Integration of High Penetration of Solar and Wind Power in Power Systems: Experiences and Challenges

Lecture 1-2 + Tutorial 1

Lennart Söder
Professor in Electric Power Systems
KTH, Royal Institute of Technology, Stockholm, Sweden

Set-up of Lectures L1-L2 + T1

Lecture L1: Electricity general challenges, wind power general

Lecture L2: Voltage control with wind power

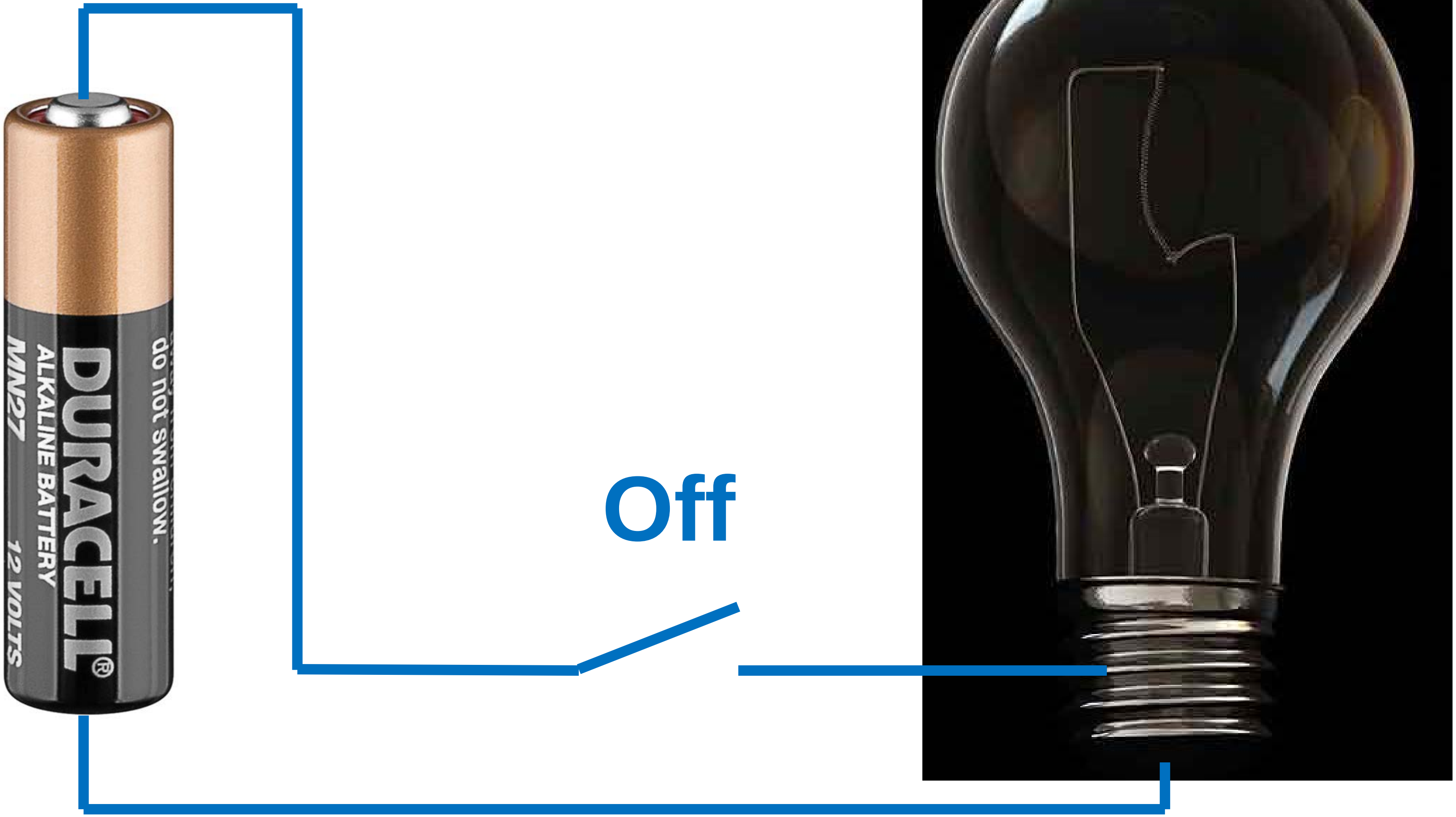
Tutorial T1: Application of voltage control in radial grids with wind power

