CONTROL AND OPTIMIZATION IN SMART-GRIDS

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Introduction - Myself

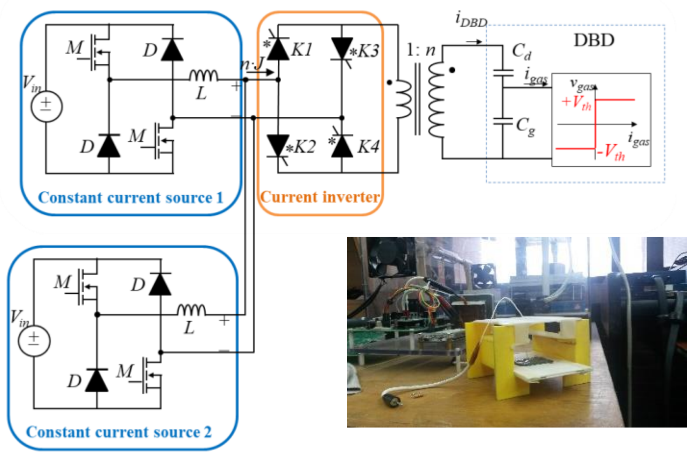
Fredy Ruiz

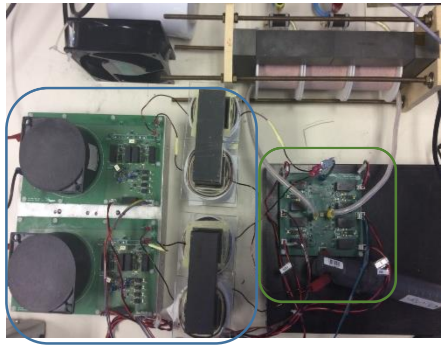
- ➢Born in Facatativá (Colombia)
- ➢BSc. Electronics Engineering, Pontificia Universidad Javeriana, 1997-2002.
- ➢MSc. Electronics Engineering, Pontificia Universidad Javeriana, 2004-2005.
- ➢PhD. Computer and Control Engineering, Politecnico di Torino, 2006-2009.

CEPIT – Reseach group on Control and Power Electronics

- 3 Associate professors (PhD)
- 3 Assistant Professors (MSc)
- 12 PhD Students
- 15 MSc Students
- 1 Development Engineer

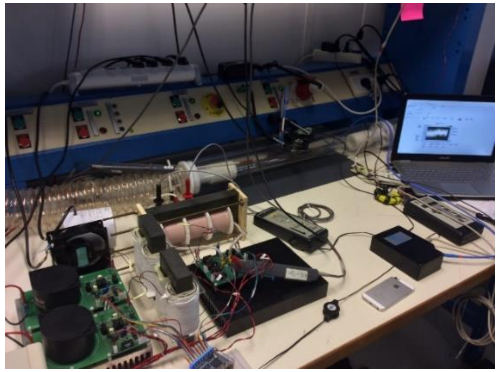
Dielectric Barrier Discharge Applications





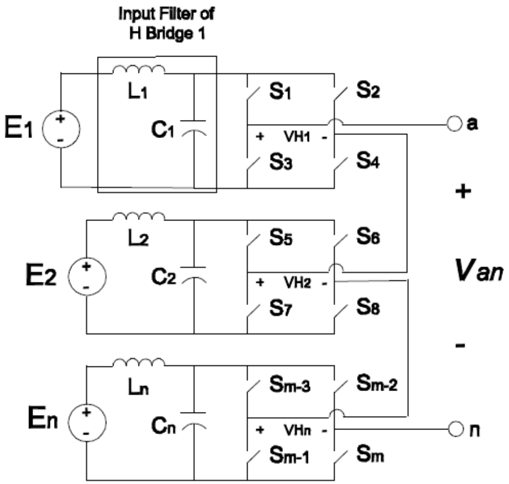
Current sources

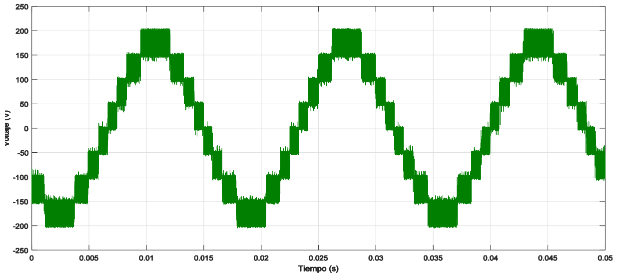
Current inverter



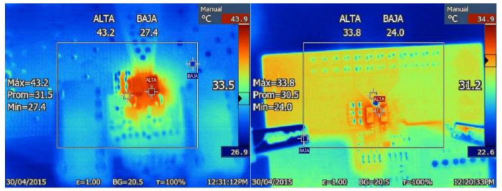
- Desing, Modeling and control of power sources for DBD systems.
  - UV production
  - Water/Air disinfection
- Cooperation with LAPLACE Lab. (Toulouse, Francia)
- Budget ~ € 100.000
- PI: Prof. Rafael Díez, rdiez@javeriana.edu.co

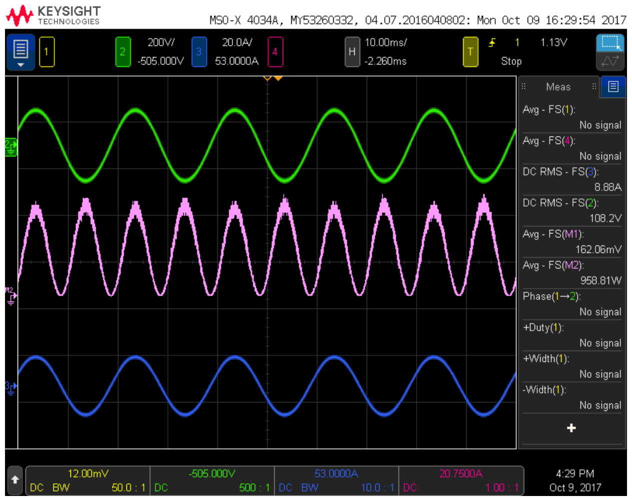
Energy Management System based on Storage Technologies





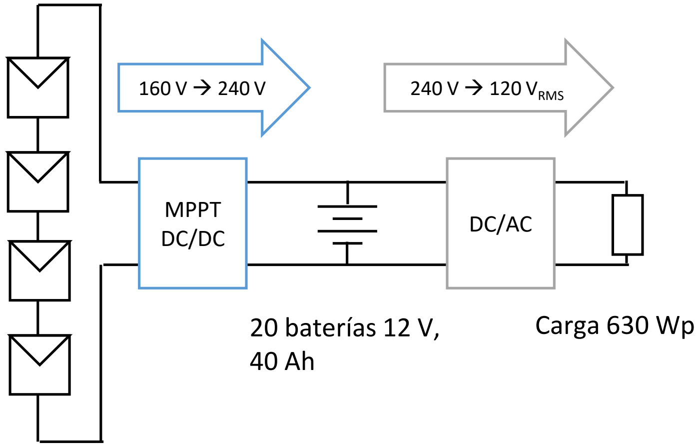
Wide-bandgap semiconductors

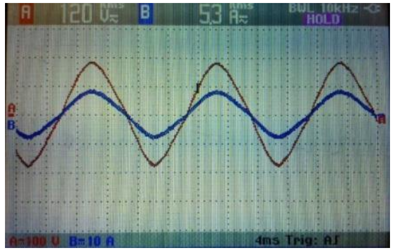




- ➢ To Develop Hardware and Control solutions for the effective integration of PV sources to the grid, employing battery storage.
  - ➢ Multilevel inverters
  - ➢ Battery modeling and management, SOC and SOH estimation
  - ➢ Scheduling and control of charge-discharge profiles
  - ➢ Frequency and voltaje regulation services
- ➢ Budget ~ € 83.000
- ➢ PI: Diego Patiño, patino-d@javeriana.edu.co

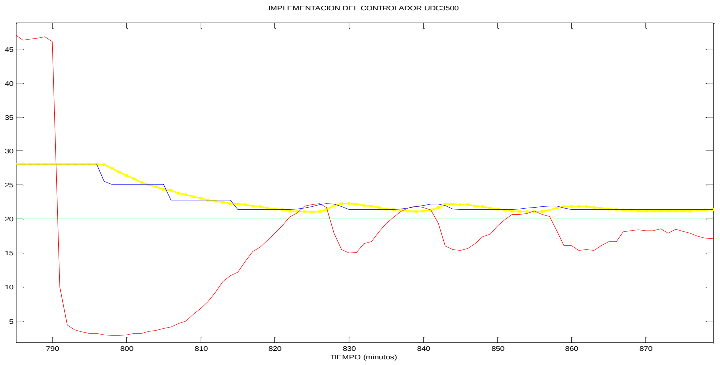
Sustainable Strategies for the Use of Electrical Energy Resources for Low-income Population





- To develop isolated PV-powered systems for rural schools,
  - Custom Power Electronics
  - Embedded generation and demand forecast
  - MPC based Energy Management System
- Budget ~ € 1.200.000 (3 partners)
- CO-PI: Fredy Ruiz, ruizf@javeriana.edu.co

Recombinant Protein Production Optimization in Pichia Pastoris, based on in silico models



$$\max_{x(i)} \{X(N) + P(N)\}$$

$$Subject\ to$$

$$\mu = m_{max} * \frac{C_s}{d*C_S^2+C_s+k_s} * \frac{C_{od}}{C_{od}+k_{od}} \qquad k = 1,\ldots,\tau$$

$$\dot{X} = \mu * x - D * x$$

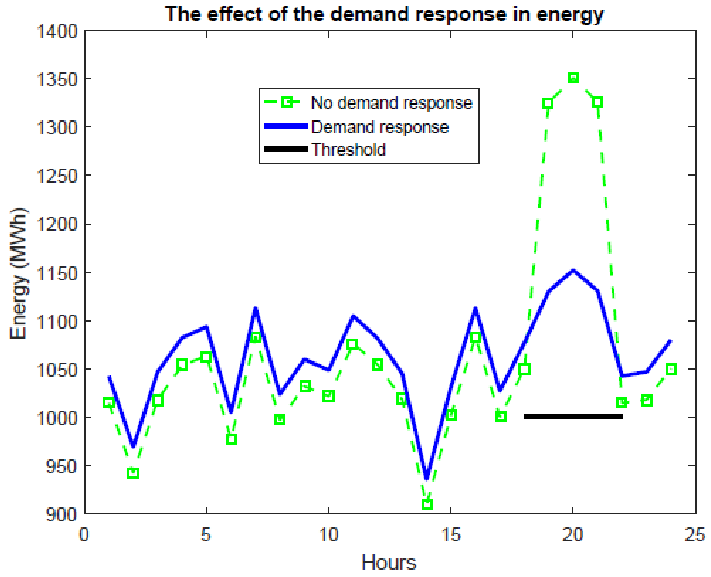
$$\dot{V} = F_{in}$$

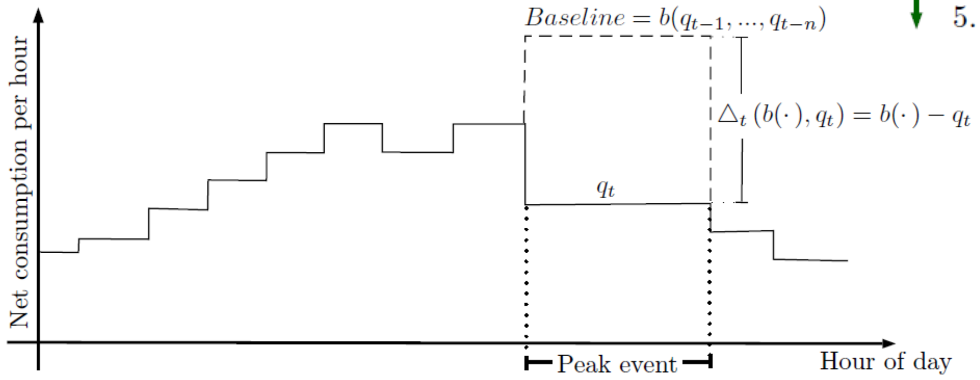
$$S = F_{in} * (\frac{100}{V} - 0{,}1 * r_s * X)$$

