Resilient Electricity Systems

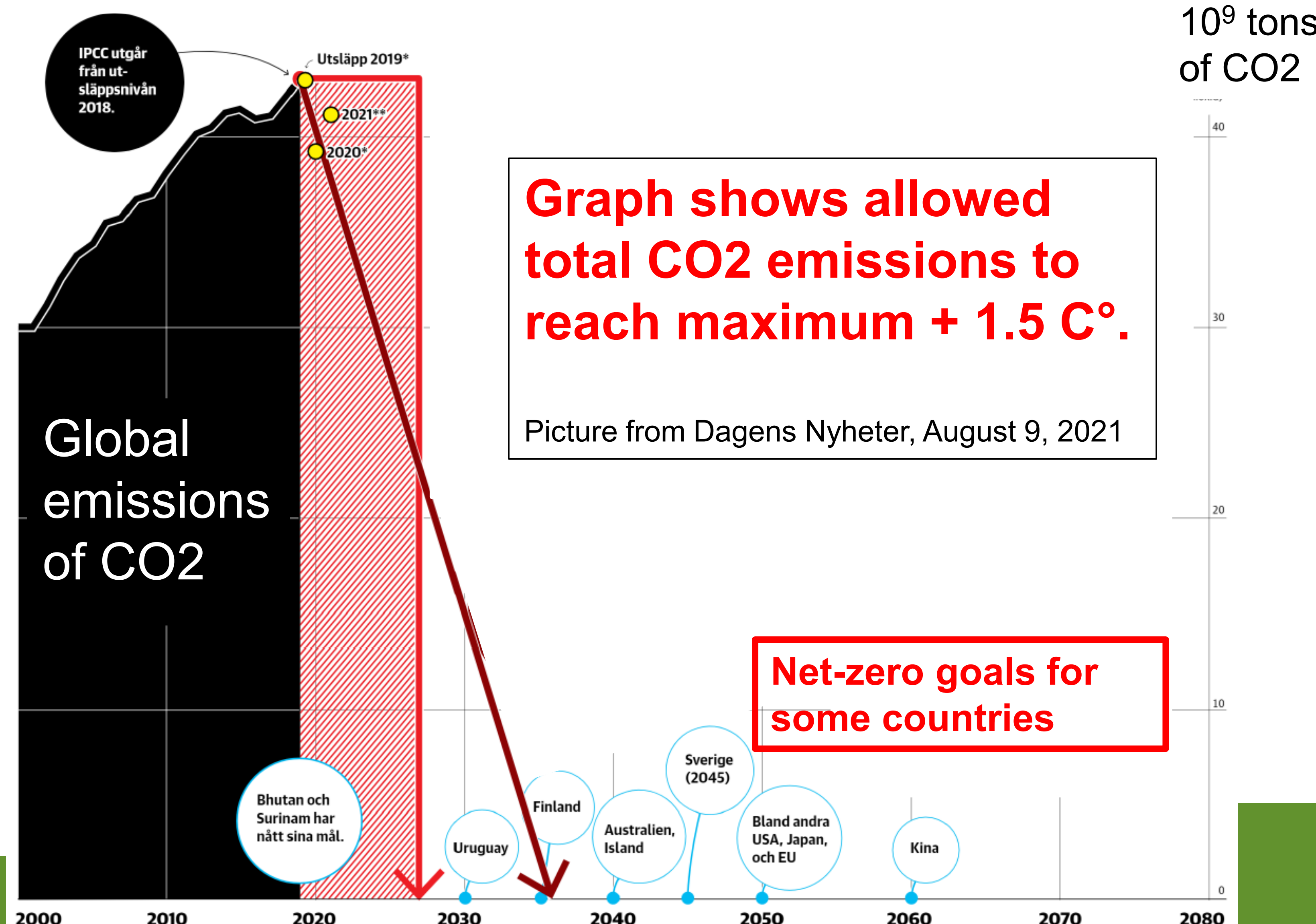
SEEEP High Level Summer School

"Energy Transition: Resilient Energy Systems"

Stockholm & Eindhoven – August 15-26, 2022

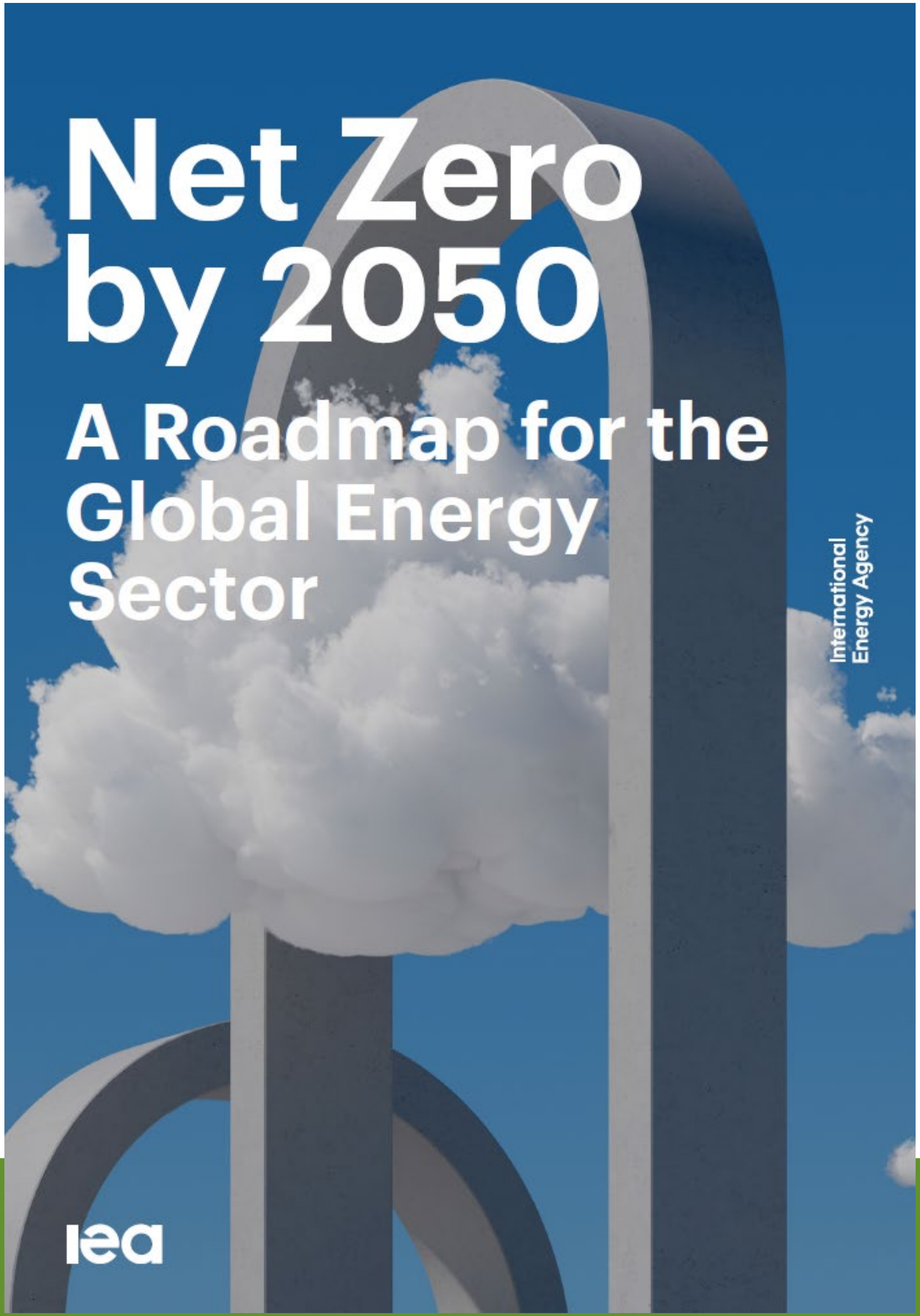
Lennart Söder
Professor in Electric Power Systems
Lsod@kth.se, https://www.kth.se/profile/lsod/

IPCC report, published Monday August 9, 2021



Report from IEA – International Energy Agency

May 2021



Assumed cost development: p 201

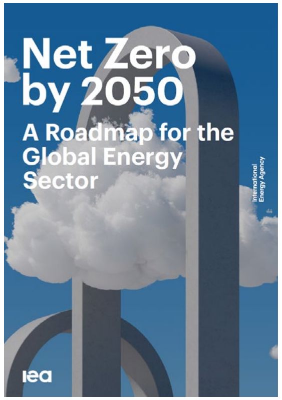


Table B.1 ▷ Electricity generation technology costs by selected region in the NZE

	Financing rate (%)	Capital costs ($/kW)			Capacity factor (%)			Fuel, CO_2 and O&M ($/MWh)			LCOE ($/MWh)		
	All	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
European Union													
Nuclear	8.0	6 600	5 100	4 500	75	75	70	35	35	35	150	120	115
Coal	8.0	2 000	2 000	2 000	20	*n.a.*	*n.a.*	120	205	275	250	*n.a.*	*n.a.*
Gas CCGT	8.0	1 000	1 000	1 000	40	20	*n.a.*	65	95	120	100	150	*n.a.*
Solar PV	3.2	790	460	340	13	14	14	10	10	10	55	35	25
Wind onshore	3.2	1 540	1 420	1 300	29	30	31	15	15	15	55	45	40
Wind offshore	4.0	3 600	2 020	1 420	51	56	59	15	10	5	75	40	25
China													
Nuclear	7.0	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	7.0	800	800	800	60	*n.a.*	*n.a.*	75	135	195	90	*n.a.*	*n.a.*
Gas CCGT	7.0	560	560	560	45	35	*n.a.*	75	100	120	90	115	*n.a.*
Solar PV	3.5	750	400	280	17	18	19	10	5	5	40	25	15
Wind onshore	3.5	1 220	1 120	1 040	26	27	27	15	10	10	45	40	40
Wind offshore	4.3	2 840	1 560	1 000	34	41	43	25	15	10	95	45	30

IEA – Resulting energy supply

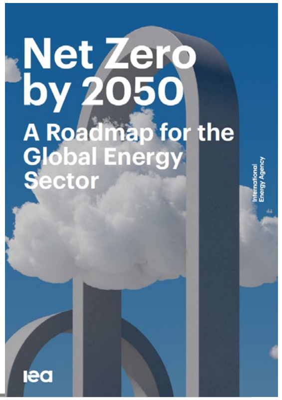
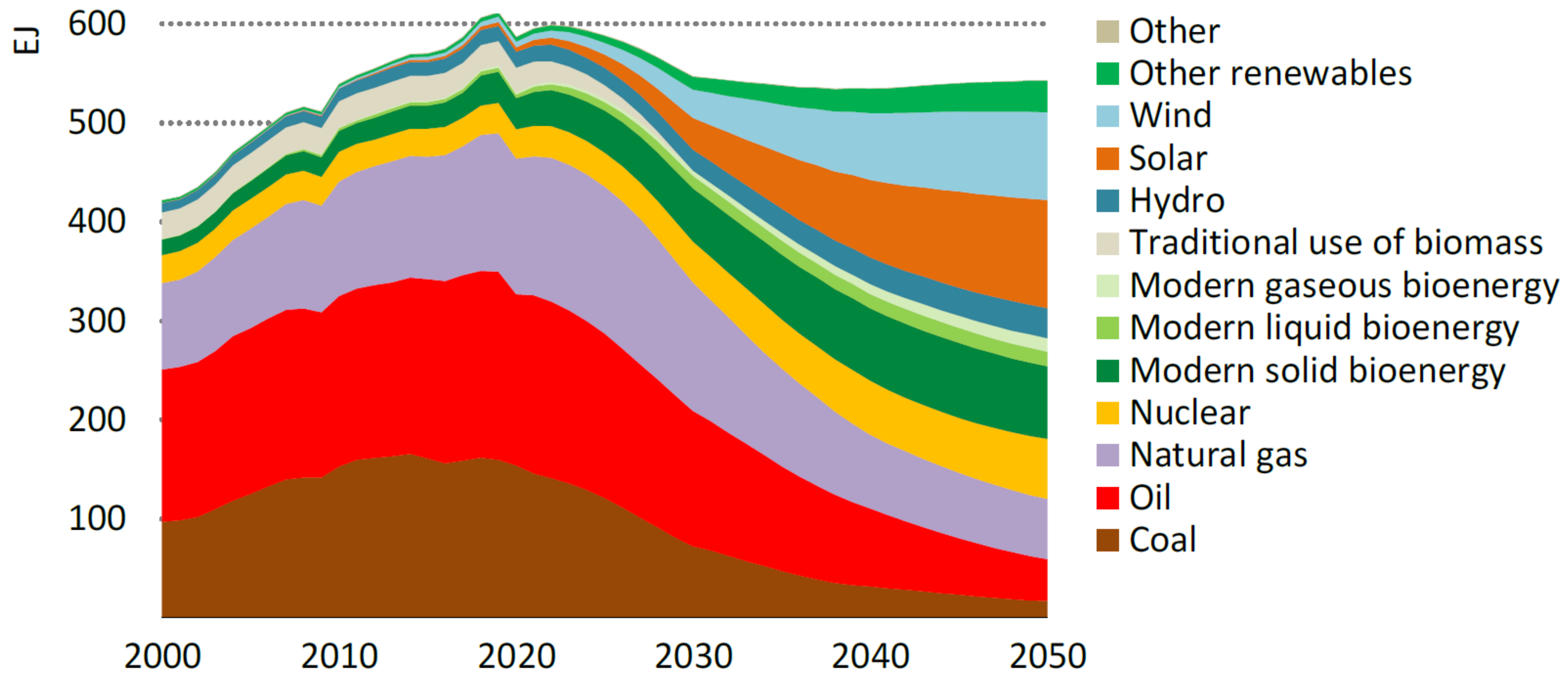
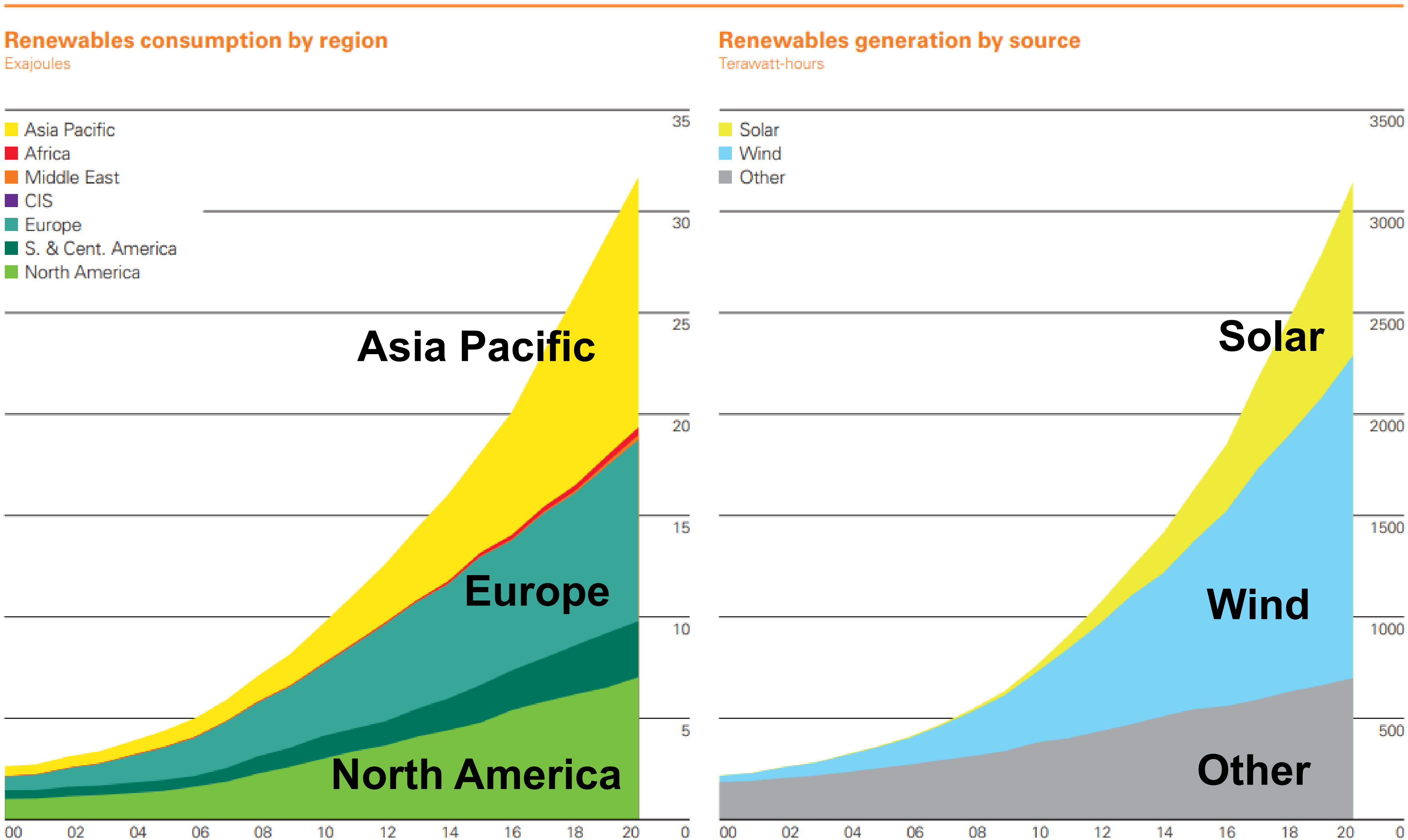