Electricity

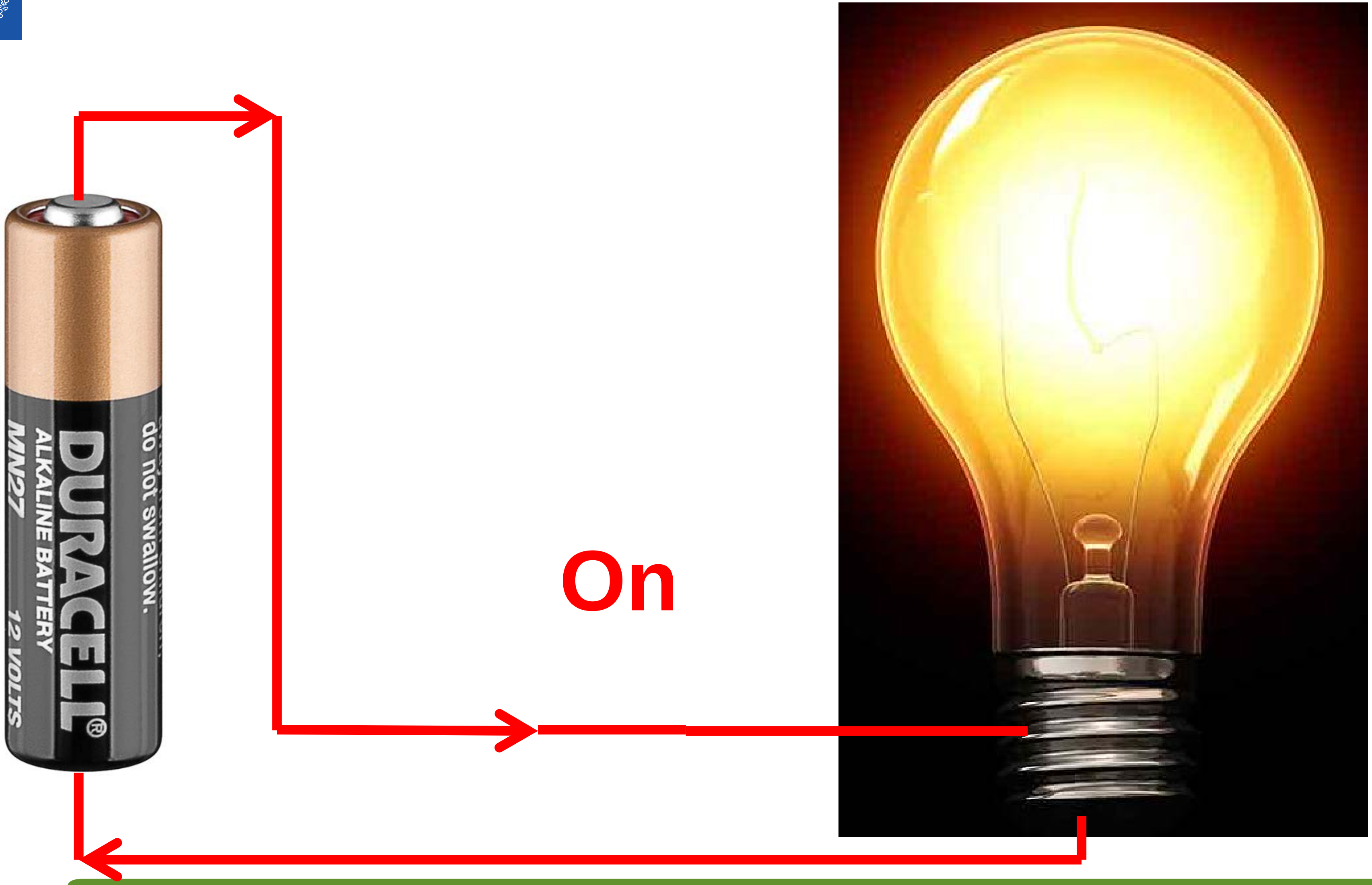
November 13, 2017

by Lennart Söder
Professor Electric Power Systems, KTH

Electricity comes with the speed of light

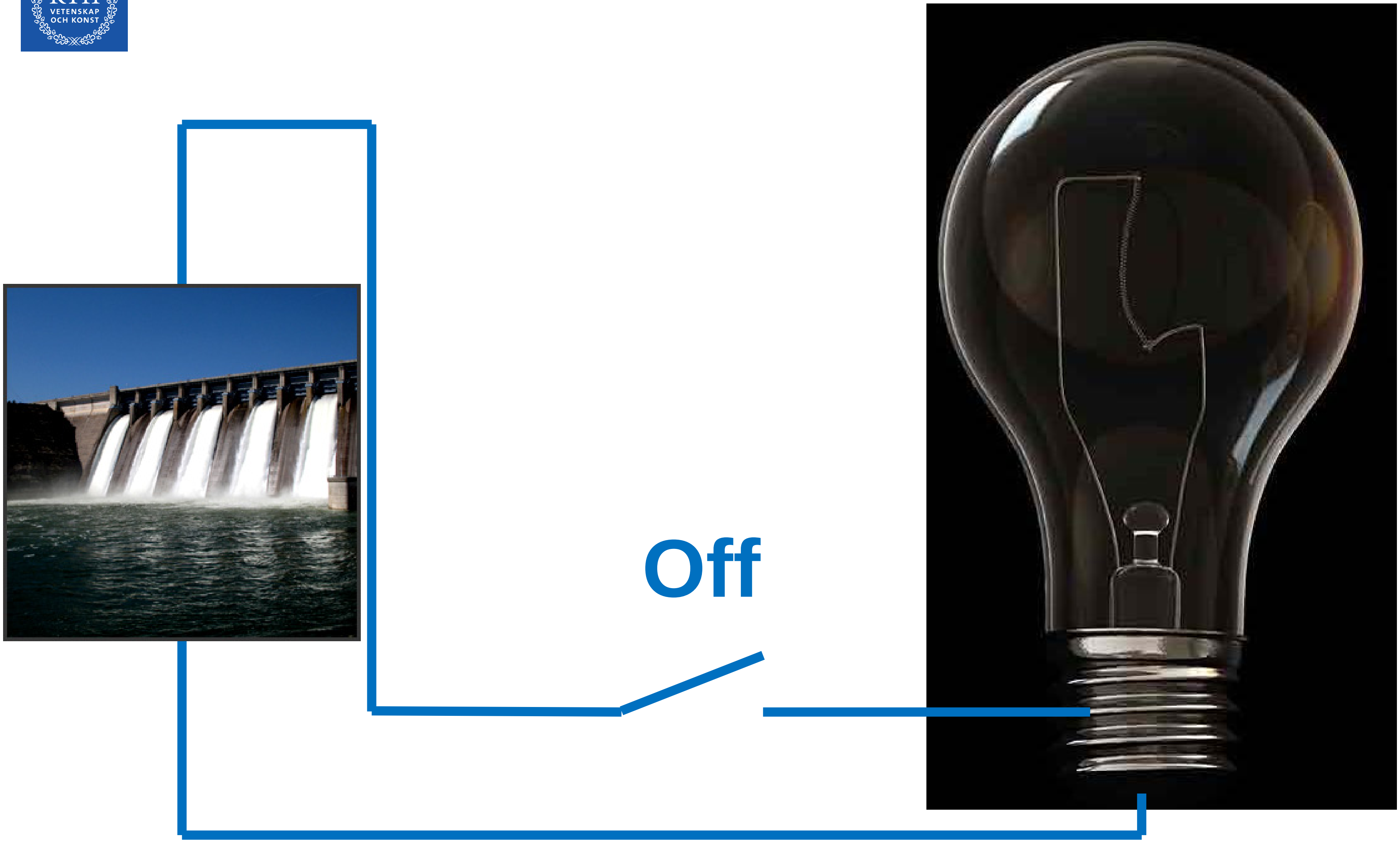


Electricity comes with the speed of light



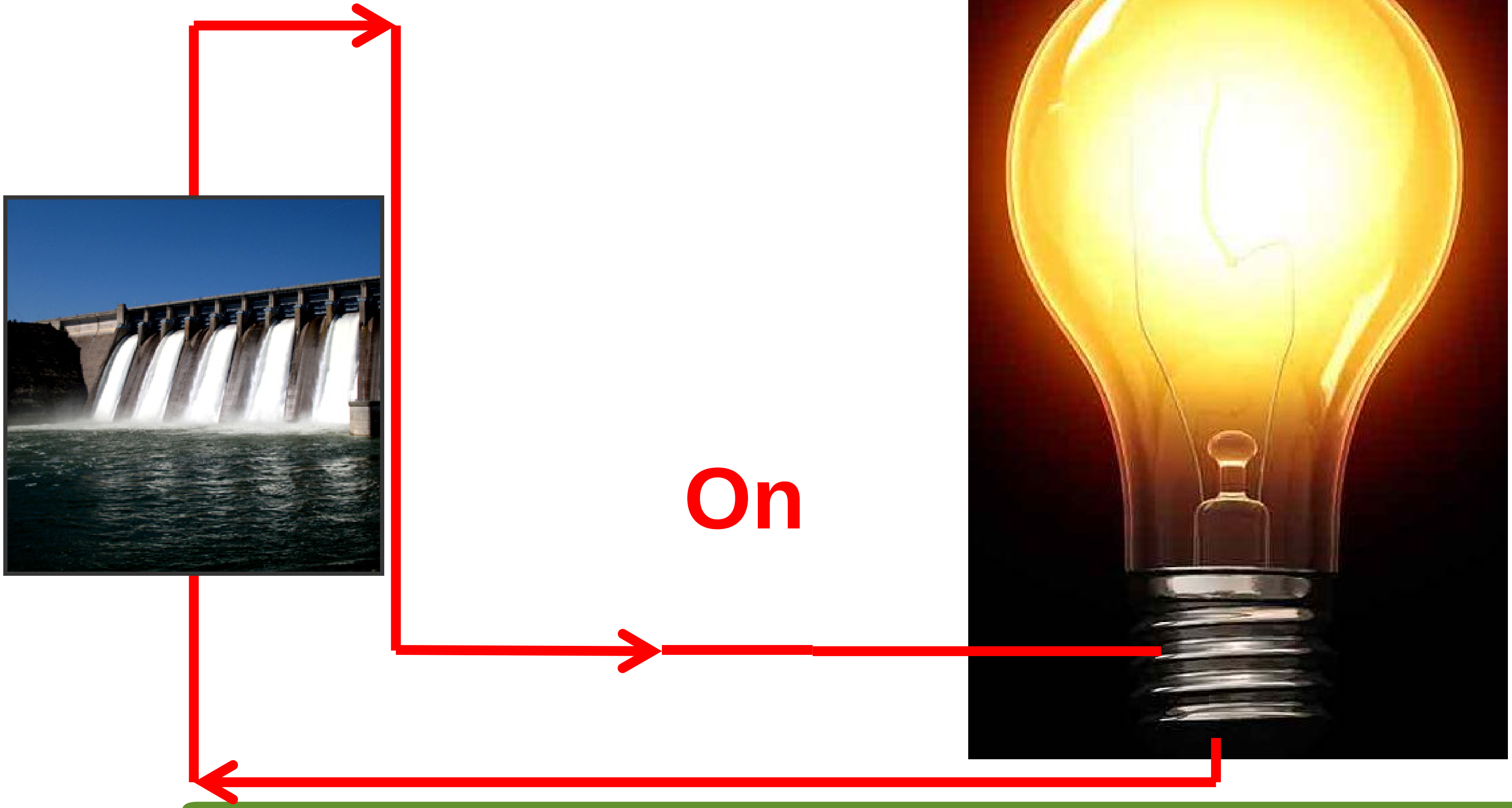
On

Electricity comes with the speed of light



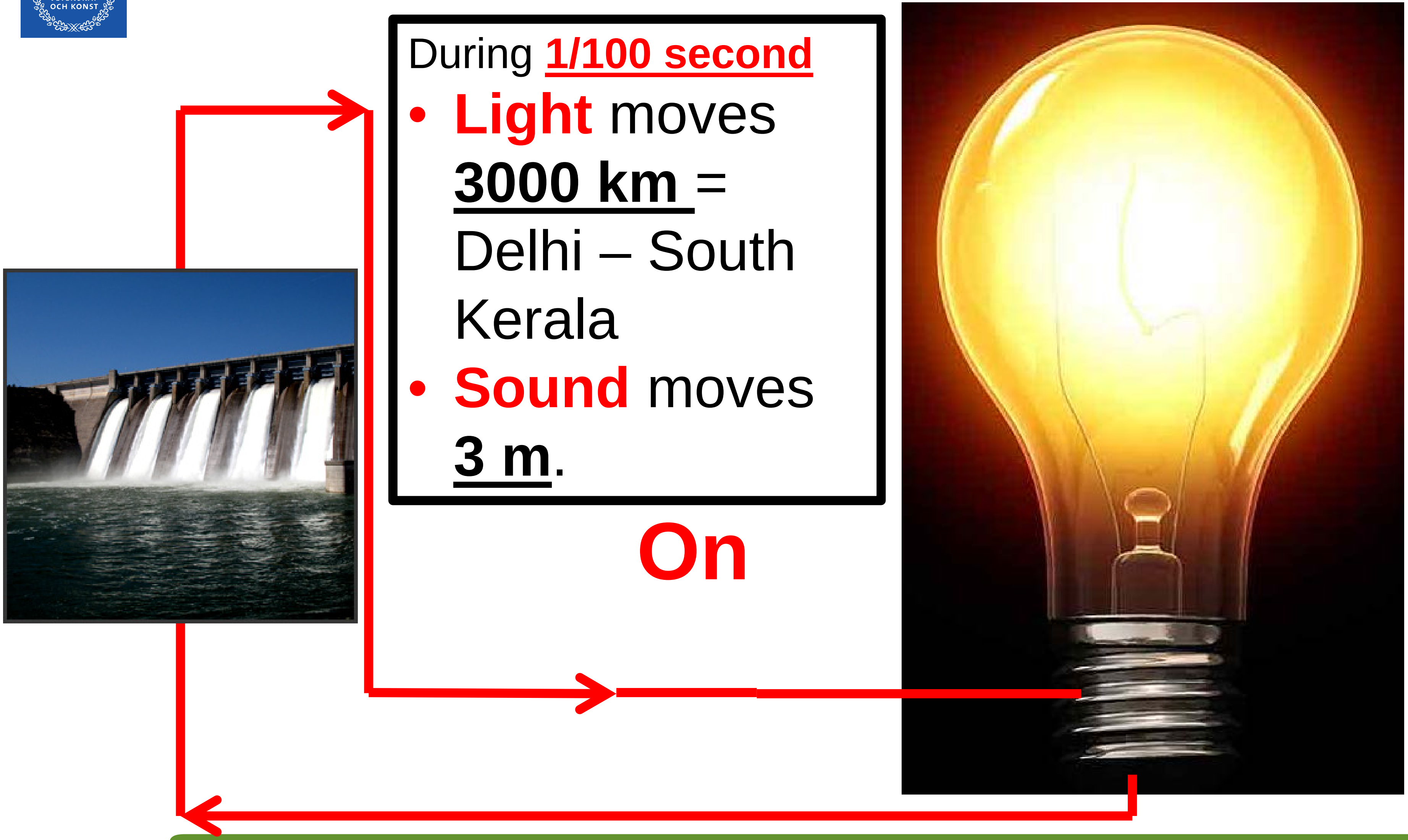
Off

Electricity comes with the speed of light



On

Electricity comes with the speed of light

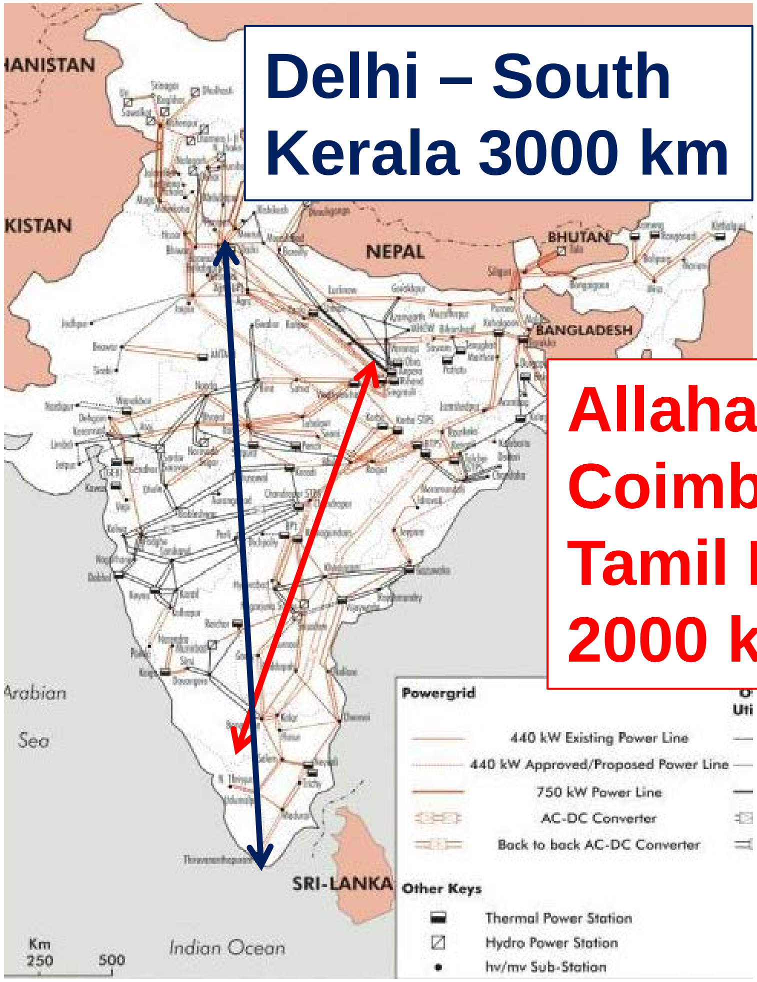


During <u>**1/100 second**</u>

- **Light** moves **<u>3000 km</u>** = Delhi – South Kerala
- **Sound** moves **<u>3 m</u>**.

On

Sizes of India and North Europe

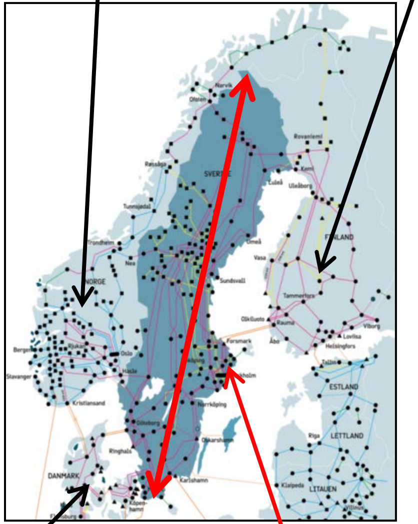


Delhi – South Kerala 3000 km

Allahabad – Coimbatore, Tamil Nadu 2000 km

Norway

Finland

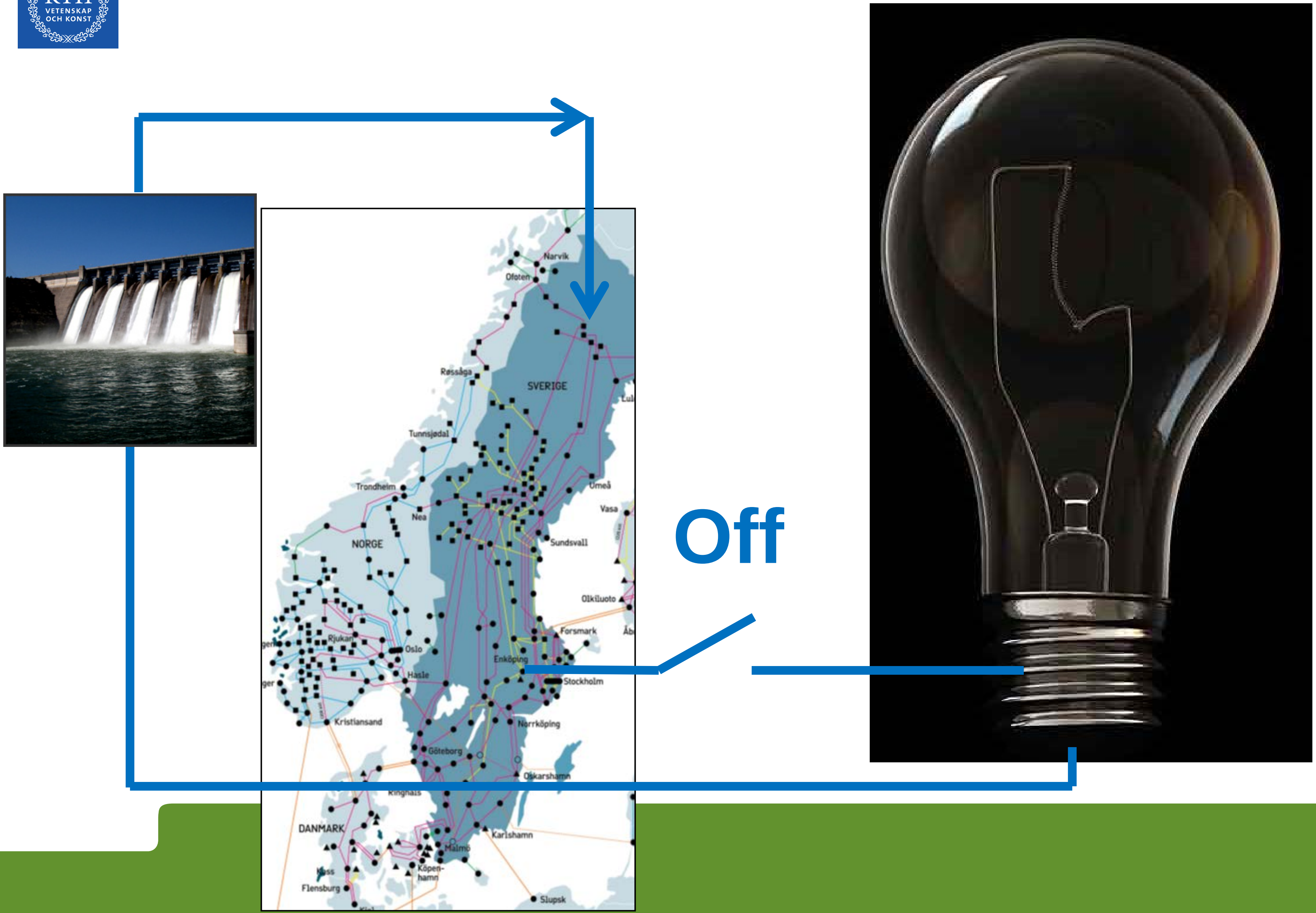


Sweden 2000 km

Denmark

KTH-Stockholm

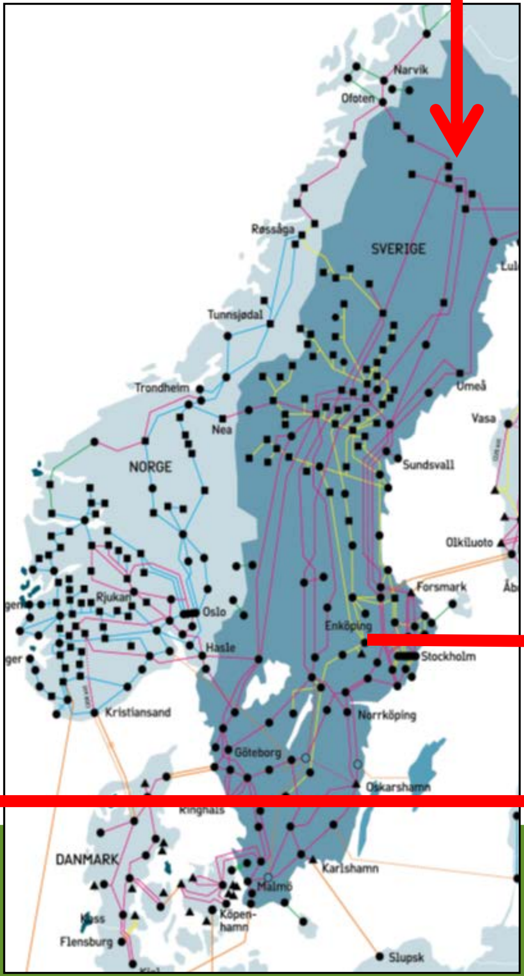
Electricity comes with the speed of light