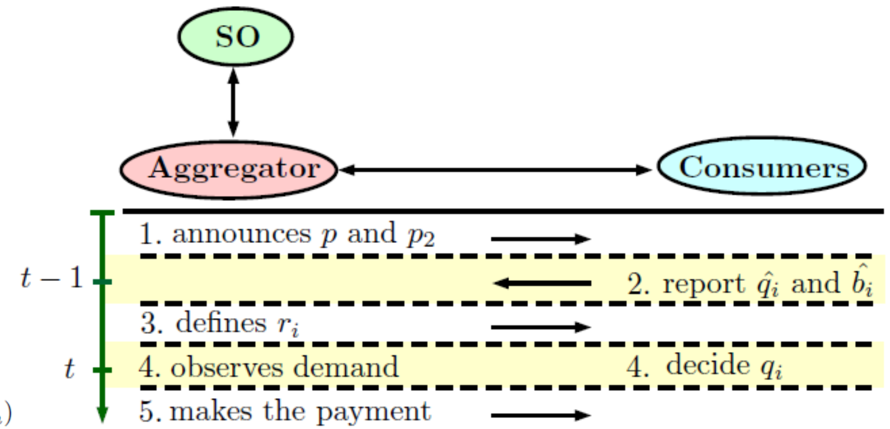
$$C_{od} = K_{la} * (100 - C_{od}) - (100 * r_{o2} * X)$$

- To increase protein production by re-design of growth conditions in biorreactor.
  - Gray-box models, data-driven.
  - Growth profiles obtaind by Optimal control formulation
  - MPC real-time control
- Budget ~ € 24.000 (Cooperation with Institute for the Study of Inborn Errors of Metabolism, PUJ).
- PI: Fredy Ruiz, ruizf@javeriana.edu.co

Universal Access to Electricity



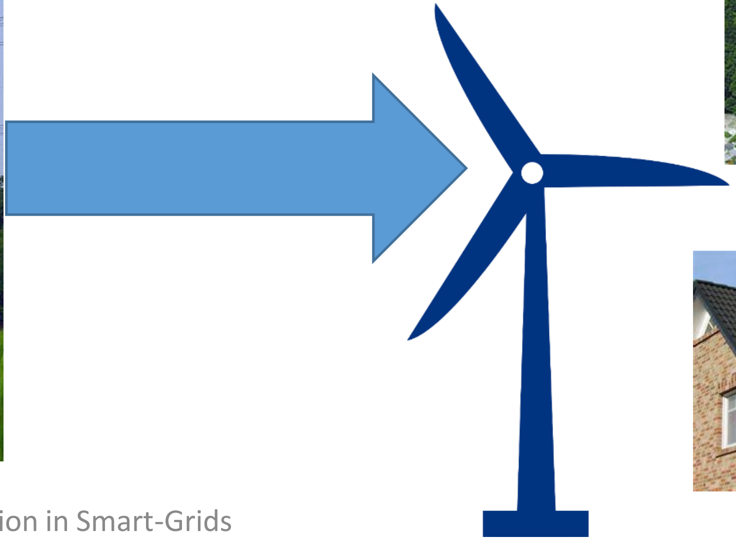




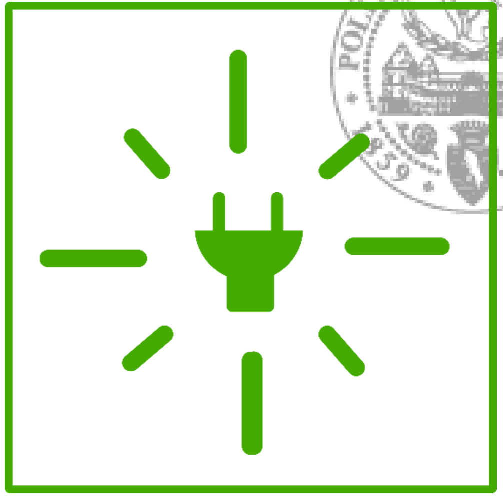
- To develop strategies (Energy and Demand-Response services) to improve the cost of renewables-based energy provision in isolated rural zones.
  - Micro-grid sizing considering demand response
  - Demand response contract design
  - Direct load control
- Budget ~ € 70.000 (Cooperation with Industrial Engineering - PUJ)
- PI: Rabie Nait-Abdallah, rnait-abdallah@javeriana.edu.co

Introduction

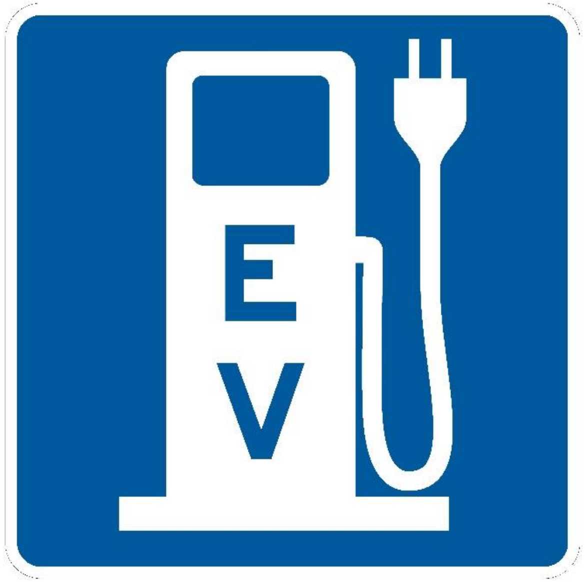
- There is a strong pressure to reduce the use of fossil fuels for energy supply:
  - Electricity
  - Transportation
  - Heating
  - …



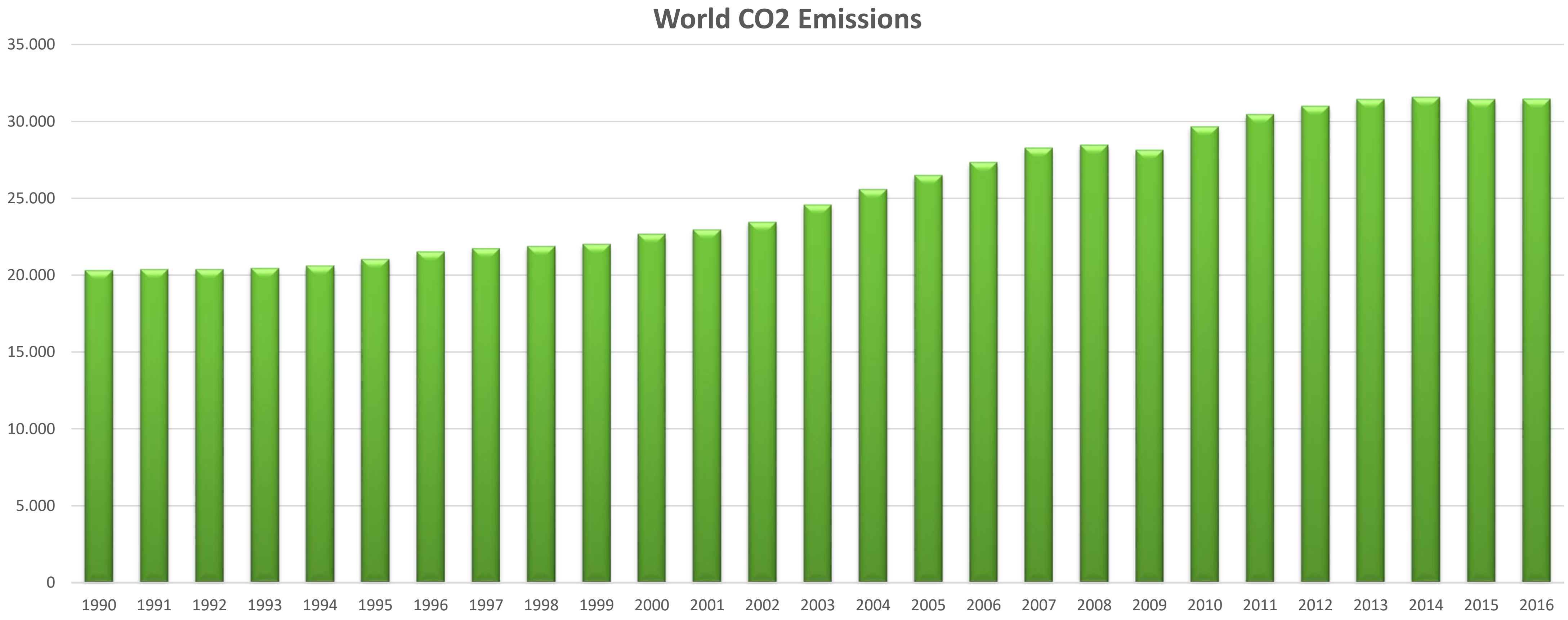
Introduction



• This implies a shift to electrification of many services and improved eficiency in processes:



CO2 emissions from fuel combustion (MtCO2)



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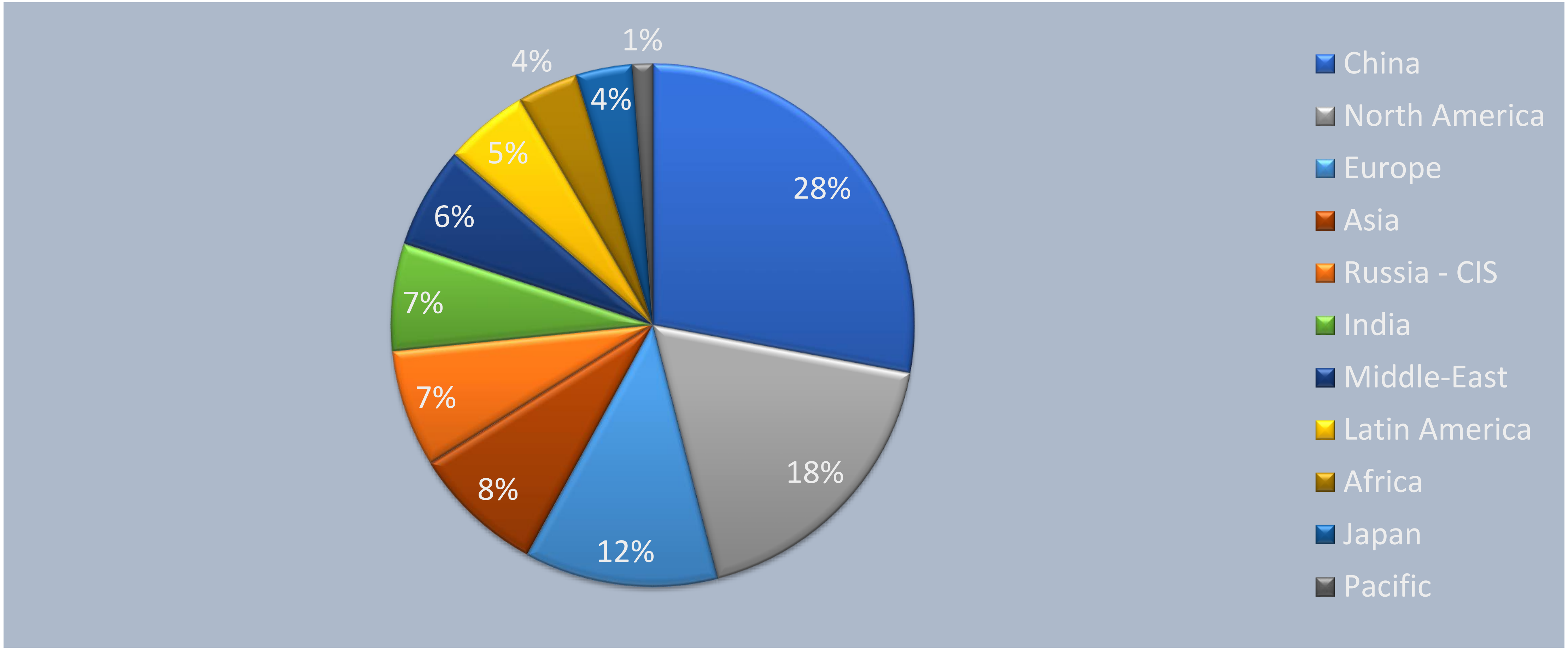
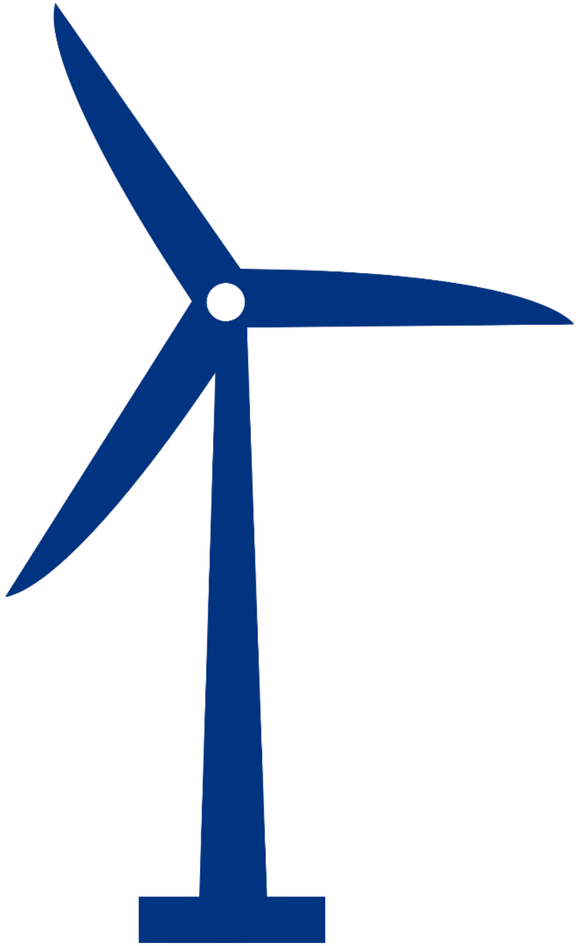