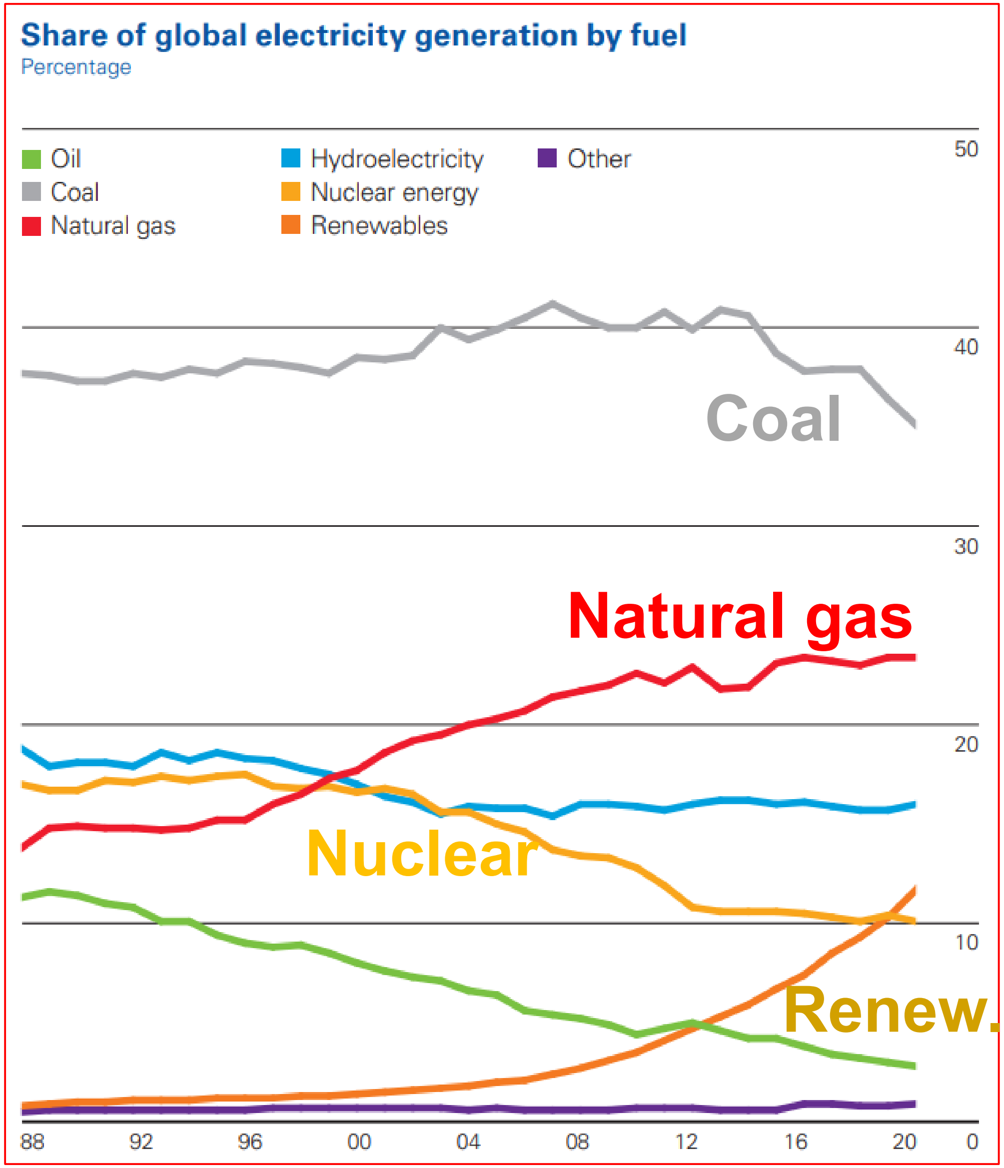
Figure 2.5 ▹ Total energy supply in the NZE



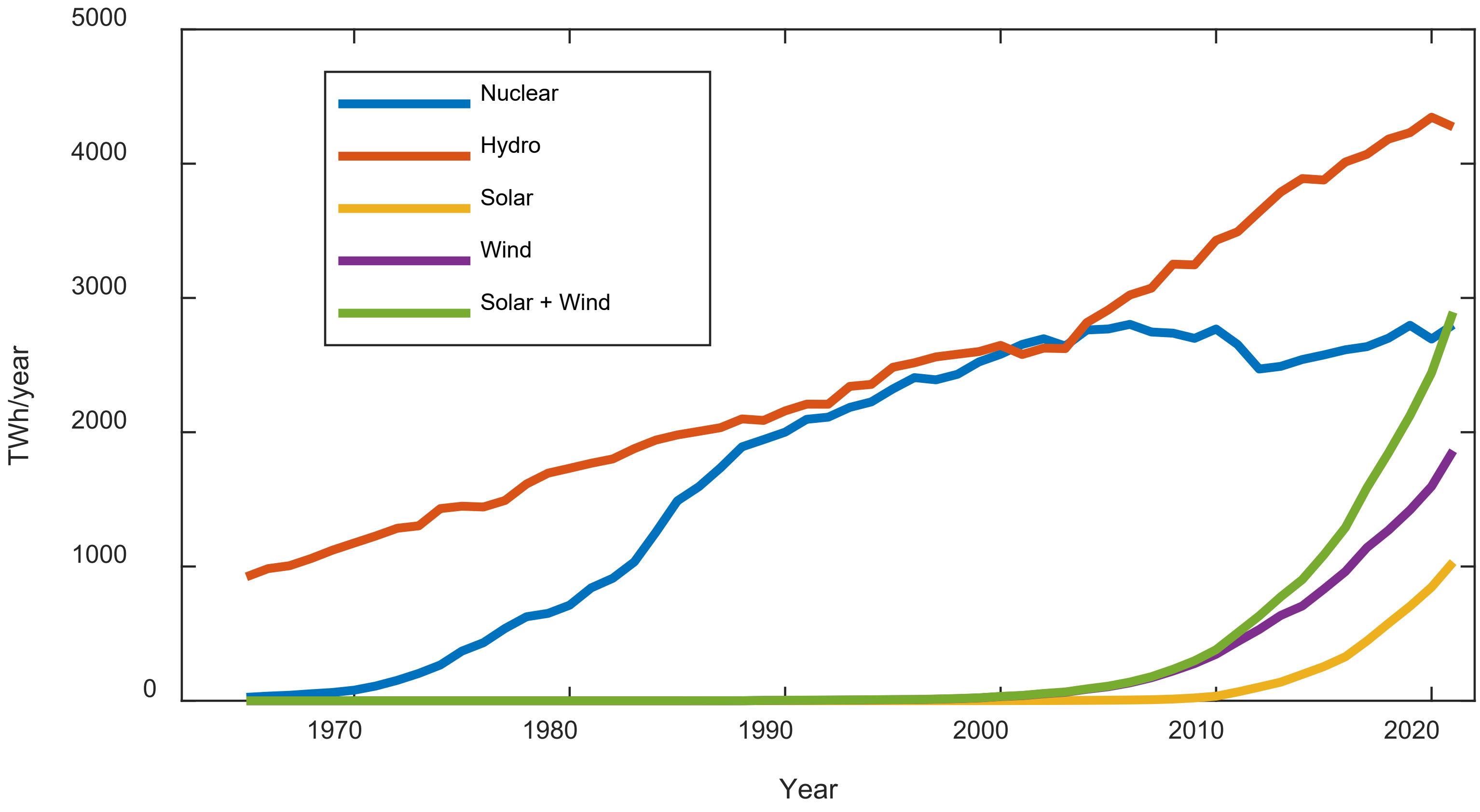
Statistics from BP concerning world use of renewable sources: 2000 - 2020



BP: global share of different electric generations sources, 1988-2020



Global statistics of nuclear and renewable electric energy: 1965 – 2021 [Source: BP]



Concerning
“Electricity production for net-zero-CO2"

Engineers/researchers should:

Concerning "Electricity production for net-zero-CO2"

Engineers/researchers should:

1. **Solve the right problems**

Concerning "Electricity production for net-zero-CO2 "

Engineers/researchers should:

1. Solve the right problems
2. Solve the problems right

Concerning "Electricity production for net-zero-CO2"

Engineers/researchers should:

1. **Solve the right problems**
2. **Solve the problems right**

"**Problem**" = The increased need for "**Energy storage and flexibility**" which very much depends on significantly larger amounts of solar and wind power.

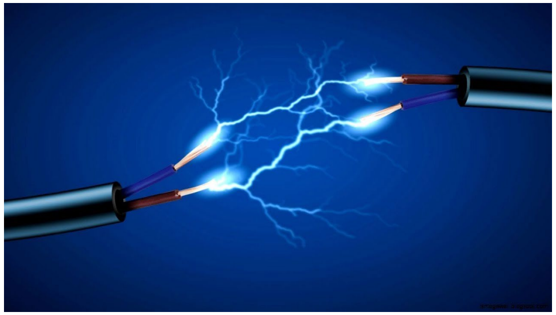
Resilient Electricity Systems

SEEEP High Level Summer School

"Energy Transition: Resilient Energy Systems"

Stockholm & Eindhoven – August 15-26, 2022

Lennart Söder
Professor in Electric Power Systems
Lsod@kth.se, https://www.kth.se/profile/lsod/