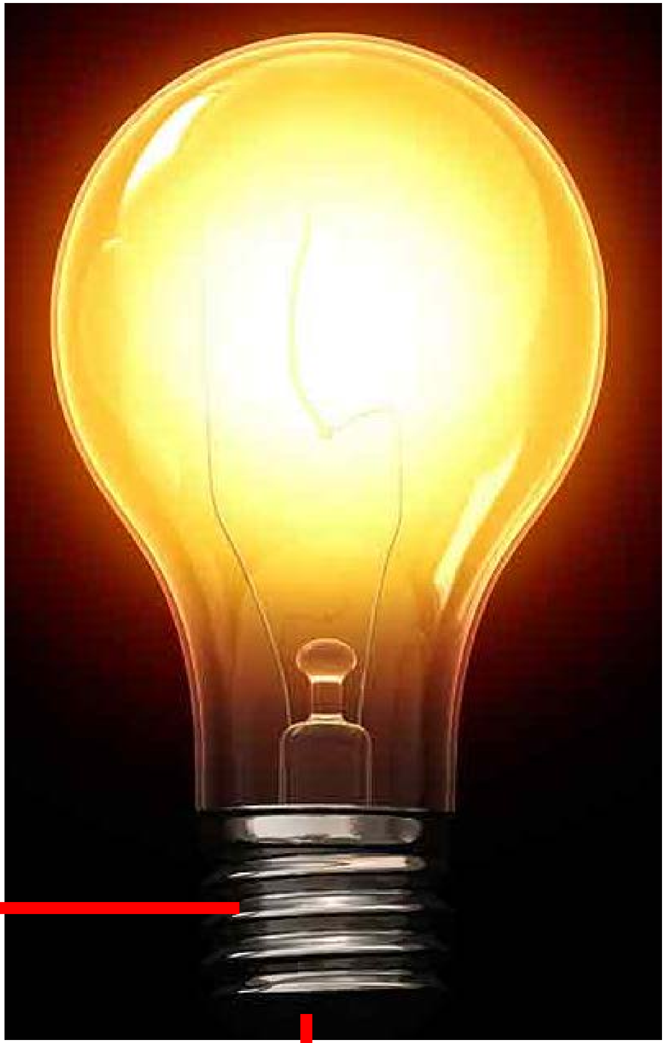
Off

Electricity comes with the speed of light

From North Sweden

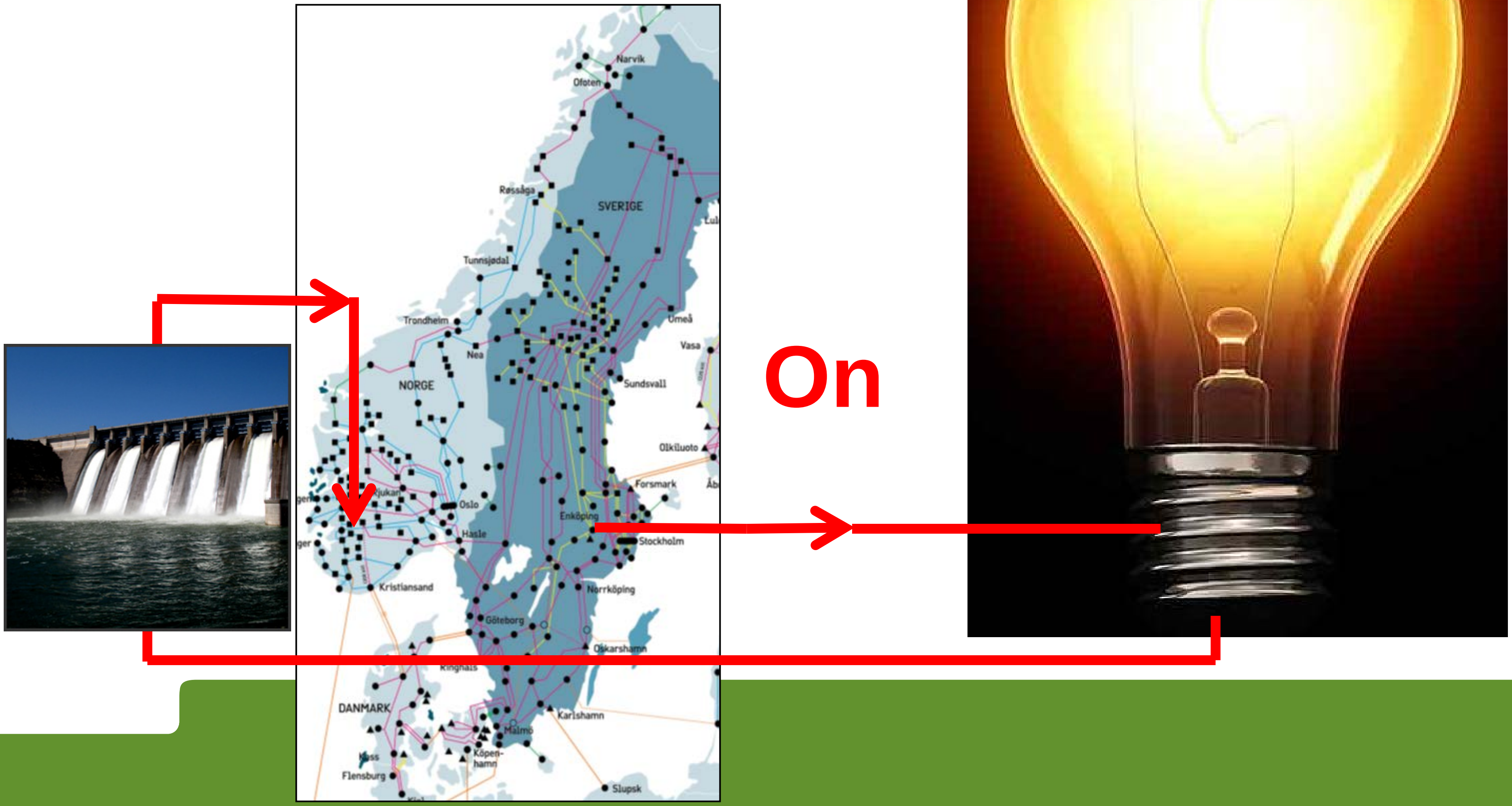


On



Electricity comes with the speed of light

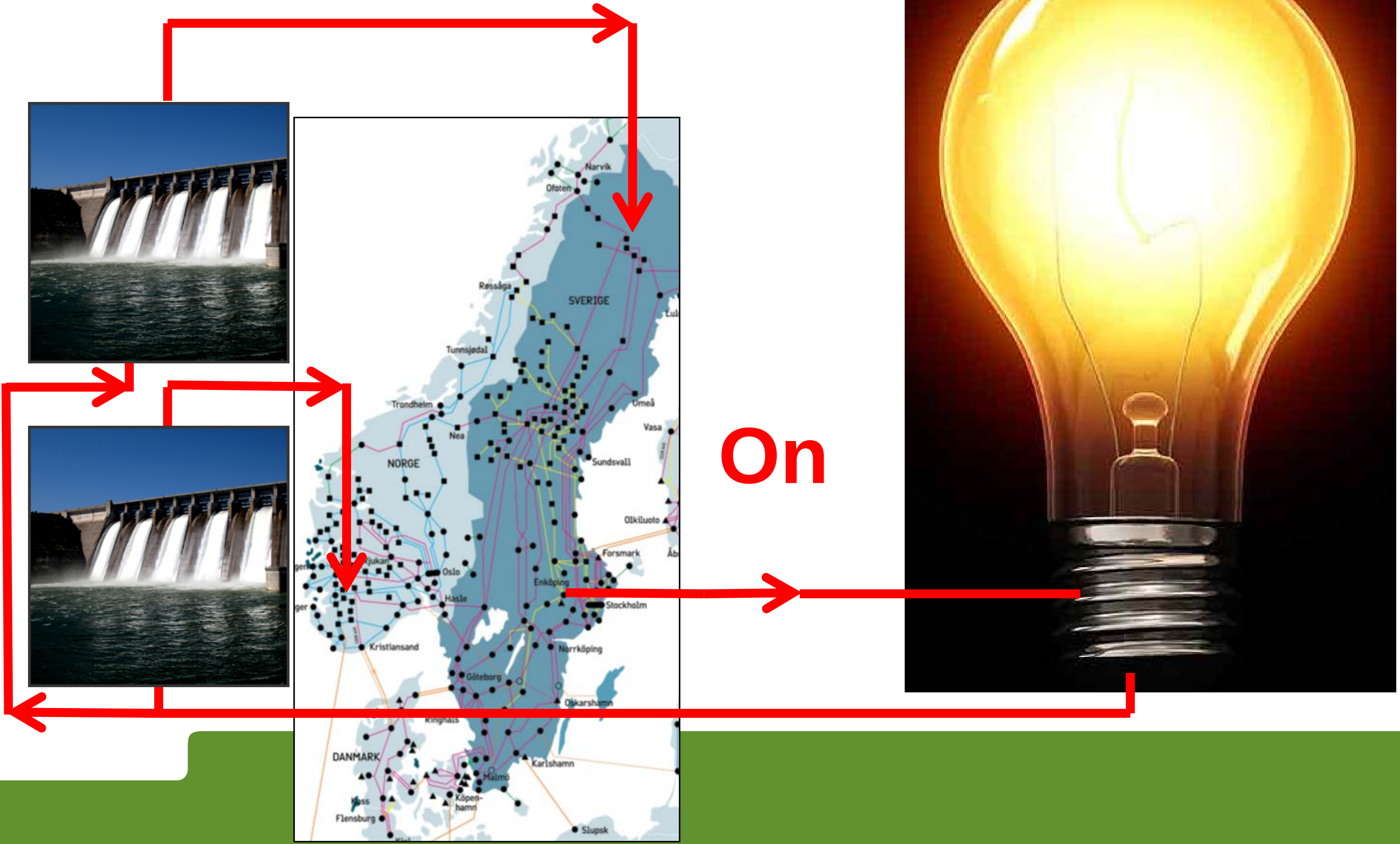
Or from Norway?



On

Electricity comes with the speed of light

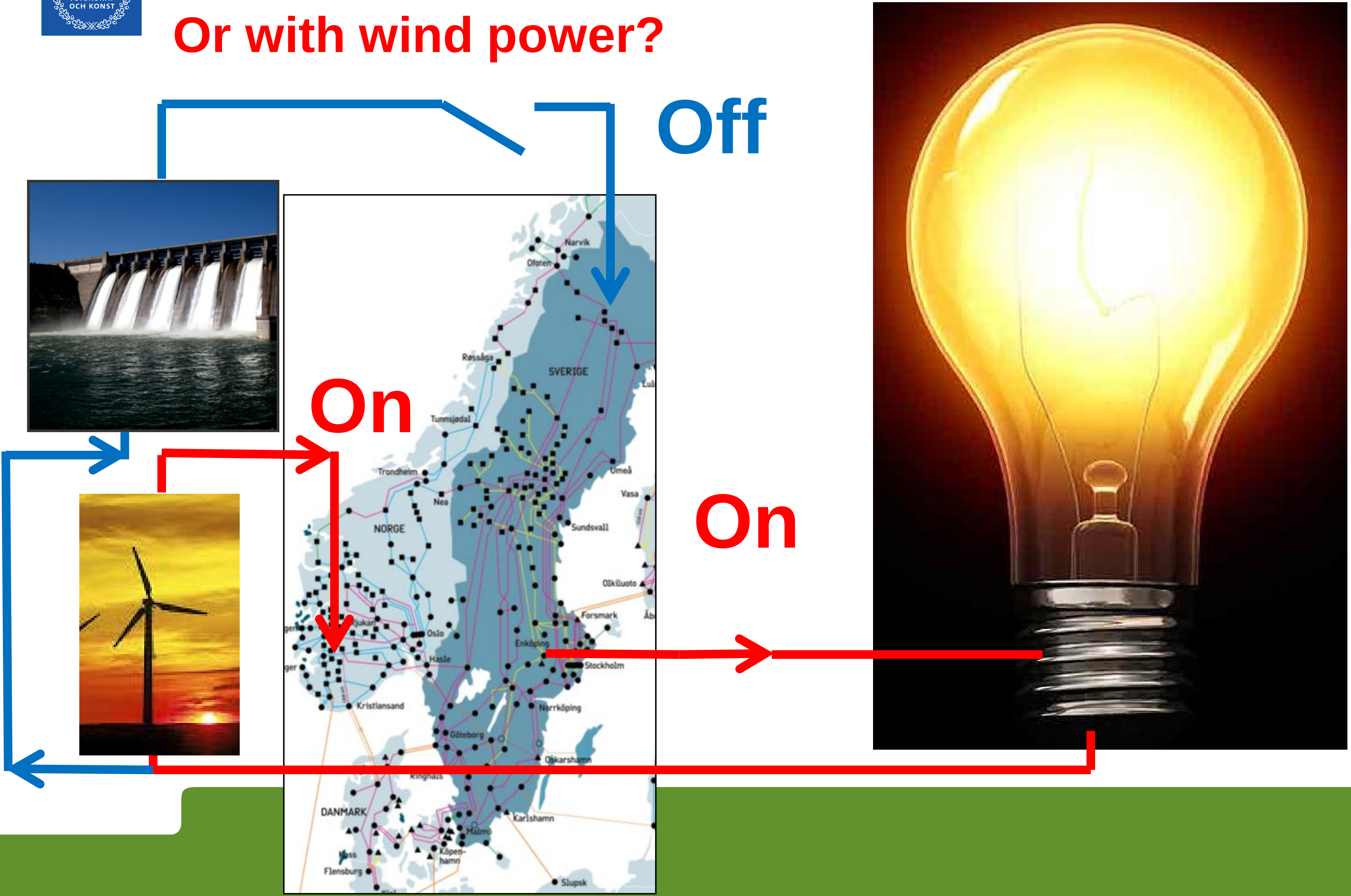
Or Sweden + Norway?



On

Electricity comes with the speed of light

Or with wind power?



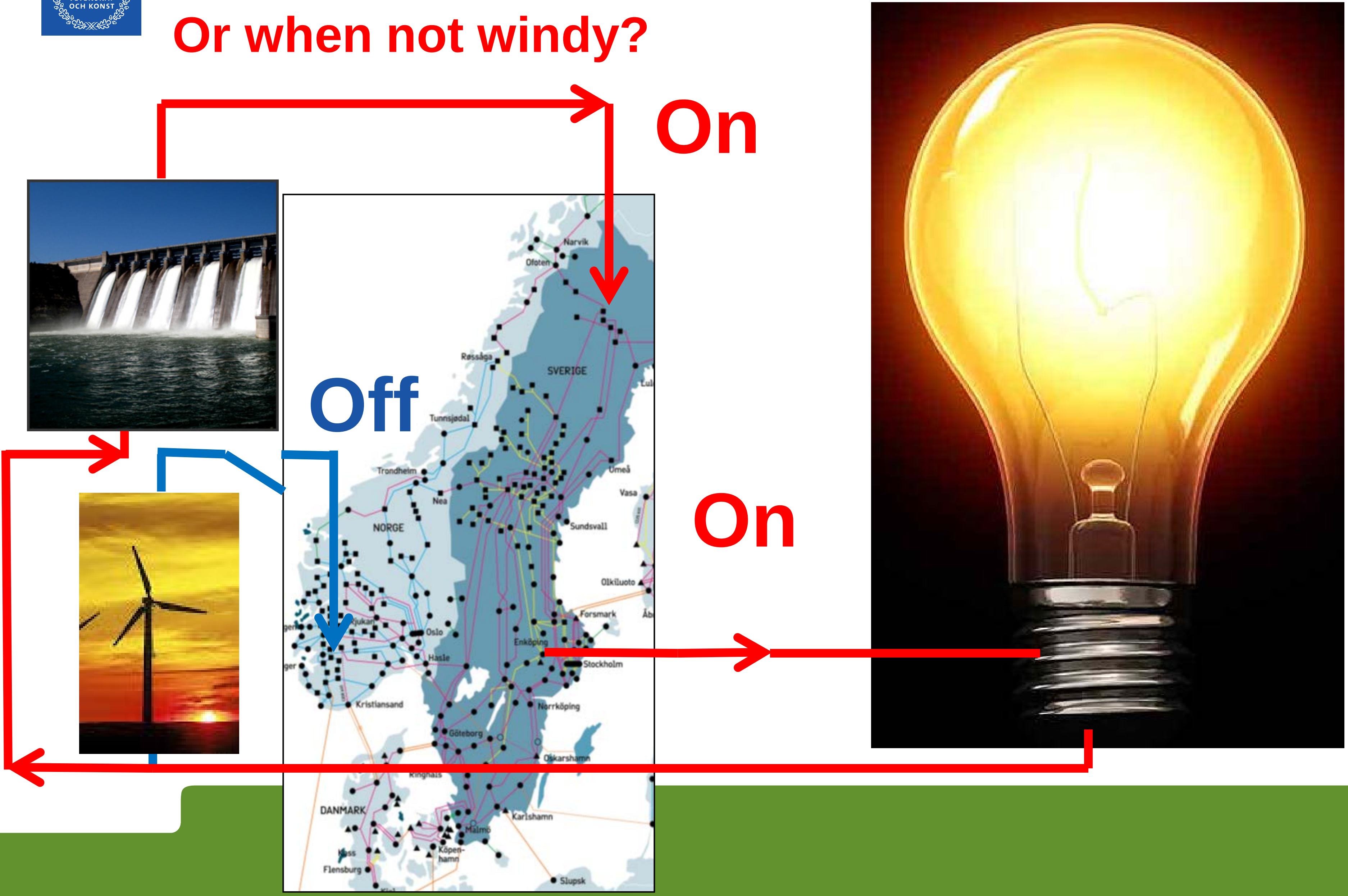
Off

On

On

Electricity comes with the speed of light

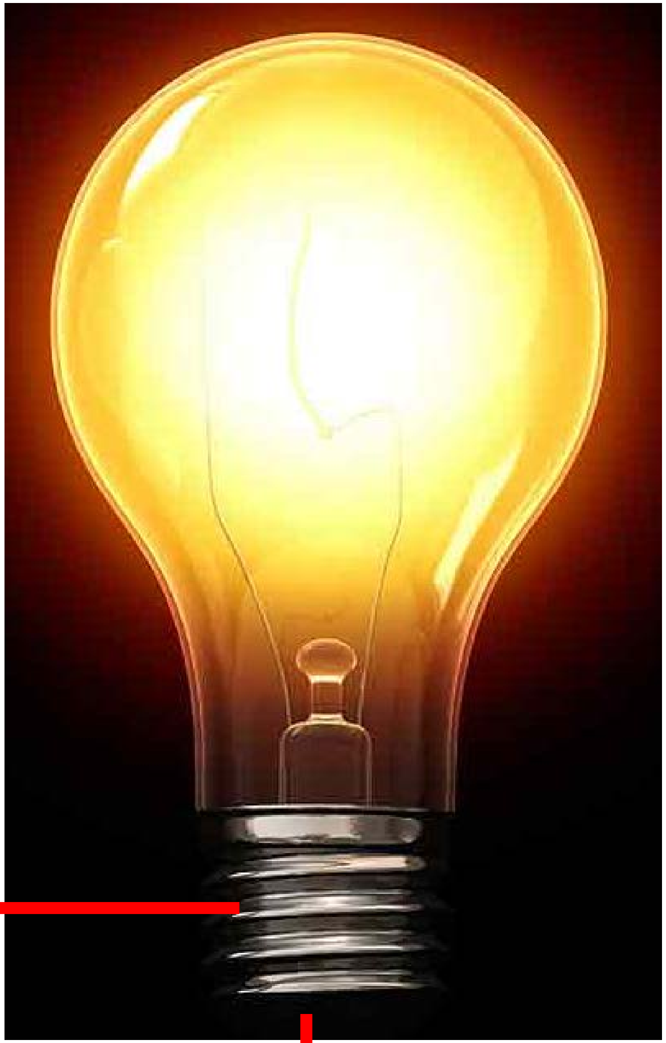
Or when not windy?