Generation shift

Renewable energies offer a sustainable energy source

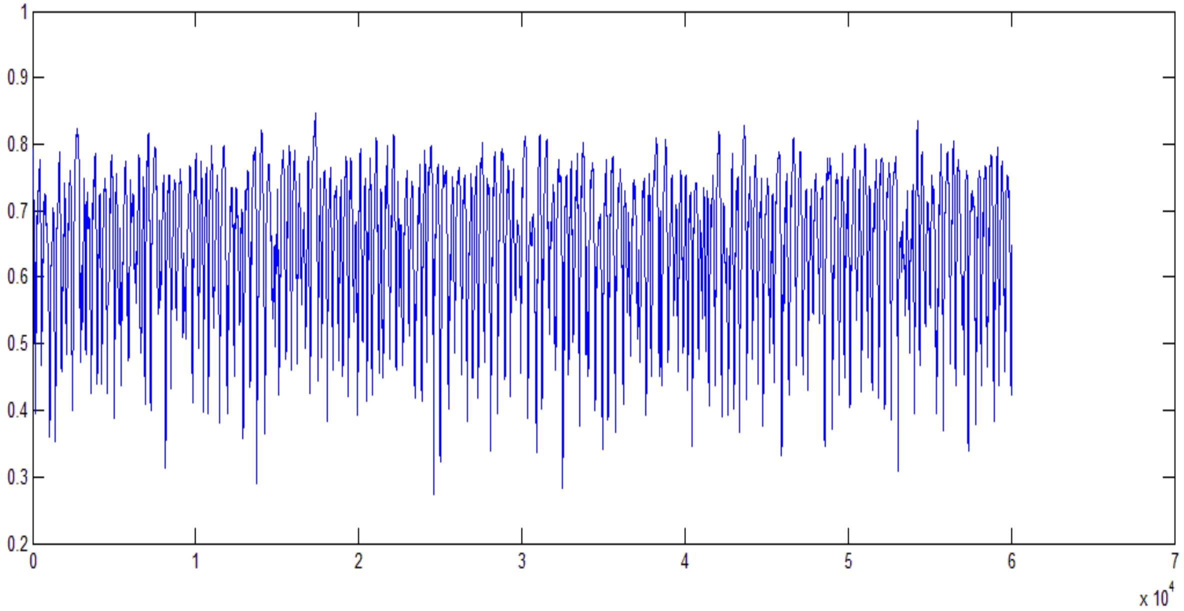
- Solar
- Wind
- Tidal
- ….



Generation Shift

However, most renewable sources are not controllable:

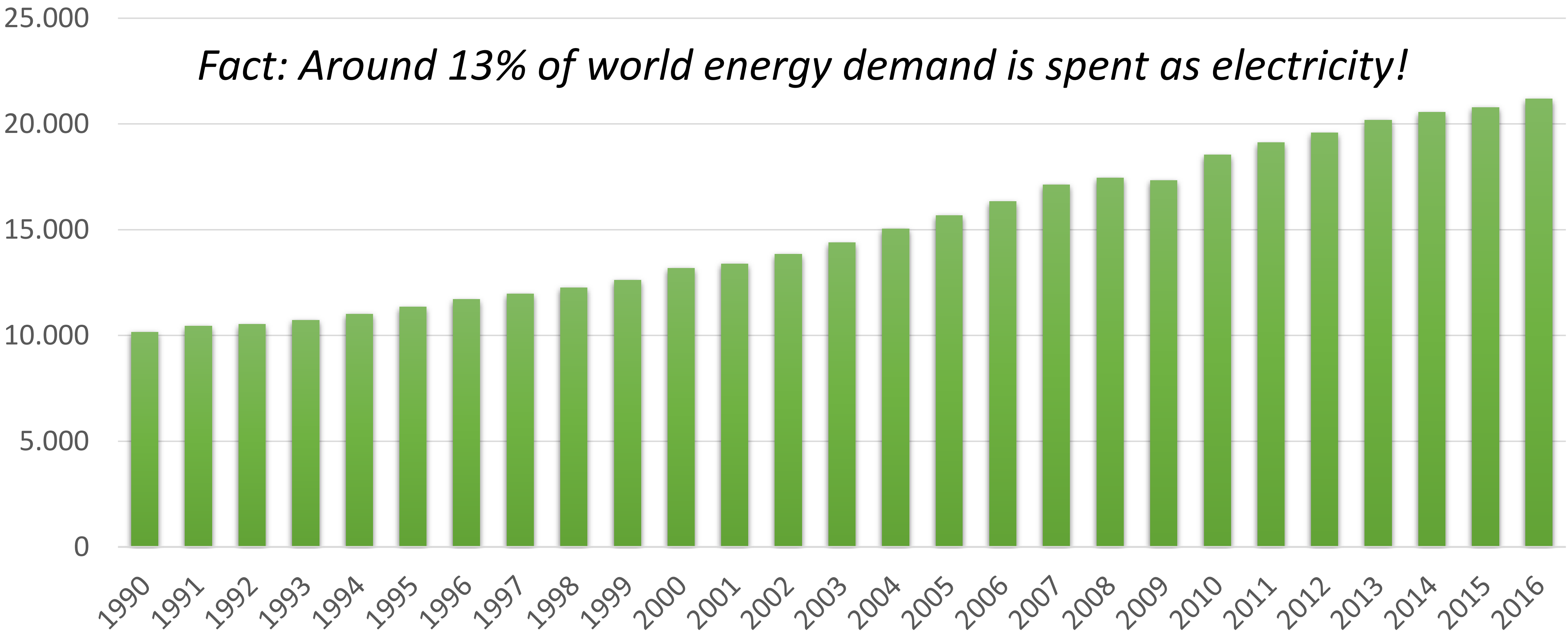
- Subject to random variations of weather
- Daily trends
- Seasonal drifts
- …



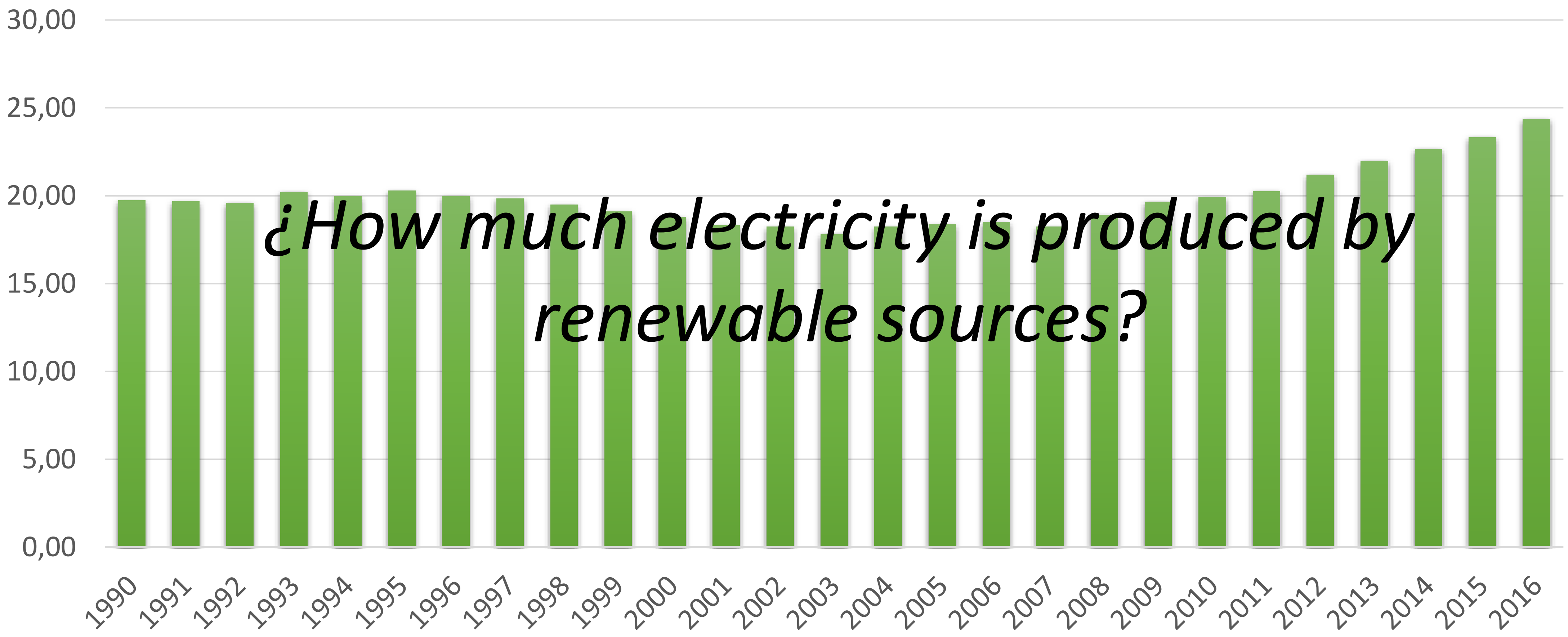
World Energy Requirements (Mtoe*)

** 1Mtoe=11.63 TWh*

World Electricity Demand (TWh)

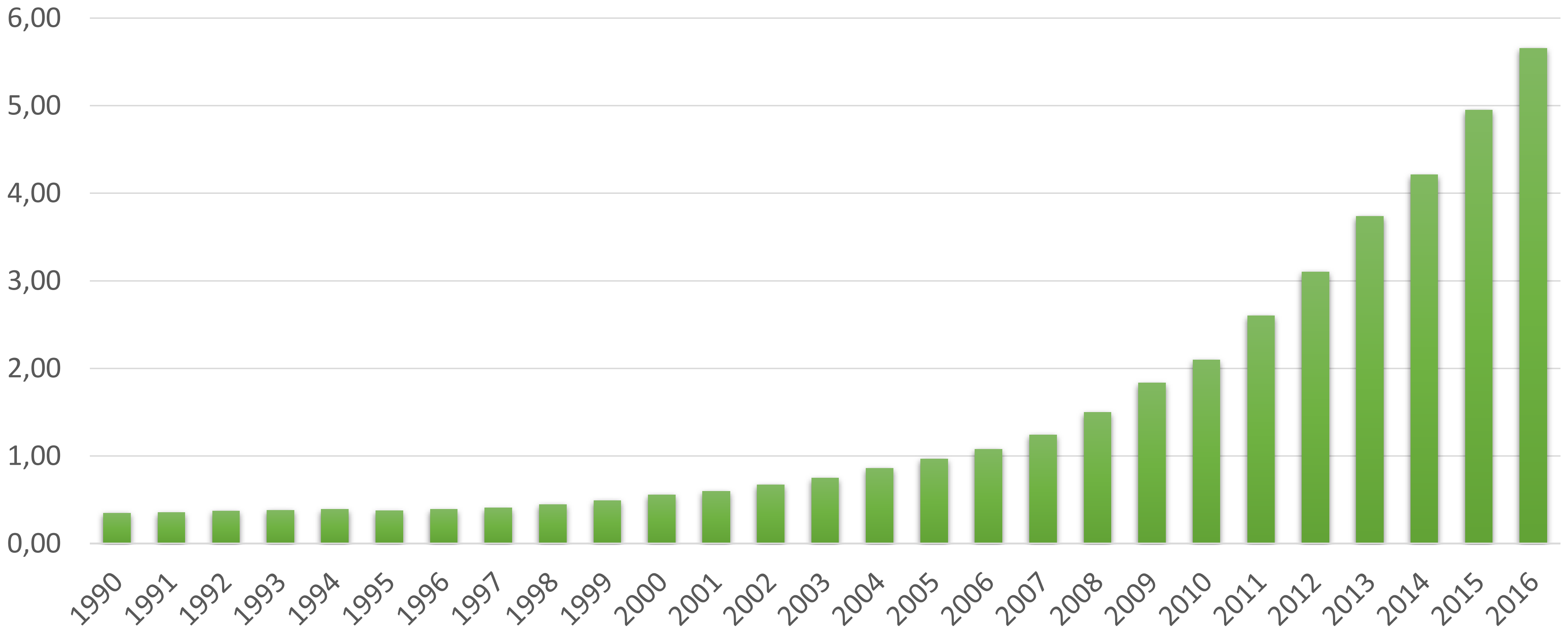


Share of renewables in electricity production (%)



¿How much electricity is produced by renewable sources?