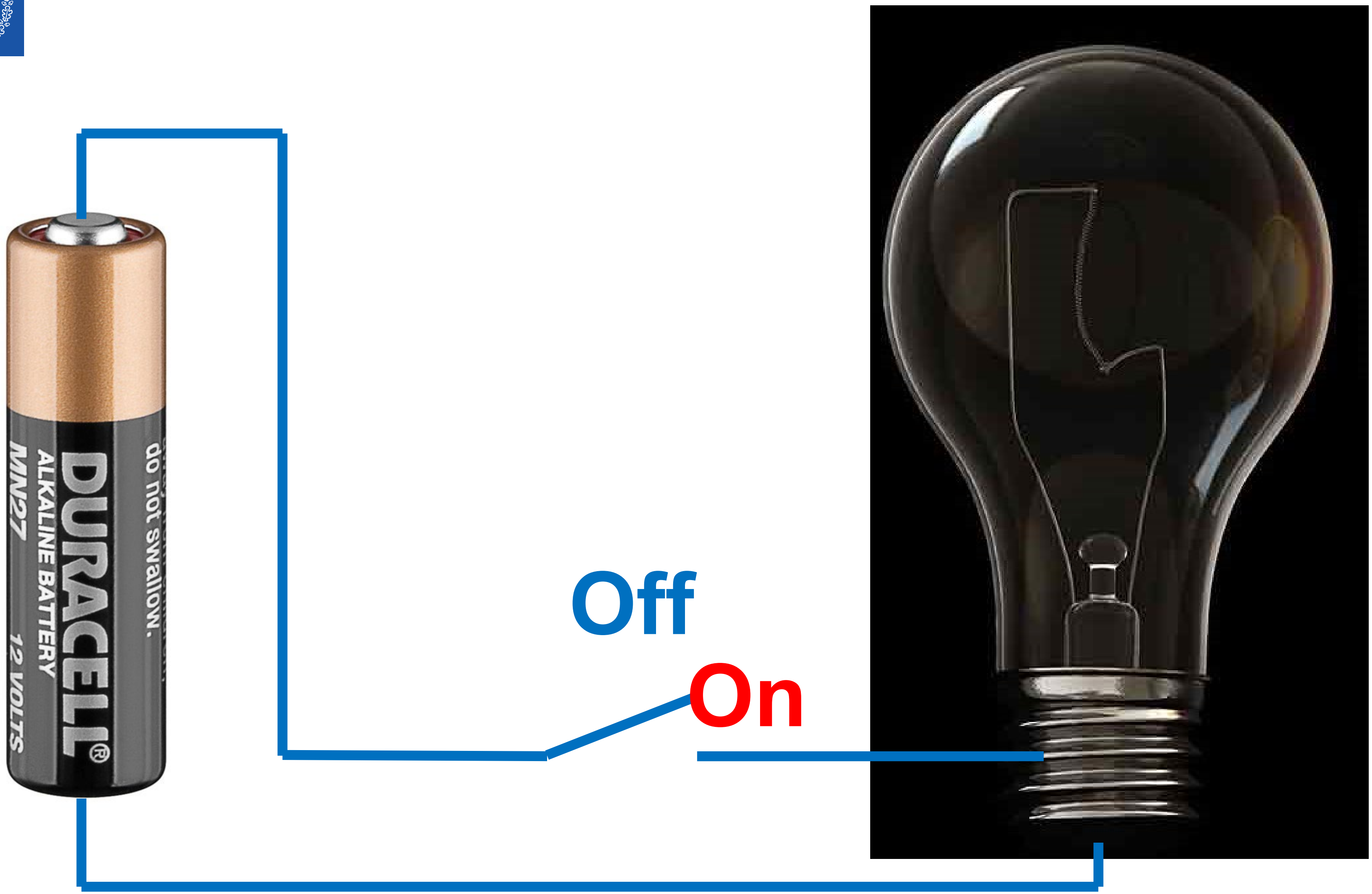


Electricity

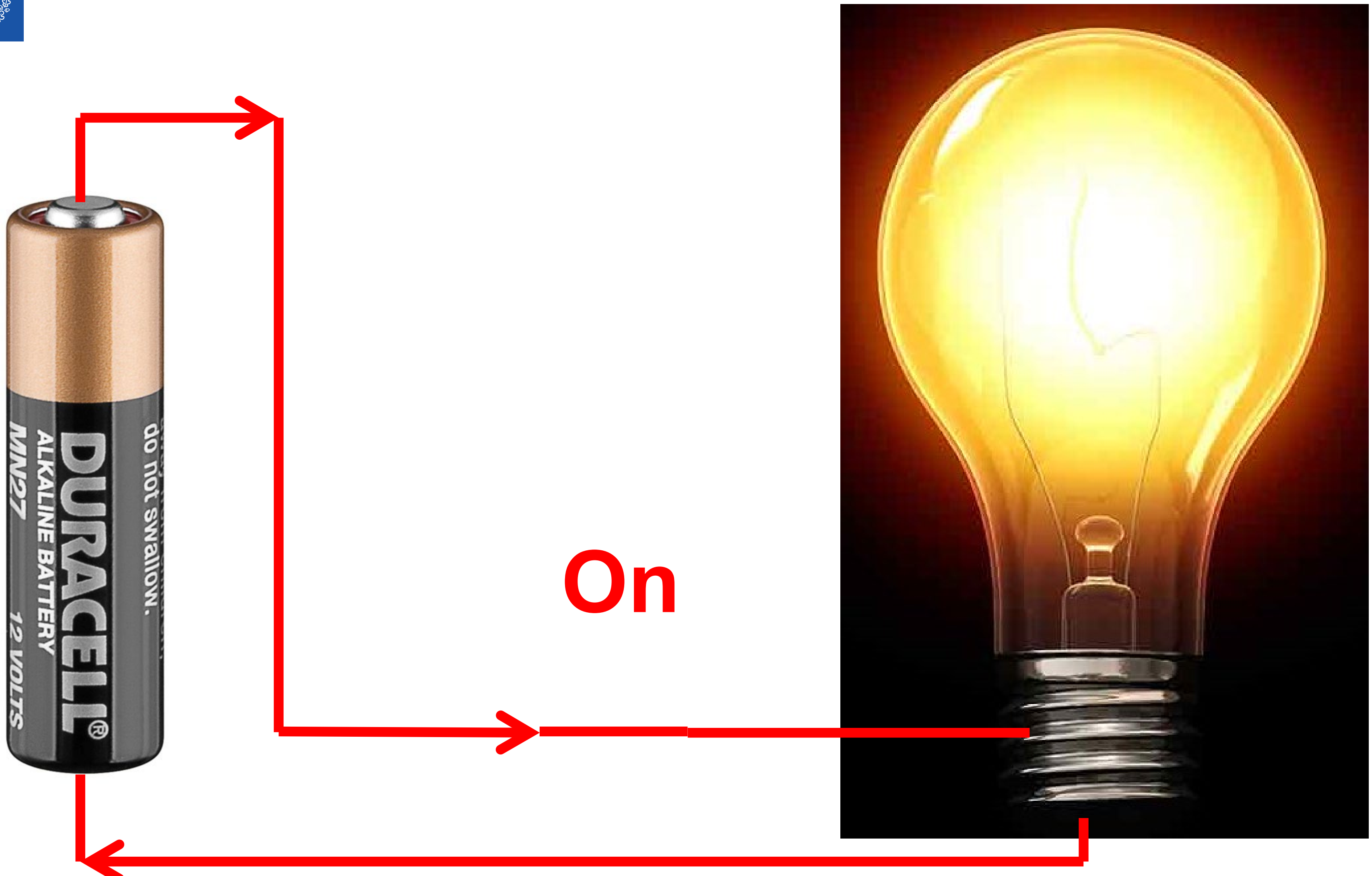
August 16, 2022

by Lennart Söder
Professor Electric Power Systems, KTH

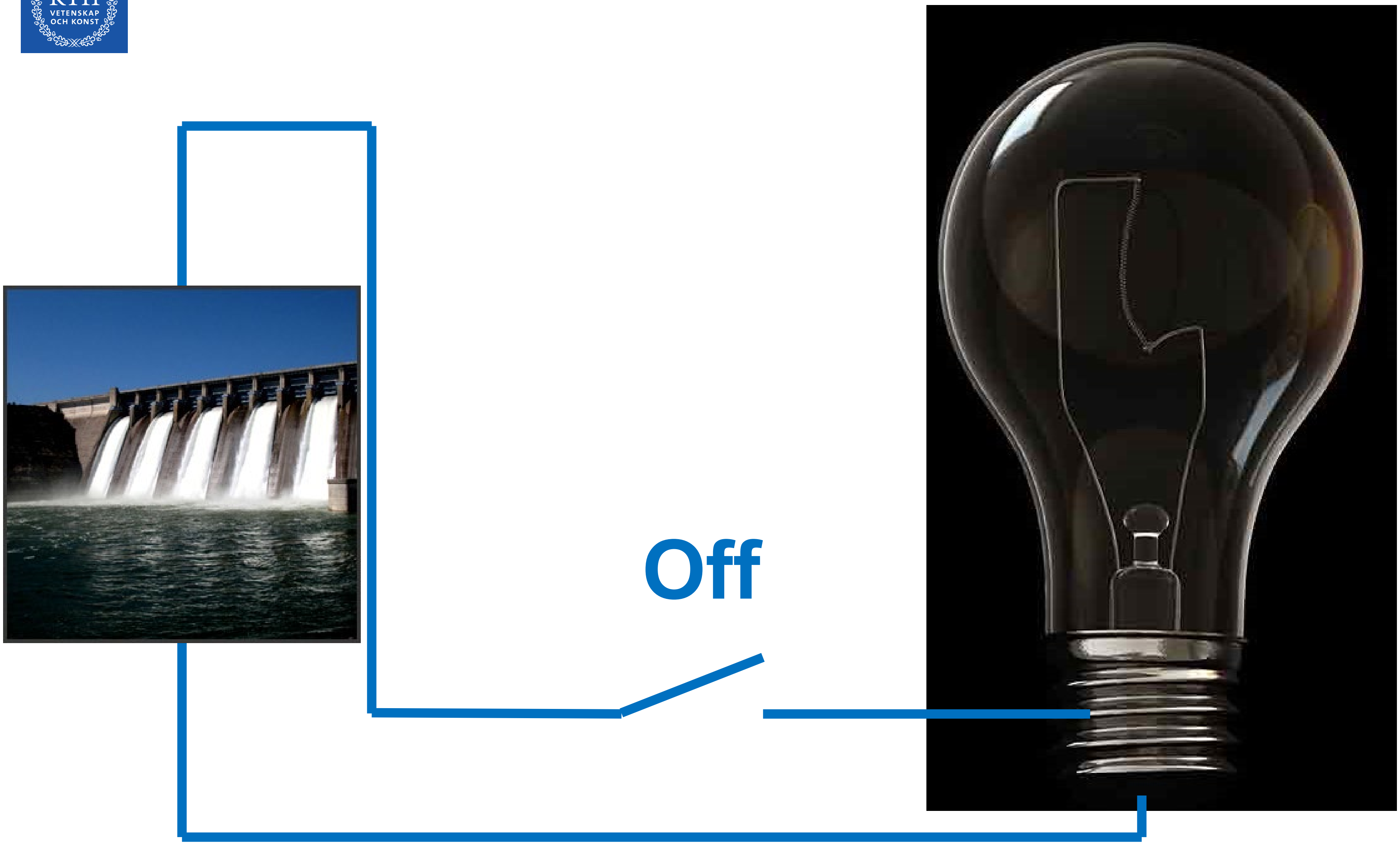
Electricity comes with the speed of light



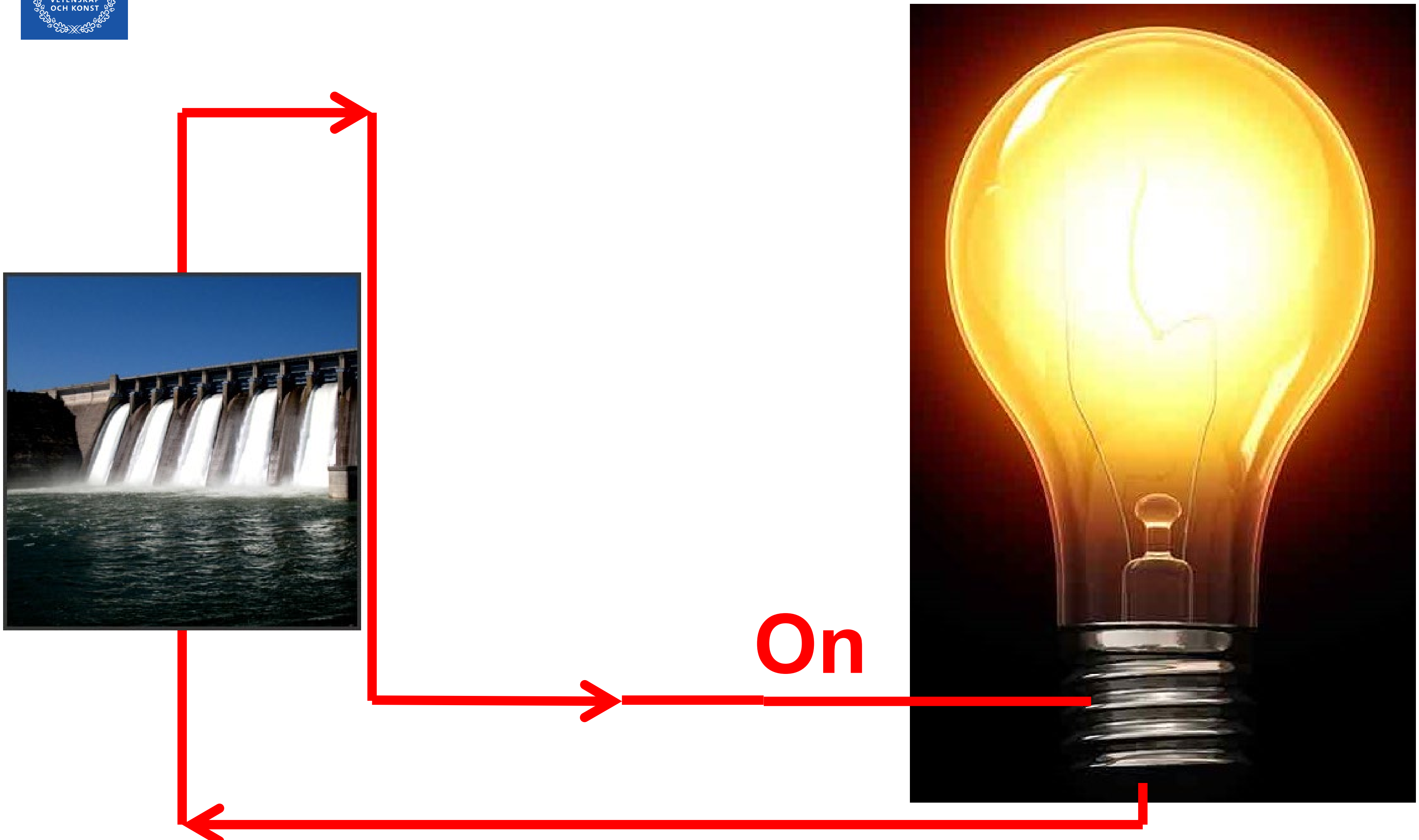
Electricity comes with the speed of light



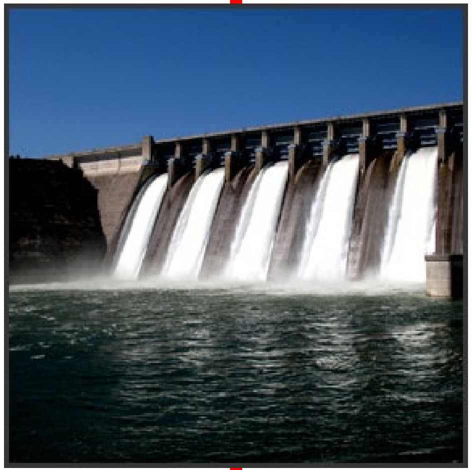
Electricity comes with the speed of light



Electricity comes with the speed of light



Electricity comes with the speed of light

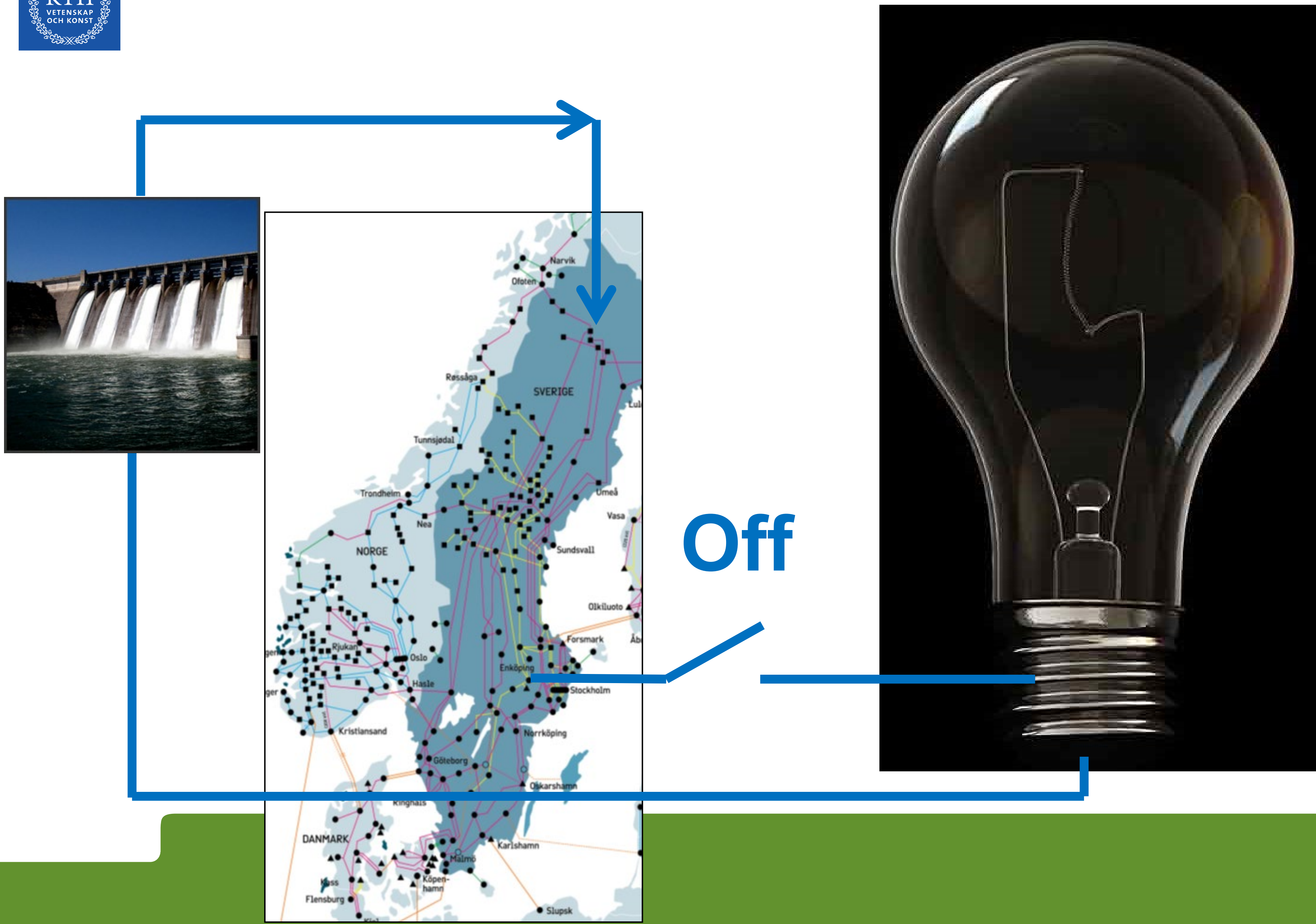


During **1/100 second**

- **Light** travels **3000 km** = Stockholm – Madrid **(Beijing-Shanghai: 1070 km)**
- **Sound** travels **3 m**.

