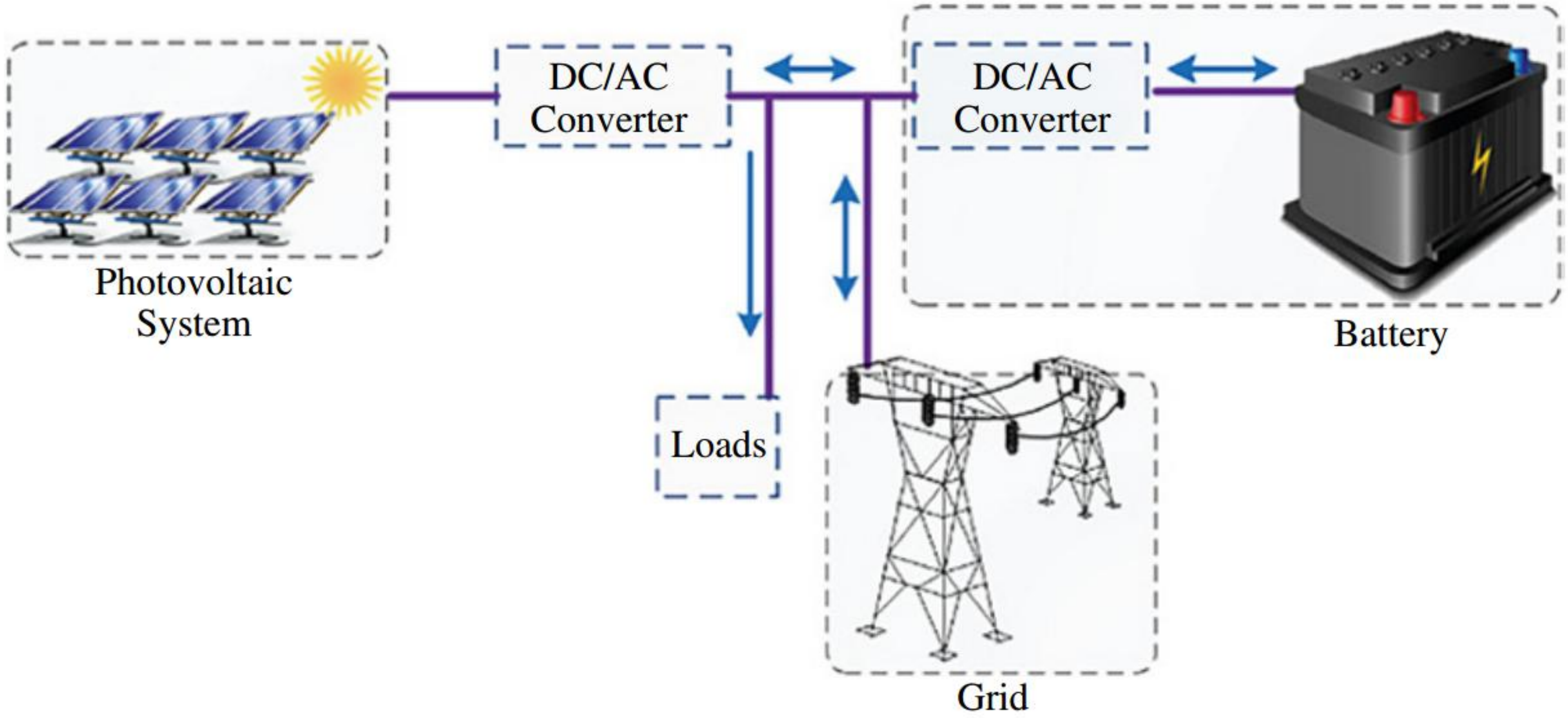


- Converting DC into AC
- Performing the grid connection
- MPPT

Energy storage

More in “Materials and Systems for the Energy Transition” and “Electrical Energy Storage”

- To settle peaks and valleys of supply
- Combined with power electronics
- Grid support: grid’s voltage and frequency, spinning reserve, resilience …
- Financial benefits (automatic pricing signals
- Power congestion avoiding upgrades in the grid
- Challenges: policies, business models, financing mechanisms



S. S. Refaat et al.
Smart grid and enabling technologies

Energy storage

Energy storage

More in "Materials and Systems for the Energy Transition" and "Electrical Energy Storage"

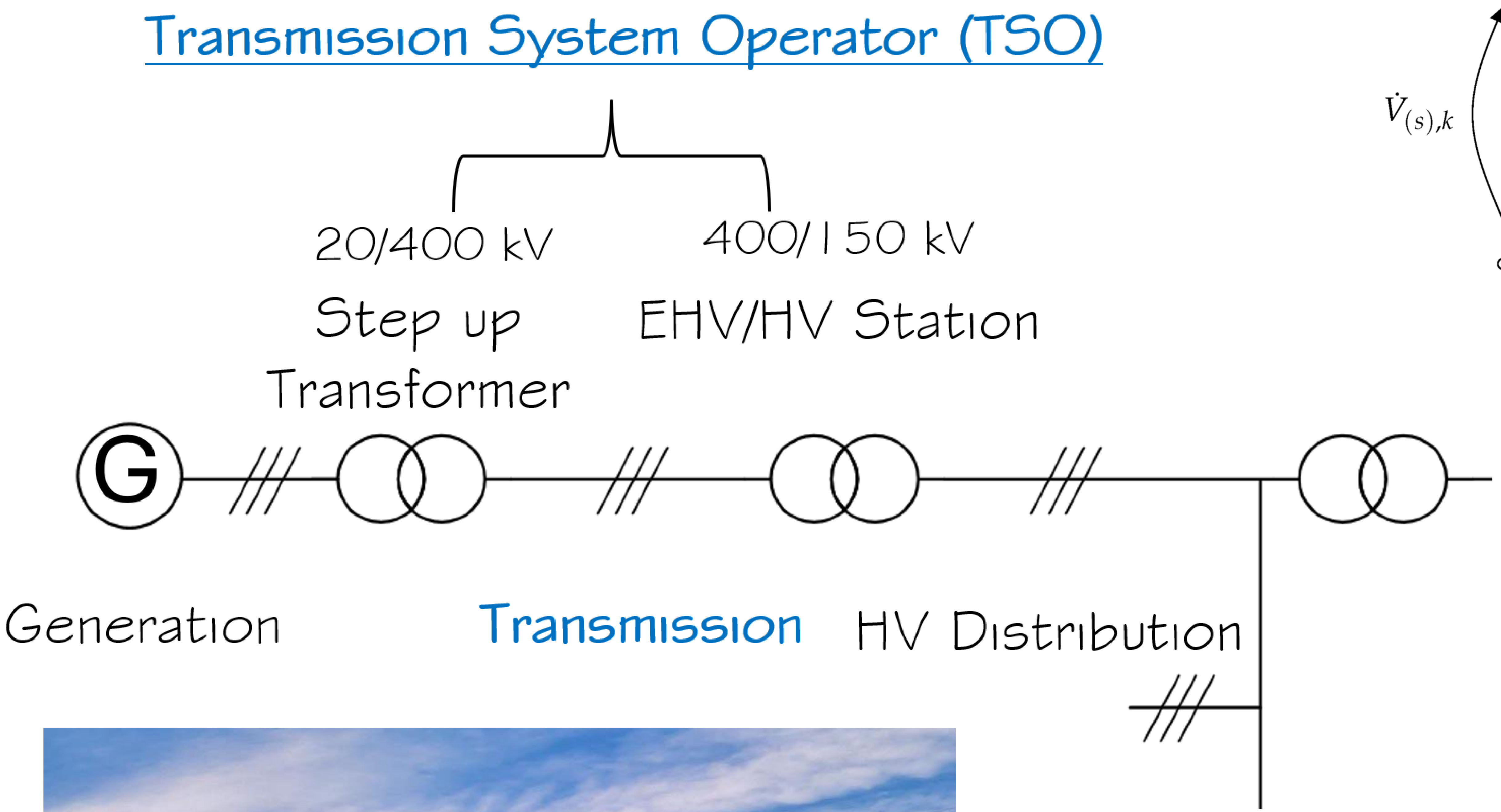
Storage can contribute to shift and or to level the electric energy demand making it somehow **asynchronous** with respect to production

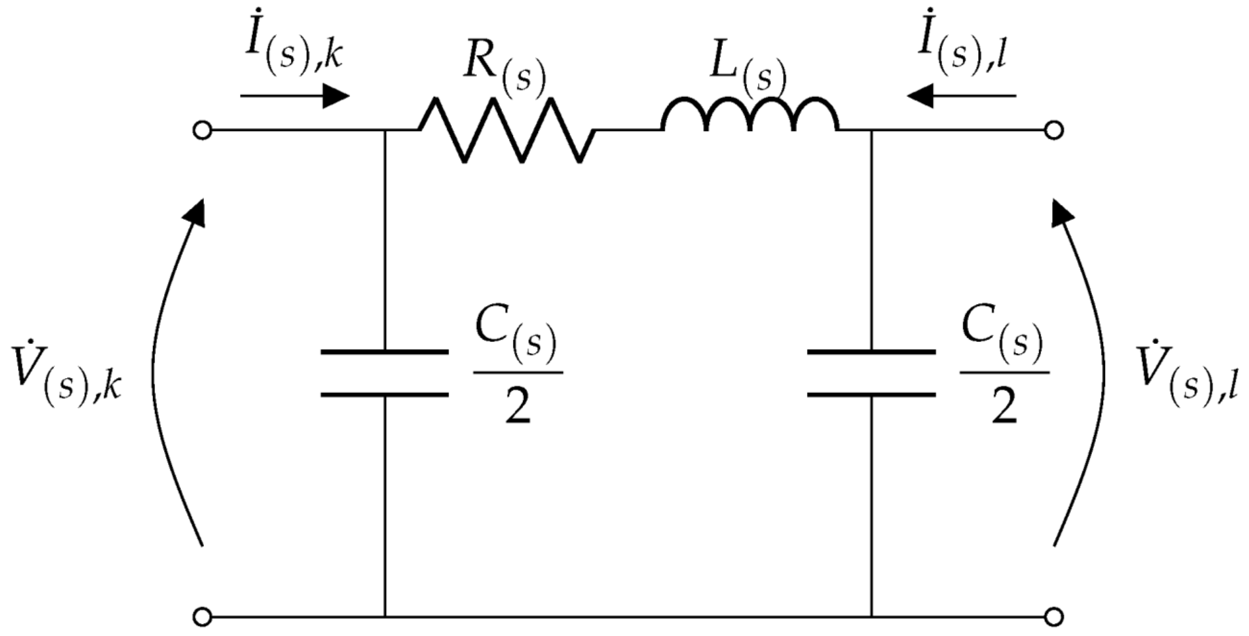
There are two kinds of applications:

- Power applications: **peak shaving**
- Energy application: **time shift**

Engineering Energy Transition

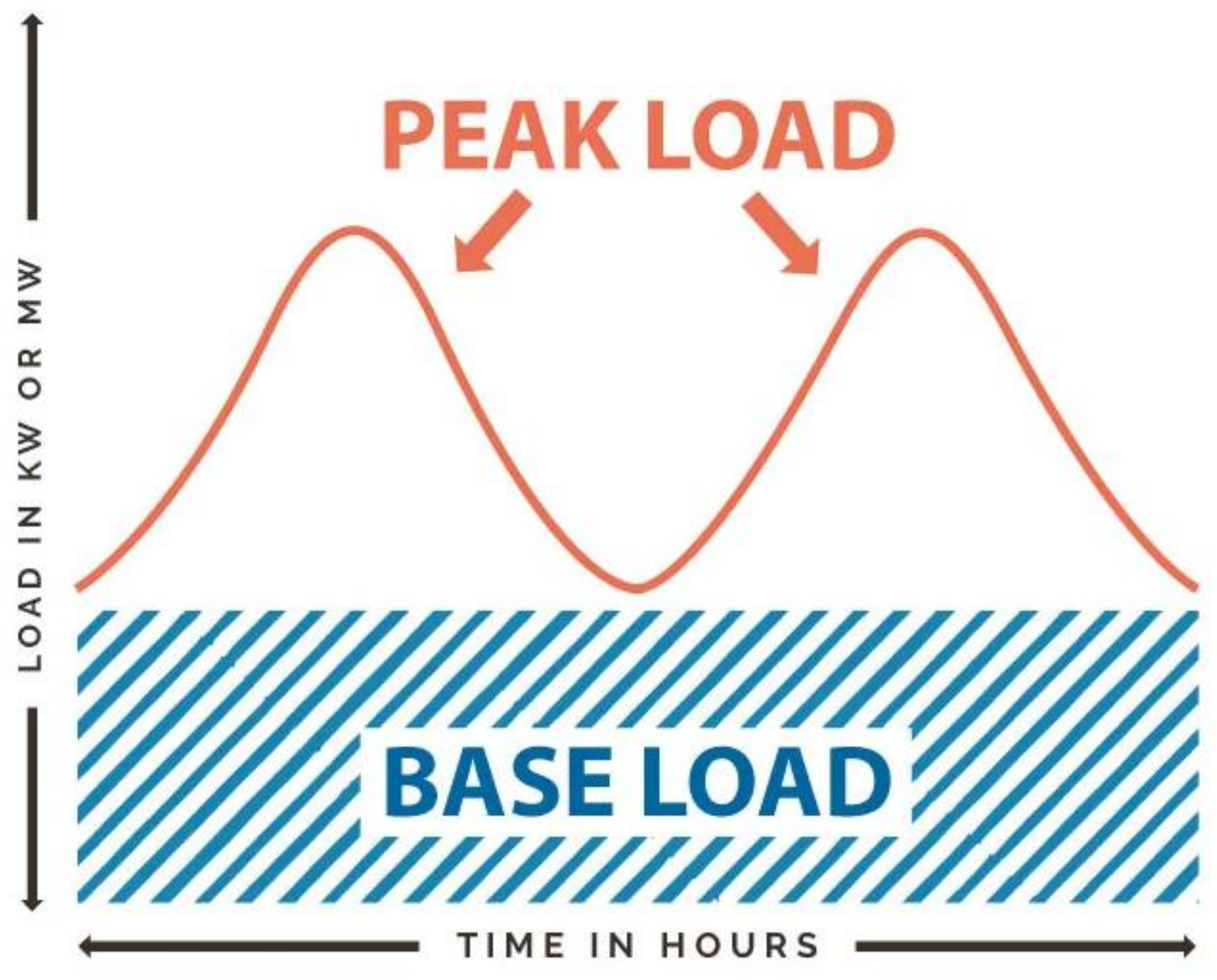
Power transmission (EHV)

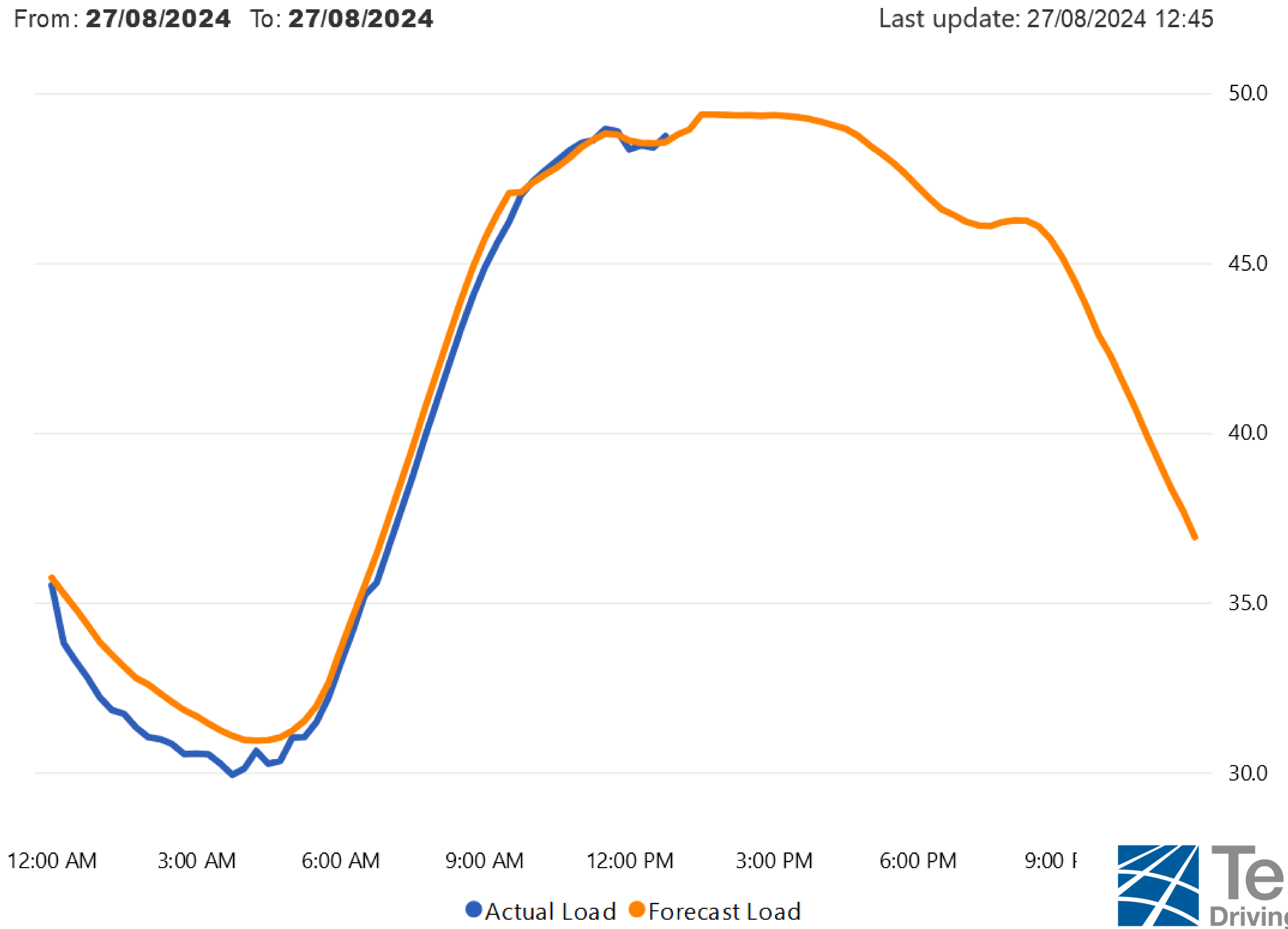




- “Low frequency”: the line is “short” compared to the wavelength of voltages and currents