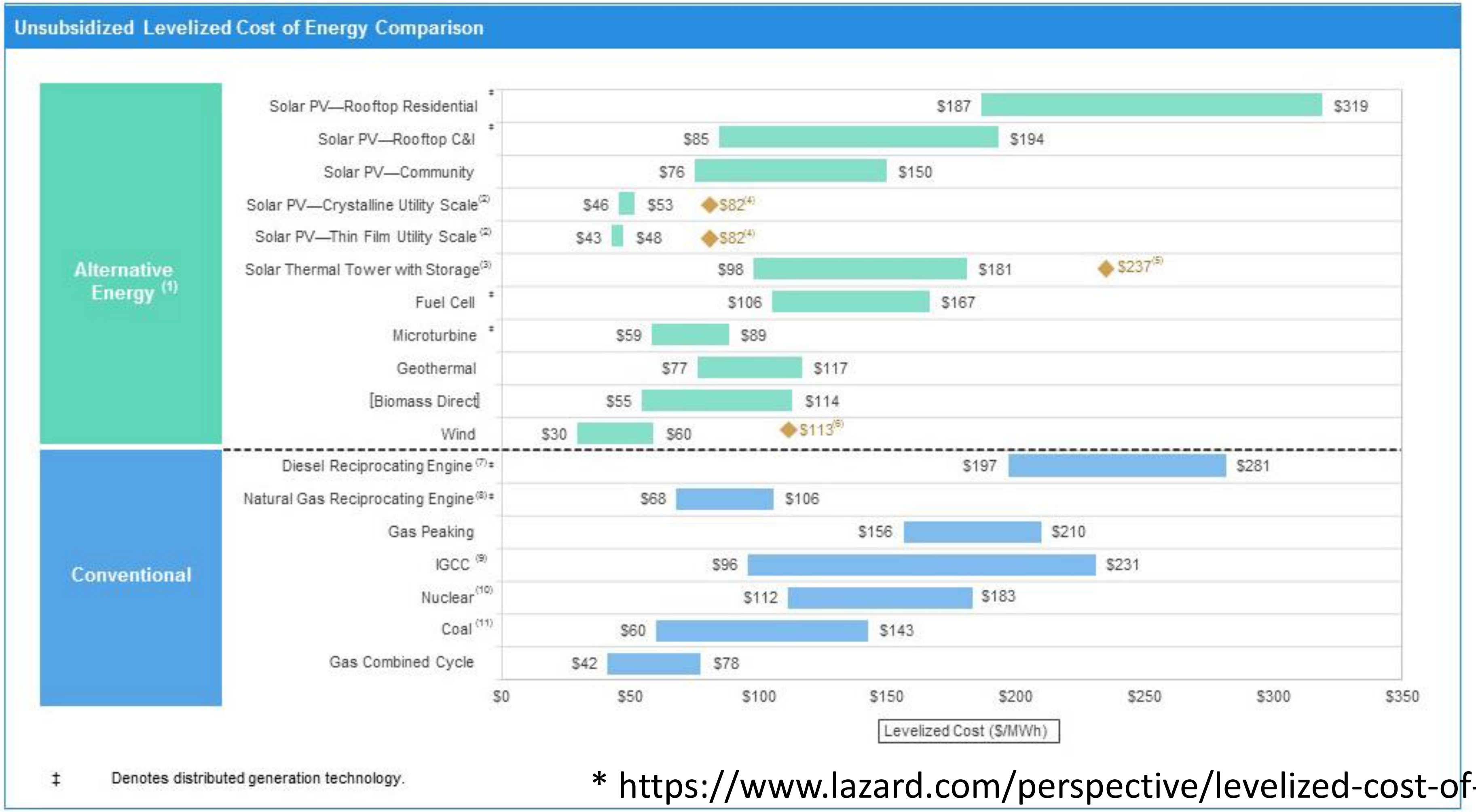
Share of wind and solar in electricity production (%)



Shift to 100% renewables

- There is an explosion of solar and wind installations.
- Prices of solar generation have gone down:
  - *US$ 250 / MWh in 2008*
  - *US$ 50 / MWh in 2017*
- Lower than traditional sources:
  - *Coal: US$ 60-140 / MWh*
  - *Nuclear: US$ 110-180 / MWh*

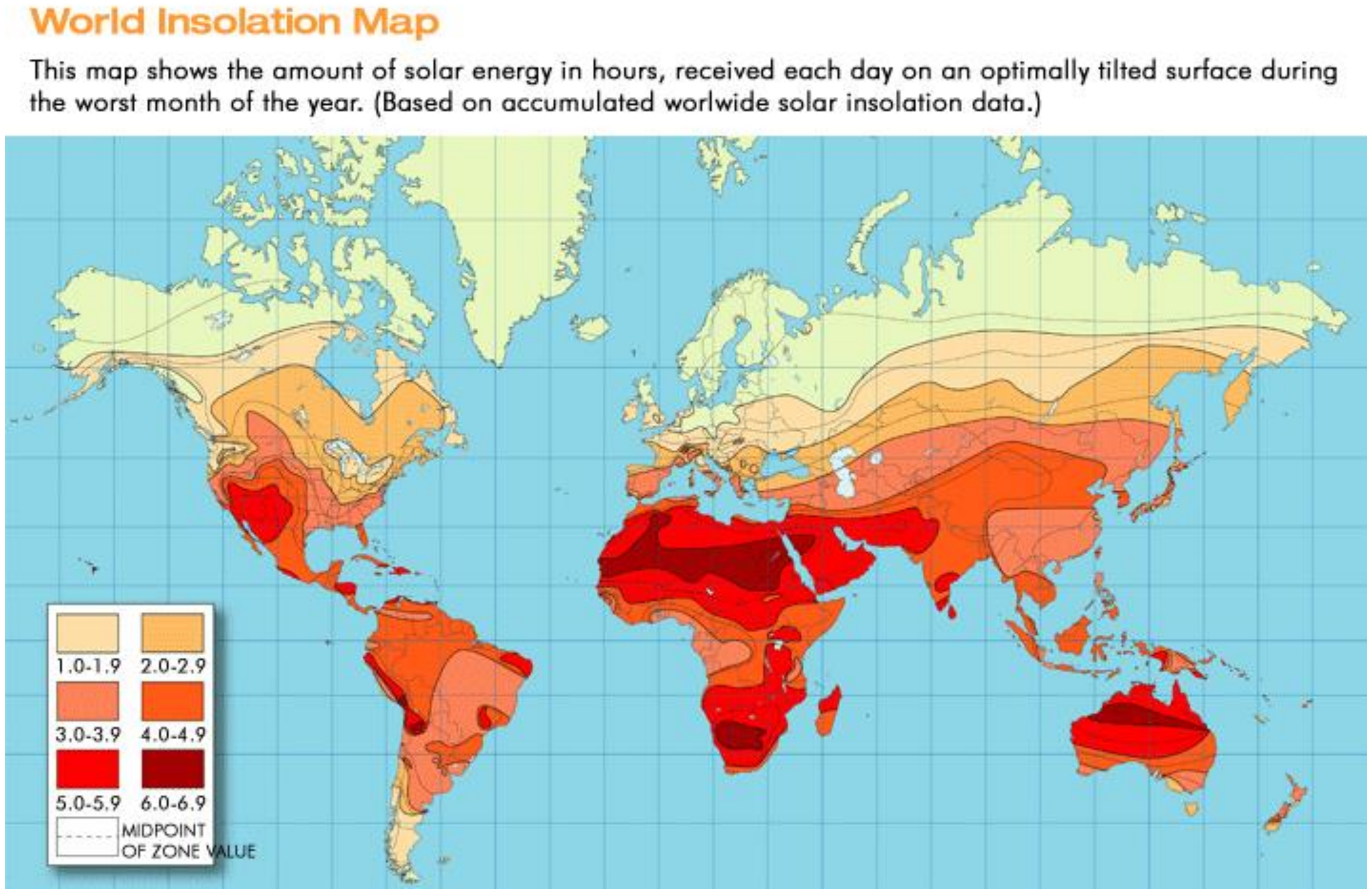
Energy cost for 2017*



* https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

Why don't we just switch to 100% renewables?

What area is required to supply all the world energy requiremets with photovoltaic resources?



http://www.solardirect.com/outdoor-lighting/solar/street/area-light/solar-insolation-map.html

Supplying electricity demand with PV

- Demand in 2016 was

21.190 TWh

- Daily, that is

58 TWh

- In Italy, that energy must be generated in about

3 – 4 hours.

- Required peak power capacity is

16.6 TW

- Using standard solar panels with

Peak power = 225 W

Panel area = 1.65 m^2

- The amount of panels required is

NP=7.350e6

- With a net area requirement of:

Area = 121.300 km^2

Is this area too much?????

Supplying electricity demand with PV

- Assuming a land efficiency of 70%, the gross required area is

$$173.200\ km^2$$

- It's about 60% of Italy land surface
- It's less than 0.12% of world land surface
- Area can be reduced by half assuming high insolation regions

Supplying world energy demand with PV

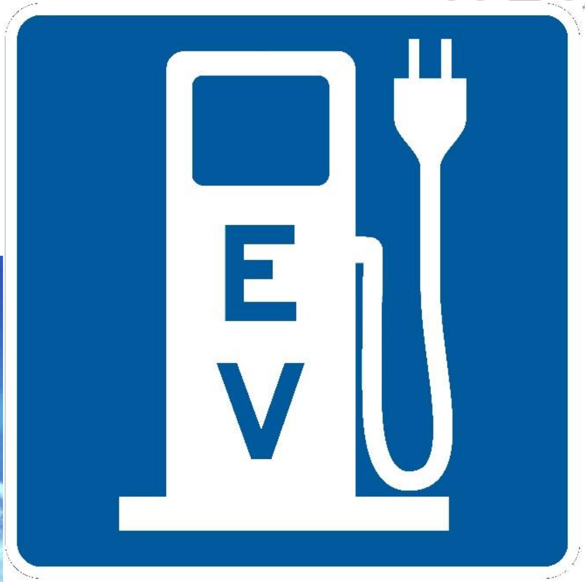
- For the total world energy needs
- Assuming 5 equivalent hours of insolation
- The required area is about:

  1million km²

- It's 11% of Sahara desert

What makes electric energy different from other commodities?