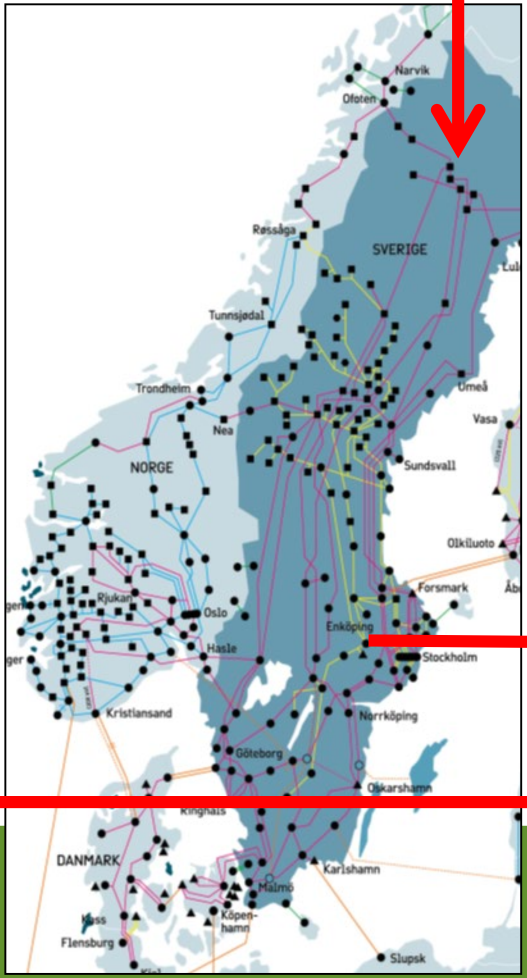
On

Electricity comes with the speed of light



Electricity comes with the speed of light

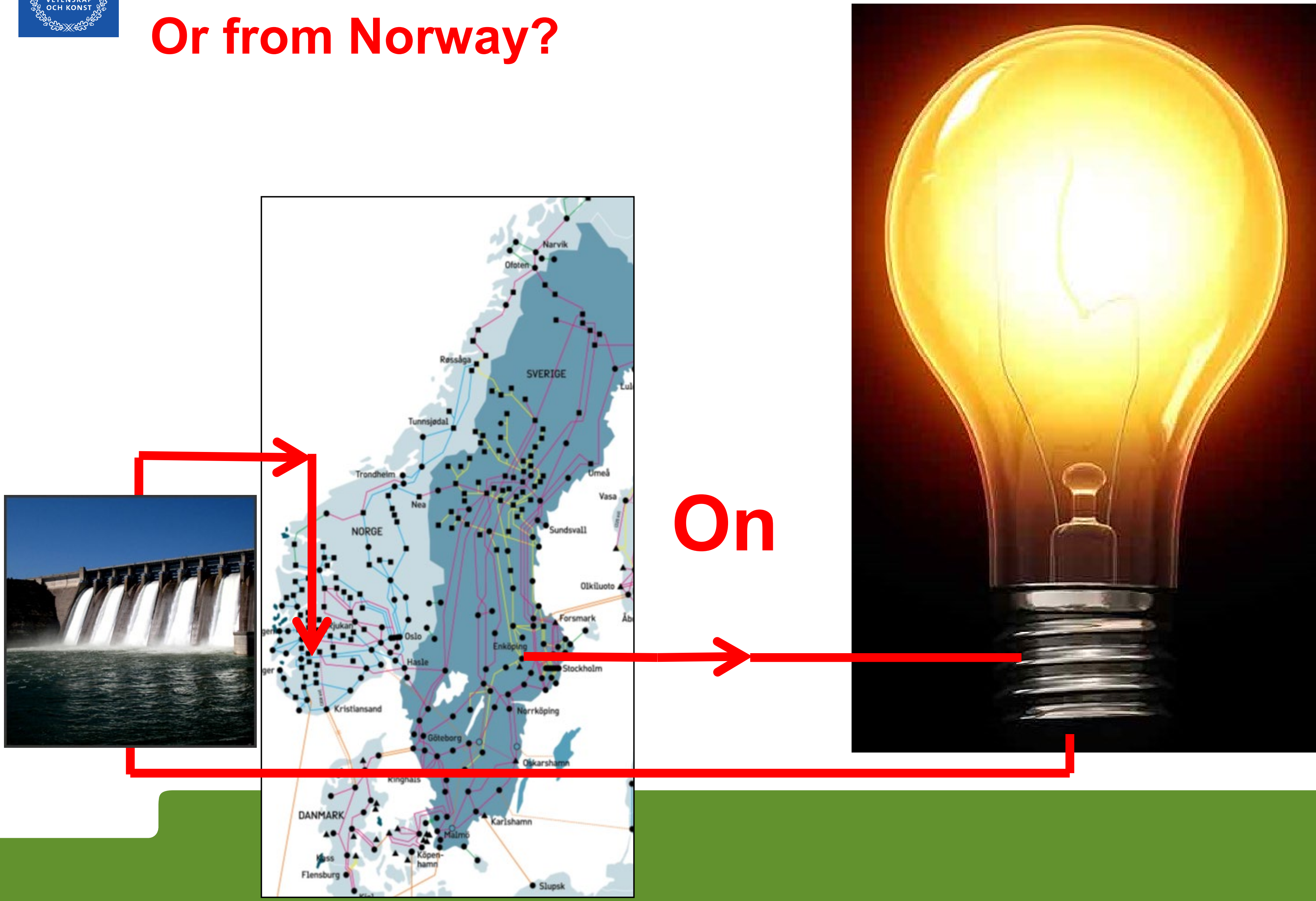
From North Sweden



On

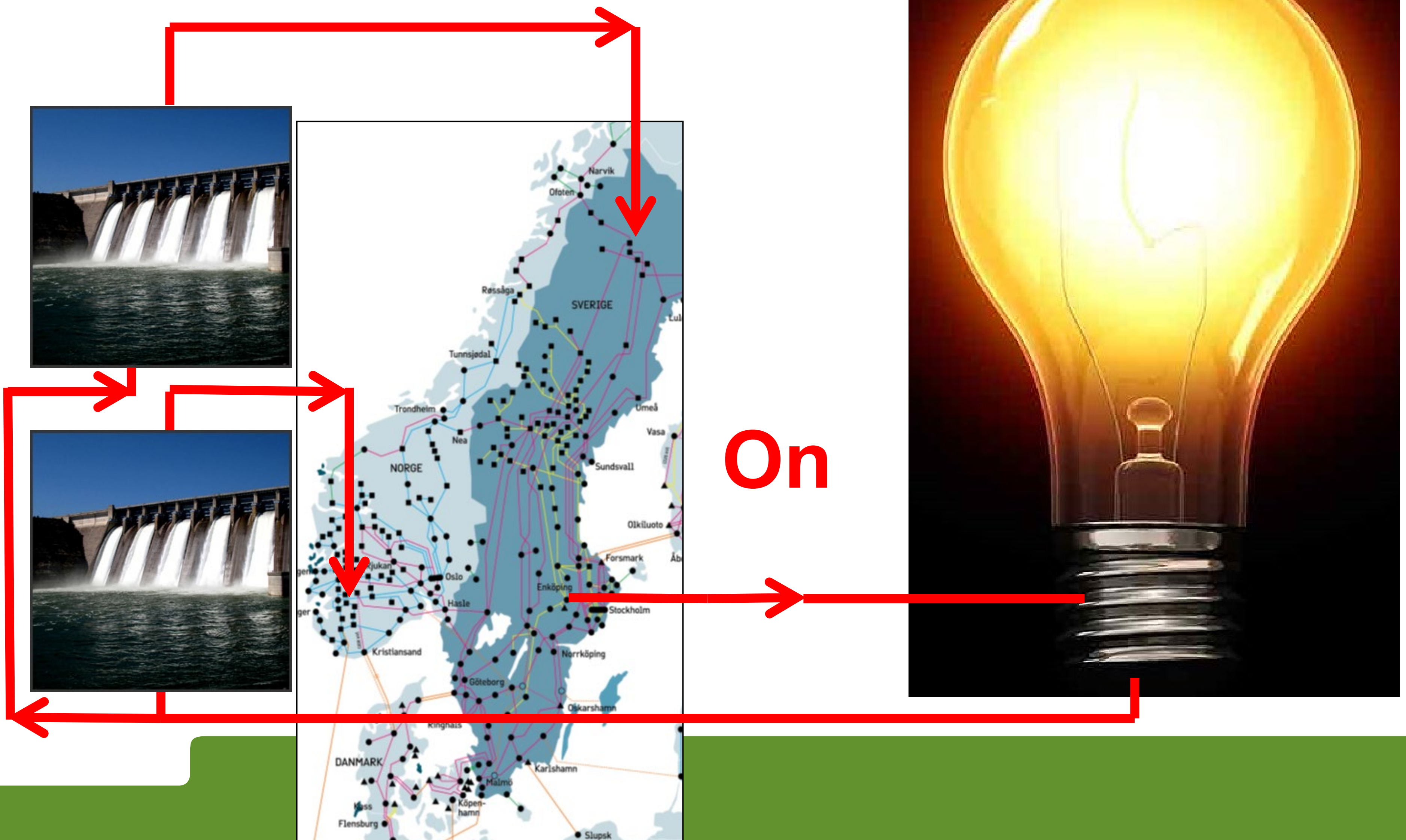
Electricity comes with the speed of light

Or from Norway?



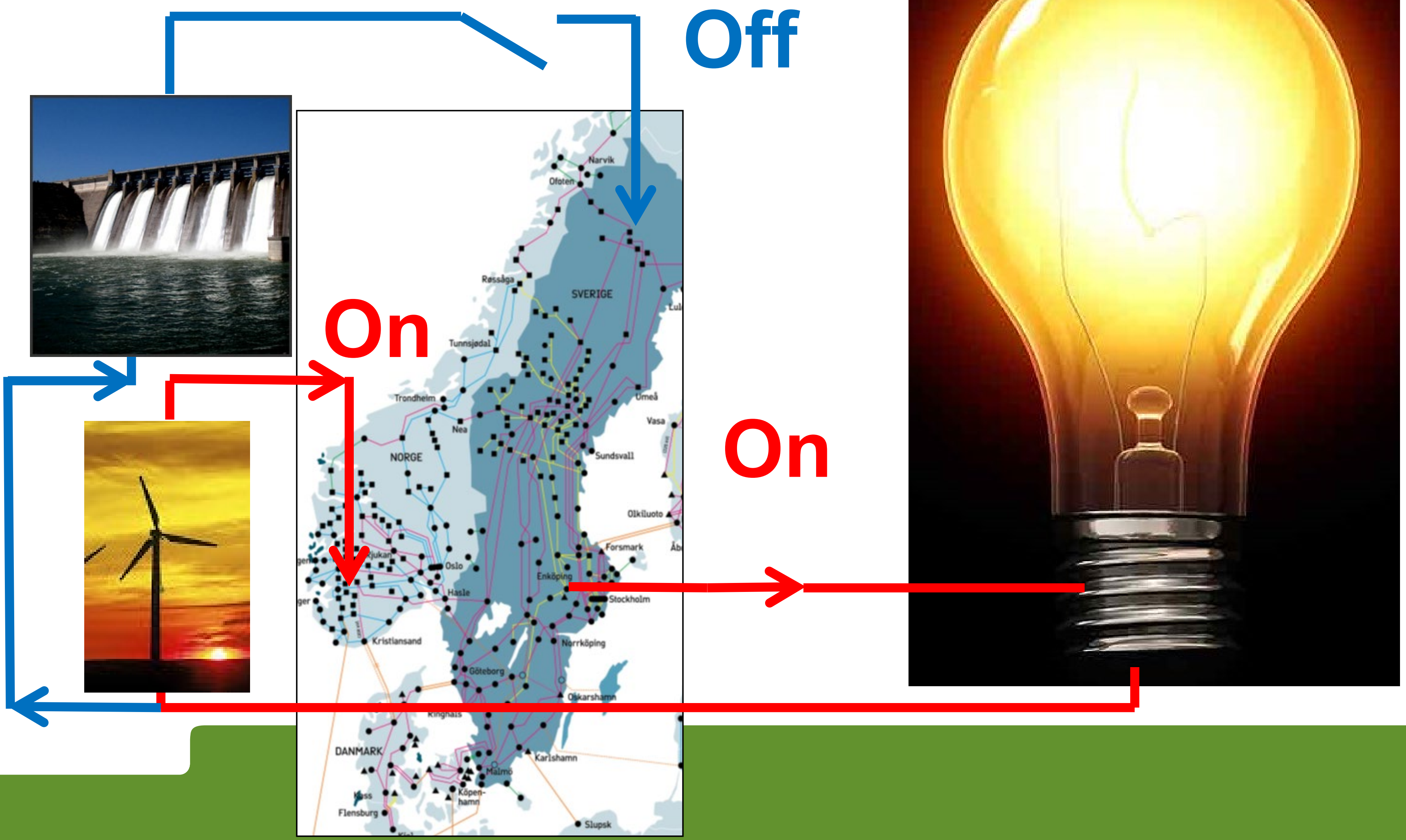
Electricity comes with the speed of light

Or Sweden + Norway?



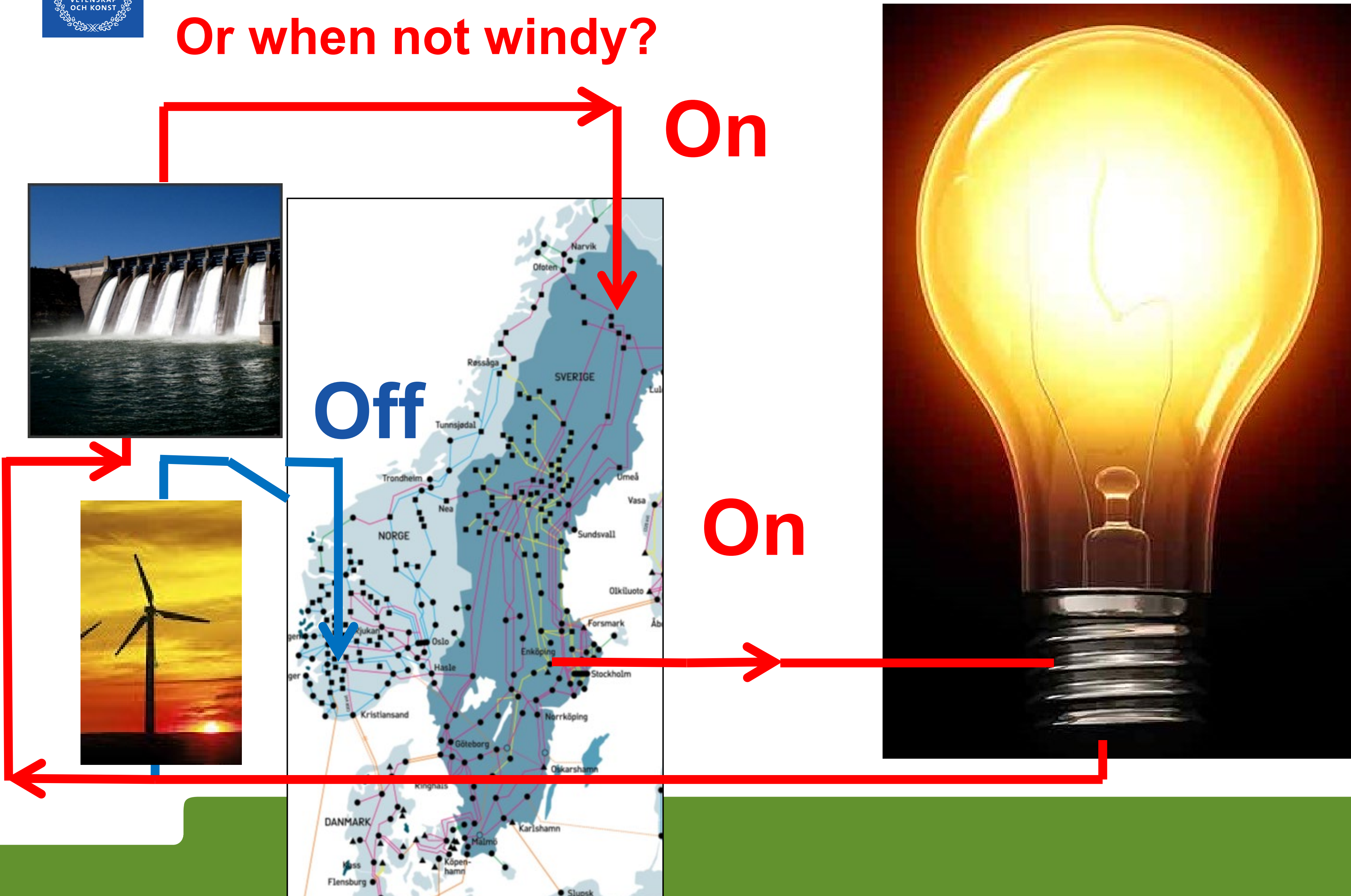
Electricity comes with the speed of light

Or with wind power?