Transmission load curve



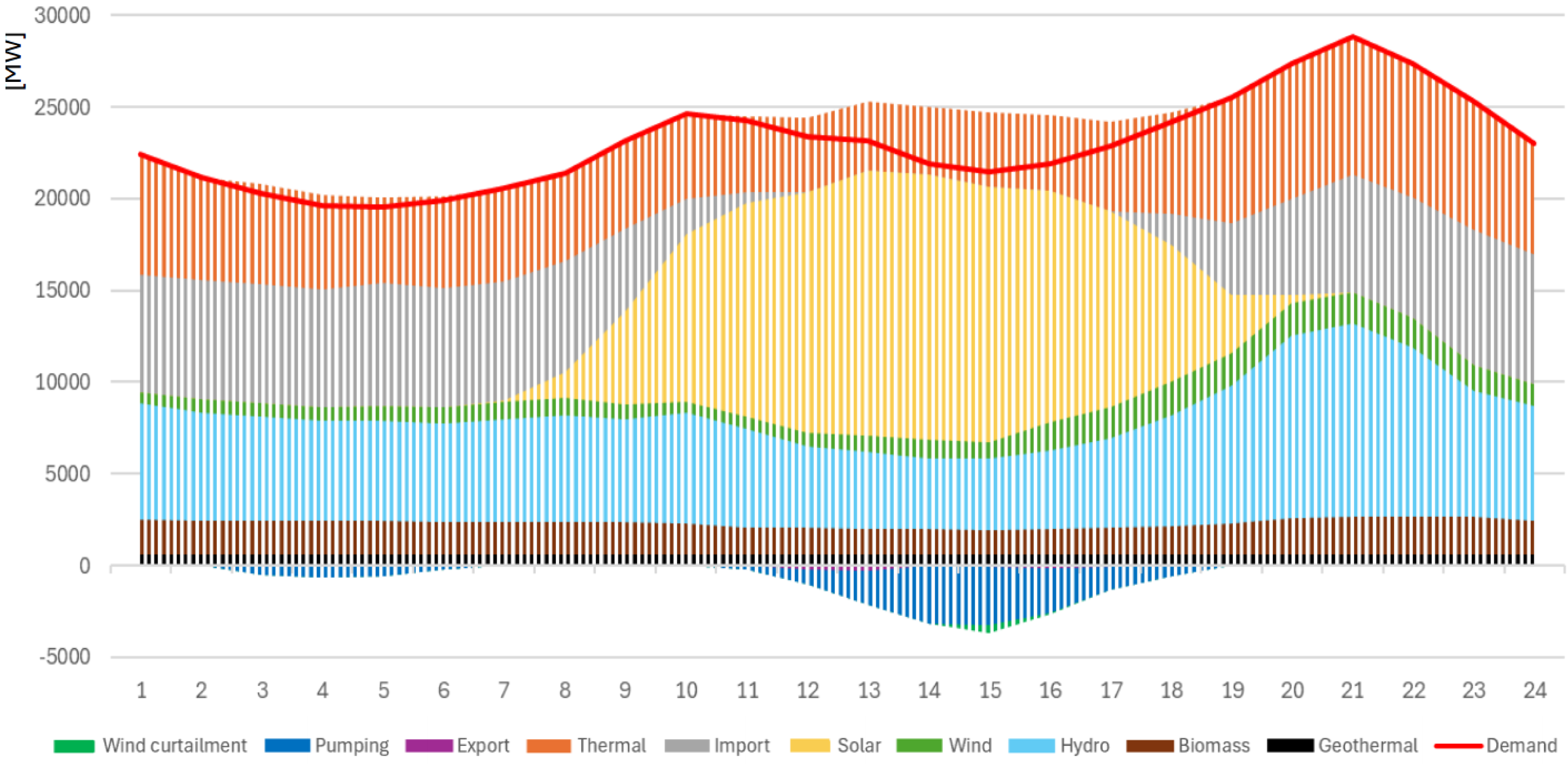


Terna Driving Energy

Engineering Energy Transition

Generation curve

- Base load
- Peak load
- Variable load
- Reserve



Terna Driving Energy

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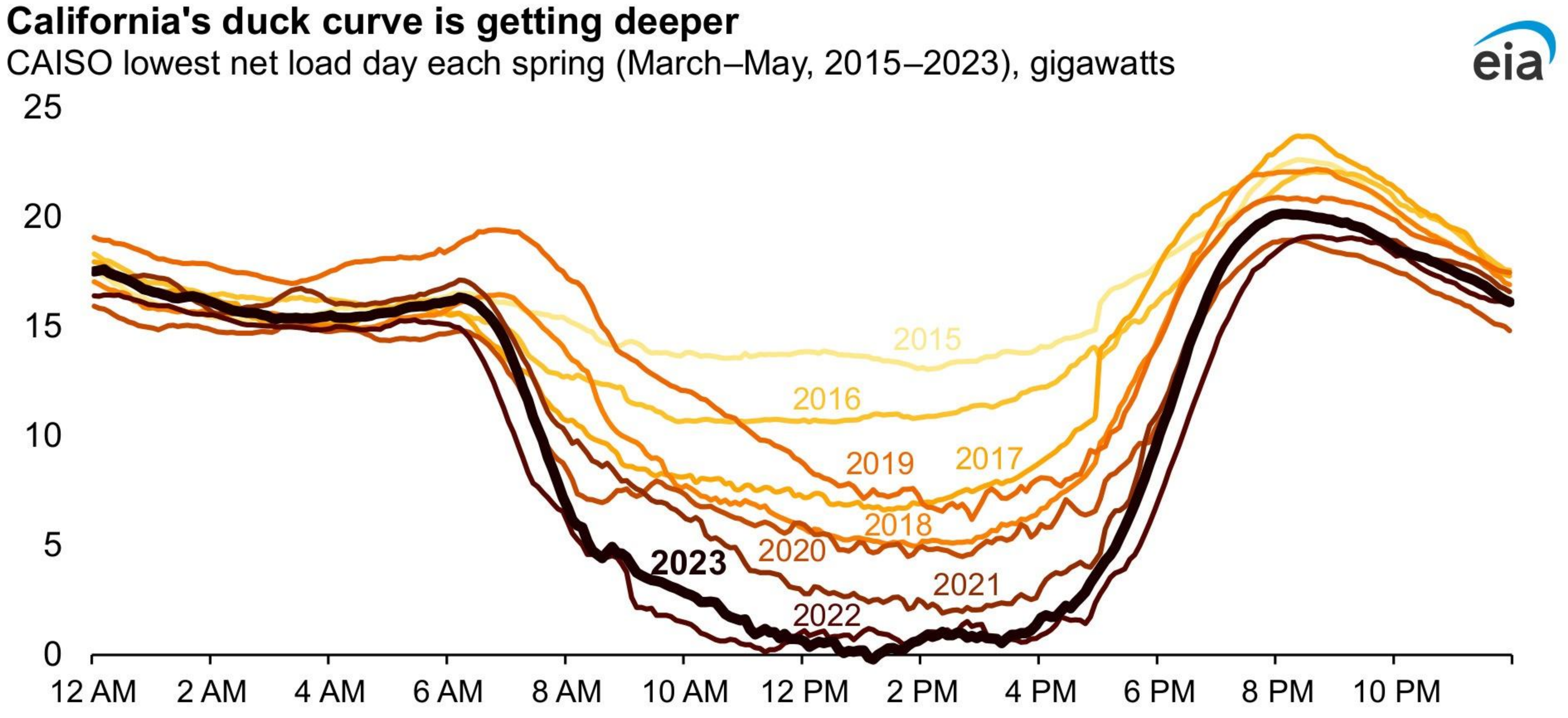
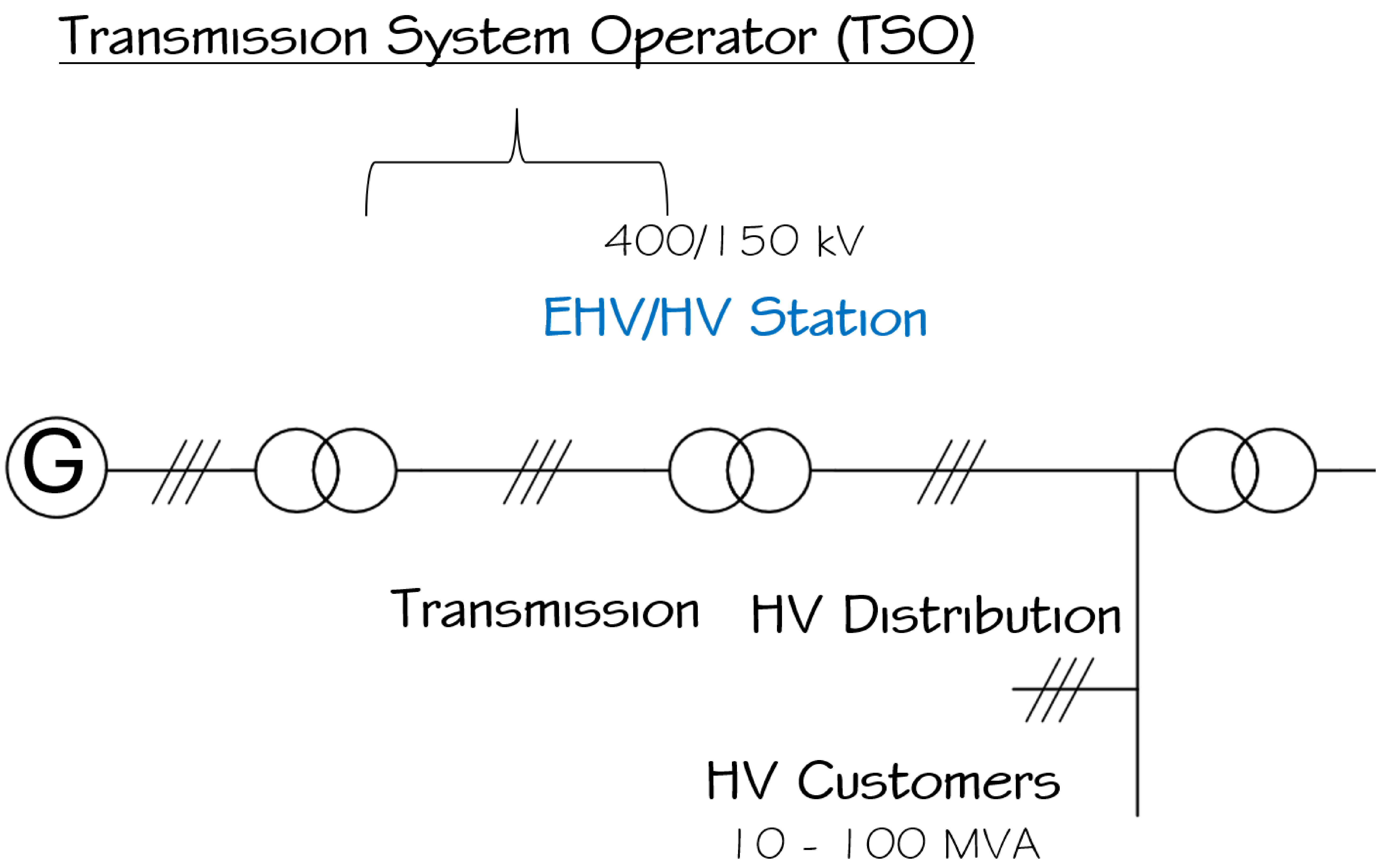