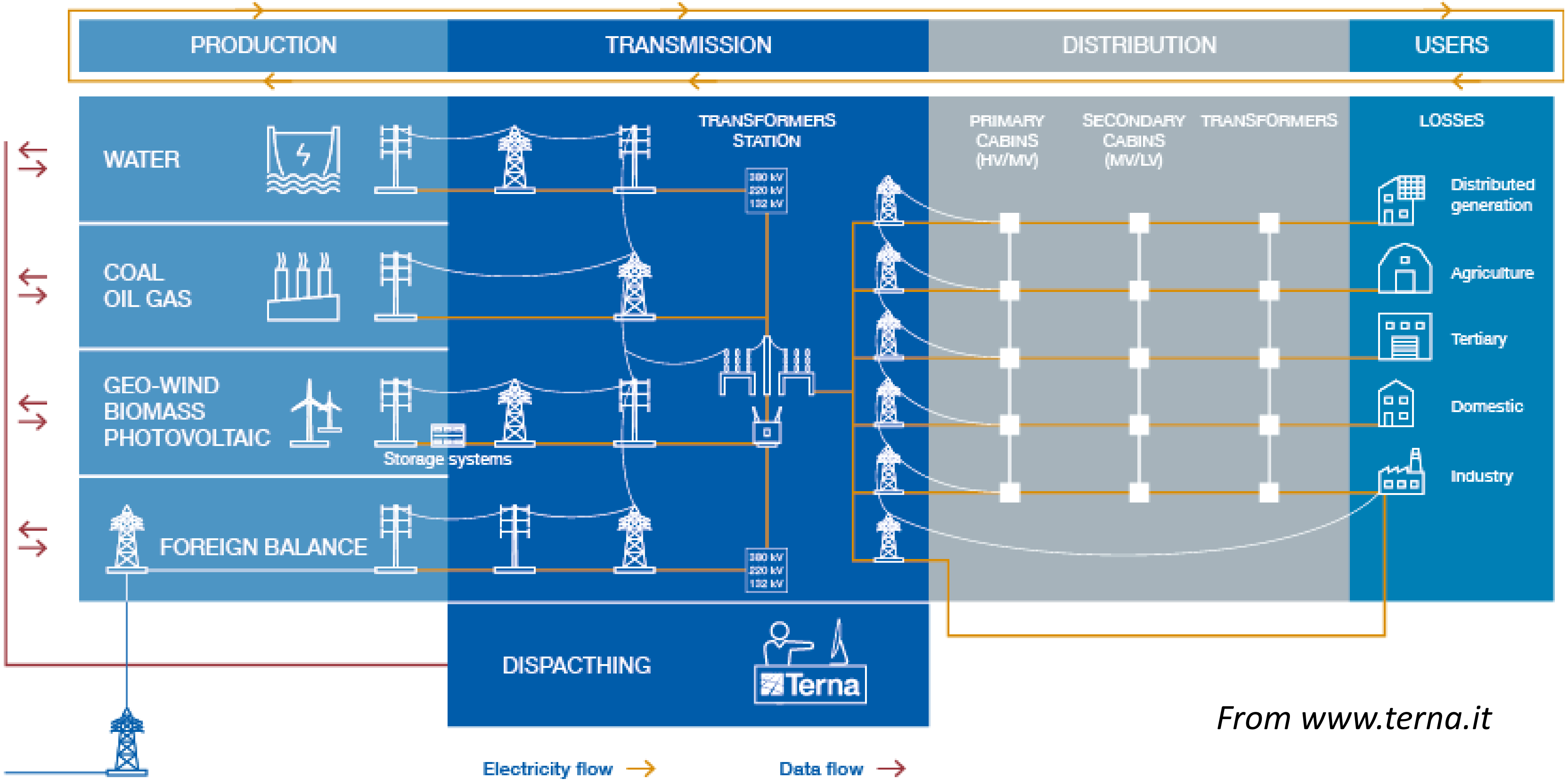
How is energy produced, transported, consumed?



Electricity can not be stored for latter use!!!!

At least not like oil, food,…..

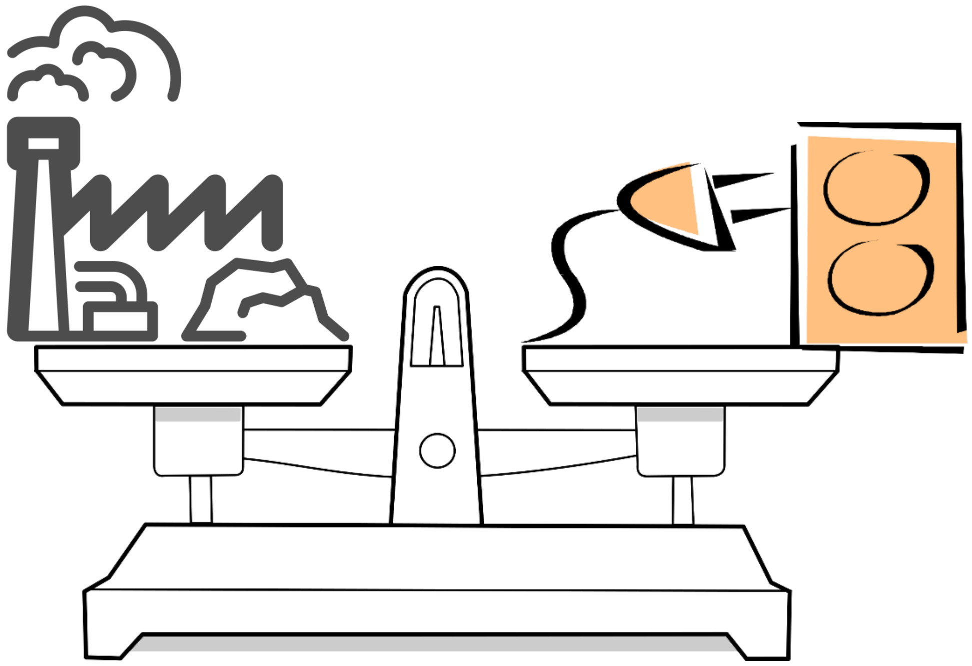
Power systems



From www.terna.it

Power Balance

Generation and load must always be balanced.

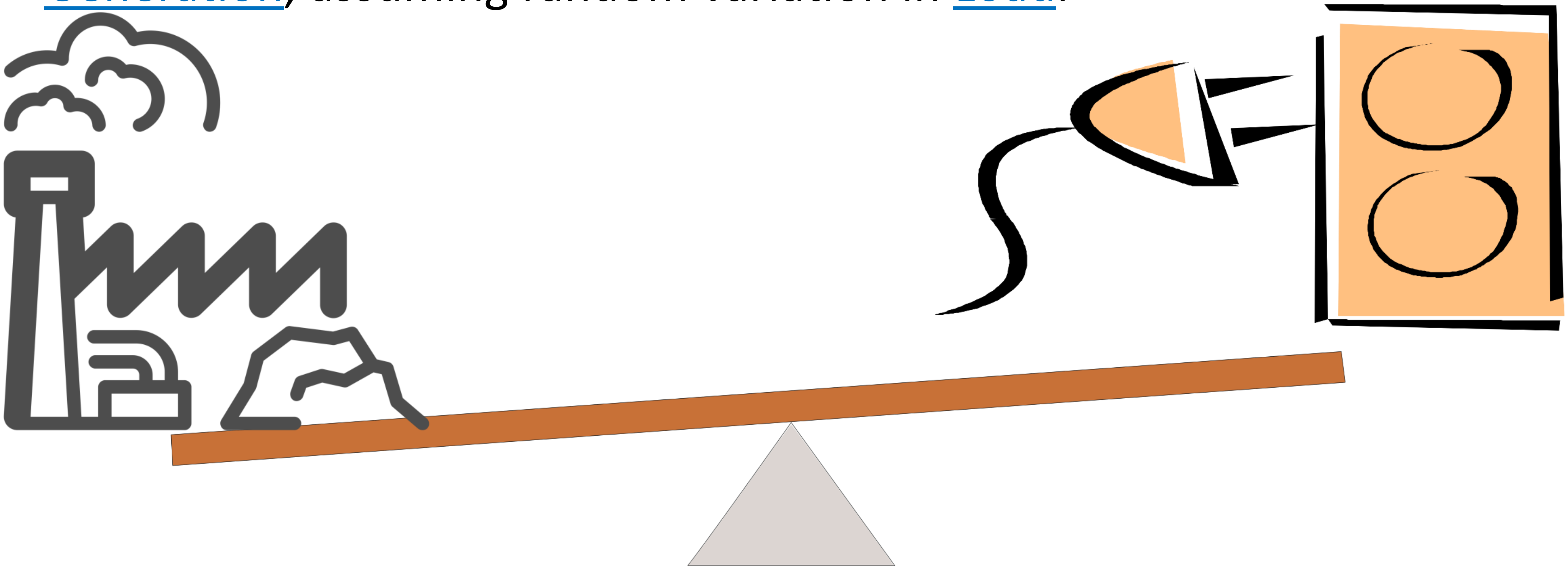


Otherwise there is high risk of failure:

- Frequency drift
- Generators go off-line
- Cascade effect
- Black Out!!

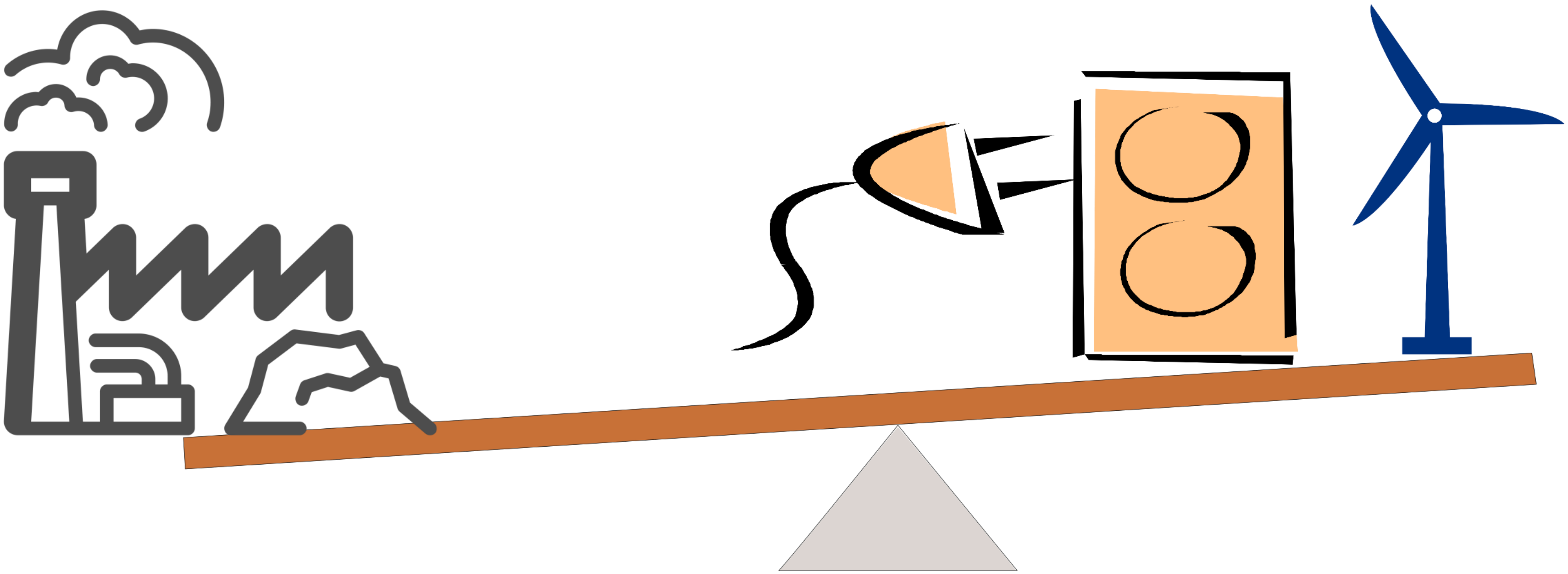
System Operation

- Traditionally, balance of power systems has been performed by Generation, assuming random variation in Load.



Power Balance

- With the introduction of renewables, the model has not changed.