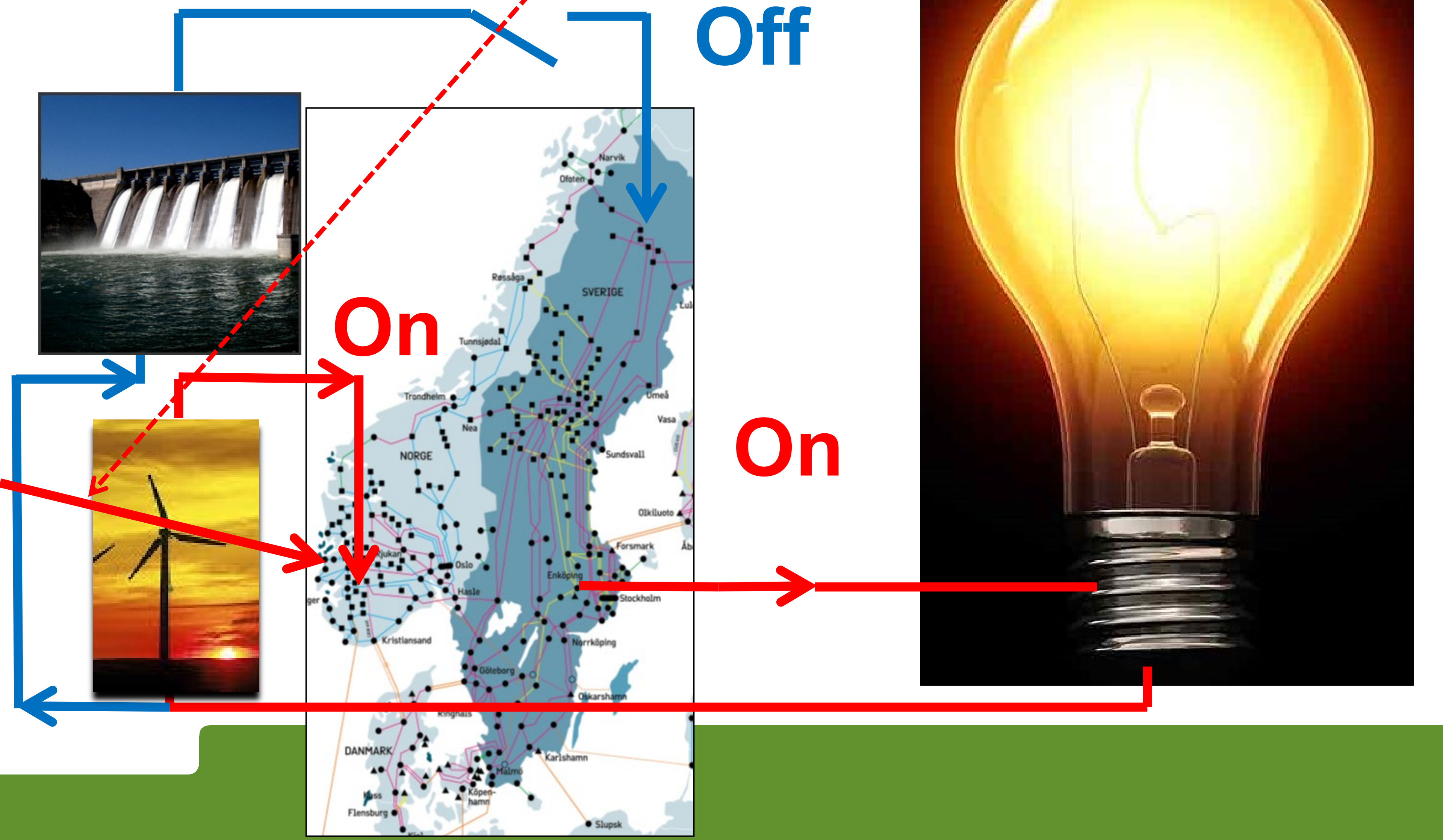
Electricity comes with the speed of light

Or when not windy?



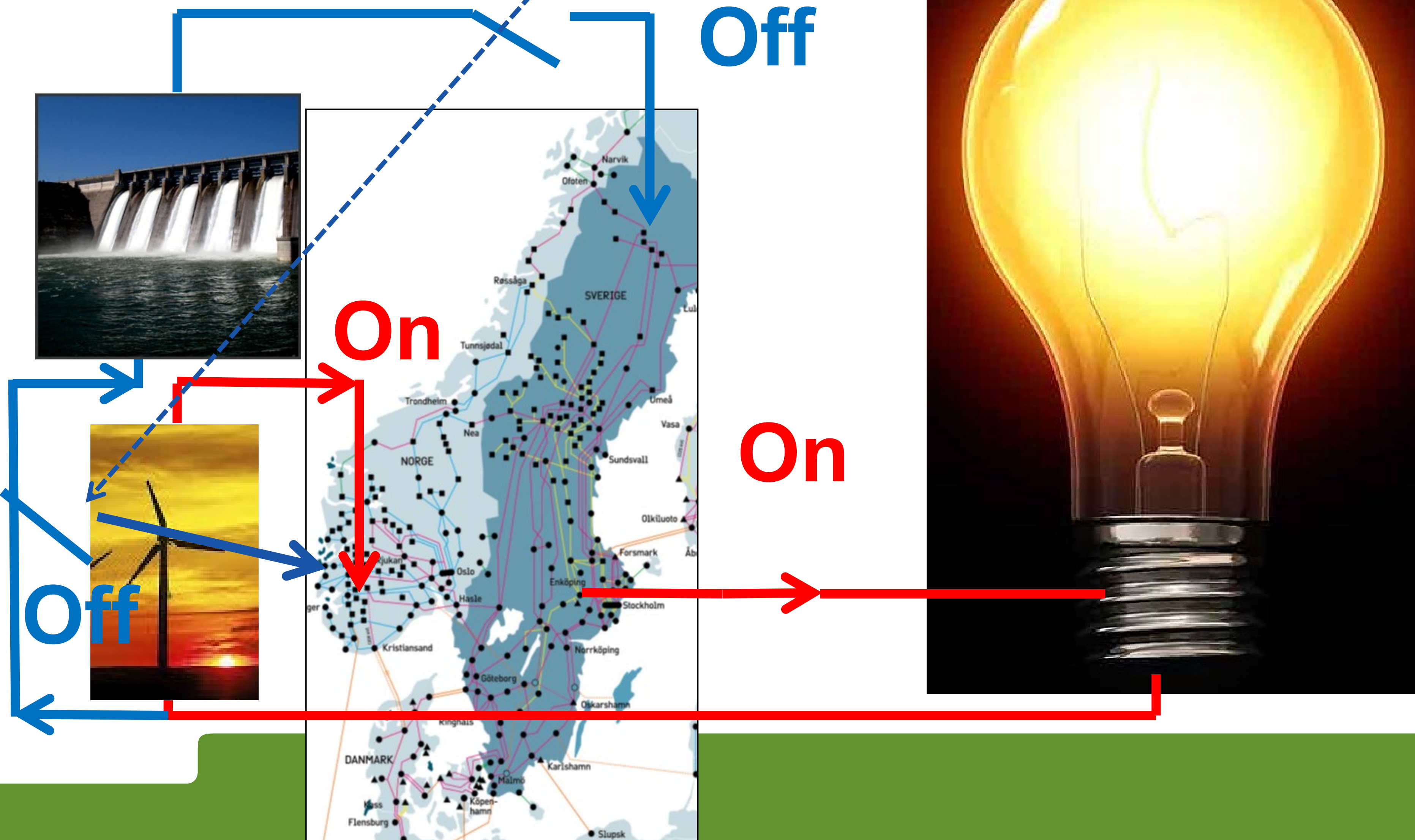
Electricity comes with the speed of light

Assume import from UK
North Sea Link 1400 MW



Electricity comes with the speed of light

Assume **sudden outage** on import from UK



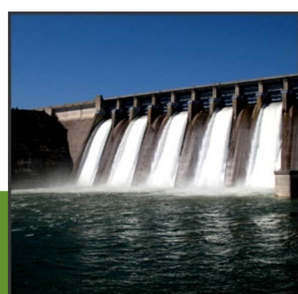
Electricity comes with the speed of light

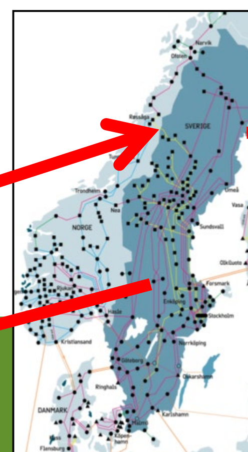
Assume **sudden outage** on import from UK

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

Summary:

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



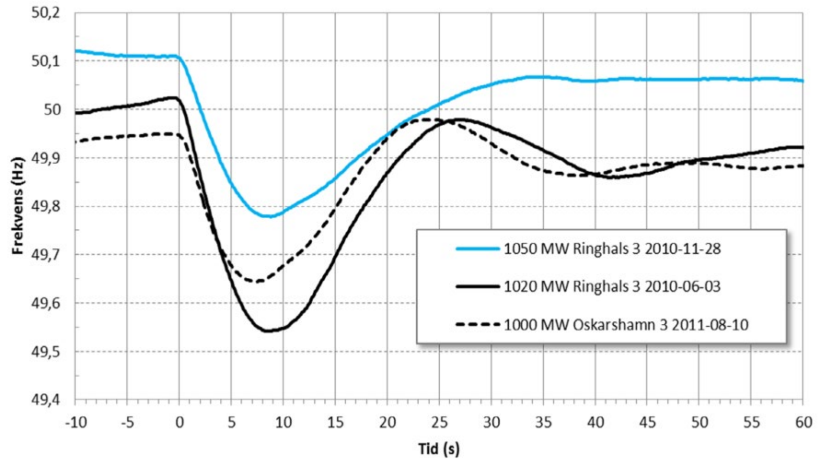


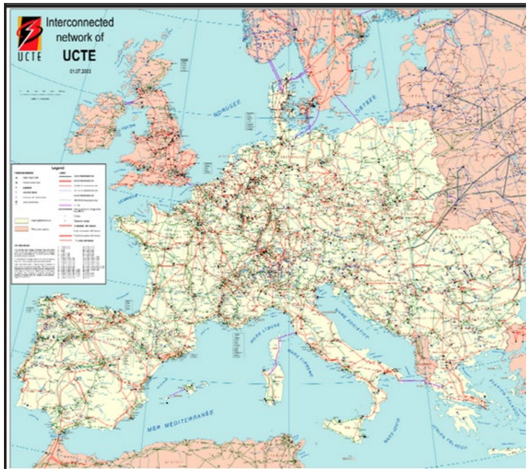
Summary of system challenges at large (> 30-40% of yearly energy) amounts of wind and solar power

1. **Continuous balance** is needed in all systems since power moves with speed of light and no storage.
2. Keep **enough** system **capacity** at low wind/solar
3. Keep **enough reserves** at high wind/solar
4. **Economically** correct **transmission capacity**
5. **Wind/solar spillage** at single digit percents is probably relevant

Content:

- Aim of power system
- China – Europe parallel
- Power System balancing
- Wind power impact





Aim of a power system

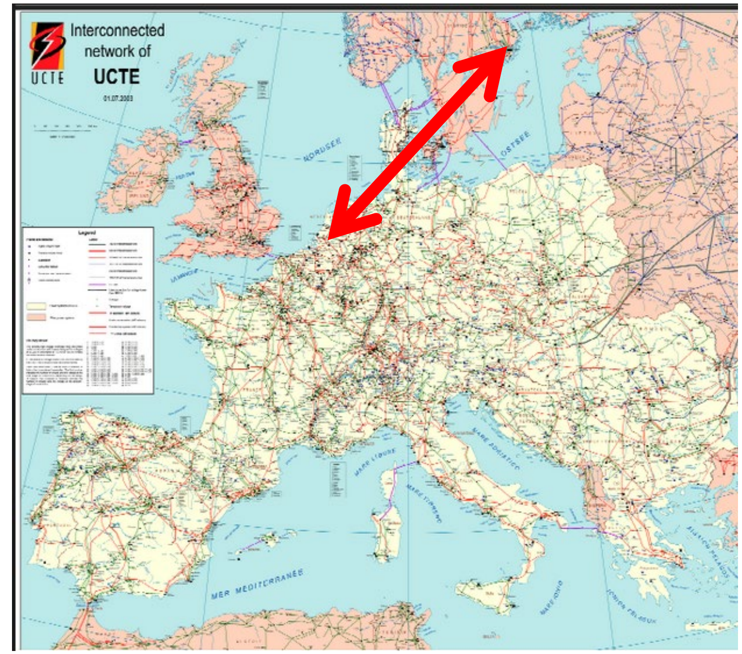
1. The consumers should get the requested power (e.g. a 60 W bulb), when they push the on-button. This should work no matter outages in power stations, it is windy etc = keep a **balance between total production and total consumption**.
2. The consumers should get an **acceptable voltage**, e.g. 230 V, in the outlet.
3. Point 1-2 should be kept with a **realistic reliability**. This is **never** 100,000... percent,
4. Point 1-3 should be kept in an **economic and sustainable** way.

System comparison:

Beijing-Shanghai: 1070 km

Stockholm-Eindhoven: 1180 km

System comparison:

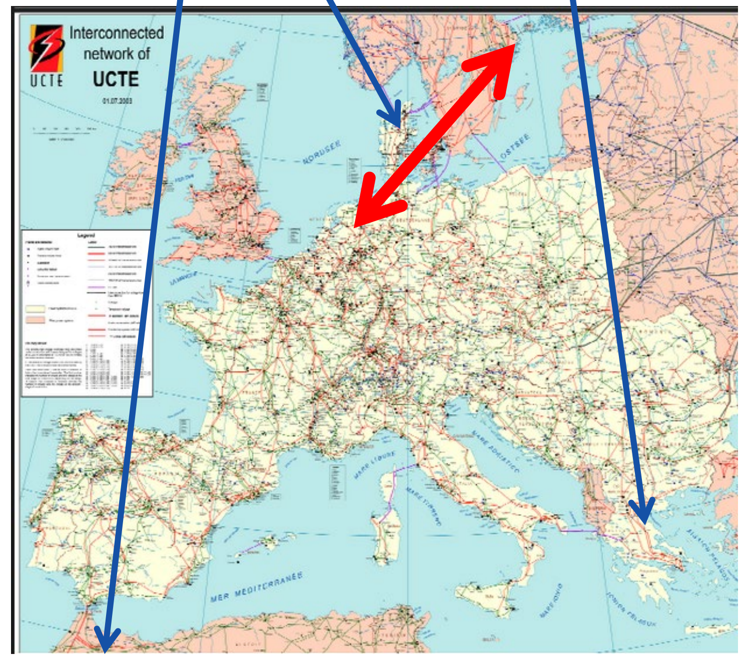


Beijing-Shanghai: 1070 km

Stockholm-Eindhoven: 1180 km

System comparison:

AC system: same frequency



Beijing-Shanghai: 1070 km

Stockholm-Eindhoven: 1180 km

Renewable energy systems

- Energy is ”produced” where the resource is
- The energy has to be transported to consumption center
- The energy inflow varies, which requires storage and/or flexible system solutions

- This is valid for hydro power, **wind power**, **solar power**

Example

Nordic hydro power (inflow) can vary 86 TWh between different years (Δ2001 to 1996)