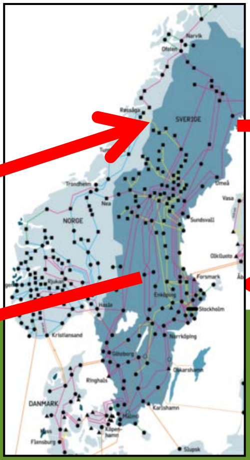


Electricity comes with <u>the speed of light</u>

Summary:

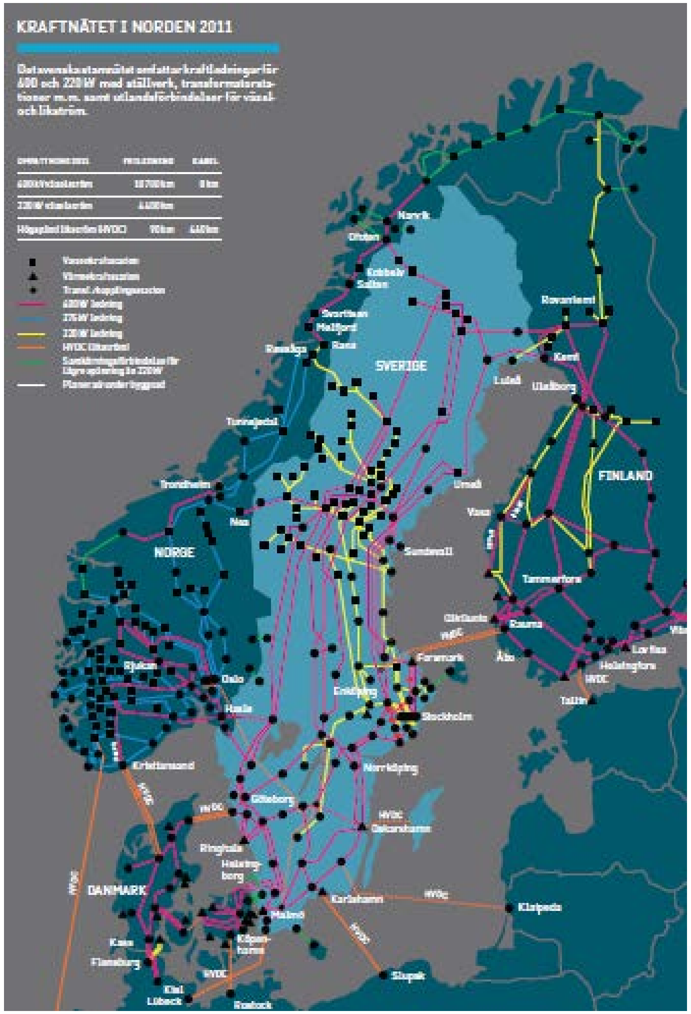
- **”Electricity” is an instant transport system (with some losses)**
- **”Electricity” is NOT an ”energy source”**
- **”Power consumption” must theryby, for each second, be met by med ”Power production”**
- **Power grids makes it possible to use distant sources**



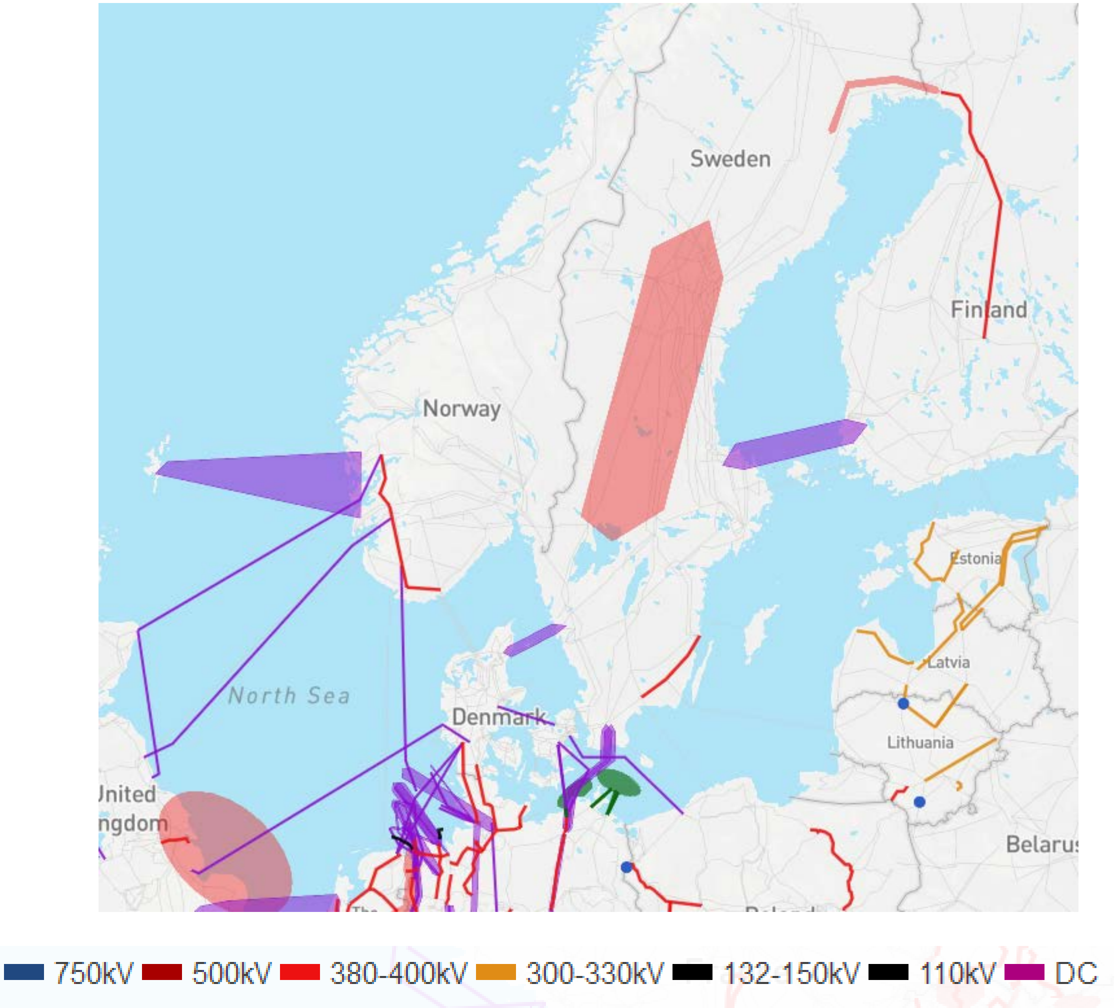


Nordic interconnections

Current



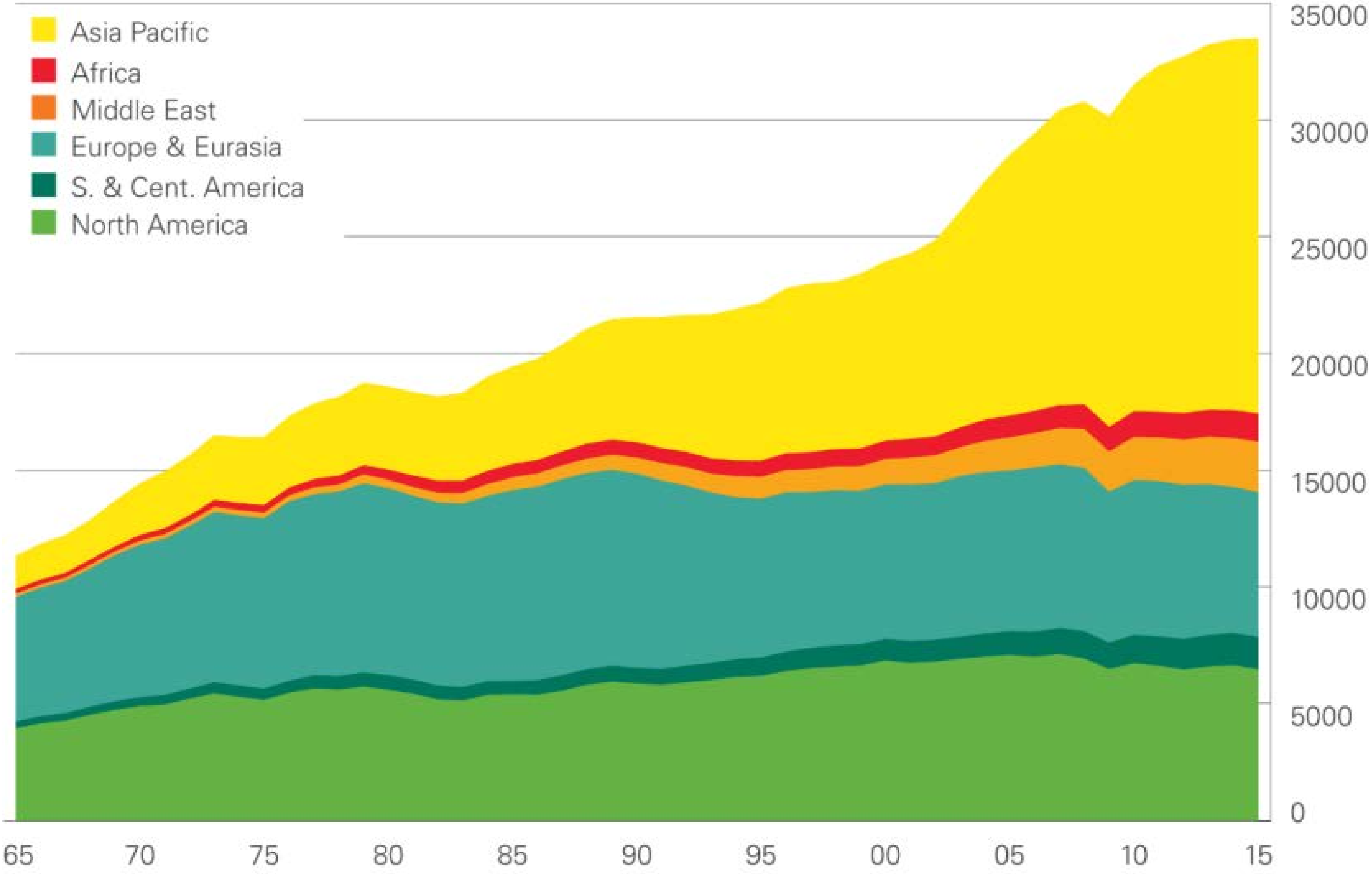
New up to 2030



Aim of a power system

1. The consumers should get the required power (e.g. a 60 W bulb), when the push the on-button. This should work no matter there is an outage in a plant, wind is changing etc. = keep a **balance between total production and total consumption**.
2. The consumers must have a **realistic voltage**, e.g. around 230 V, in the outlet.
3. Point 1-2 should be obtained at a **realistic reliability.** This is **never** 100,000... percent,
4. Point 1-3 should be obtained in an **economic and sustainable** way.

Global CO_2 emissions from energy consumption [Mton] 1965-2015 (increase +0,1% 2015)



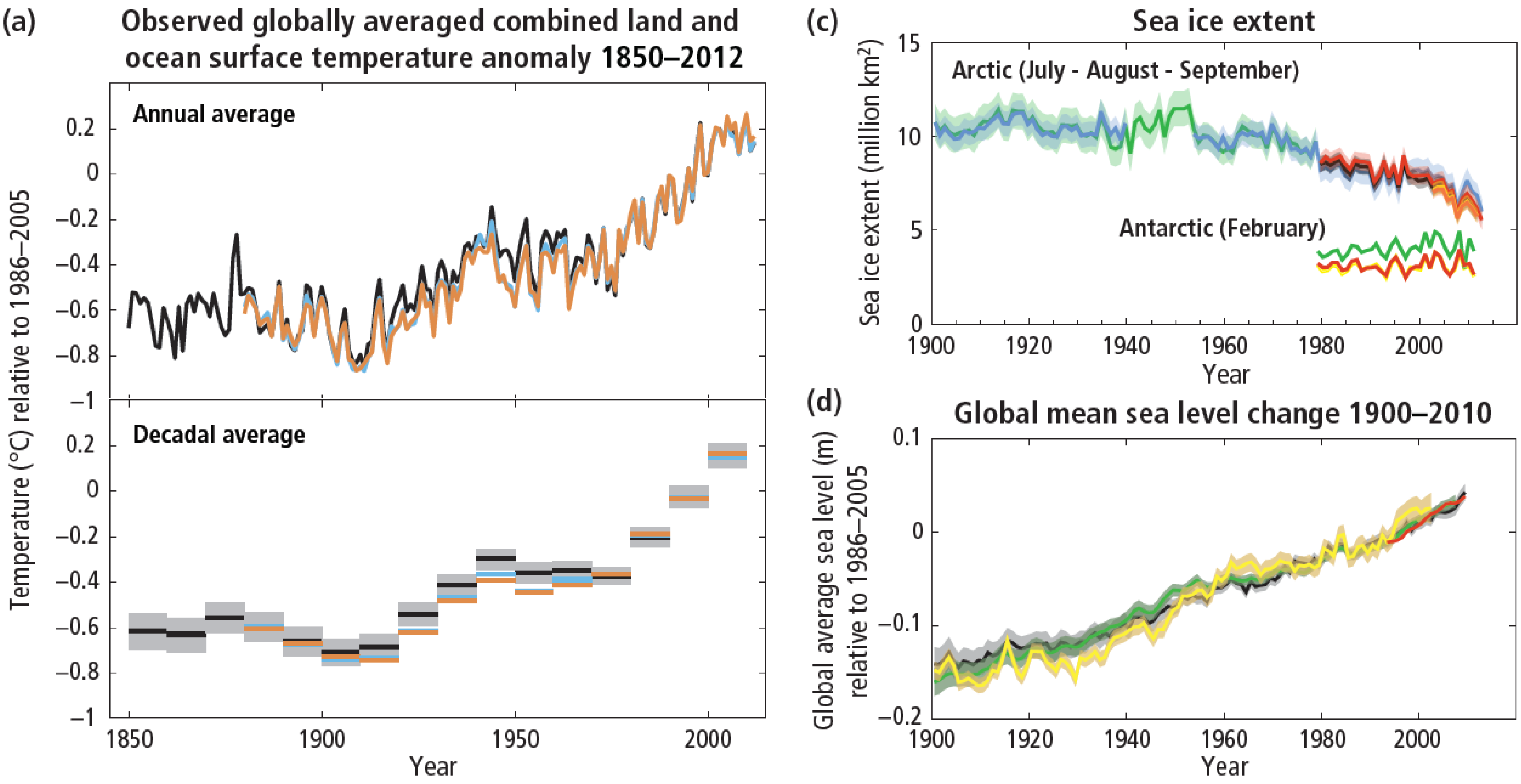
Source: http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

CO_2 emissions per capita from energy consumption [ton/cap,year]

Area / country	Emissions/capita
World	3,88
Africa	1,04
Russia	11,05
US	17,05
China	6,65
India	1,69
Germany	9,34
Norway	7,05
Sweden	4,88