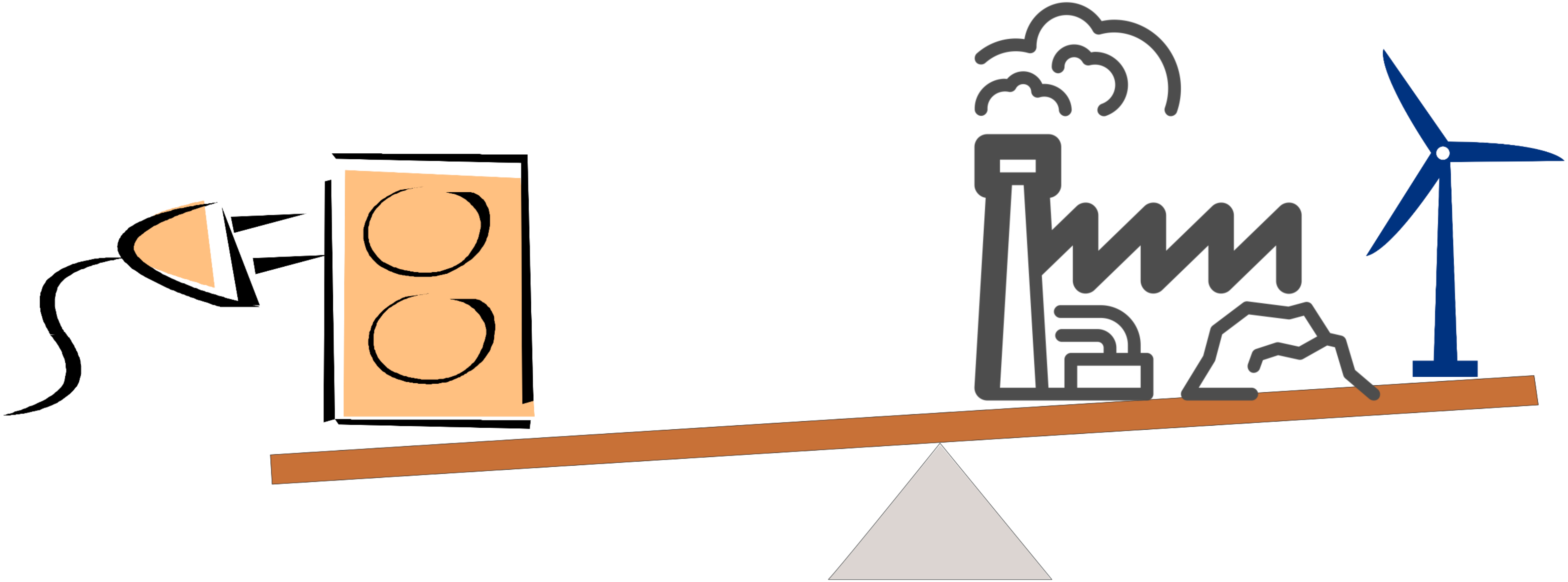
Power Balance

- With the introduction of renewables, the model has not chang

Higher requirements of “tradicional” generation for balance!!!!

Demand Response

New paradigm: Consumers are an active part of system operation!!!



Course Context

Smart-Grids with high share of renewable generation

↓

Non-Controllable sources

↓

Imbalance between load and generation

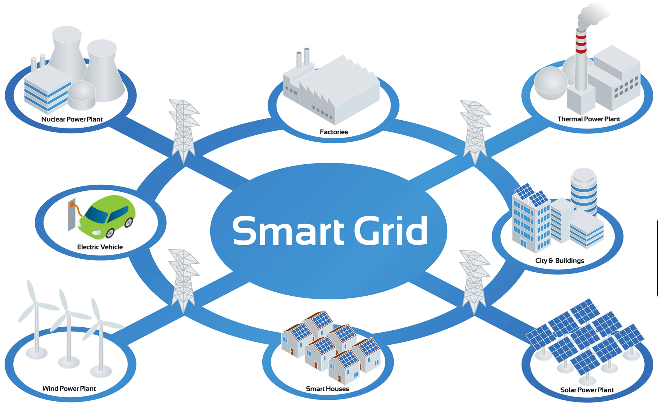
↓

DR - Ancillary services

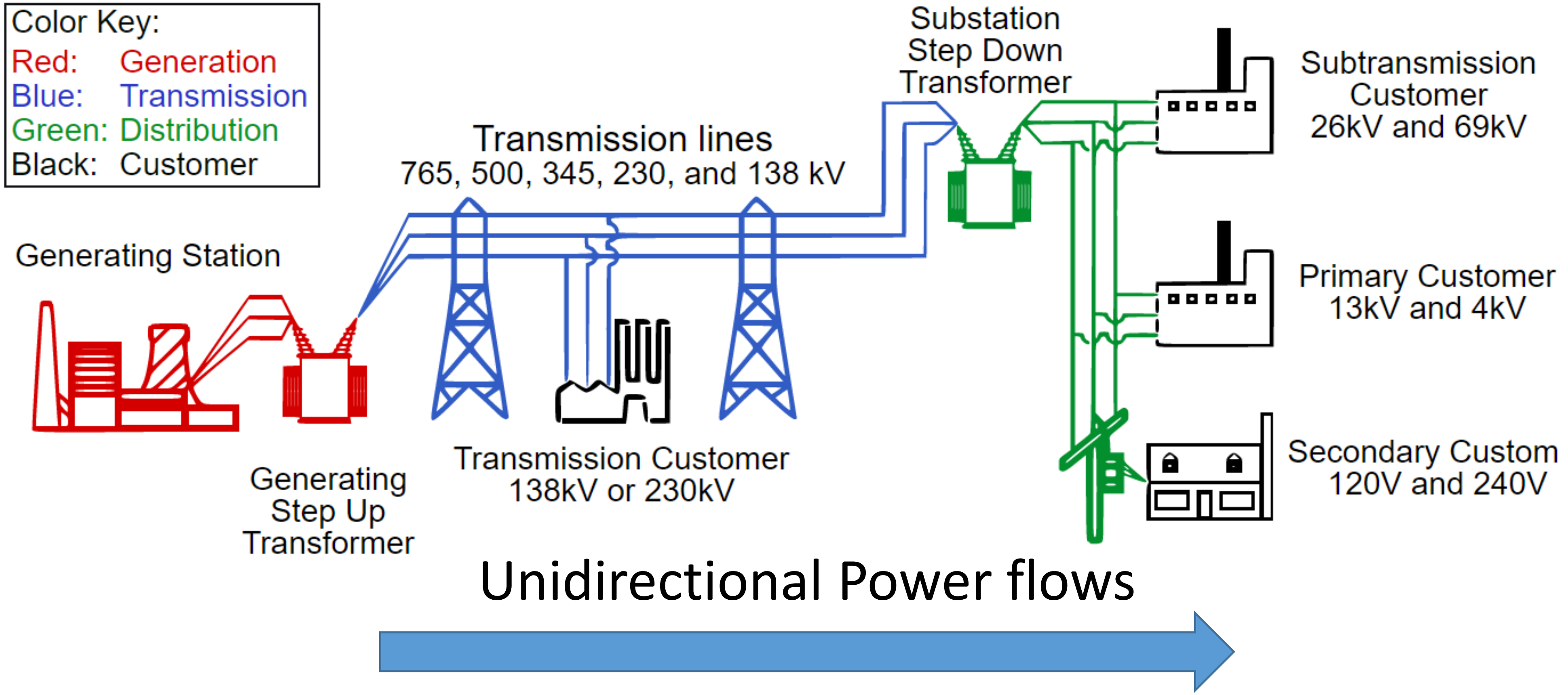
↓

Flexible Loads

Direct Load Control ← Flexible Loads → Incentive-based Load Control

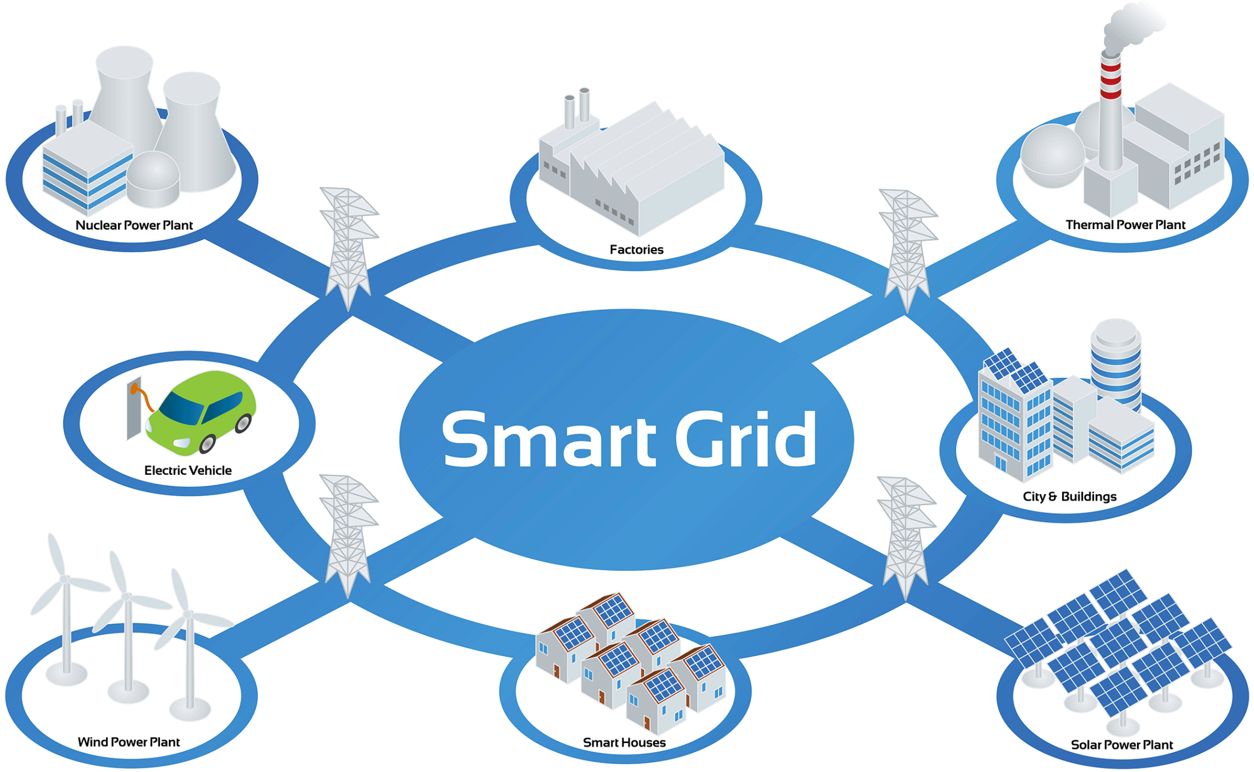


Traditional grid



Taken from "Final Report on the August 14, 2003 Blackout in the United States and Canada" Dated April 2004"

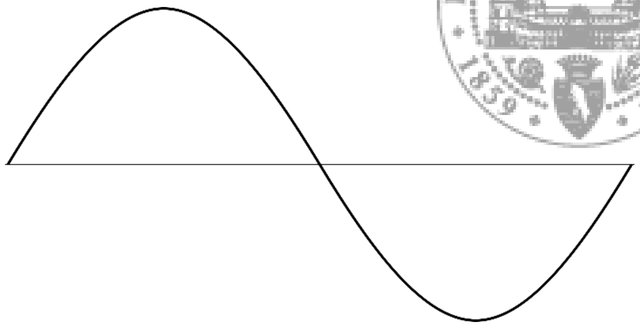
Smart-Grid

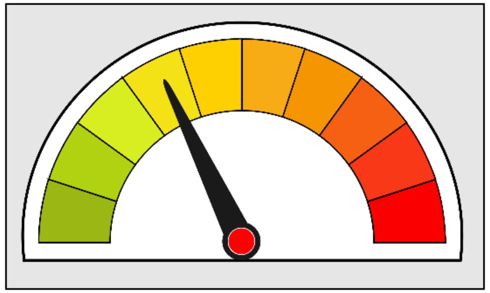


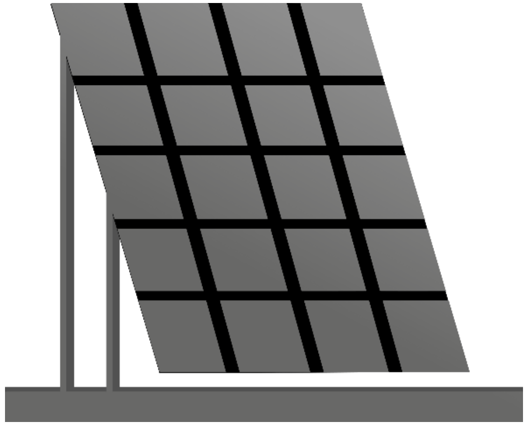
Multi-directional flows of Power *and* ***information***.