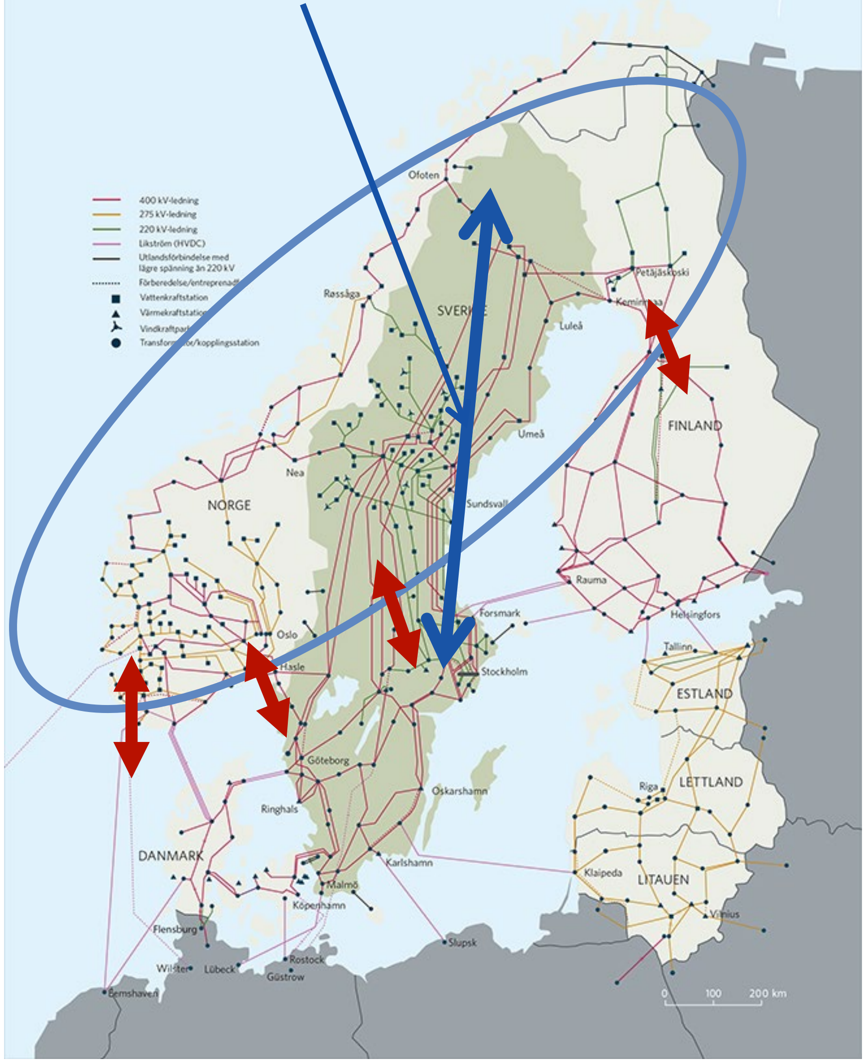
Transport from NV to SE + continent

Energy balancing with thermal power in i Dk + F + Ge + Pl + NL + Ee + Lt + UK

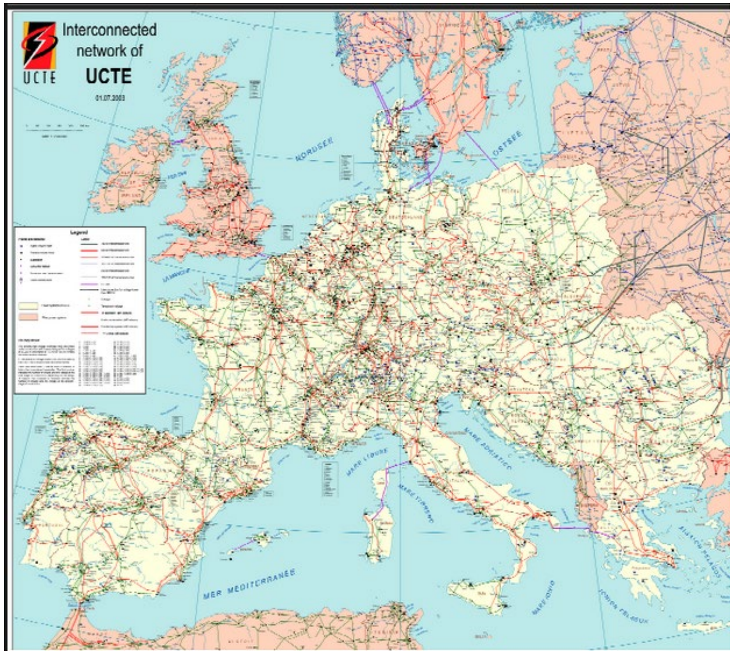
➔ **Sweden and our neighbors have had a need for coopera-tion since decades**

Beijing-Shanghai: 1070 km

Stockholm-Kiruna: 950 km



Power system challenges



Keep the balance:

- Production = consumption
- Electricity cannot be stored!
- Exactly when a bulb is lighned some generator will deliver the power
- Exactly when a power plant is stopped (or wind power decreases), the corresponding power will be delivered from another plant instead.

Power system challenges

Keep the balance:

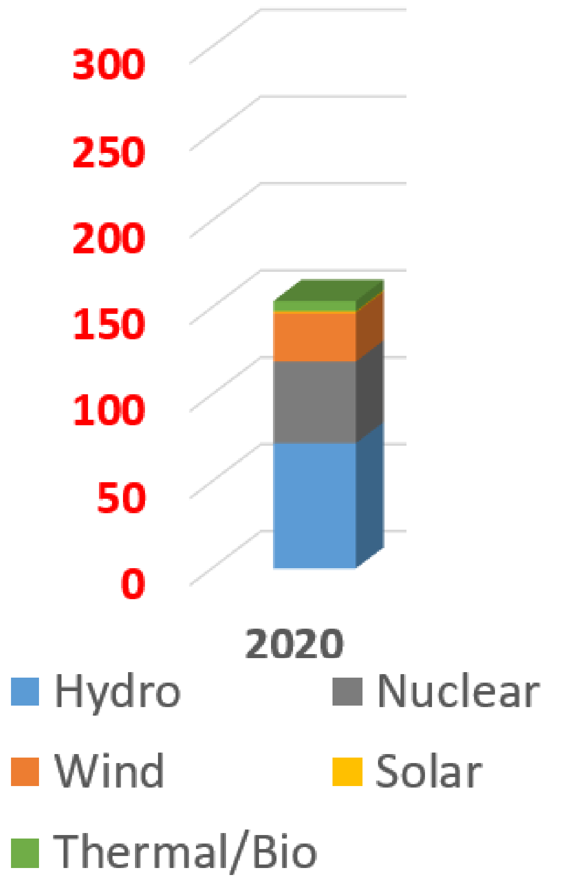
- Production = consumption
- Electricity cannot be stored!
- Exactly when a bulb is lighned some generator will deliver the power
- Exactly when a power plant is stopped (or wind power decreases), the corresponding power will be delivered from another plant instead.

Swedish power system scenarios for 2045, report from TSO “Svenska Kraftnät”

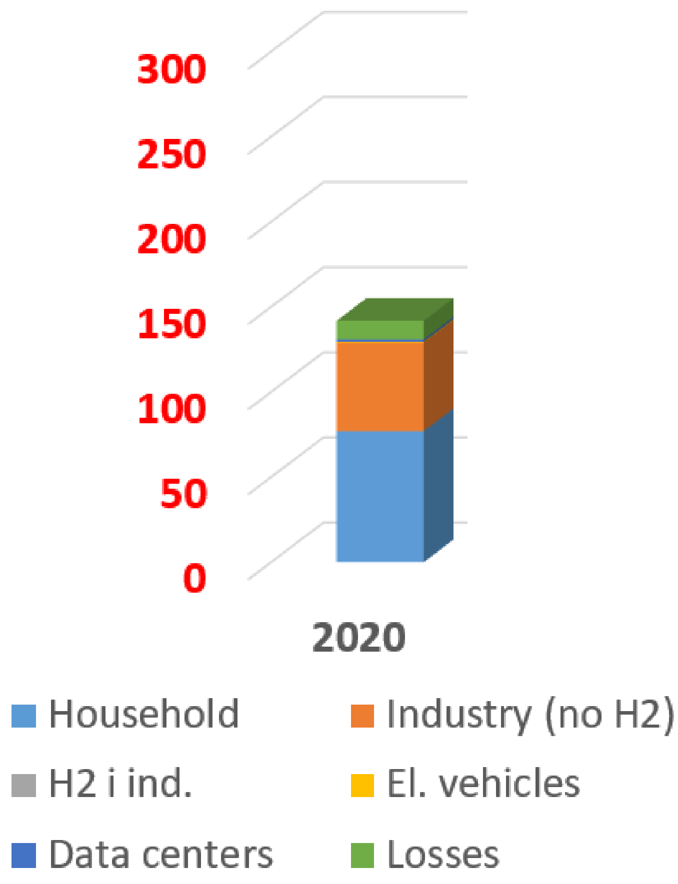
Lennart Söder
Professor Electric Power Systems, KTH

Swedish power production and consumption 2020

Production



Consumption



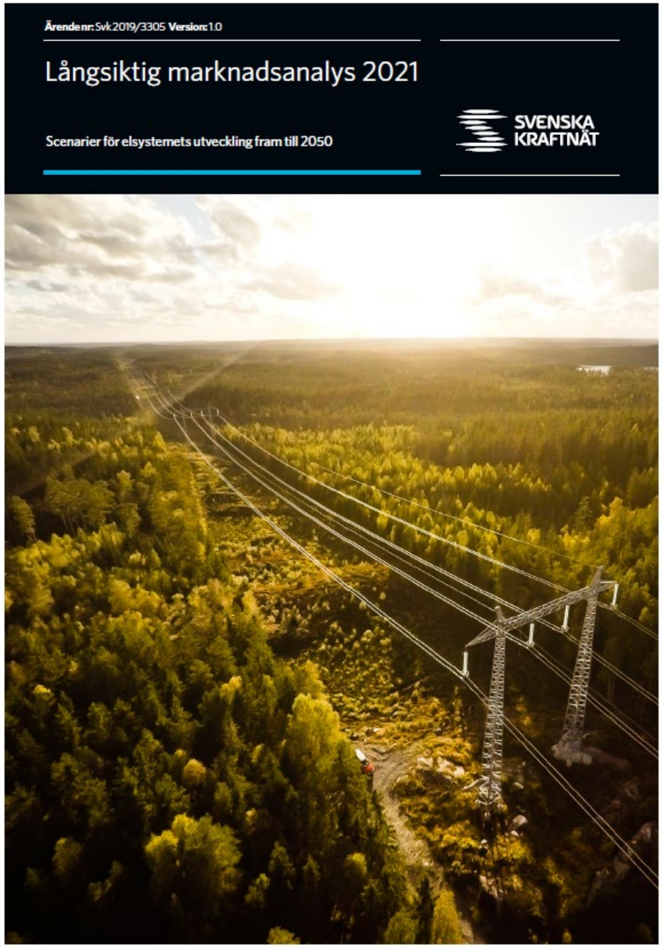
Four studied scenarios for the future

4 scenarios studied for 2025-2050:

- Small scale renewable
- Roadmap mixed
- Electrification planable
- Electrification renewables

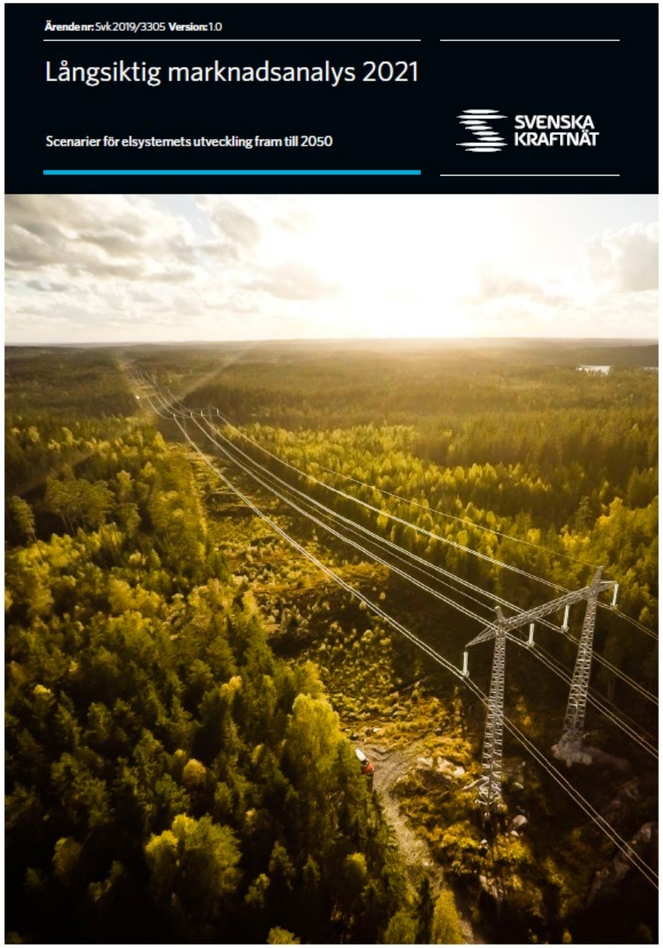
Aim: **investigate expansion needs**, the transmission capacity in the scenarios may be underdeveloped, especially in 2045. The scenarios must show what needs may exist, not what the power system and market look like after the needs are met.

”Long Term market analysis”, from May 2021



Four studied scenarios for the future

”Long Term market analysis”,
from May 2021

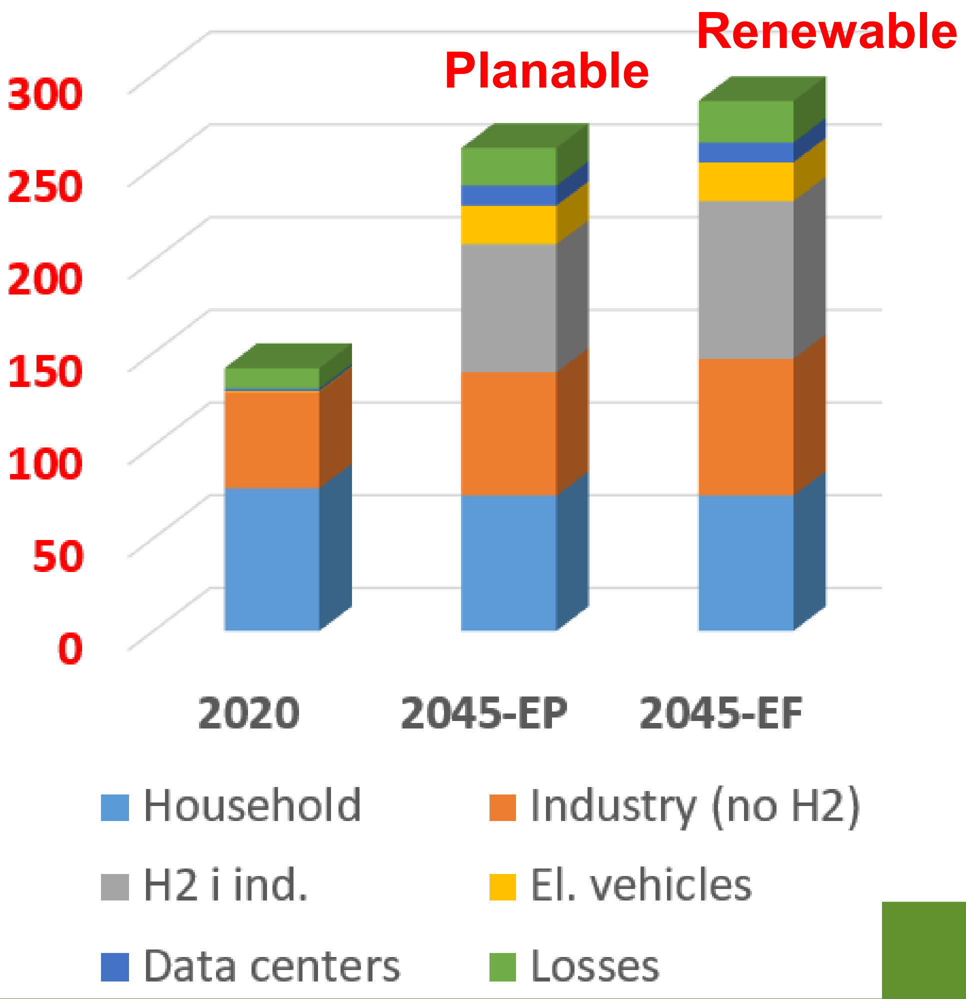


4 scenarios studied for 2025-2050:

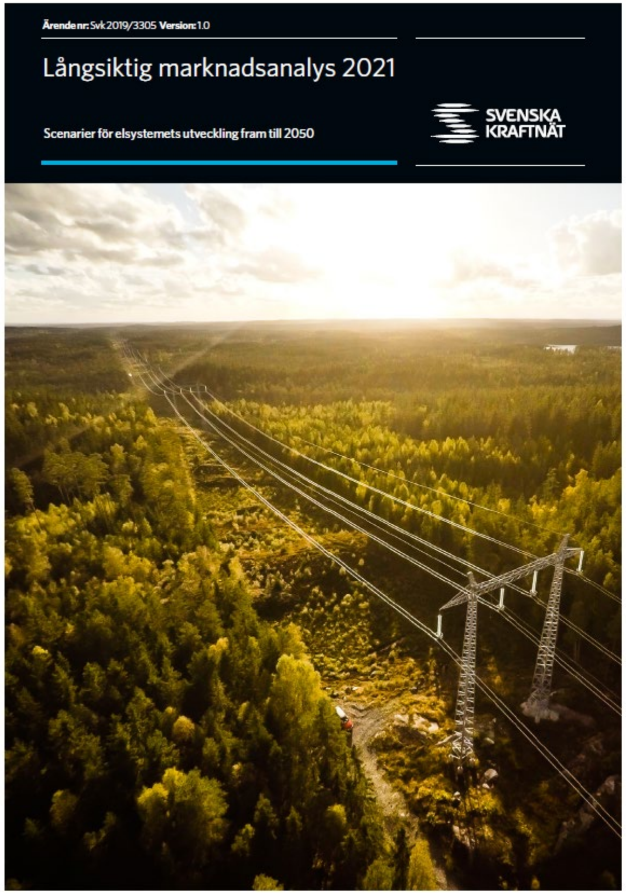
- Small scale renewable
- Roadmap mixed
- **Electrification planable**
- **Electrification renewables**