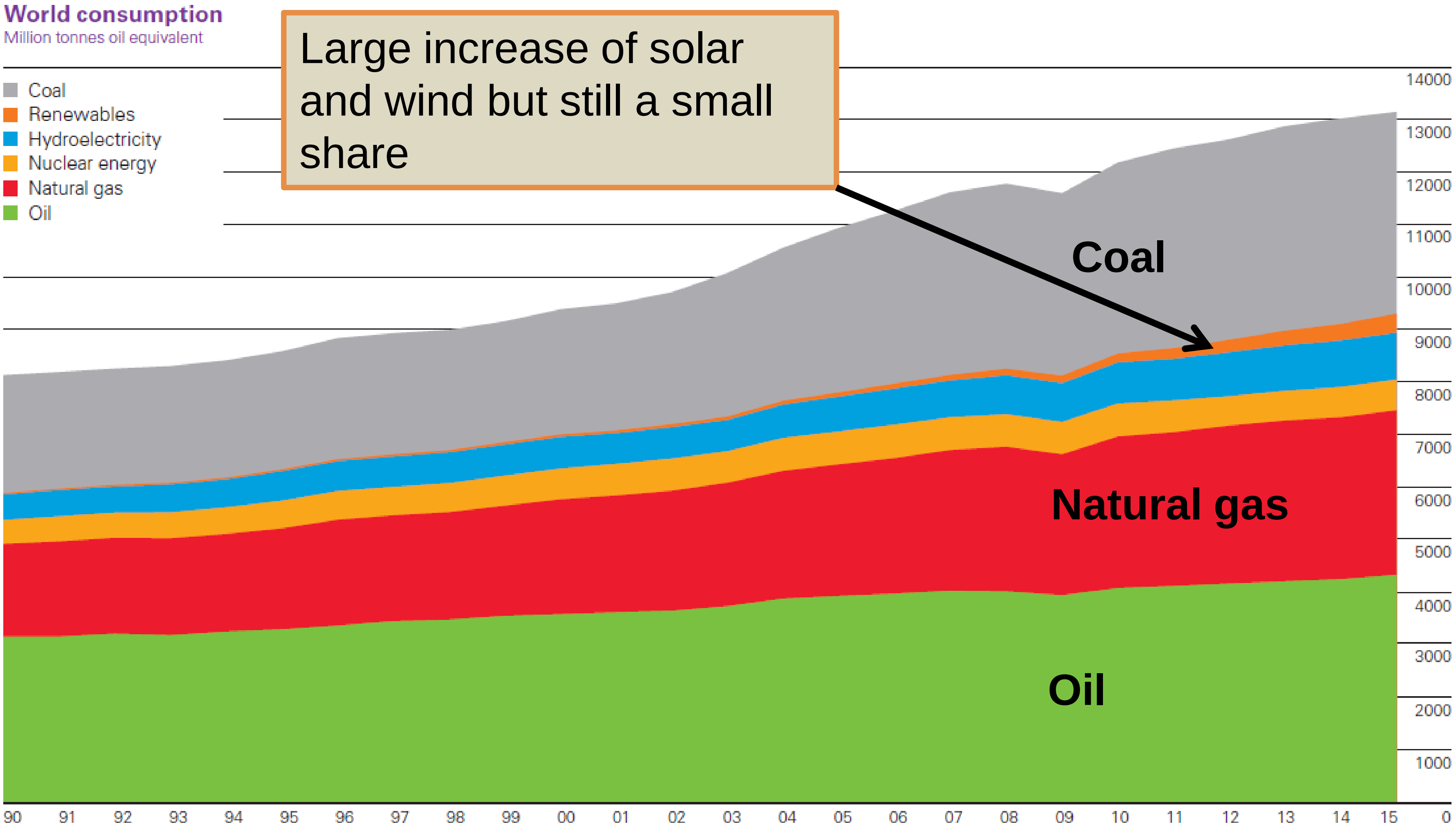
Source: http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Change of temperature, sea ice extent and sea level from 1850/1900 to 2010/2012



Source: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf

World energy consumption: 1990-2015 (+60%)

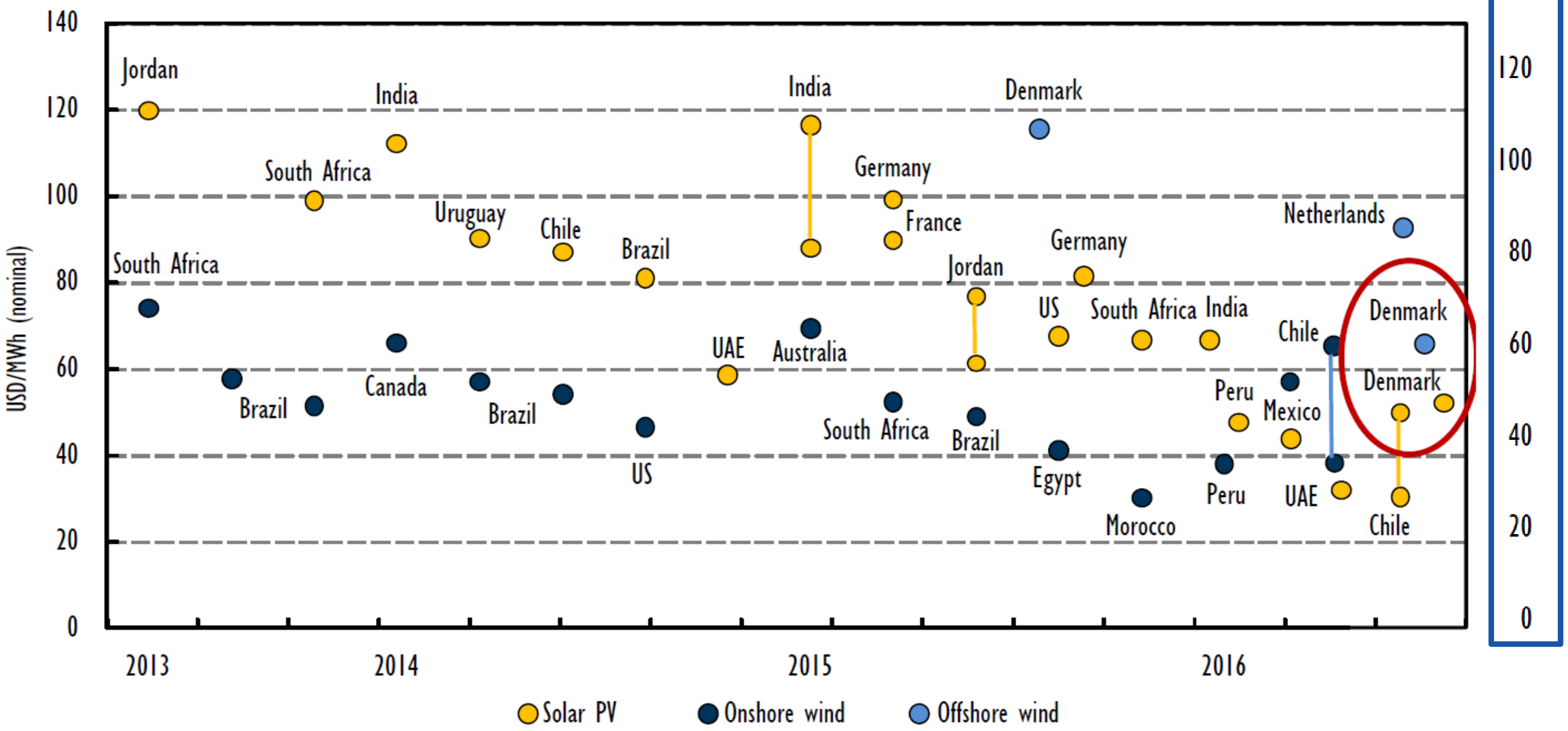


Large increase of solar and wind but still a small share

Policy transition from government-set tariffs to policy-driven auctions/tenders

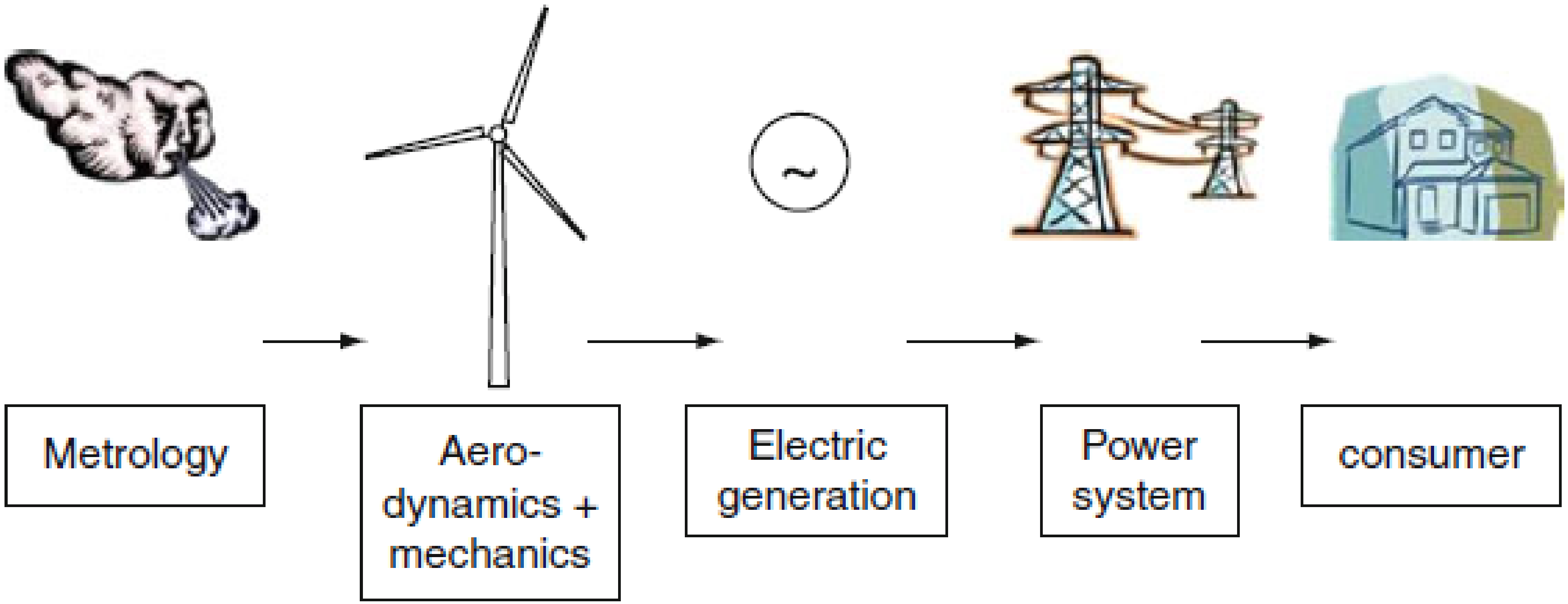
RENEWABLE ENERGY
Medium-Term Market Report
2016

Recent announced long-term contract prices for new renewable power to be commissioned over 2016-2019



Best results occur where price competition, long-term contracts and good resource availability are combined

Wind Power Systems



Metrology

Aero-
dynamics +
mechanics

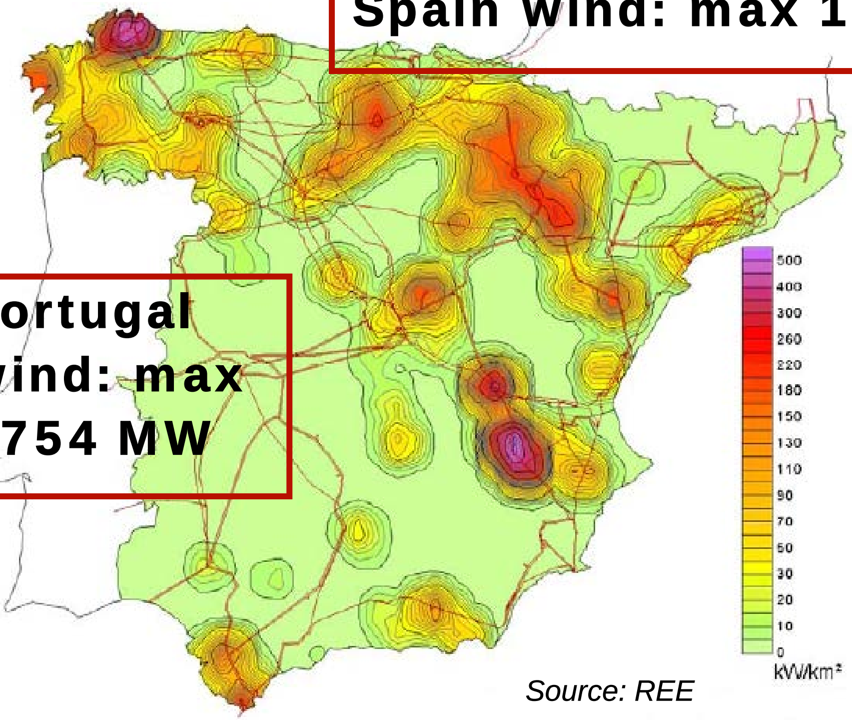
Electric
generation

Power
system

consumer

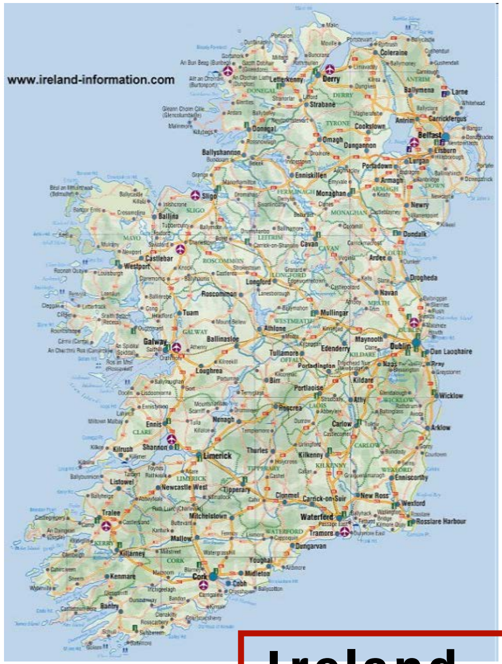
Wind power in some European countries

Spain wind: max 16636 MW



Source: REE

Portugal wind: max 3754 MW



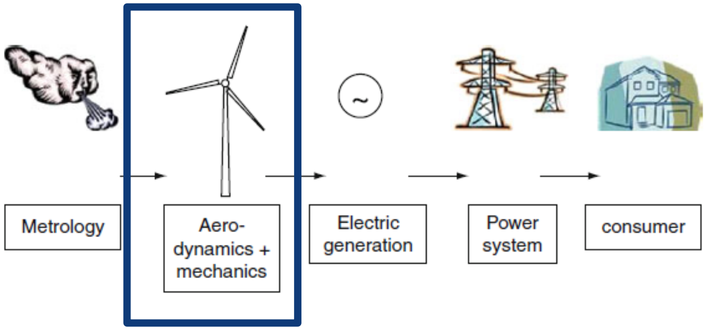
Ireland wind: max 1588 MW

	Wind energy 2015
Sp	24 %
Po	25 %
Ir	21 %
Dk	45 %
Sw	10 %

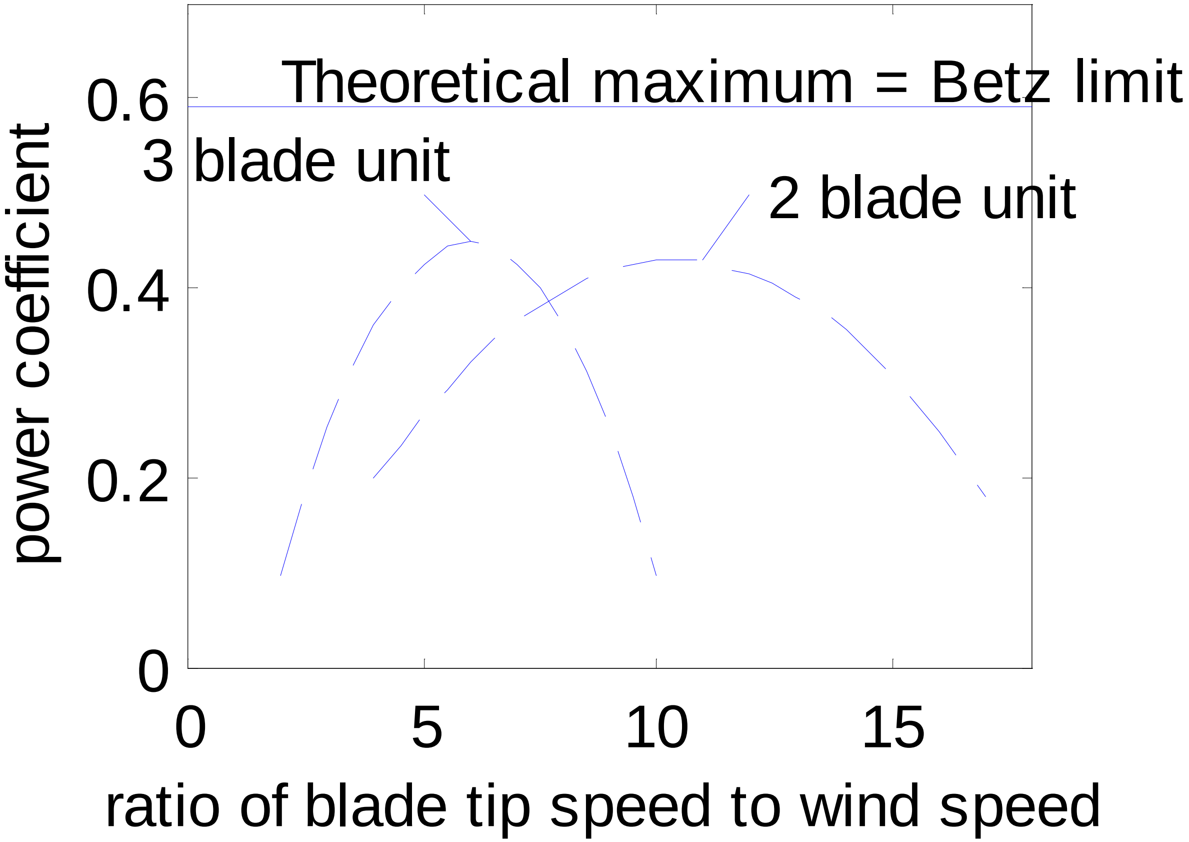
Wind Power Systems

- The Wind Energy Resource
- Aerodynamics
- Electric Power Generation
- Control of a Wind Power Unit
- Control of a Wind farm
- Grid Connection
- The Value of Wind Power
- Environmental Impact