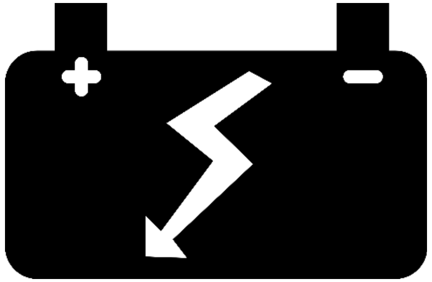
Enabling technologies

- Smart-meters
- PMU
- Smart appliances
- Flexible loads
- Power electronics
- Storage: Batteries fly-wheels, …









Course topics

- Session 1: Introduction to Power systems
  - Context and motivation
  - Power flow analysis
  - Economic dispatch
- Session 2: Renewable sources
  - Stochastic models of variable sources
  - Dispatching random sources
- Session 3: Energy dispatch
  - Risk-limiting dispatch
  - Matlab session

Course topics

- Session 4: Incentive-based demand response
  - Modeling demand
  - Peak time rebates
  - Contract design for demand response
- Session 5: Flexible loads
  - Modeling flexibility
  - Load dispatch
  - Case study: Electric vehicles
- Session 6: Micro-grids
  - Lean energy concept
  - Joint generation and load dispatch

Power Flows Analisys

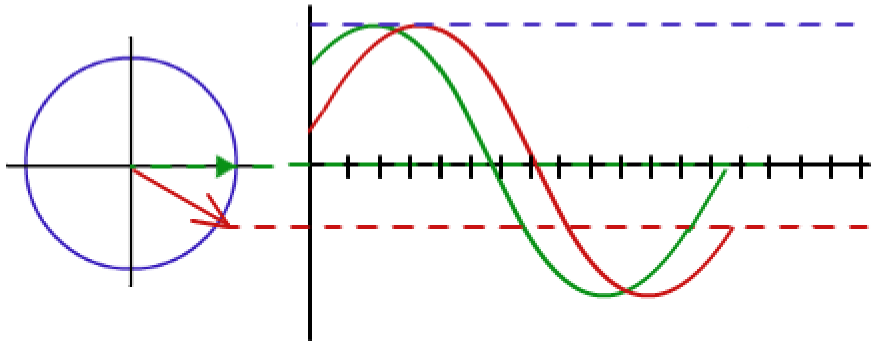
- Electric grids are very complex
- 3-phase systems
- Connected by transmission lines
- Usually more than 100 generators
- More than 1.000 nodes

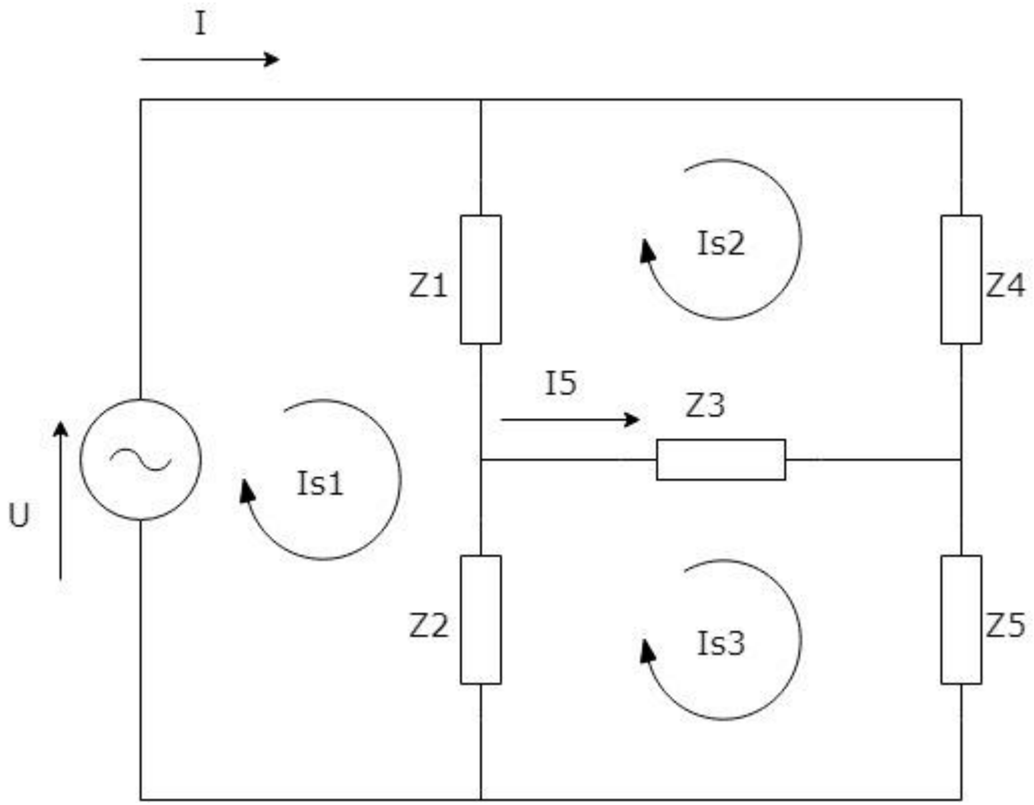
Power Flows Analisys

How do we schedule generators to deliver power correctly supplying 100% of demand?

Power Flow Analysis

- Flows are defined by Kirchoff's laws
- Steady-state assumption
- Constant frequency
- Phasorial models

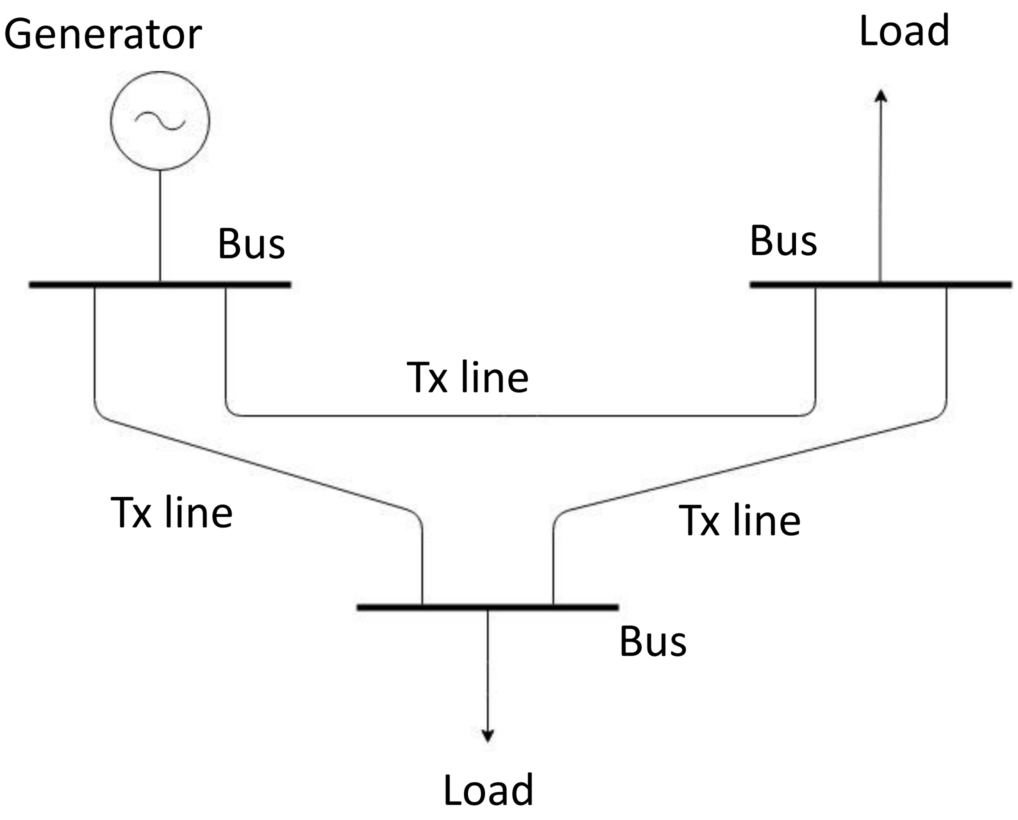




Power Flows Analisys

Electric grids are represented by single-bus diagrams:

- Nodes: Bus with votage V_B
- Links: Transsmission lines with given admittance y_T
- Generators: inject power P_G to nodes
- Loads: drain power P_L from nodes



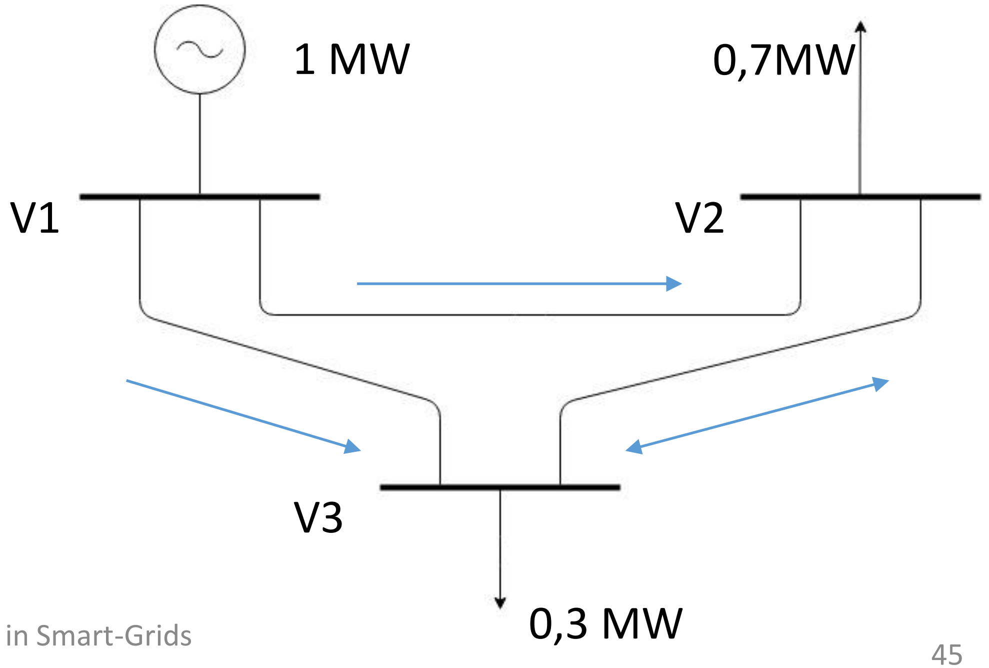
Power Flow Analysis

- Flows are defined by Kirchoff's laws
  - $P_{ij} = |V_i||V_j|\left(G_{ij}\cos\left(\theta_i - \theta_j\right) + B_{ij}\sin(\theta_i - \theta_j)\right)$ -> *Active power*
  - $Q_{ij} = |V_i||V_j|\left(G_{ij}\sin\left(\theta_i - \theta_j\right) - B_{ij}\cos(\theta_i - \theta_j)\right)$ -> *Reactive power*

Where

- $Y_{ij} = G_{ij} + jB_{ij}$
- G_{ij} Tx line Conductance
- B_{ij} Tx line Susceptance

- What unknowns do we have?

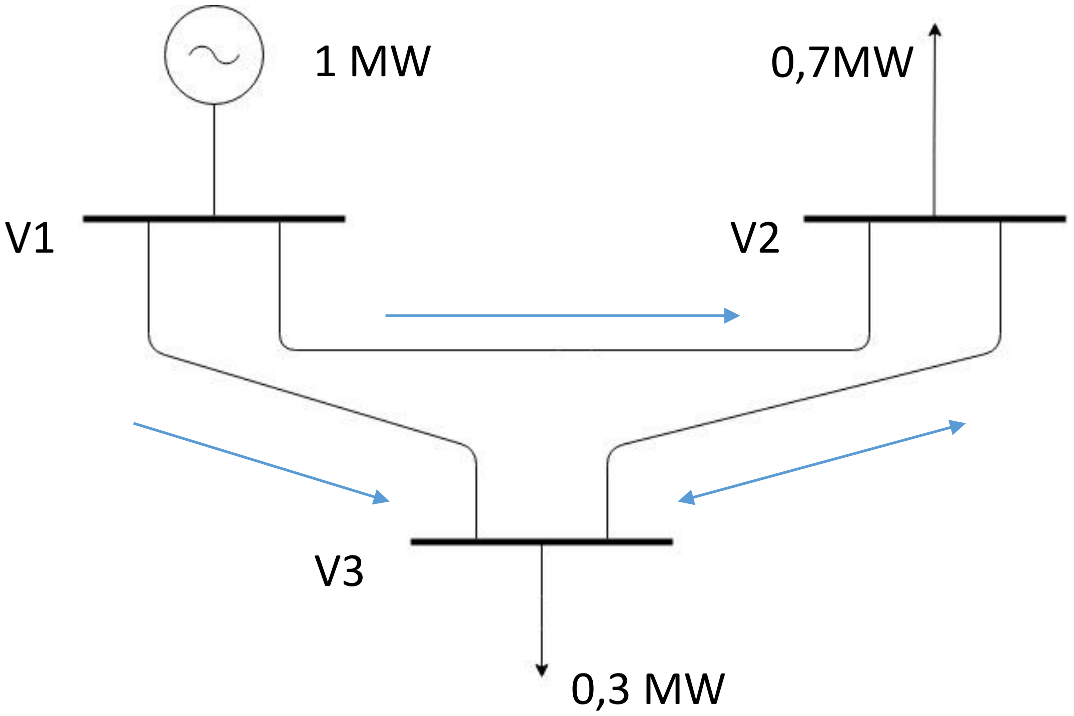


Power Flow Analysis

Even with these simplification it is a complex model!!