Duck curves are getting deeper

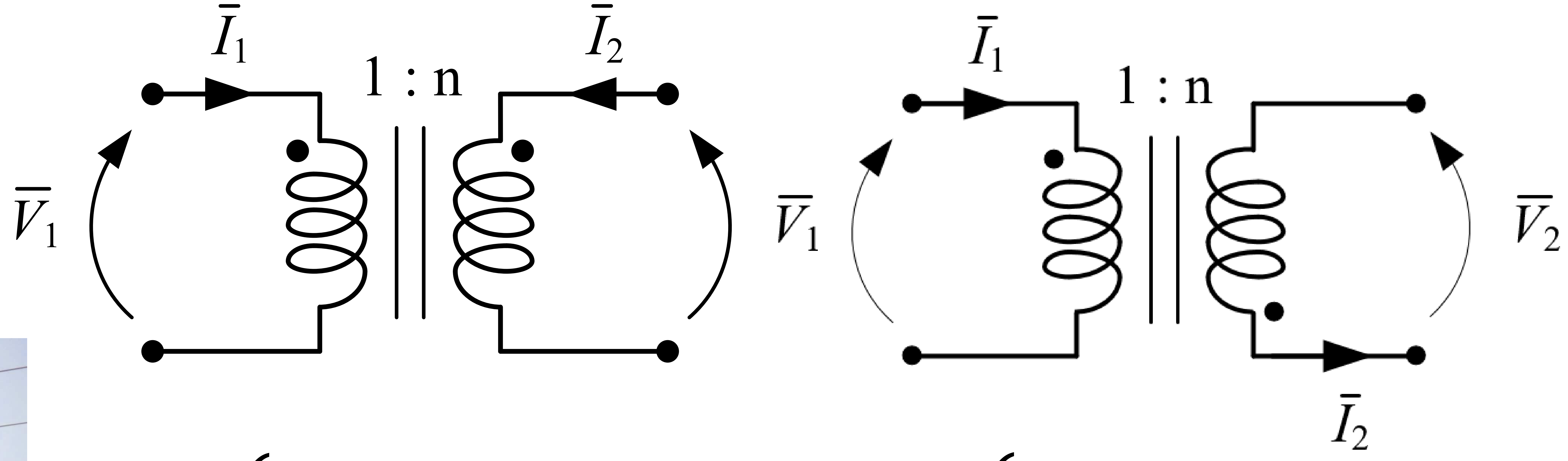


Duck curves are getting deeper

EHV – HV power stations



Transformers



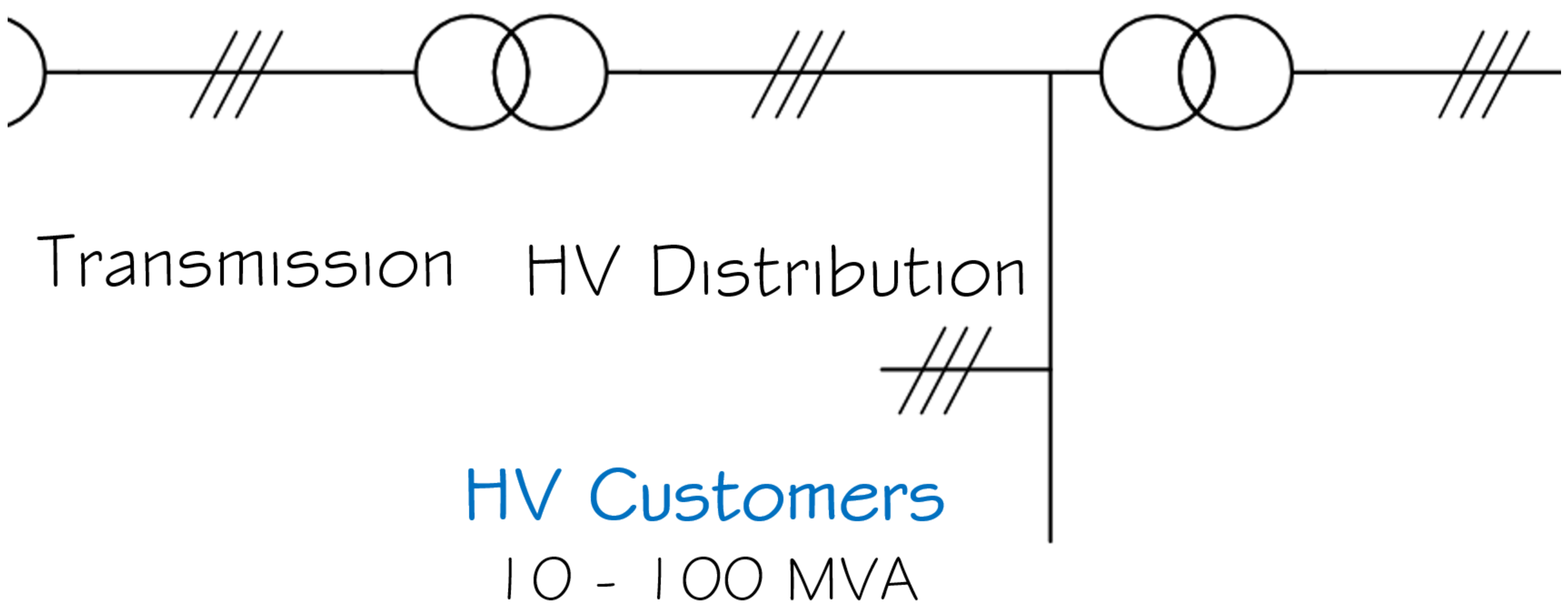
$$\begin{cases} \bar{V}_2 = n\bar{V}_1 \\ \bar{I}_2 = -\dfrac{1}{n}\bar{I}_1 \end{cases}$$

$$\begin{cases} \bar{V}_2 = -n\bar{V}_1 \\ \bar{I}_2 = \dfrac{1}{n}\bar{I}_1 \end{cases}$$