Two studied scenarios for the future
Electrification

Consumption assumptions

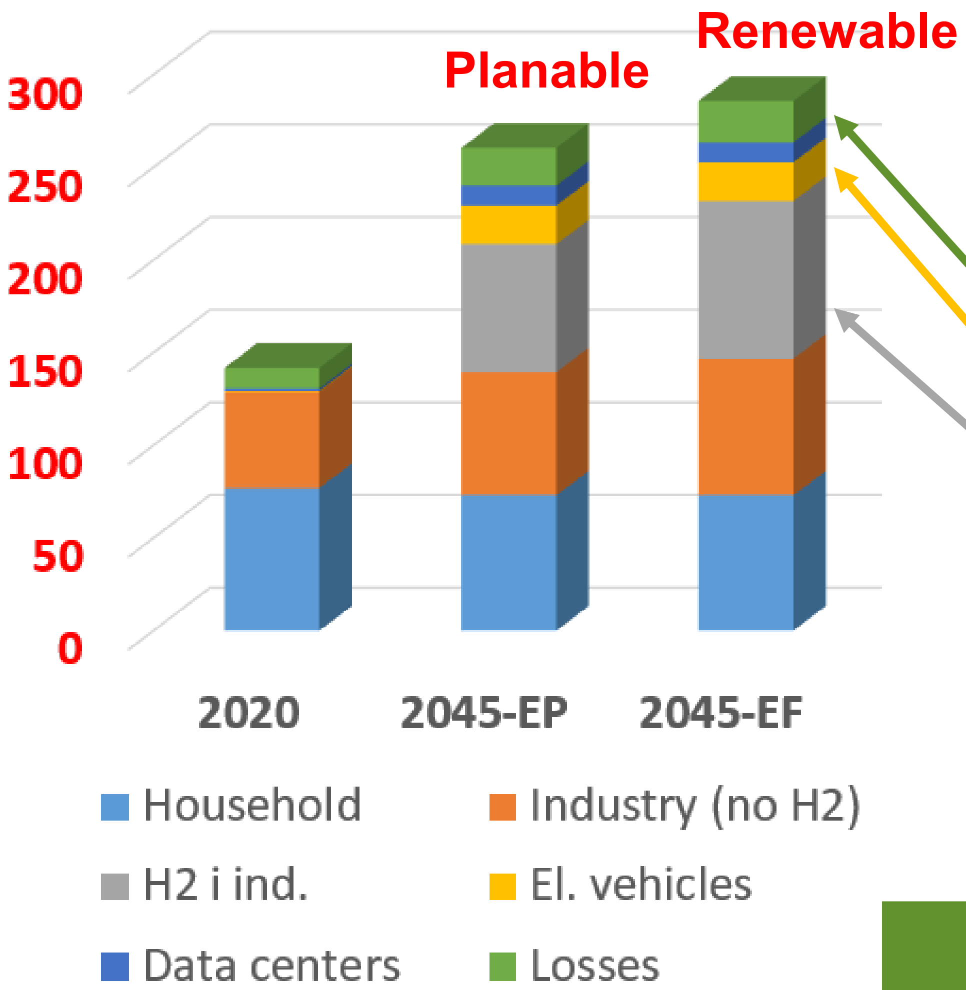


”Long Term market analysis”, from May 2021



Two studied scenarios for the future
Electrification

Consumption assumptions



Increased consumption 2020-2045-EF: 144 TWh

- Part of losses
- 21 TWh: vehicles
- 85 TWh: hydrogen

➔ **79% of increase** is hydrogen or vehicles, ➔ **flexible consumption**

Presentation from Vattenfall at a hydrogen online seminar: December 11, 2020 (translated)

Making steel without coal

HYBRIT
FOSSIL-FREE STEEL

HYBRIT – Power system integration and flexibility

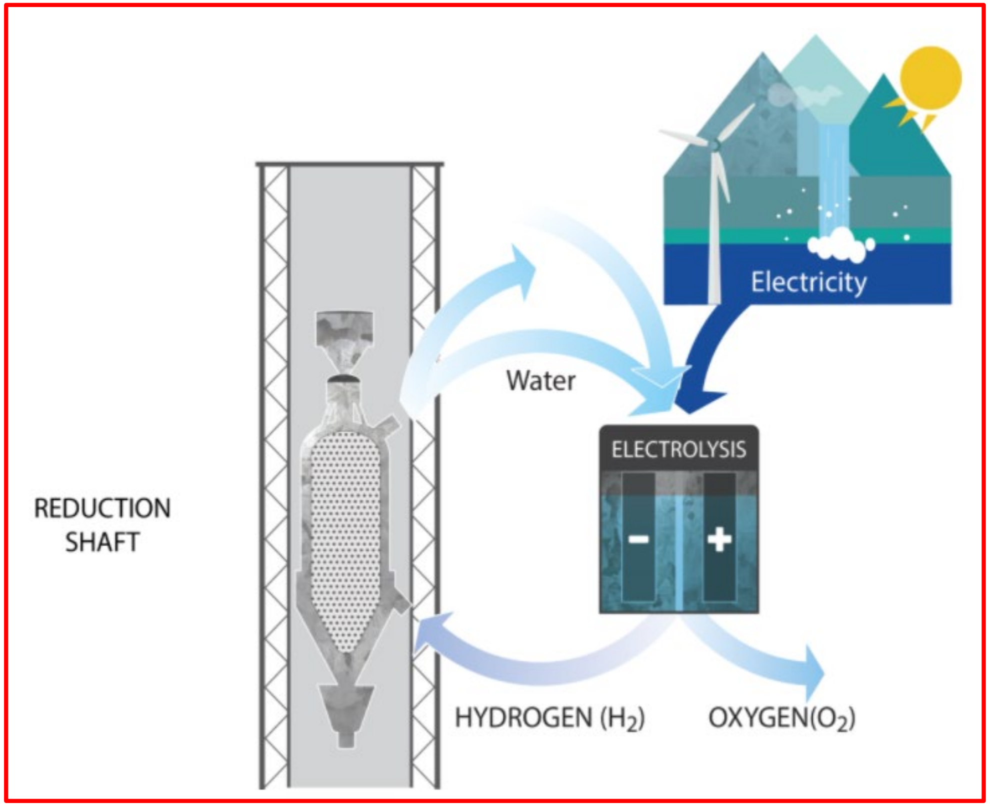
Tobias Rehnholm

Making steel without coal

HYBRIT is conducting trials on the **direct reduction of iron ore pellets** using hydrogen in our pilot plant in Luleå, Sweden.

The trials will run during 2020-2024, starting with fossil-free hydrogen in spring 2021.

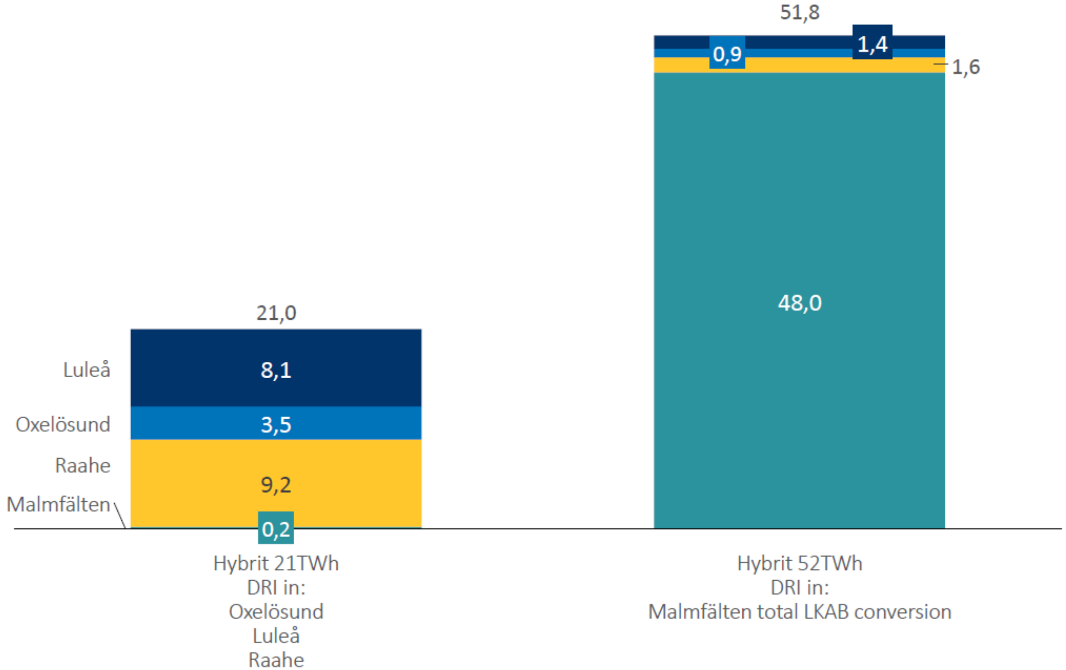
The plant has a direct reduction shaft, where the reduction takes place, and a number of electrolyzers for the production of hydrogen using fossil-free electricity.



https://www.hybritdevelopment.se/en/

Presentation from Vattenfall at a hydrogen online seminar: December 11, 2020 (translated)

Scenario analysis and market interaction



Flexibilitetsantaganden

Hybrit 21TWh
- 180% elektrolysörkapacitet
- 7 dagars vätgaslager

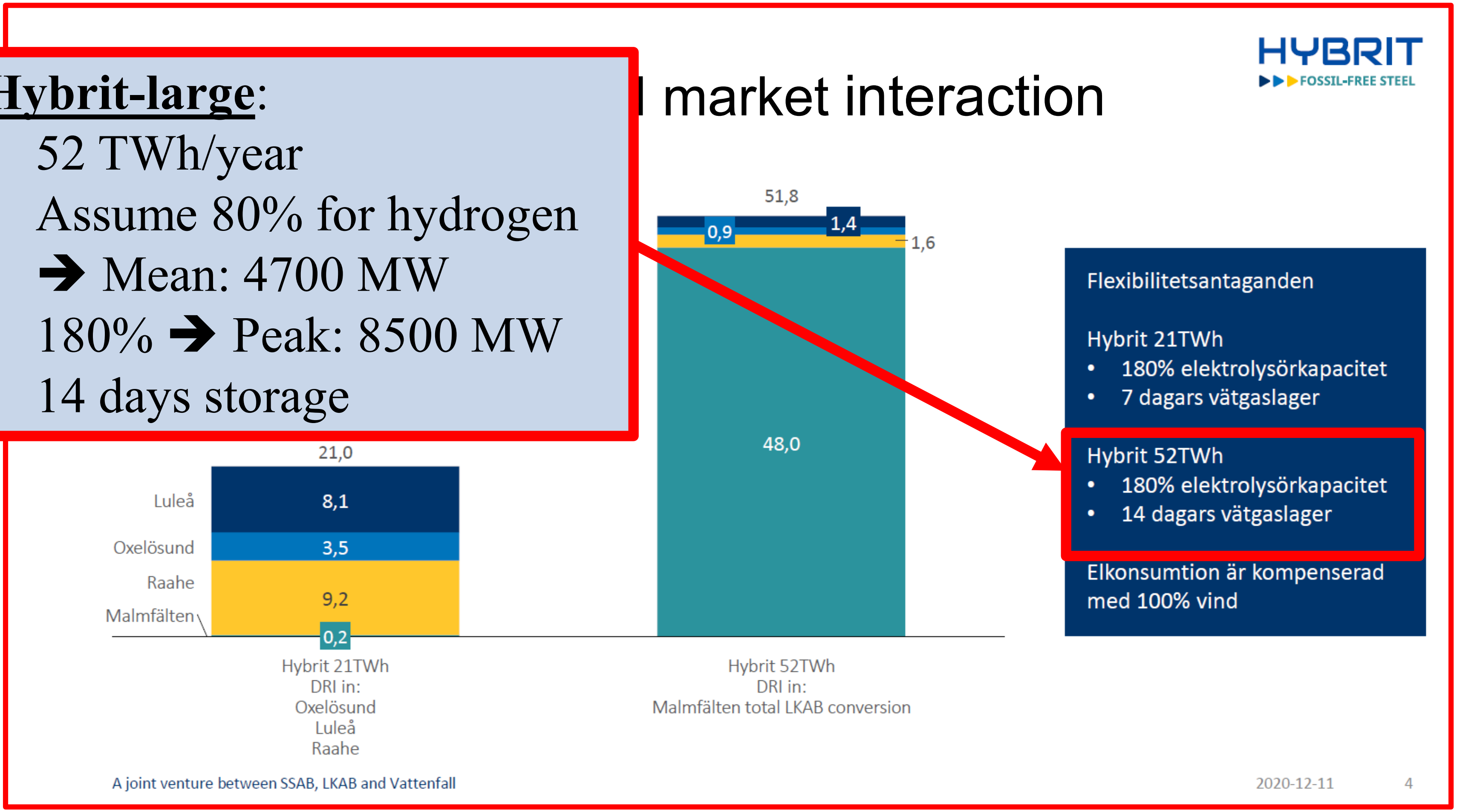
Hybrit 52TWh
- 180% elektrolysörkapacitet
- 14 dagars vätgaslager

Elkonsumtion är kompenserad med 100% vind

Presentation from Vattenfall at a hydrogen online seminar: December 11, 2020 (translated)

Hybrit-large:

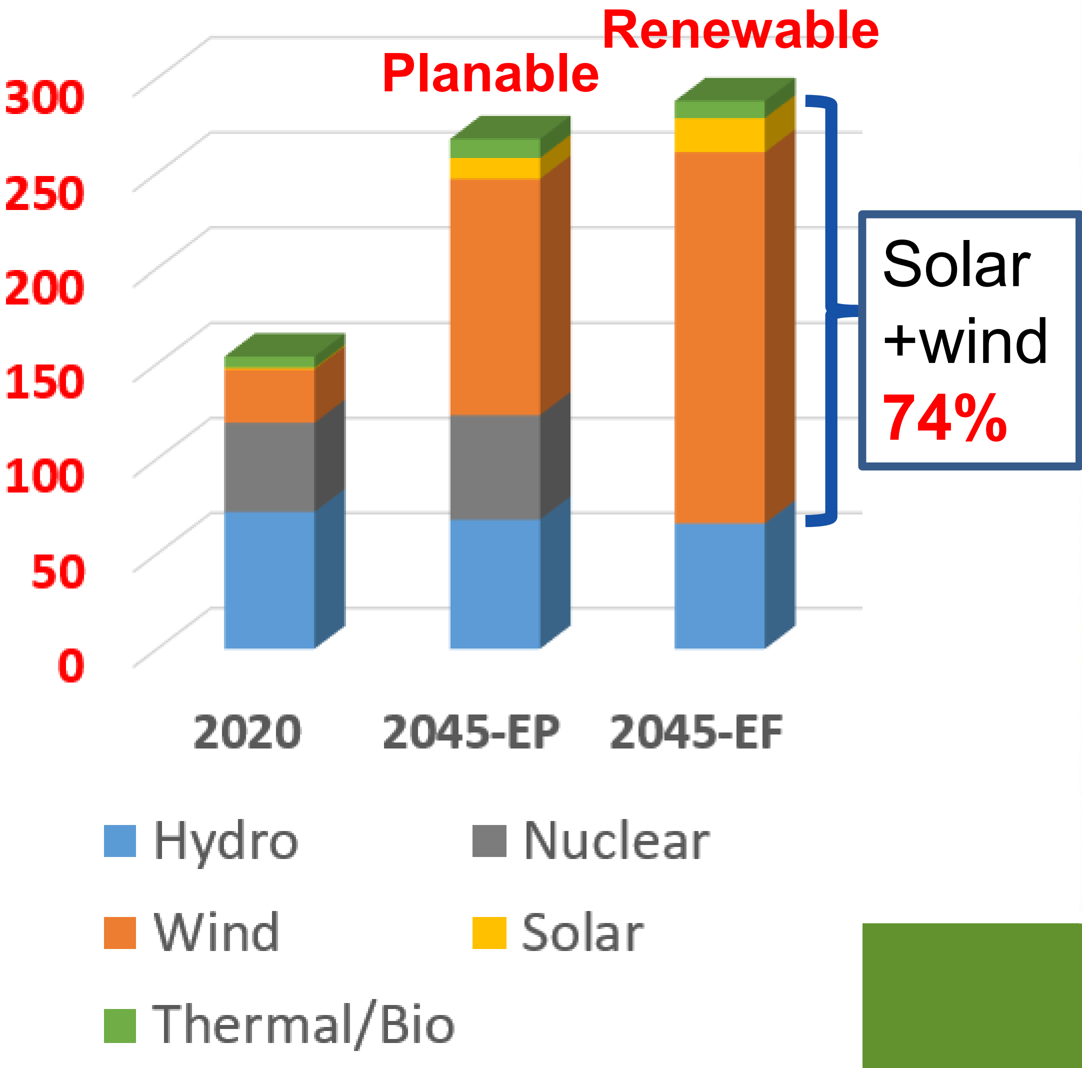
- 52 TWh/year
- Assume 80% for hydrogen
- ➔ Mean: 4700 MW
- 180% ➔ Peak: 8500 MW
- 14 days storage