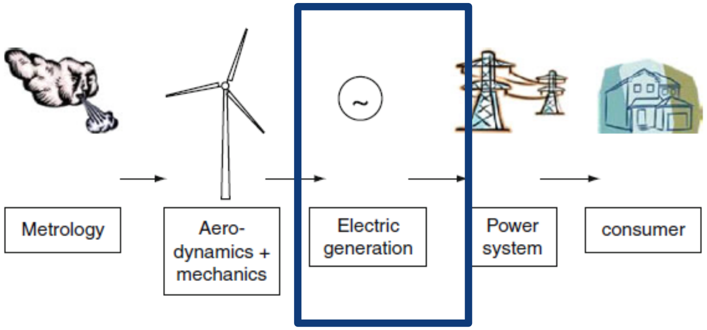
Aerodynamics - 5

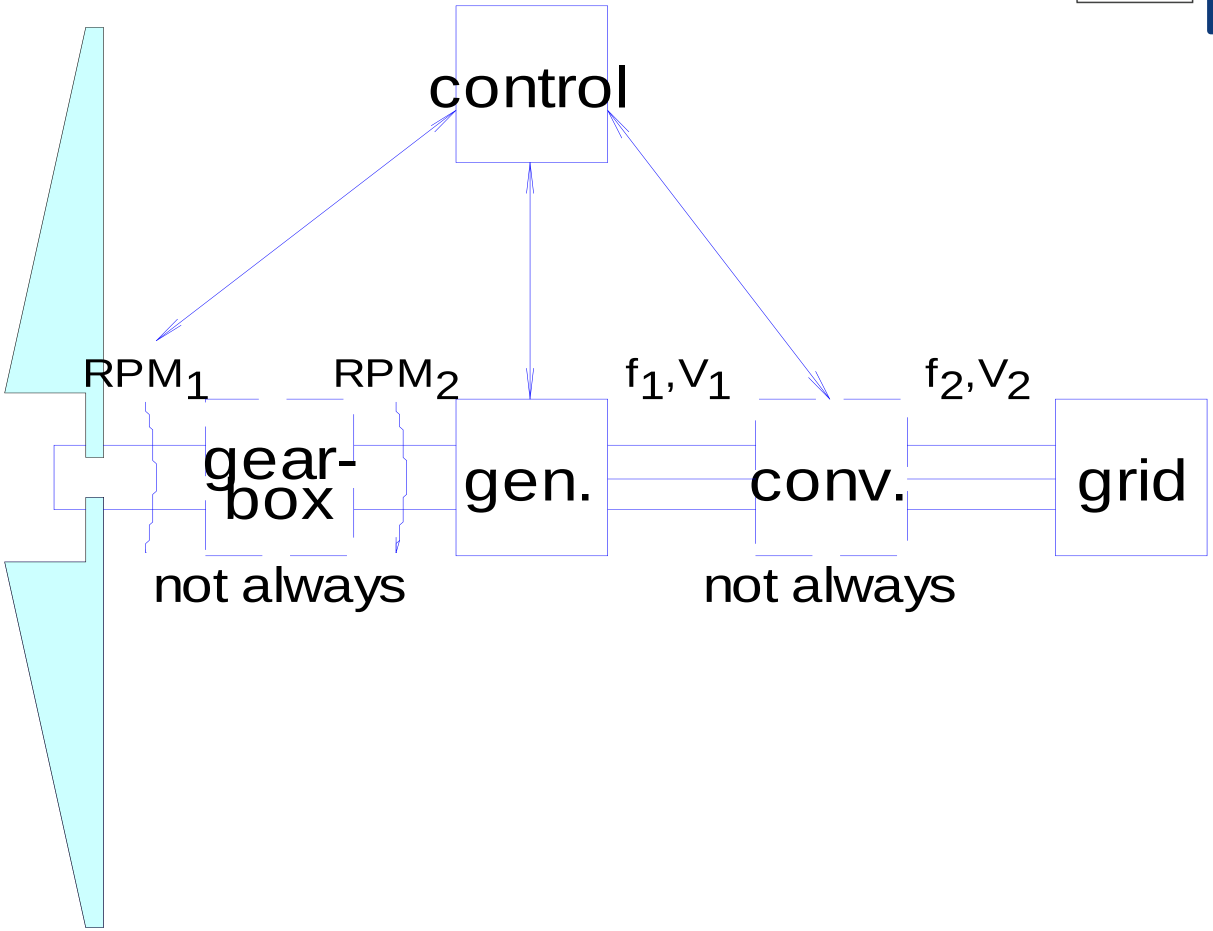


tip speed/wind speed ratio

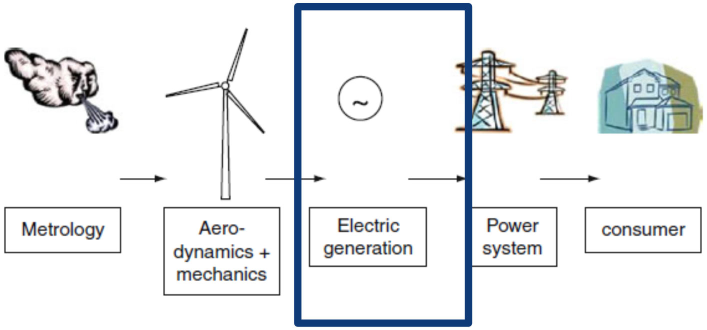


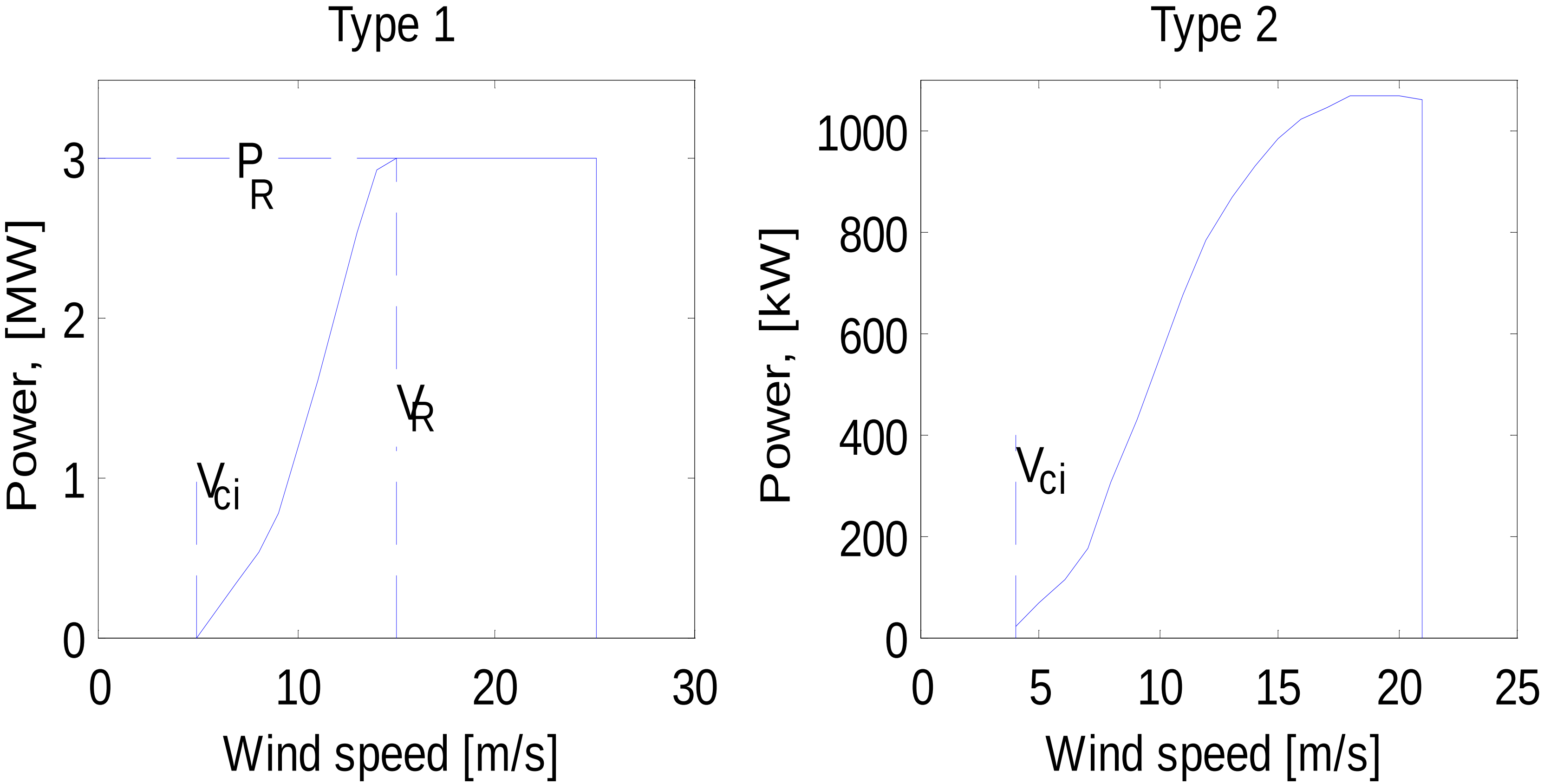
Electric power generation - 1





Control of a wind power unit





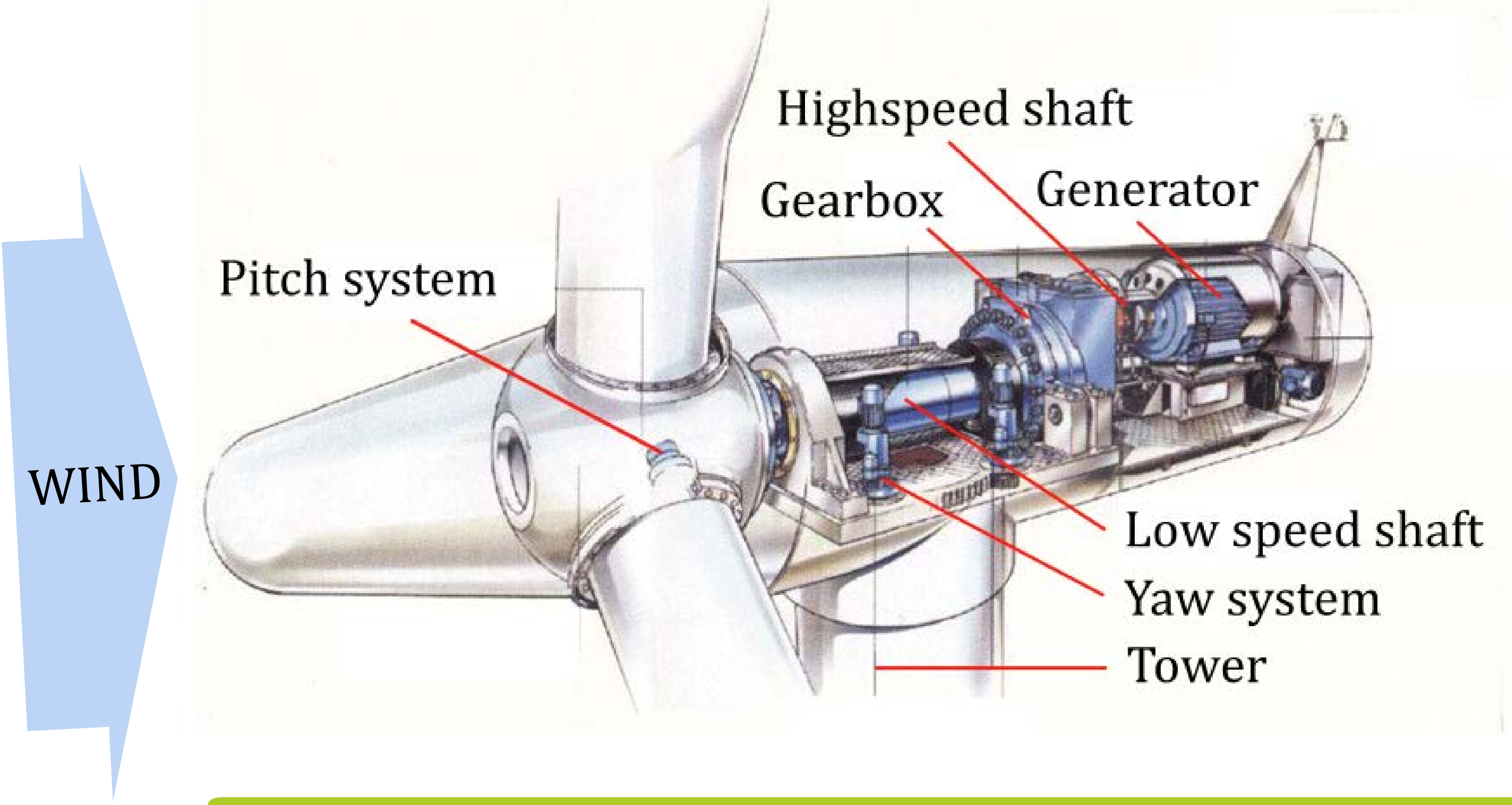
KTH ROYAL INSTITUTE
OF TECHNOLOGY

Power Generation

Wind Power Systems

Stefan Stanković
e-mail: stanko@kth.se

Electro-mechanical system of a wind turbine

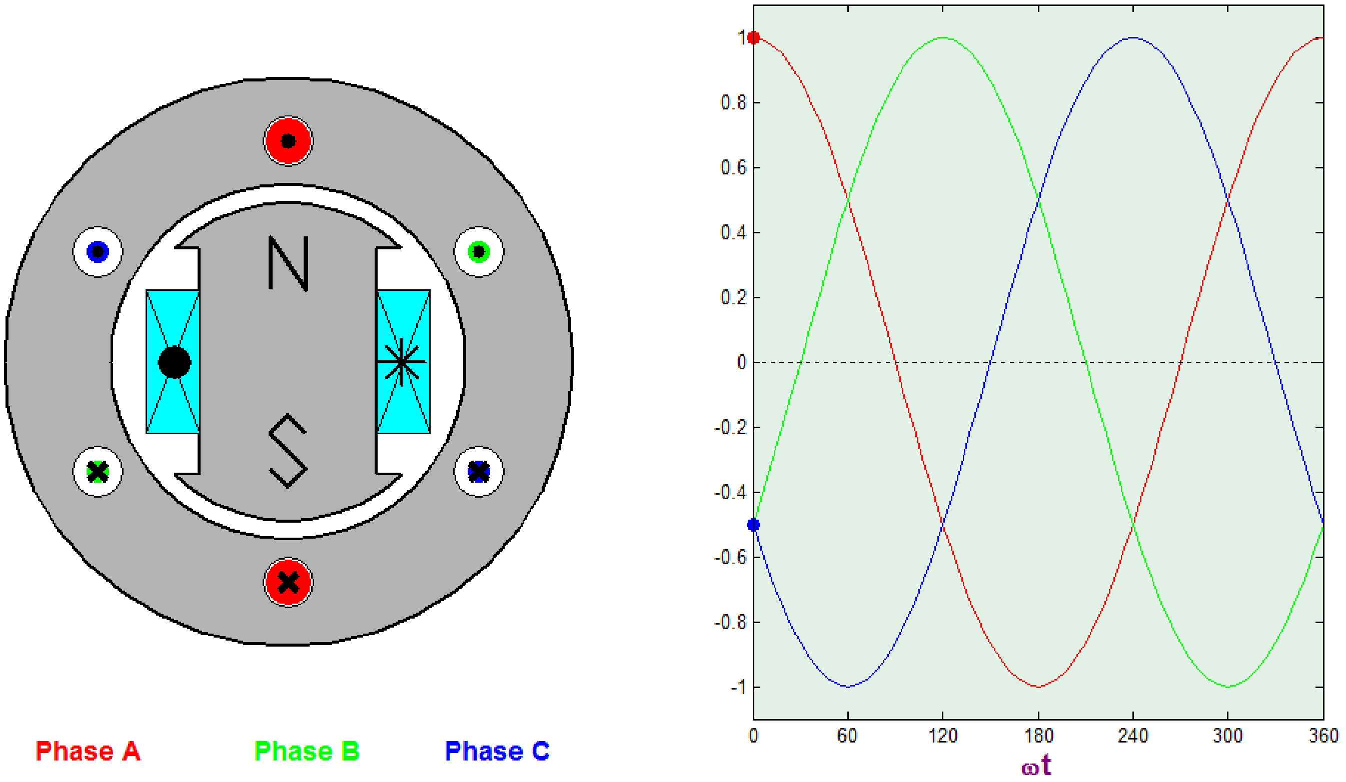


Types of Electrical Machines

Synchronous machines

Asynchronous machines

Rotating magnetic field



Rotating magnetic field induces
electromotive forces (E) in stator windings
(Faraday’s law of induction –> generalisation -> Maxwell-Faraday’s law)