- Transformers convert electrical energy at one voltage to some other voltage
- Higher voltages means lower currents and lower losses

HV customers

Distribution System Operator (DSO)



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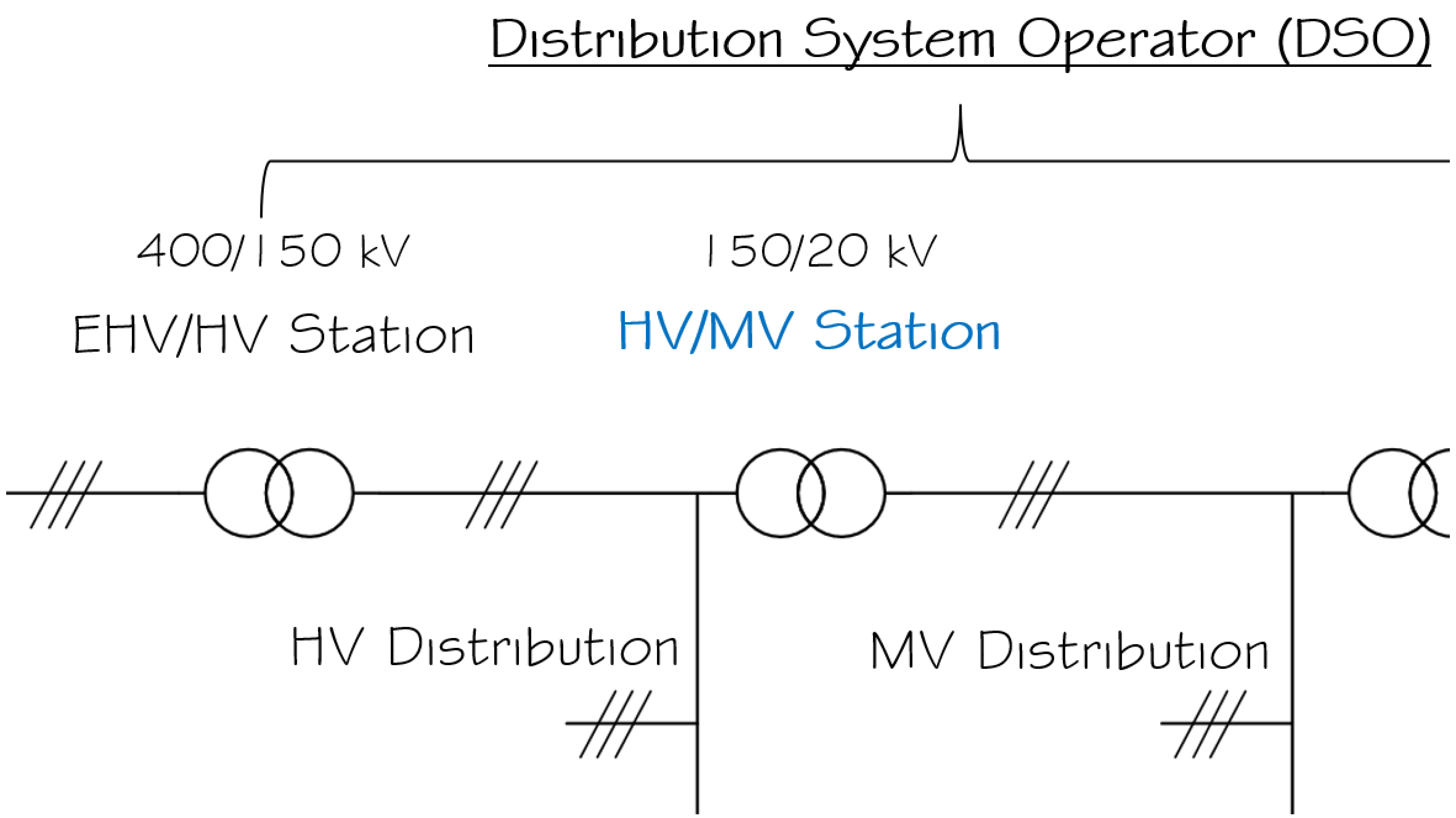
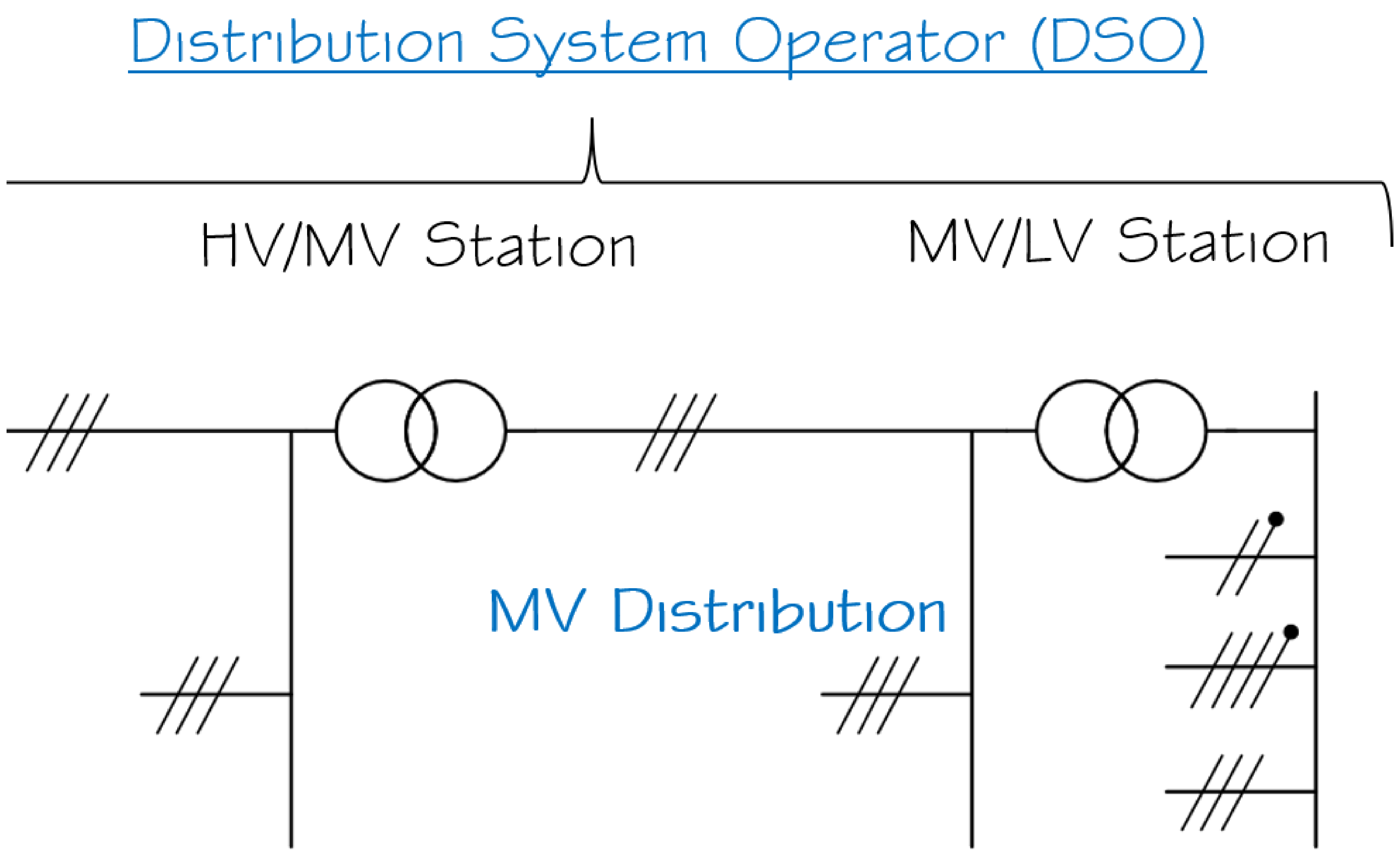
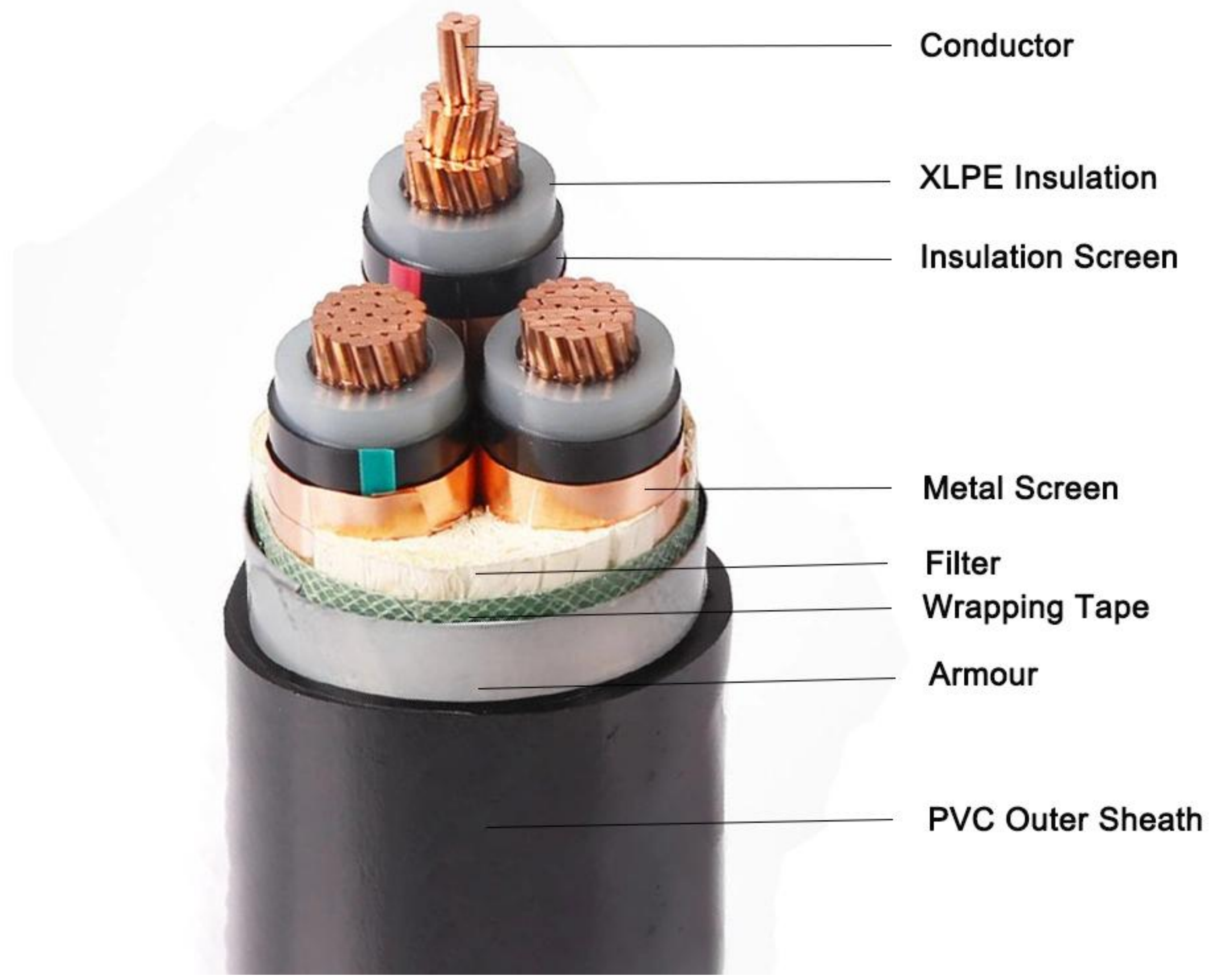
HV – MV power stations (primary)