In addition:

- $|V_i| \approx |V_j| \approx 1$
- $G_{ij} \approx 0$
- $\cos(\theta_i - \theta_j) \approx 1$
- $\sin(\theta_i - \theta_j) \approx (\theta_i - \theta_j)$



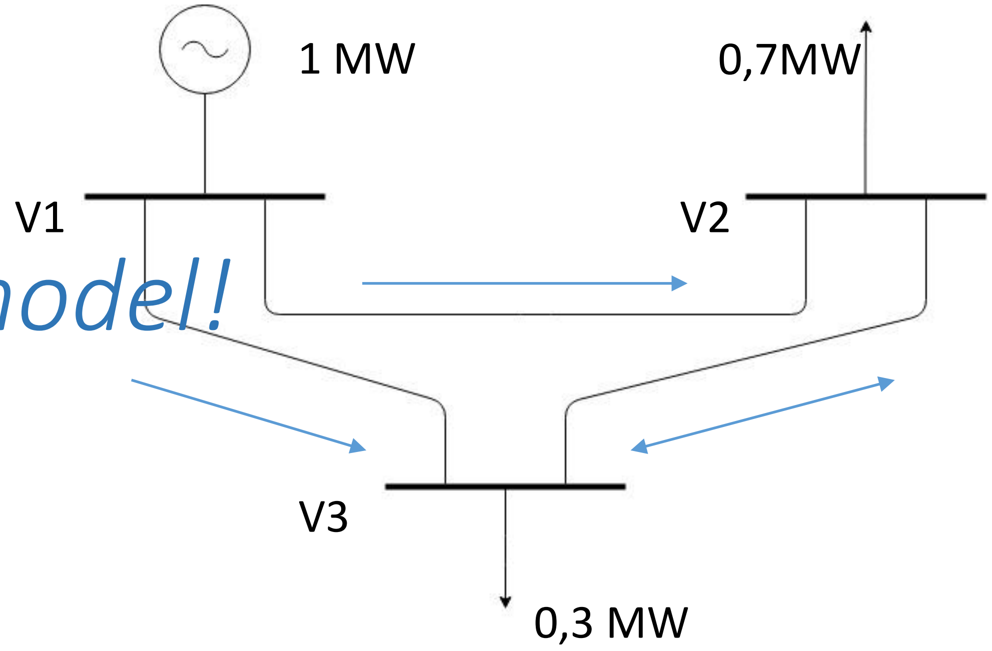
Power Flow Analysis

- Flows are defined by Kirchoff's laws
  - $P_{ij} = B_{ij}(\theta_i - \theta_j)$
  - $Q_{ij} = -B_{ij}$

Where

DC power flow model!

  - Q_{ij} constant
  - P_{ij} given by linear equation
- What unknowns do we have?



Power Flow Analysis

Flows are defined by Kirchoff's laws

$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} B_{11} + B_{12} + B_{13} & -B_{12} & -B_{13} \\ -B_{21} & B_{21} + B_{22} + B_{23} & -B_{23} \\ -B_{13} & -B_{32} & B_{31} + B_{32} + B_{33} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

- In general, this matrix is singular!!!
- What really matters is the phase difference $(\theta_i - \theta_j)$
- Slack bus: $\theta_1 = 0$

Power Flow Analysis

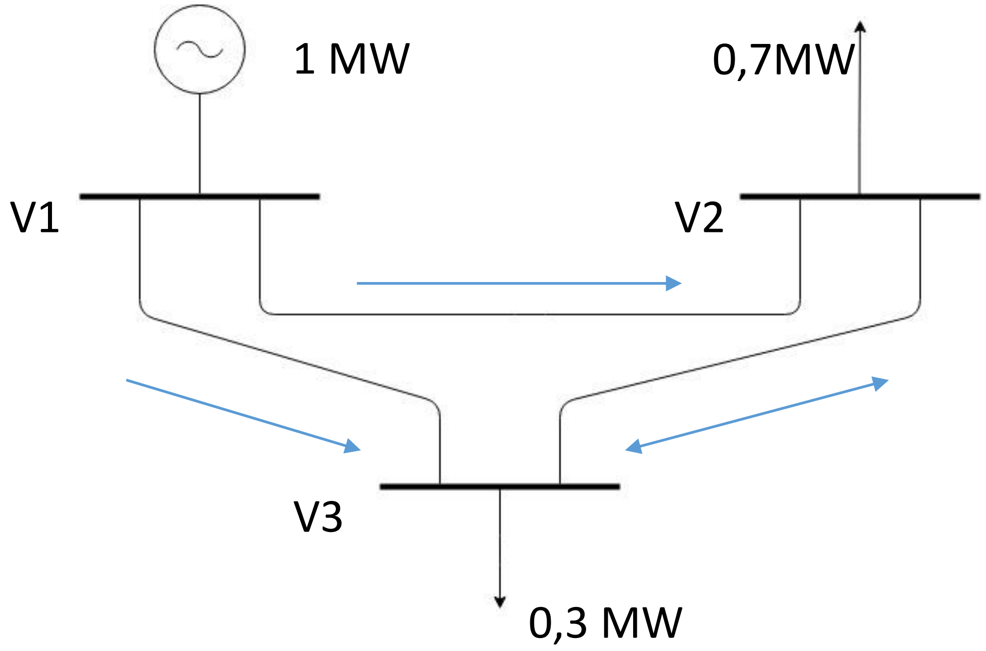
Result:

- Varying phase it is possible to modify power flows

Constraints in flows:

- Tx lines have a limited capacity
- When programming production, limits on power flows must be taken into account:

$$P_{ij} \leq P_{ij}^{Max}$$



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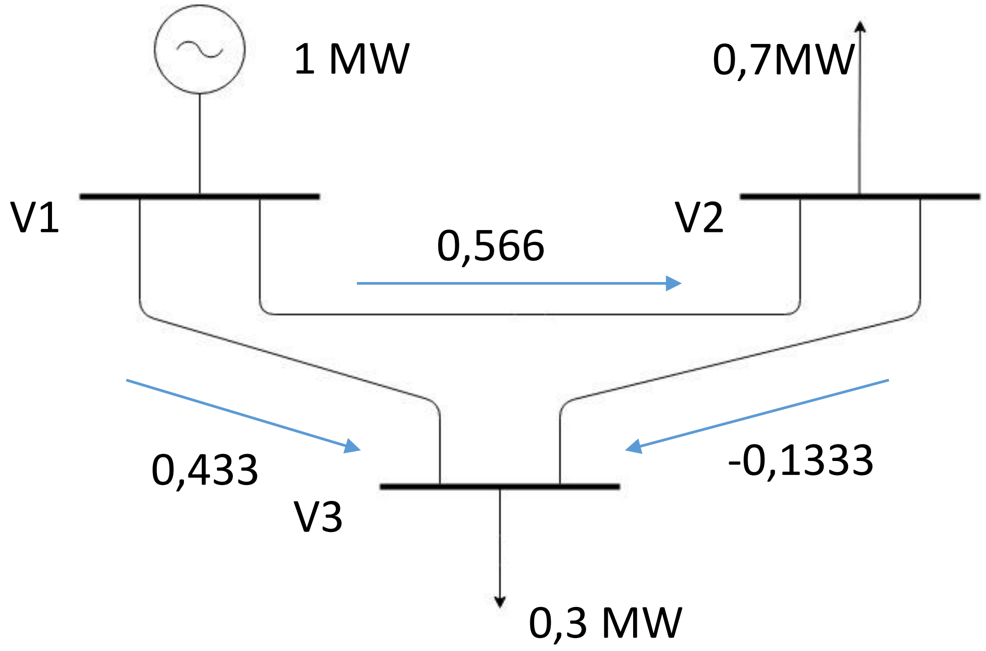

System Operation

- Energy production is managed by a System Operator (SO)
- Its aims are to guarantee:
  - energy balance in the grid
  - Reliable operation
  - Fault tolerance
- In un-regulated systems these objectives are achieved in open markets

System Operation

- At least two markets exist in any grid:
  - Day-ahead market: planned production given demand forecast
  - Real-time market: energy balance market to correct imbalances caused by unpredicted load variations, failures, …
- Other possible markets are:
  - Reserves
  - Frequency regulation
  - Demand Response
  - …

Day-ahead Market

- Given a demand forecast D_k
- And a set of generators $G_1, G_2, G_3, \dots, G_N$
- What is the lowest cost generation program that supplies the demand?

This is the economic dispatch problem!

Economic Dispatch

Each generator has an operational cost that varies with technology:

- Thermal plants usually have quadratic costs

$$C(p_j) = a_{1j} + a_{2j}p_j + a_{3j}p_j^2$$

- Hydroelectric plats usually have linear costs

$$C(p_j) = a_{1j} + a_{2j}p_j$$

- Solar or wind plants usually have fixed costs only

$$C(p_j) = a_{1j}$$

Economic Dispatch

$$\min J = \sum_{k=1}^{K} \sum_{j=1}^{N} C(p_{jk})$$ *Sum of generation costs*

Subject to

$$\sum_{j=1}^{N} p_{jk} = D_k \qquad \forall k$$ Energy Balance

$$p_j{}^{min} \leq p_{jk} \leq p_j^{max}$$ Operational constraints

Economic Dispatch

- What information does the SO requires from each generator?
- How should the SO pay generators?
  - Pay as bid: discriminatory price.
  - Uniform price: single clearing price.
  - VCG: Social value.
- Can generators benefit from false cost information?
  - Gaming issues!!!

Economic Dispatch

$$\min J = \sum_{k=1}^{K} \sum_{j=1}^{N} C(p_{jk})$$

Subject to

$$\sum_{j=1}^{N} p_{jk} = D_k \qquad \forall k$$

$$p_j{}^{min} \leq p_{jk} \leq p_j^{max}$$

How can we include topology constraints?

Economic Dispatch

$$\min J = \sum_{k=1}^{K} \sum_{j=1}^{N} C(p_{jk})$$

Subject to

$$\sum_{j=1}^{N} p_{jk} = D_k \qquad \forall k$$

$$p_j^{min} \leq p_{jk} \leq p_j^{max}$$

Plants can not be switched ON-OFF at any rate, how can we include that constraint?

Economic Dispatch

$$\min J = \sum_{k=1}^{K} \sum_{j=1}^{N} C(p_{jk})$$

Subject to

$$\sum_{j=1}^{N} p_{jk} = D_k \qquad \forall k$$

$$p_j^{min} \leq p_{jk} \leq p_j^{max}$$

How do we decide which plants to turn on?

Economic Dispatch

$$\min J = \sum_{k=1}^{K} \sum_{j=1}^{N} C(p_{jk})$$

Subject to

$$\sum_{j=1}^{N} p_{jk} = D_k \qquad \forall k$$

$$p_j{}^{min} \leq p_{jk} \leq p_j^{max}$$

- Can we use the same approach to dispatch renewable sources?
- Can we fix p_j ?

Give possible solutions…

Conclusions

- A transition to 100% renewable energy is feasible BUT:
  - Solar and wind are not controllable sources
  - Existing energy dispatch methods can not directly be extended to renewables
  - Distributed generation causes multi-directional flows
  - Demand can be used as a balancing resource

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