4 Types of Conversion Systems

1. Induction Generator (Squirrel Cage)
2. Wound-Rotor Induction Generator with Variable Rotor Resistance
3. Doubly Fed Induction Generator (DFIG)
4. Synchronous or Induction Generator with Full Scale Converter on Stator Side

Type 1: Pro and Cons

Cons:

- Needs reactive power to operate
- Not suitable for high turbulence areas:
  - has steep T(ω) characteristics -> big mechanical stresses
  - big fluctuations in output electrical power
  - if attached to a weak grid, big fluctuation of voltage might occur (voltage flickers)
- Not so efficient (non-variable speed)
- Needs soft starter

Pros:

- Simple, robust, reliable and relatively cheap

Type 2: Pros and Cons

Cons:

- Can be used only for speeds bigger then rated speed. For speeds lower then rated, it operates like type 1
- Additional active power losses (increased rotor resistance)

  Pitch control used when power reaches rated to minimize heating
- Additional maintenance costs (slip rings and brushes)
- Consumes reactive power
- Usually, also needs a soft starter

Type 2: Pros and Cons

Pros:

- Better efficiency then type 1 (availability to control rotor speed)
- Less mechanical stress on the drive train
- Less fluctuation of output power and voltage

Type 3: Rotor Converter (overview)

- Needs in speed control are not more then +/- 30% of rated(synchronous) speed
- It implies that rotor converter is dimensioned to about 30% of generator rated power
- Controls torque and speed of the rotor
- Supplies active and reactive power in both directions (operation in all four quadrants)
- No need for soft starter

- Sensitive to faults in the grid
- Rises the overall expense of the concept

Type 3: Pros and Cons

Pros:

- More controllable and more efficient
- Can support reactive power (control variation in terminal voltage
- Decoupled mechanical and electrical system (less variations in output active power and less stress on mechanical system)
- Less noise then previous concepts

Cons:

- More expensive
- Less robustness
- Bigger maintenance costs
- Sensitive to faults and atmospheric overvoltage

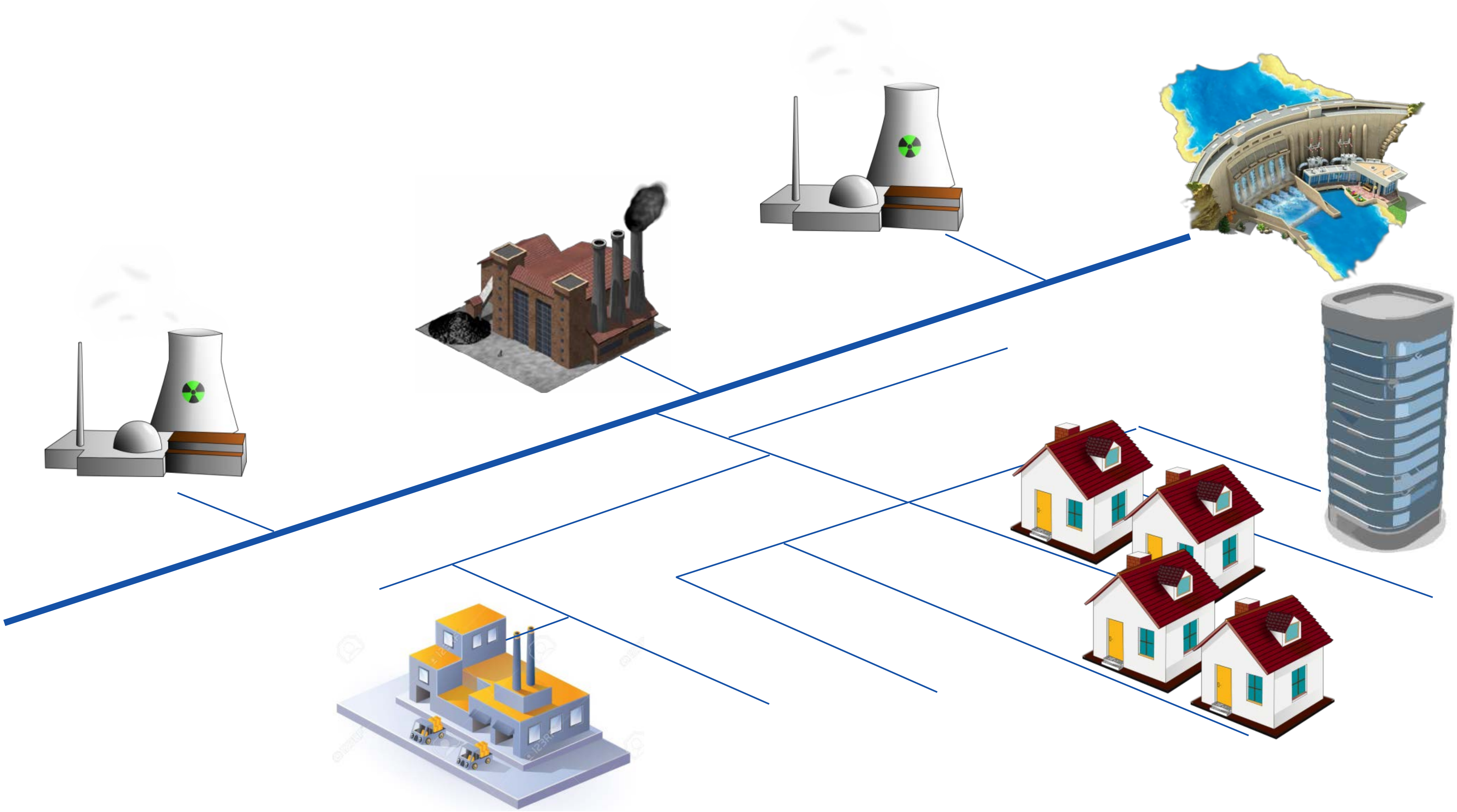
KTH ROYAL INSTITUTE
OF TECHNOLOGY

Reactive power capabilities of distribution grids with wind power

Integration of Renewable Energy Systems Research Group

Stefan Stanković
e-mail: stanko@kth.se

Conventional Power Systems



Modern Trends - Sustainable Future

Problems?

Voltage control at transmission level

Solutions?

- Keep generators as synchronous condensers
- Install SVC stations at transmission level
- Provide reactive support from distribution grids and wind power systems located at lower voltage level

Motivation

- **Technical**
  - Voltage profile controllability
  - Using full resources of equipment in wind generator
  - Reliability
- **Economical**
  - Less investment costs (not installing SVC)
  - Less maintenance costs (not having Synchronous Condenser)
  - Participation of distribution systems in developing reactive power markets
  - Increased rate of return of investment in wind power

Our current work:
Assess distribution grids' reactive capability

Synchronous generator capability curve

Reactive power capability of **distribution grid**

Investigation of grid parameters influence on reactive power capability of distribution grid:

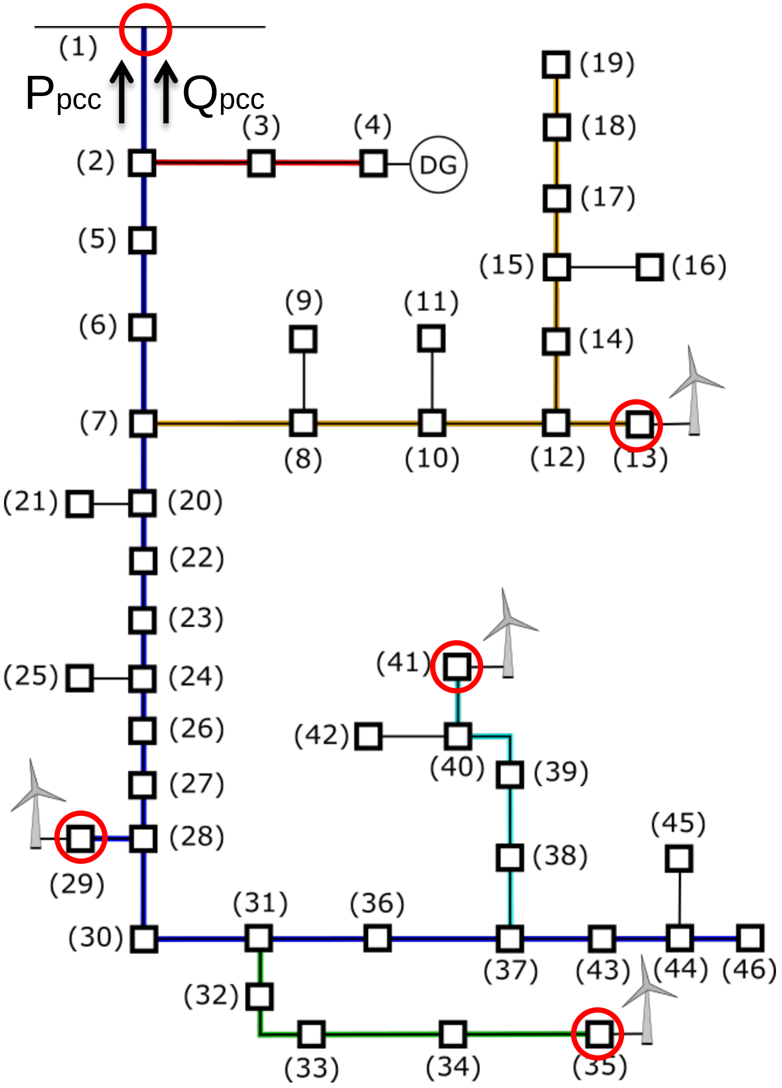
1. On-load tap changer settings
2. Length and R/X ratios of the line sections
3. Disposition of distributed generation (wind power)
4. Disposition of loads

Numerical analysis

Analysis done on model of ***typical Swedish rural 10 kV distribution grid (Vattenfall)***

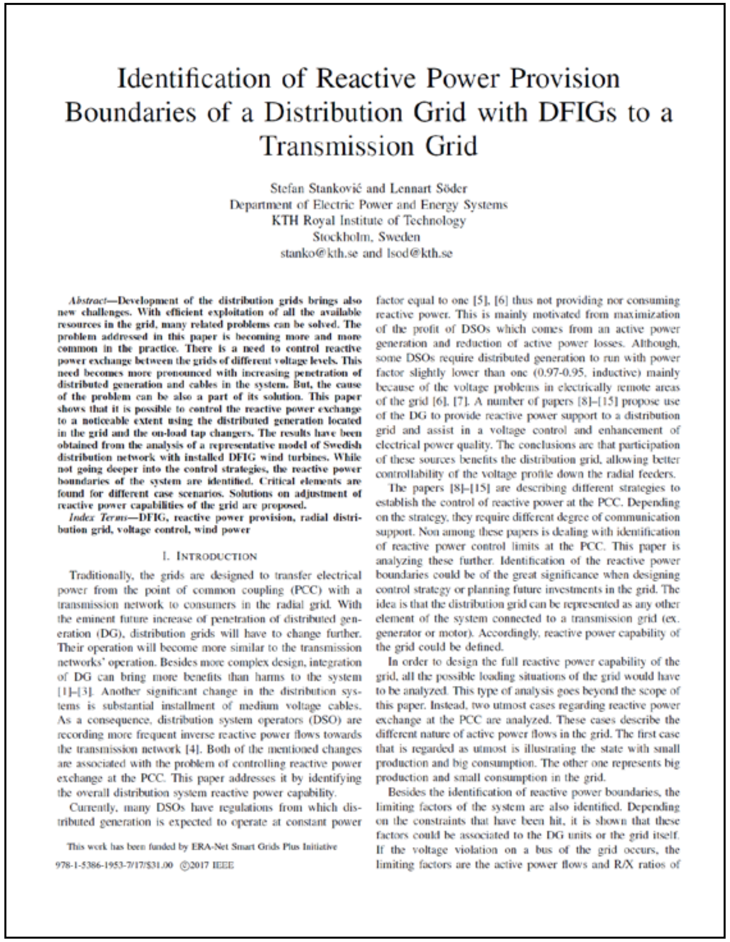
Optimization problem:

$$
\begin{aligned}
obj. \quad & \min(Q_{PCC}), \quad \max(Q_{PCC}) \\
s.t. \quad & \sum P_{inj_i} = 0 \\
& \sum Q_{inj_i} = 0 \\
& U_{min_i} < U_i < U_{max_i}, \\
& Q_{min_j} < Q_j < Q_{max_j}, \\
& \\
& \forall i \in Bus, \forall j \in Gen
\end{aligned}
$$



Assessed influences

- System loading conditions:
  1) min consumption, 80% production
  2) max consumption, no production
- Reactive power boundaries of DG
- On-load tap changer (OLTC) influence
- R/X ratios of the lines
- Disposition of DG and loads



Identification of Reactive Power Provision Boundaries of a Distribution Grid with DFIGs to a Transmission Grid

Stefan Stanković and Lennart Söder
Department of Electric Power and Energy Systems
KTH Royal Institute of Technology
Stockholm, Sweden
stanko@kth.se and lsod@kth.se

***Abstract*—Development of the distribution grids brings also new challenges. With efficient exploitation of all the available resources in the grid, many related problems can be solved. The problem addressed in this paper is becoming more and more common in the practice. There is a need to control reactive power exchange between the grids of different voltage levels. This need becomes more pronounced with increasing penetration of distributed generation and cables in the system. But, the cause of the problem can be also a part of its solution. This paper shows that it is possible to control the reactive power exchange to a noticeable extent using the distributed generation located in the grid and the on-load tap changers. The results have been obtained from the analysis of a representative model of Swedish distribution network with installed DFIG wind turbines. While not going deeper into the control strategies, the reactive power boundaries of the system are identified. Critical elements are found for different case scenarios. Solutions on adjustment of reactive power capabilities of the grid are proposed.**

***Index Terms*—DFIG, reactive power provision, radial distribution grid, voltage control, wind power**

I. INTRODUCTION

Traditionally, the grids are designed to transfer electrical power from the point of common coupling (PCC) with a transmission network to consumers in the radial grid. With the eminent future increase of penetration of distributed generation (DG), distribution grids will have to change further. Their operation will become more similar to the transmission networks' operation. Besides more complex design, integration of DG can bring more benefits than harms to the system [1]–[3]. Another significant change in the distribution systems is substantial installment of medium voltage cables. As a consequence, distribution system operators (DSO) are recording more frequent inverse reactive power flows towards the transmission network [4]. Both of the mentioned changes are associated with the problem of controlling reactive power exchange at the PCC. This paper addresses it by identifying the overall distribution system reactive power capability.

Currently, many DSOs have regulations from which distributed generation is expected to operate at constant power factor equal to one [5], [6] thus not providing nor consuming reactive power. This is mainly motivated from maximization of the profit of DSOs which comes from an active power generation and reduction of active power losses. Although, some DSOs require distributed generation to run with power factor slightly lower than one (0.97-0.95, inductive) mainly because of the voltage problems in electrically remote areas of the grid [6], [7]. A number of papers [8]–[15] propose use of the DG to provide reactive power support to a distribution grid and assist in a voltage control and enhancement of electrical power quality. The conclusions are that participation of these sources benefits the distribution grid, allowing better controllability of the voltage profile down the radial feeders.

The papers [8]–[15] are describing different strategies to establish the control of reactive power at the PCC. Depending on the strategy, they require different degree of communication support. Non among these papers is dealing with identification of reactive power control limits at the PCC. This paper is analyzing these further. Identification of the reactive power boundaries could be of the great significance when designing control strategy or planning future investments in the grid. The idea is that the distribution grid can be represented as any other element of the system connected to a transmission grid (ex. generator or motor). Accordingly, reactive power capability of the grid could be defined.