Power distribution (MV)

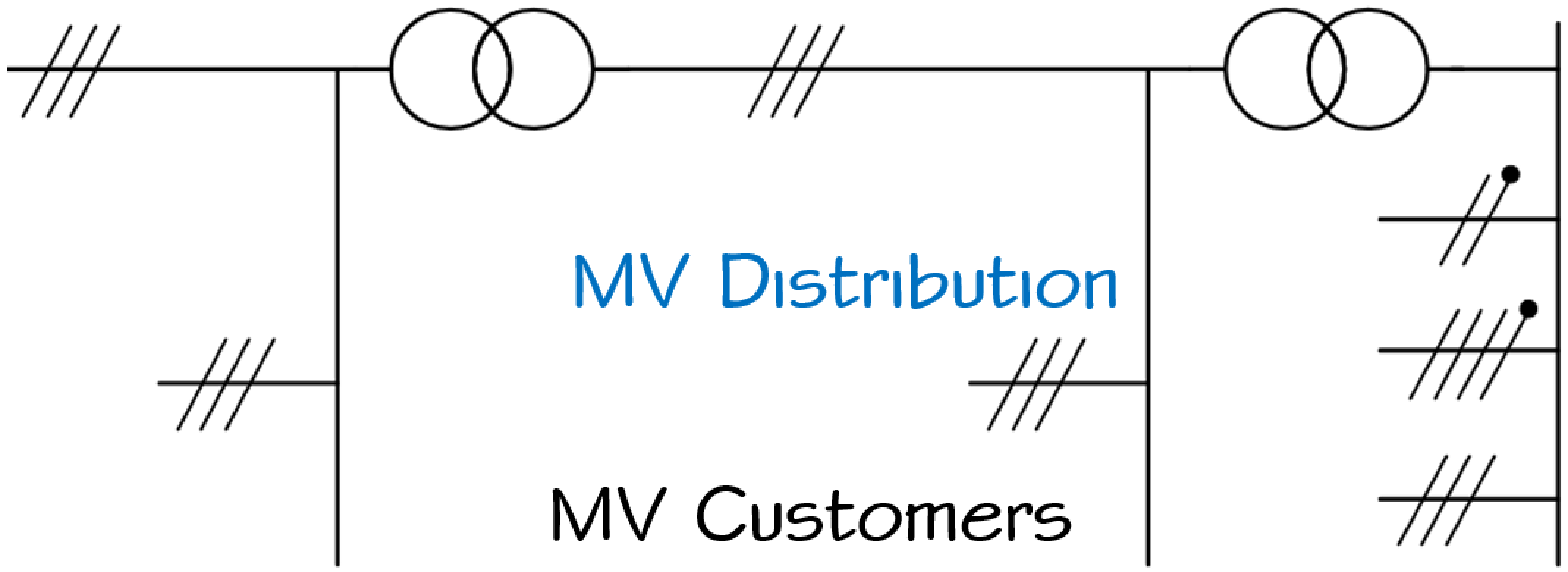




More in "Electrical System Design"
Prof. Andrea Vicenzutti

MV Customers

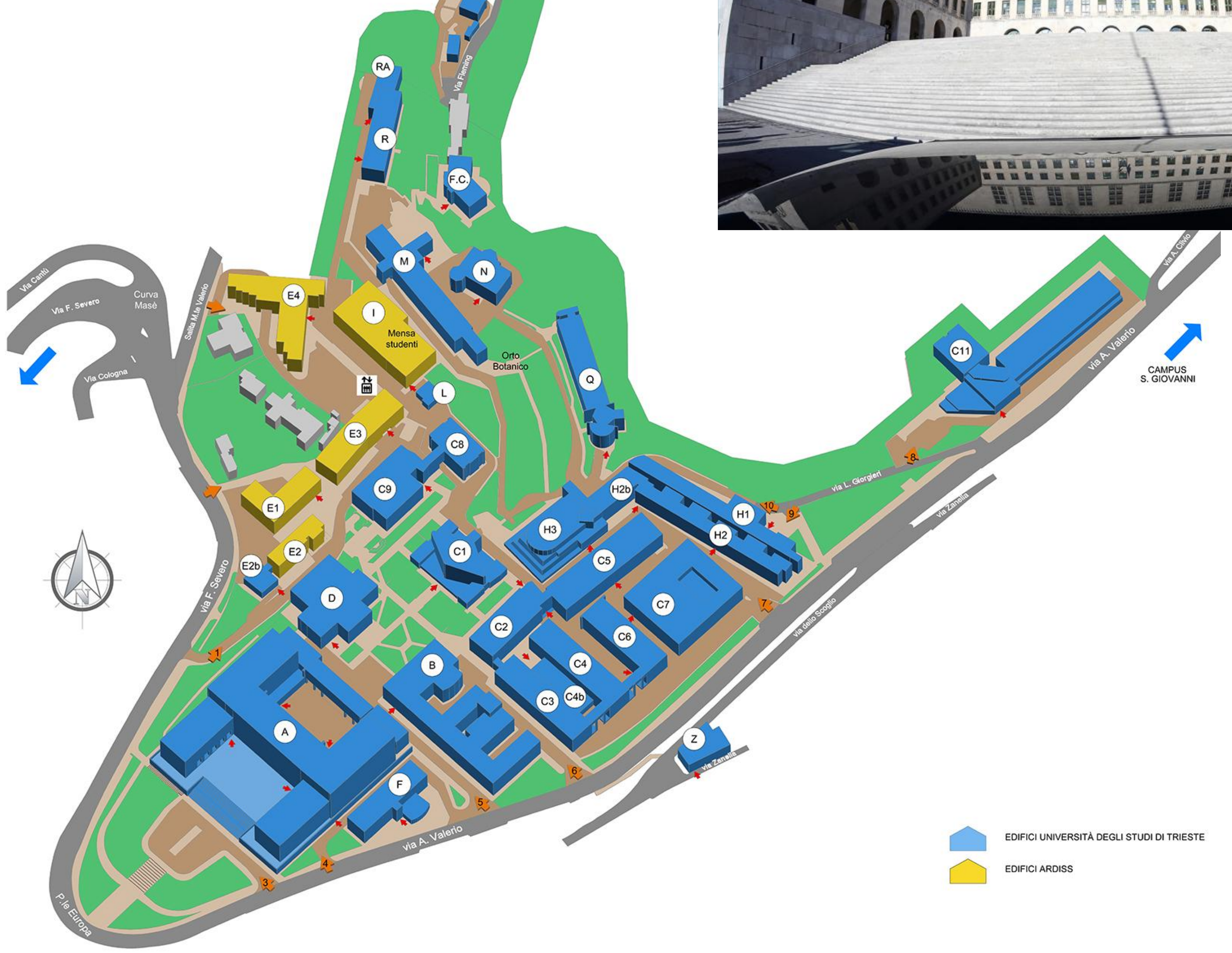
HV/MV Station

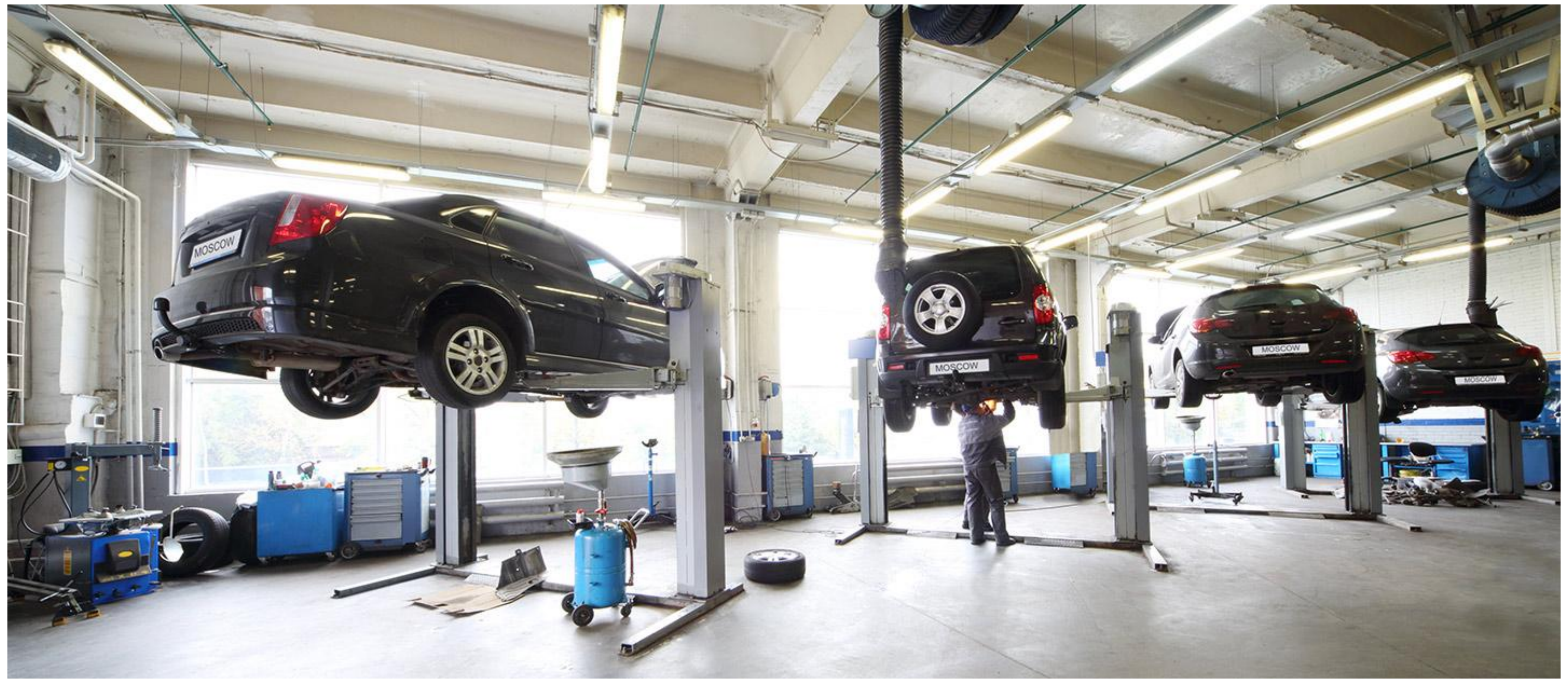


MV Distribution

MV Customers

0.1 – 10 MVA





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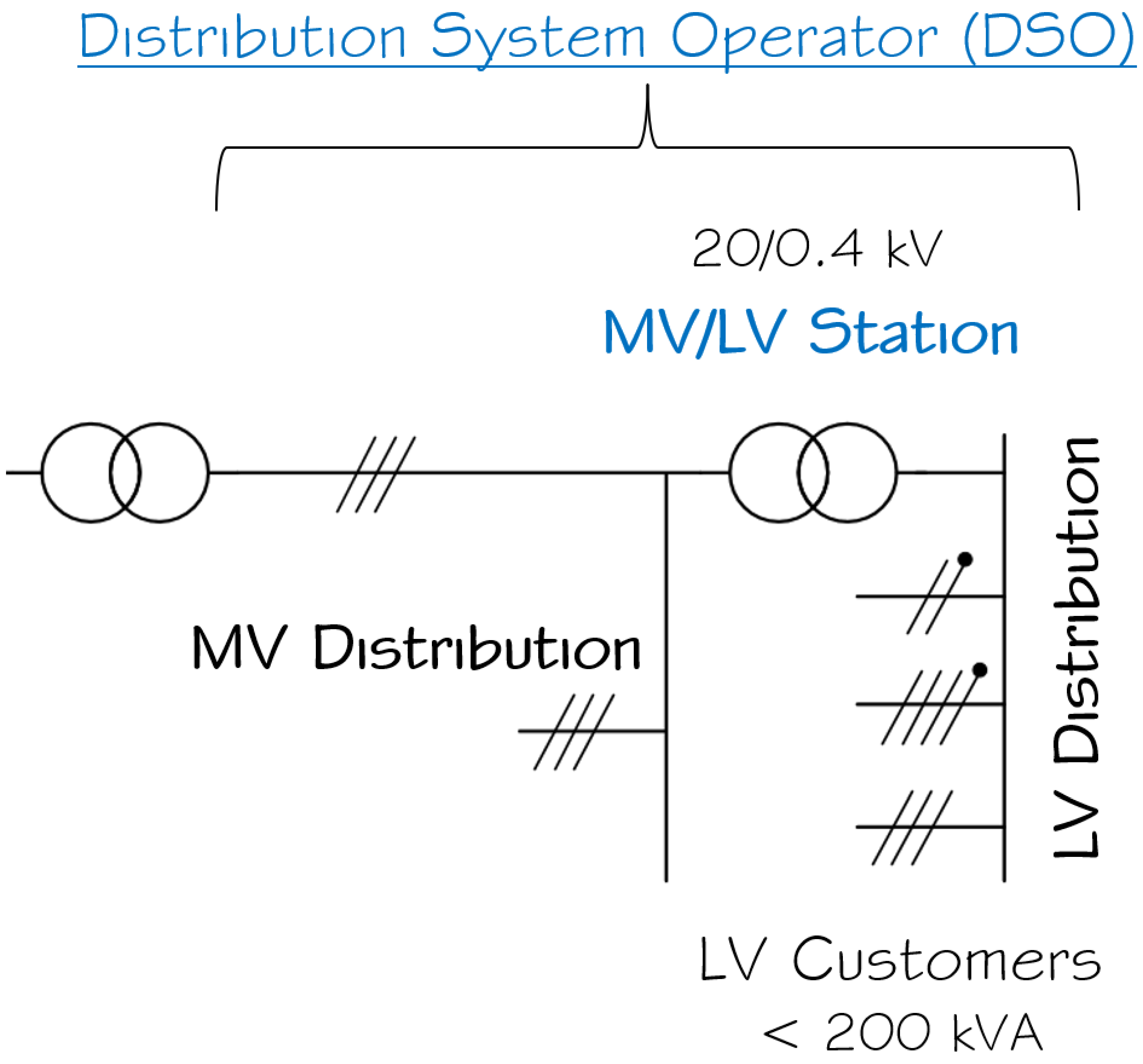
MV – LV power stations (secondary)



- TT – TN Systems

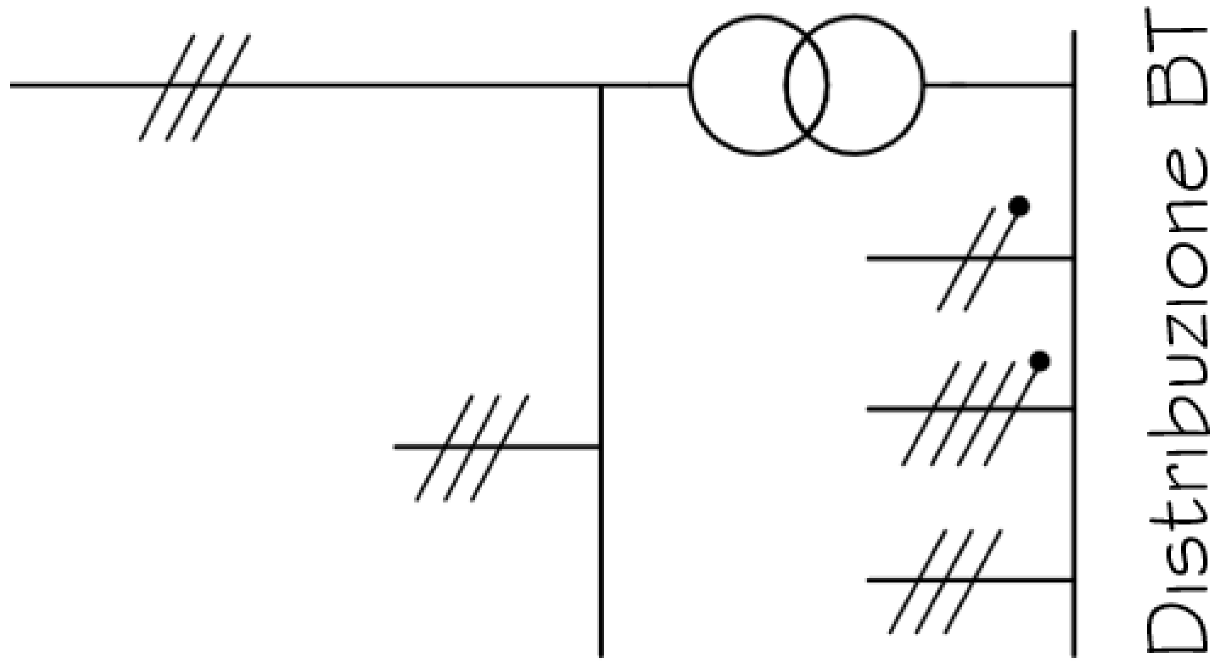
More in “Electrical System Design”
Prof. Andrea Vicenzutti

LV Customers

Distribution System Operator (DSO)

20/0.4 kV

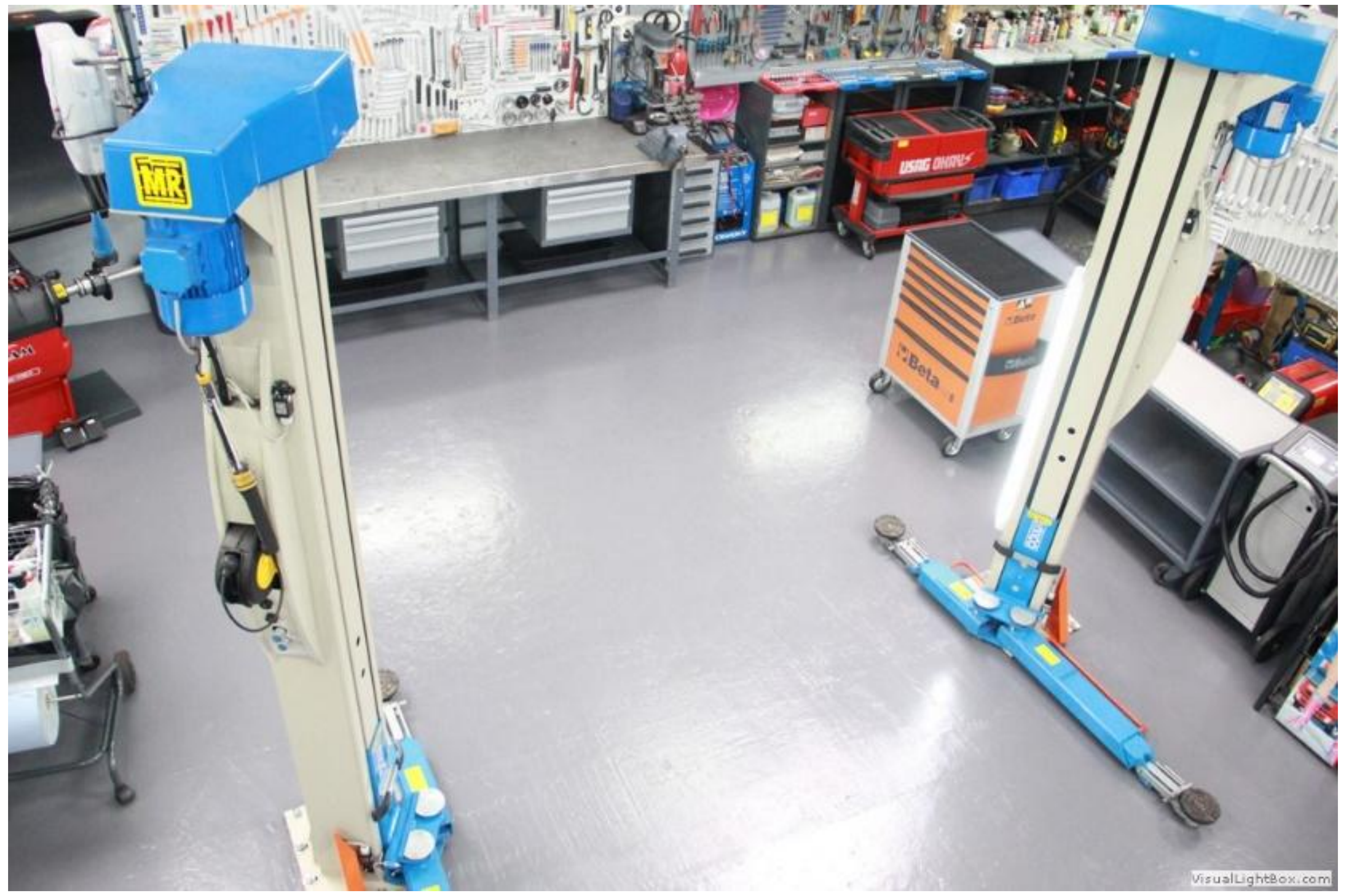
MV/LV Station



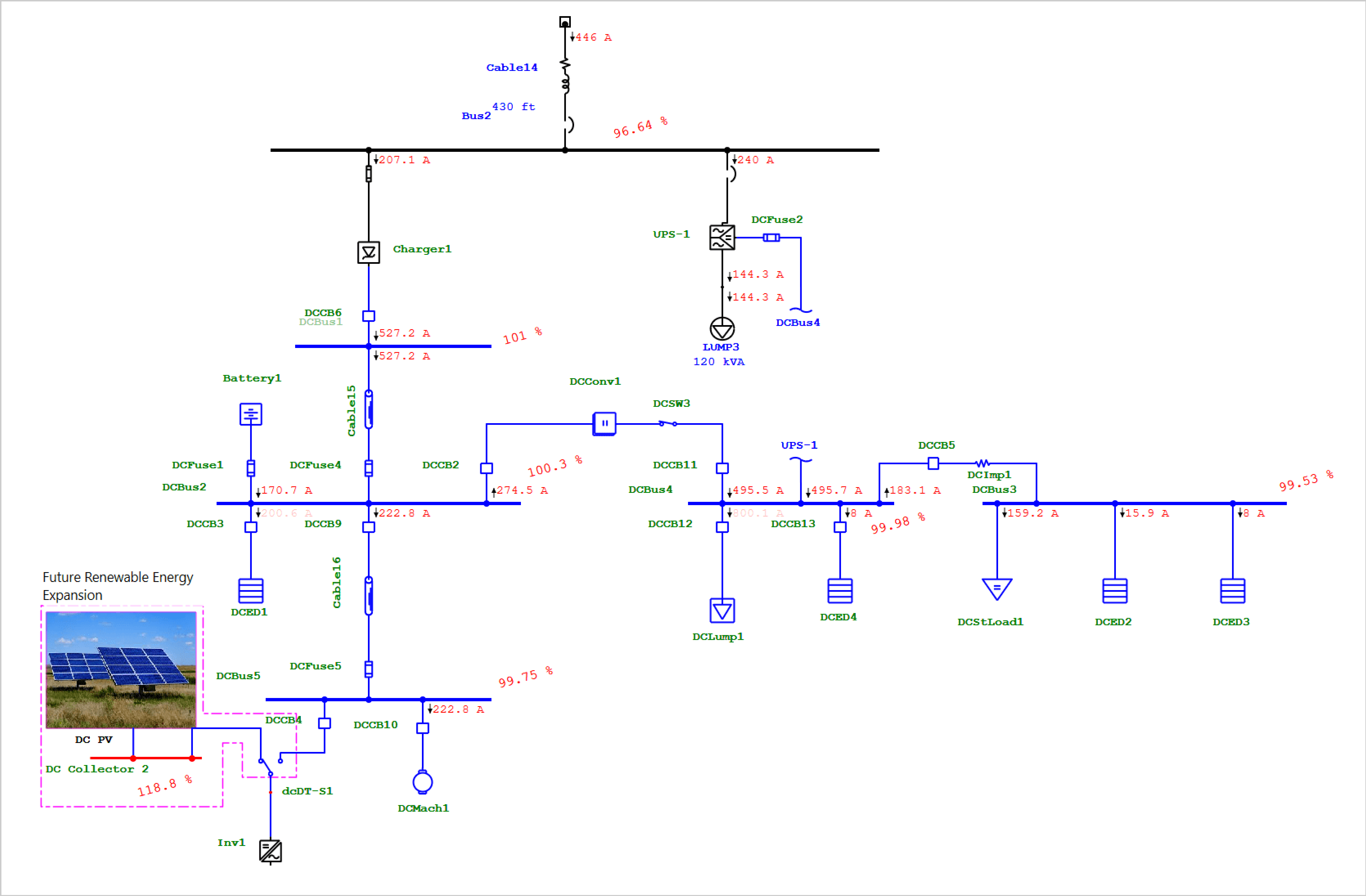
LV Customers

< 200 kVA

Residential, commercial and industrial

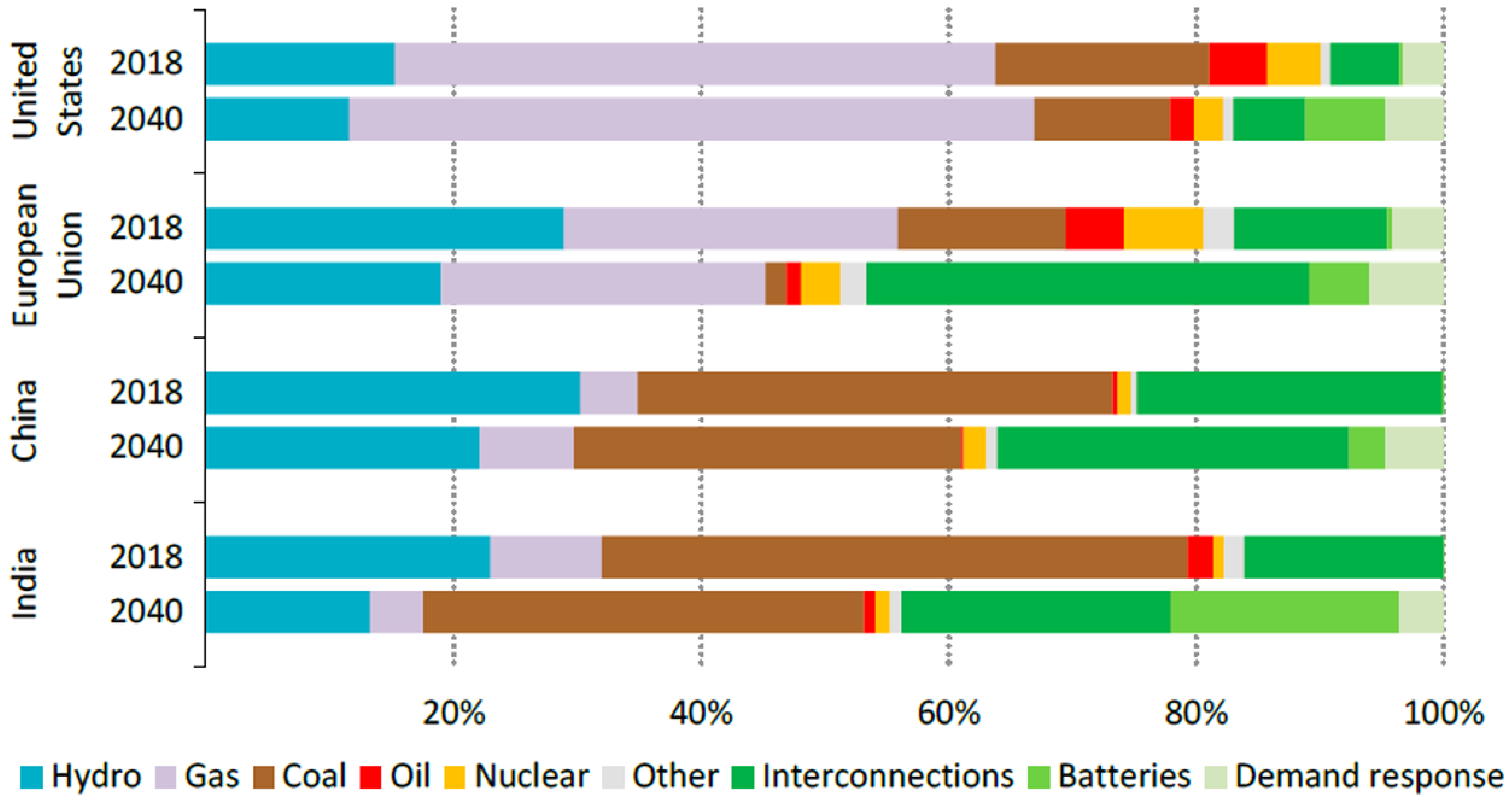


Load flow



- Understand how load flows and over which pathways
- Load flow evaluation are required in advance of any system expansion
- Load flow evaluation are required as part of generation dispatch