In order to design the full reactive power capability of the grid, all the possible loading situations of the grid would have to be analyzed. This type of analysis goes beyond the scope of this paper. Instead, two utmost cases regarding reactive power exchange at the PCC are analyzed. These cases describe the different nature of active power flows in the grid. The first case that is regarded as utmost is illustrating the state with small production and big consumption. The other one represents big production and small consumption in the grid.

Besides the identification of reactive power boundaries, the limiting factors of the system are also identified. Depending on the constraints that have been hit, it is shown that these factors could be associated to the DG units or the grid itself. If the voltage violation on a bus of the grid occurs, the limiting factors are the active power flows and R/X ratios of

This work has been funded by ERA-Net Smart Grids Plus Initiative

978-1-5386-1953-7/17/$31.00 ©2017 IEEE

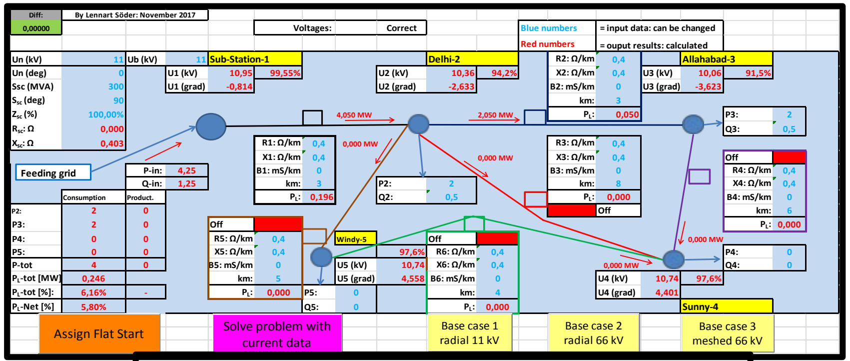
IEEE International Conference on Innovative Smart Grid Technologies IEEE ISGT Europe 2017, Turin, Italy, September 2017

Tutorial T1 on voltage control and wind power

- **Impact from wind power:**
    - Selection of power factor
    - Impact on local voltage
    - Hosting capacity
    - Impact on losses
    - Possibility to supply feeding grid with reactive power
    - Use of OLTC (On Load Tap Changers) in transformer
    - Impact from grid strength.
    - Impact from R/X quota of grid

Tutorial T1 on voltage control and wind power

- **Tool: Excel Load Flow program**



Diff: 0,00000

By Lennart Söder: November 2017

Voltages: Correct

Blue numbers = input data: can be changed

Red numbers = ouput results: calculated

Un (kV) 11
Un (deg) 0
Ssc (MVA) 300
S_{sc} (deg) 90
Z_{sc} (%) 100,00%
R_{sc}: Ω 0,000
X_{sc}: Ω 0,403

Ub (kV) 11

Sub-Station-1
U1 (kV) 10,95 99,55%
U1 (grad) -0,814

Delhi-2
U2 (kV) 10,36 94,2%
U2 (grad) -2,633

Allahabad-3
U3 (kV) 10,06 91,5%
U3 (grad) -3,623

Sunny-4
U4 (kV) 10,74 97,6%
U4 (grad) 4,401

Windy-5
U5 (kV) 10,74 97,6%
U5 (grad) 4,558

P-in: 4,25
Q-in: 1,25

	Consumption	Product.
P2:	2	0
P3:	2	0
P4:	0	0
P5:	0	0
P-tot	4	0
P_L-tot [MW]	0,246	
P_L-tot [%]:	6,16%	-
P_L-Net [%]	5,80%	

R1: Ω/km 0,4
X1: Ω/km 0,4
B1: mS/km 0
km: 3
P_L: 0,196

R2: Ω/km 0,4
X2: Ω/km 0,4
B2: mS/km 0
km: 3
P_L: 0,050

R3: Ω/km 0,4
X3: Ω/km 0,4
B3: mS/km 0
km: 8
P_L: 0,000
Off

Off
R4: Ω/km 0,4
X4: Ω/km 0,4
B4: mS/km 0
km: 6
P_L: 0,000

Off
R5: Ω/km 0,4
X5: Ω/km 0,4
B5: mS/km 0
km: 5
P_L: 0,000

Off
R6: Ω/km 0,4
X6: Ω/km 0,4
B6: mS/km 0
km: 4
P_L: 0,000

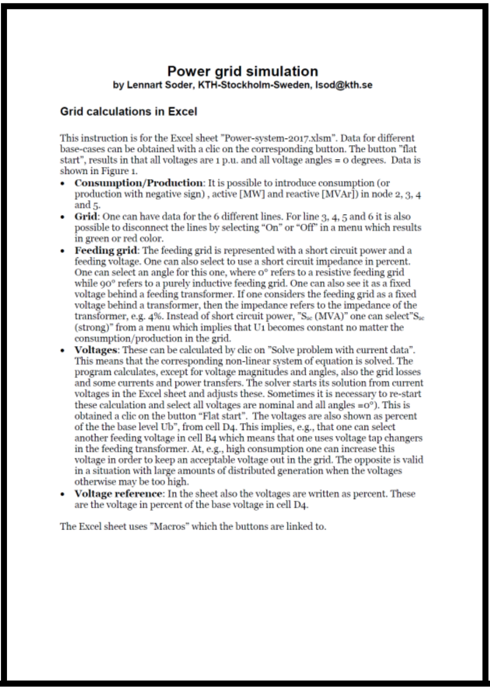
P2: 2
Q2: 0,5

P3: 2
Q3: 0,5

P4: 0
Q4: 0

P5: 0
Q5: 0

Power-system-2017.xlsm



Power grid simulation
by Lennart Soder, KTH-Stockholm-Sweden, lsod@kth.se

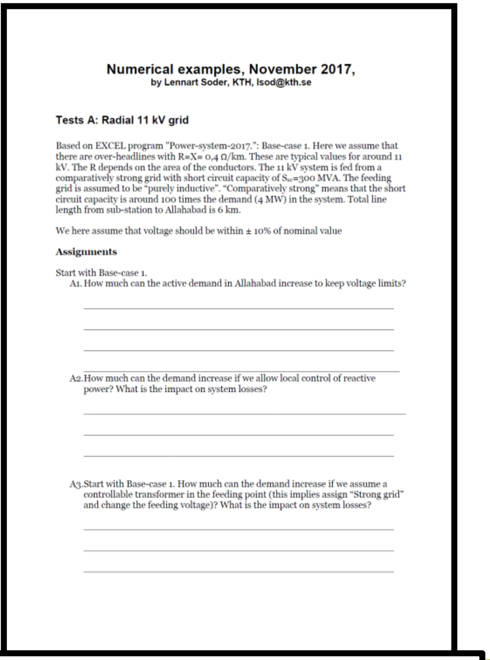
Grid calculations in Excel

This instruction is for the Excel sheet "Power-system-2017.xlsm". Data for different base-cases can be obtained with a clic on the corresponding button. The button "flat start", results in that all voltages are 1 p.u. and all voltage angles = 0 degrees. Data is shown in Figure 1.

- **Consumption/Production**: It is possible to introduce consumption (or production with negative sign) , active [MW] and reactive [MVAr]) in node 2, 3, 4 and 5.
- **Grid**: One can have data for the 6 different lines. For line 3, 4, 5 and 6 it is also possible to disconnect the lines by selecting "On" or "Off" in a menu which results in green or red color.
- **Feeding grid**: The feeding grid is represented with a short circuit power and a feeding voltage. One can also select to use a short circuit impedance in percent. One can select an angle for this one, where 0° refers to a resistive feeding grid while 90° refers to a purely inductive feeding grid. One can also see it as a fixed voltage behind a feeding transformer. If one considers the feeding grid as a fixed voltage behind a transformer, then the impedance refers to the impedance of the transformer, e.g. 4%. Instead of short circuit power, "S_{sc} (MVA)" one can select"S_{sc} (strong)" from a menu which implies that U1 becomes constant no matter the consumption/production in the grid.
- **Voltages**: These can be calculated by clic on "Solve problem with current data". This means that the corresponding non-linear system of equation is solved. The program calculates, except for voltage magnitudes and angles, also the grid losses and some currents and power transfers. The solver starts its solution from current voltages in the Excel sheet and adjusts these. Sometimes it is necessary to re-start these calculation and select all voltages are nominal and all angles =0°). This is obtained a clic on the button "Flat start". The voltages are also shown as percent of the the base level Ub", from cell D4. This implies, e.g., that one can select another feeding voltage in cell B4 which means that one uses voltage tap changers in the feeding transformer. At, e.g., high consumption one can increase this voltage in order to keep an acceptable voltage out in the grid. The opposite is valid in a situation with large amounts of distributed generation when the voltages otherwise may be too high.
- **Voltage reference**: In the sheet also the voltages are written as percent. These are the voltage in percent of the base voltage in cell D4.

The Excel sheet uses "Macros" which the buttons are linked to.

Excel-instructions-171031.pdf



Numerical examples, November 2017,
by Lennart Soder, KTH, lsod@kth.se

Tests A: Radial 11 kV grid

Based on EXCEL program "Power-system-2017.": Base-case 1. Here we assume that there are over-headlines with R=X= 0,4 Ω/km. These are typical values for around 11 kV. The R depends on the area of the conductors. The 11 kV system is fed from a comparatively strong grid with short circuit capacity of S_{sc}=300 MVA. The feeding grid is assumed to be "purely inductive". "Comparatively strong" means that the short circuit capacity is around 100 times the demand (4 MW) in the system. Total line length from sub-station to Allahabad is 6 km.

We here assume that voltage should be within ± 10% of nominal value

Assignments

Start with Base-case 1.

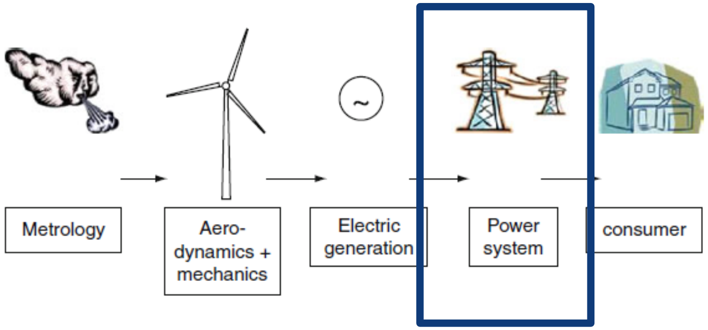
A1. How much can the active demand in Allahabad increase to keep voltage limits?

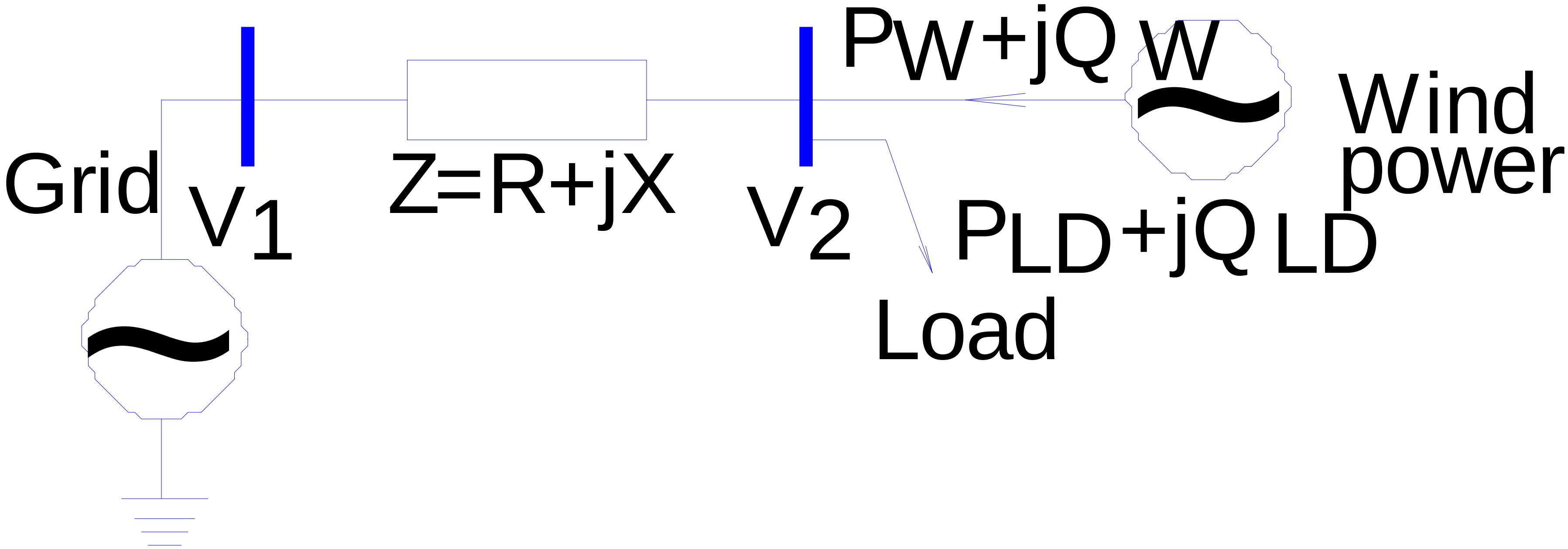
A2. How much can the demand increase if we allow local control of reactive power? What is the impact on system losses?

A3. Start with Base-case 1. How much can the demand increase if we assume a controllable transformer in the feeding point (this implies assign "Strong grid" and change the feeding voltage)? What is the impact on system losses?

Examples-171110.pdf

Grid connection - 1





Assume that voltage is known in one end of a line and P+Q in the other.

Based on this information:
Calculate the voltage in the other end.

$$\begin{cases} P_{kj} & = & \frac{U_k^2}{Z^2}R + \frac{U_kU_j}{Z^2}\left(X\sin\theta_k - R\cos\theta_k\right) \\ Q_{kj} & = & -BU_k^2 + \frac{U_k^2}{Z^2}X - \frac{U_kU_j}{Z^2}\left(R\sin\theta_k + X\cos\theta_k\right) \end{cases}$$

Solution :

$$U_k^2 = -\frac{a_4}{2a_3} \overset{+}{(-)} \sqrt{\left(\frac{a_4}{2a_3}\right)^2 - \frac{1}{a_3}\left(a_1^2 + a_2^2\right)}$$

$$\begin{aligned}
a_1 &= -RP_{kj} - XQ_{kj} \\
a_2 &= -XP_{kj} + RQ_{kj} \\
a_3 &= (1 - XB)^2 + R^2B^2 \\
a_4 &= 2 \cdot a_1(1 - XB) - U_j^2 + 2a_2RB
\end{aligned}$$

Here
B = 0

$$U_k = \overset{+}{(-)} \sqrt{U_k^2} \qquad P_L = R\frac{P_{kj}^2 + (Q_{kj} + BU_k^2)^2}{U_k^2}$$

Exact :

$$U_k^2 = -\frac{a_4}{2a_3} \overset{+}{(-)} \sqrt{\left(\frac{a_4}{2a_3}\right)^2 - \frac{1}{a_3}\left(a_1^2 + a_2^2\right)}$$

$$\begin{aligned} a_1 &= -RP_{kj} - XQ_{kj} \\ a_2 &= -XP_{kj} + RQ_{kj} \\ a_3 &= (1 - XB)^2 + R^2B^2 \\ a_4 &= 2 \cdot a_1(1 - XB) - U_j^2 + 2a_2RB \end{aligned}$$

Here
B = 0

$$U_k = \overset{+}{(-)} \sqrt{U_k^2}$$

Simplified :

$$U_k \approx \frac{U_j}{2} + \sqrt{\frac{U_j^2}{4} + RP_{kj} + XQ_{kj}}$$

$$\Rightarrow$$

$$\left[U_k - \frac{U_j}{2}\right]^2 \approx \frac{U_j^2}{4} + RP_{kj} + XQ_{kj}$$

$$\Rightarrow$$

$$\boxed{U_k - U_j \approx \frac{RP_{kj} + XQ_{kj}}{U_k}}$$

Concerning voltage control and reactive power

$$\boxed{U_k - U_j \approx \frac{RP_{kj} + XQ_{kj}}{U_k}}$$

High X/R quota (transmission grids U>70 kV: X/R > 10

- Active power has comparatively low impact on voltage
- Reactive power has high impact on local voltage

Low X/R quota (distribution grids and cable grids, U=11 kV: X/R ≈1, 0,4 kV: X/R ≈ 0,2

- Reactive power can be transported without a high impact on local voltage