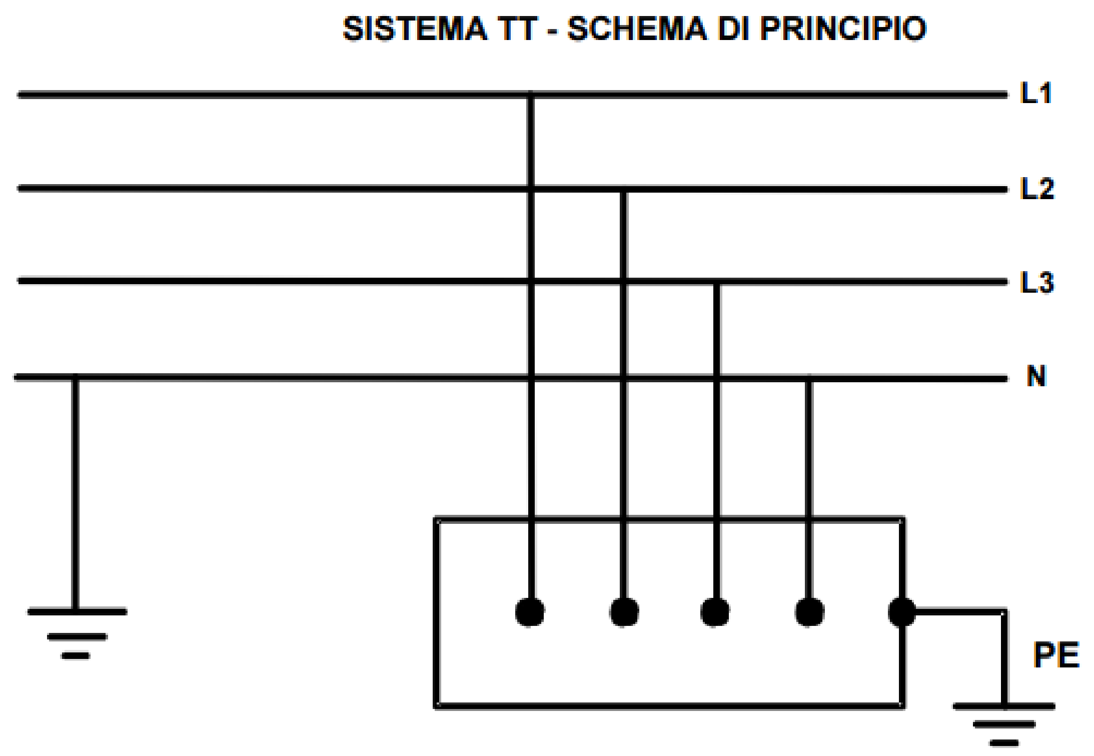
Flexibility of the power system



More in "Microgrid"
Prof. Daniele Bosich

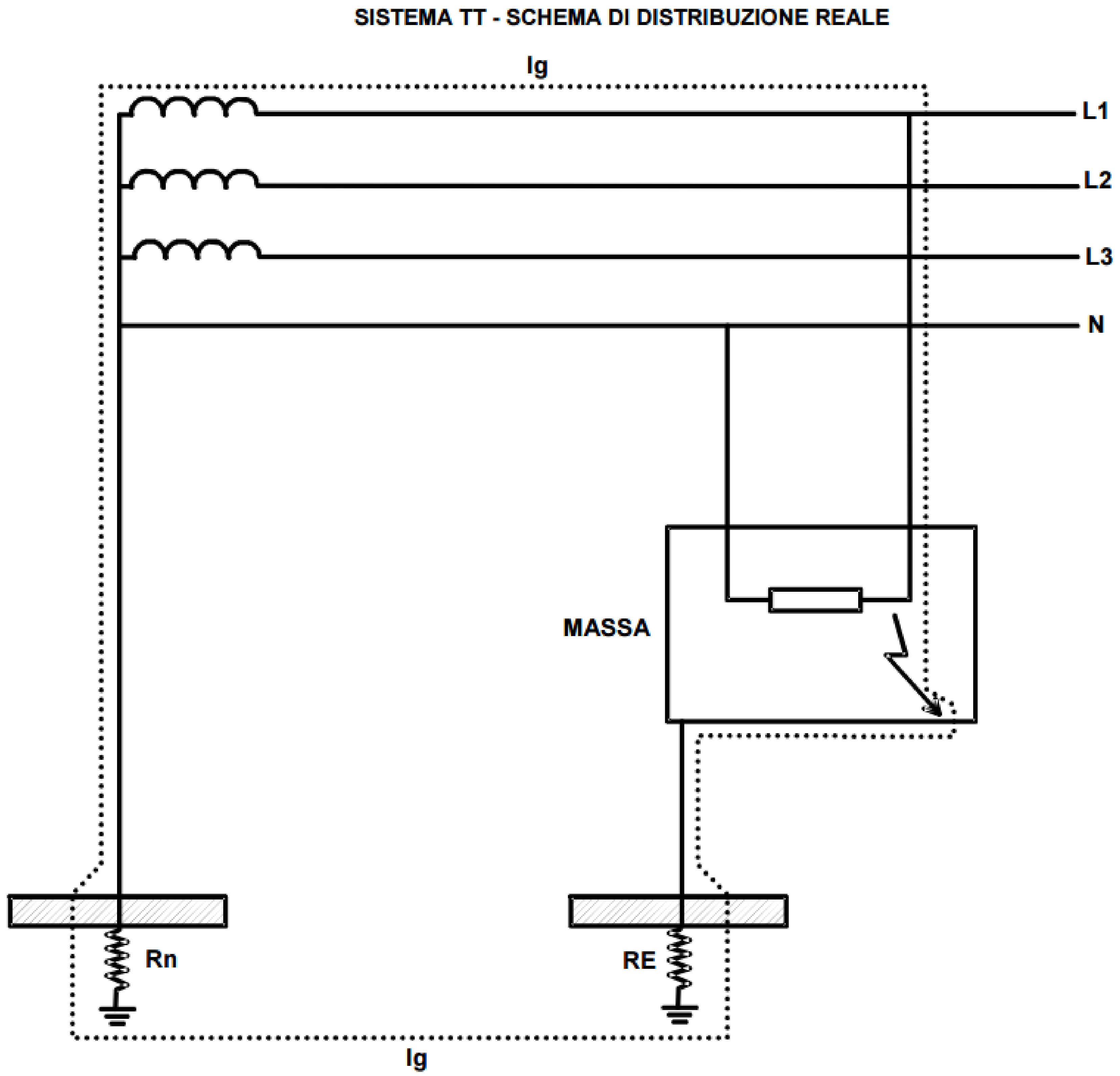
- Increasing need for flexibility
- At the distribution level: controllable generation (VPP, microgrid), storage, controllable loads, e-vehicles (V2X)
- Guarantee various services providing active (P) and reactive (Q) power support

CEI 0-21: Reference technical rules for the connection of active and passive users to the LV electrical Utilities



- Frequency variation: 50±5% (100% of the time), 50±2% (95% of the time)
- Voltage "slow" variation: U_n + 10% and U_n - 15%

Power [kW]	Grid voltage level
≤ 100	LV
> 100 and ≤ 200	LV or MV



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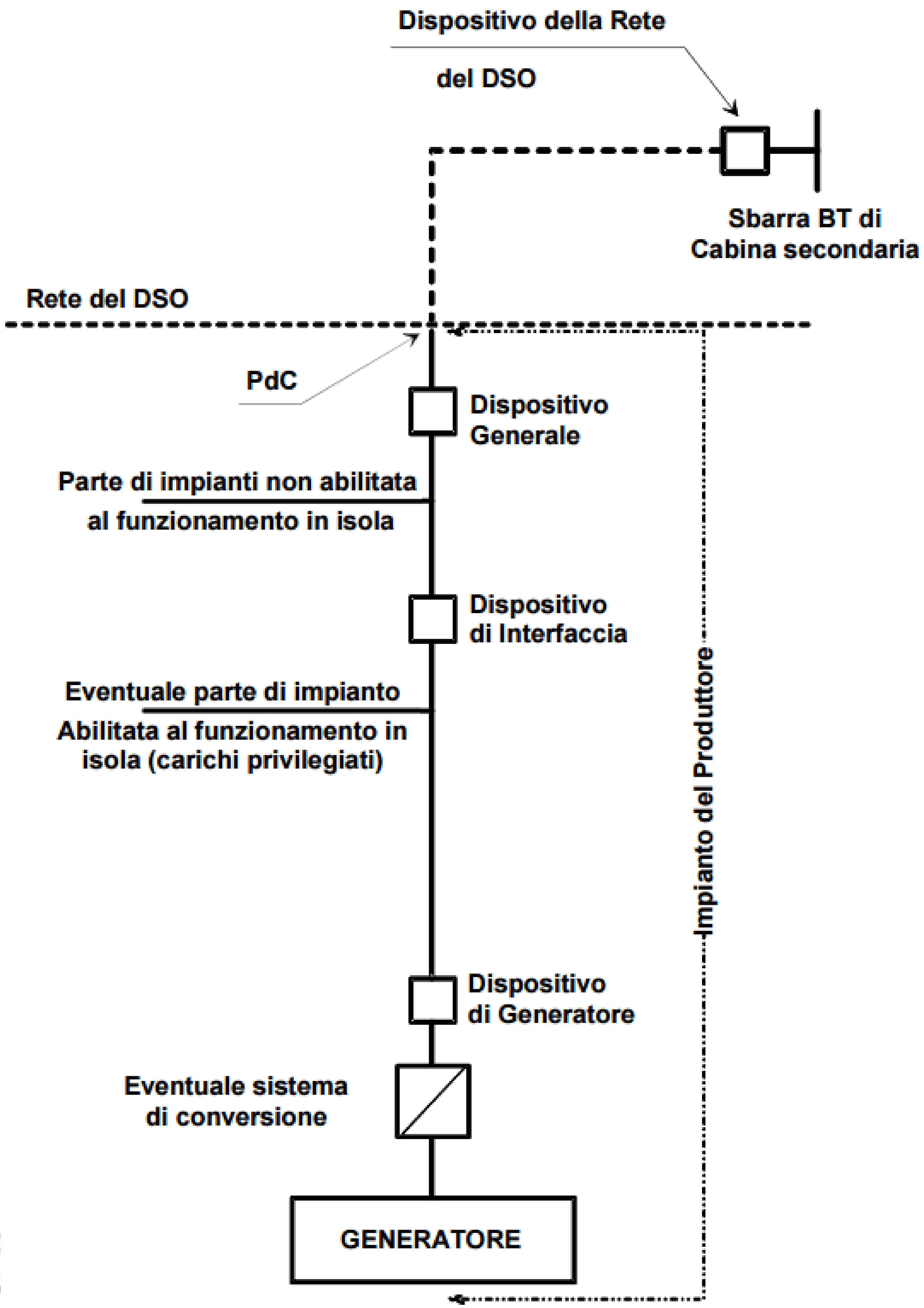
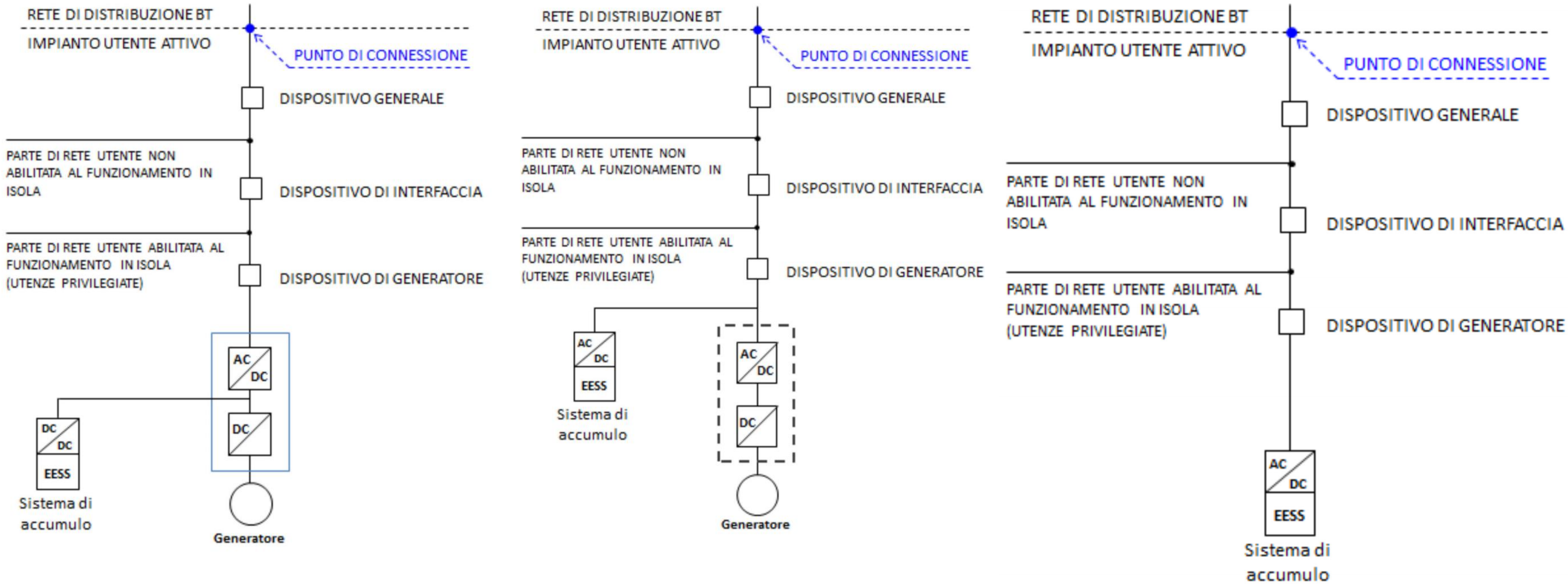
CEI 0-21: Producers connected to the DSO's grid



- "Dispositivo della rete": grid switch
- "Cabina secondaria": secondary power station
- "Rete del DSO": DSO's grid
- "PdC": connection point
- "Dispositivo generale" **DG**: main switch
- "Parte di impianto … isola": portion of the power system which cannot work in islanded mode
- "Dispositivo d'interfaccia" **DI**: interface switch
- "Parte di impianto … isola": portion of the power system which can work in islanded mode
- "Dispositivo del generatore" **DGG**: generator switch
- "Eventuale Sistema di conversione": possible inverter

CEI 0-21: electrical storage systems



- “Sistema di accumulo”: electrical storage device

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CEI 0-21: electrical storage systems

- DG: the main switch separates the consumer's plant from the grid when a failures occurring before PdC (internal failure)
- DI: the interface switch avoids the consumer can supply the grid in case of power outage on the network; it opens when in case of a fault or abnormal voltage and/or frequency values on the low voltage network
- DDG: the generator switch separates the generator from the consumer's plant and protects the generator itself