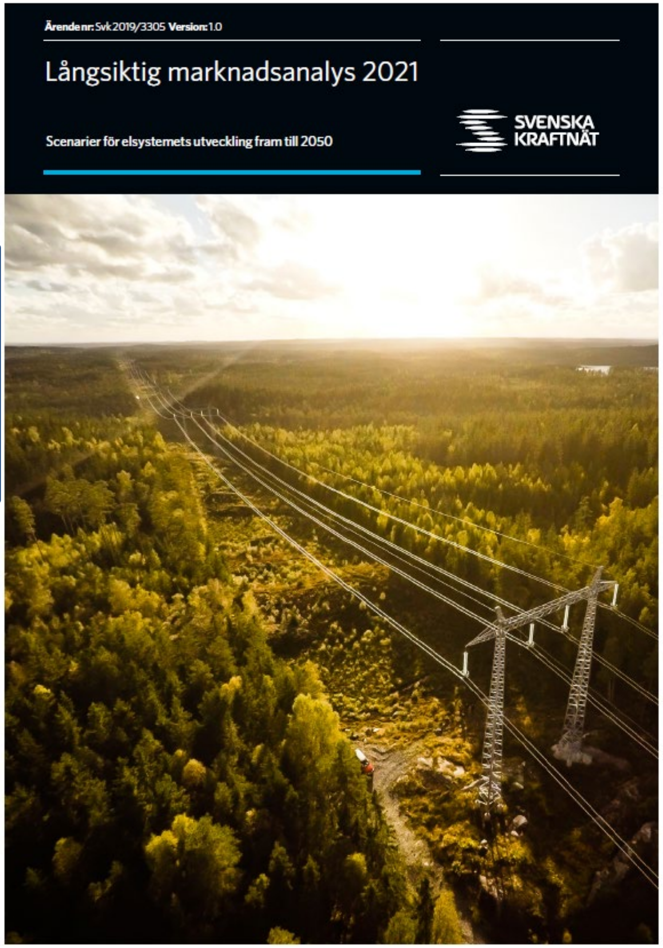


Two studied scenarios for the future
Electrification

”Long Term market analysis”, from May 2021

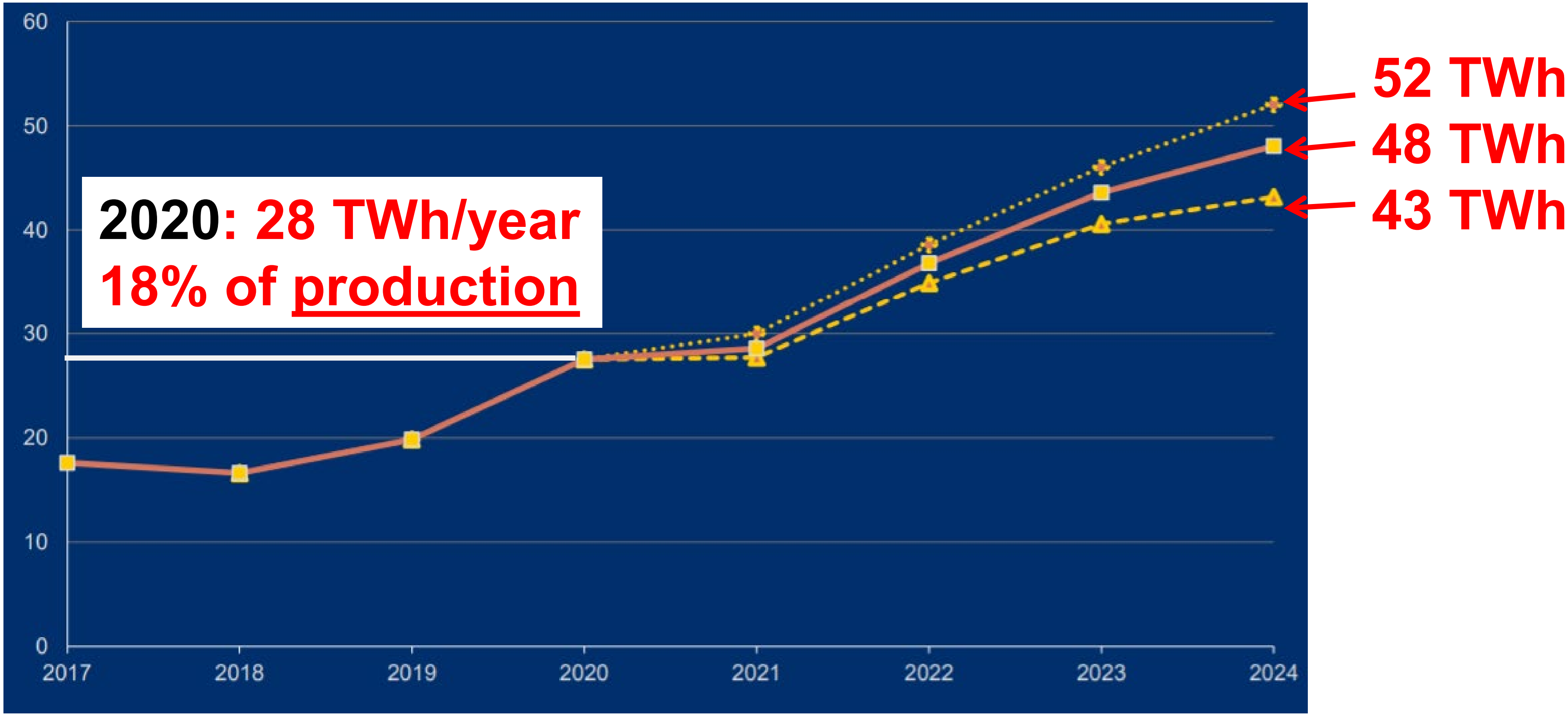
Production results/assumption





Swedish wind power forecast to 2024

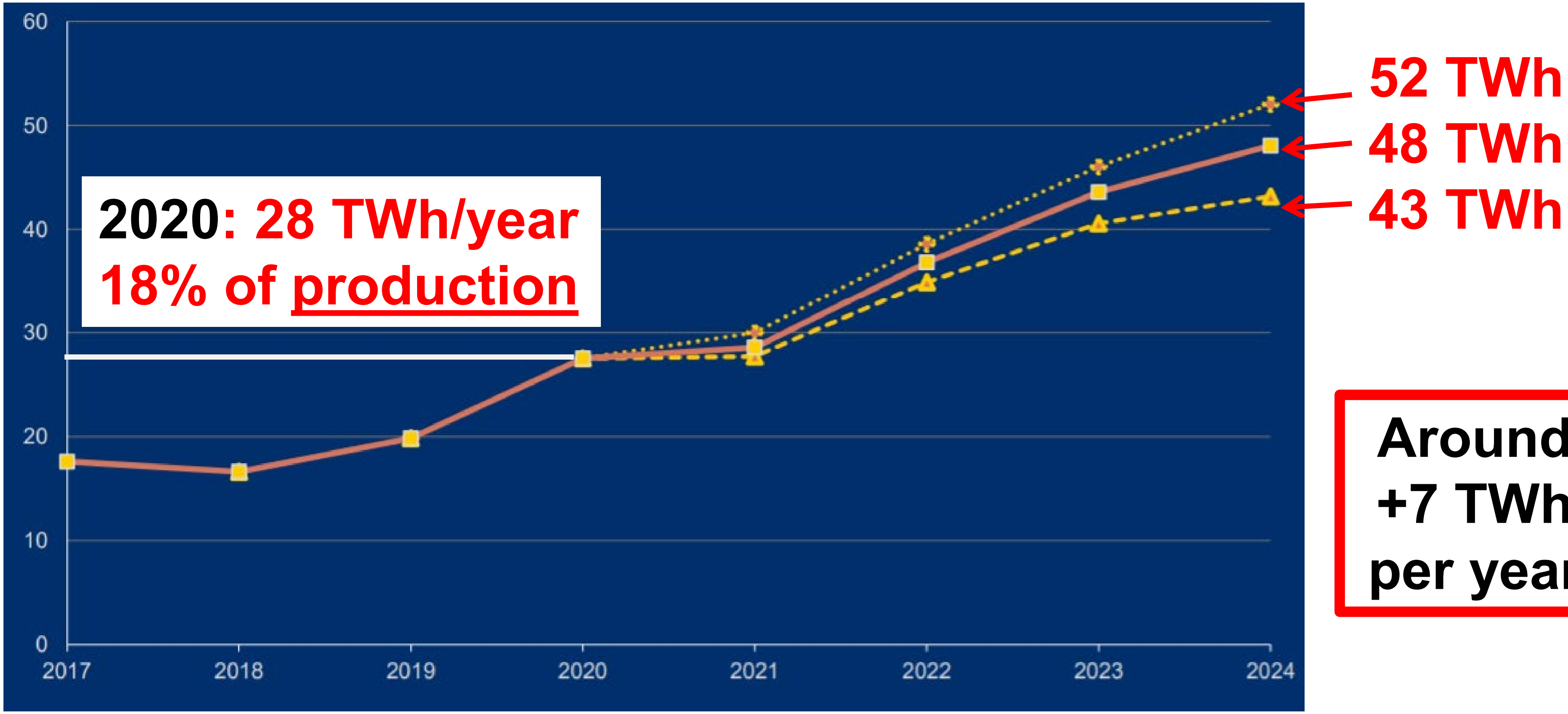
From Octuber 2021 (based on investment decisions)



https://svenskvindenergi.org/wp-content/uploads/2019/07/Statistics-and-forecast-Svensk-Vindenergi-20190705.pdf

Swedish wind power forecast to 2024

From Octuber 2021 (based on investment decisions)



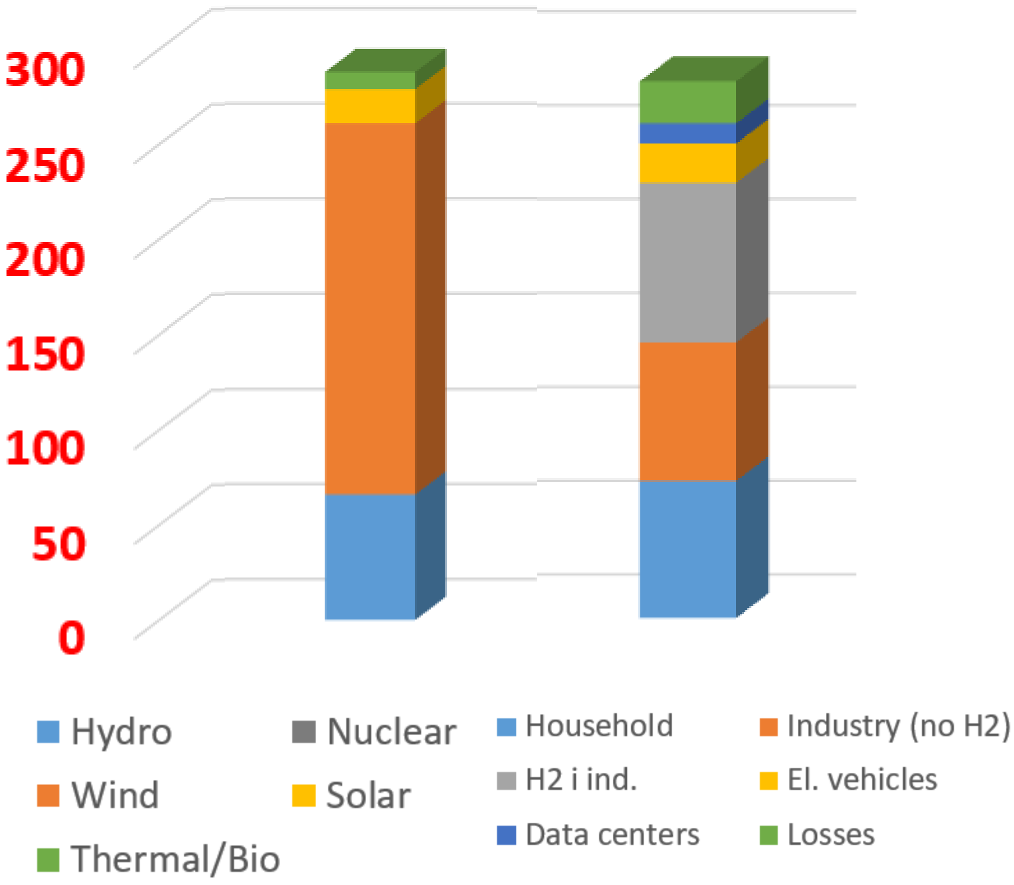
Around +7 TWh per year

https://svenskvindenergi.org/wp-content/uploads/2019/07/Statistics-and-forecast-Svensk-Vindenergi-20190705.pdf

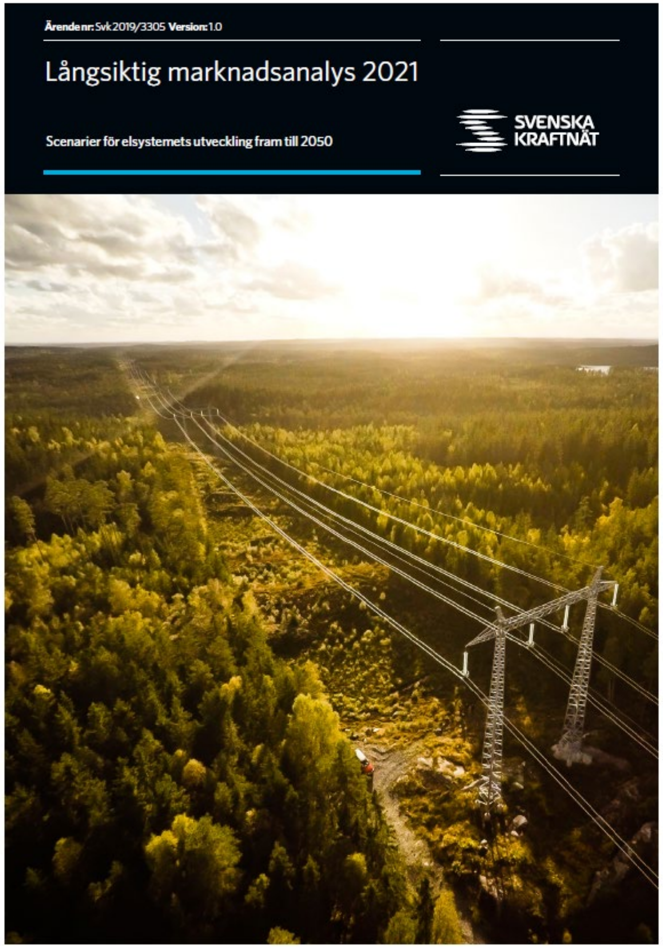
Details of scenario

Electrification - renewable

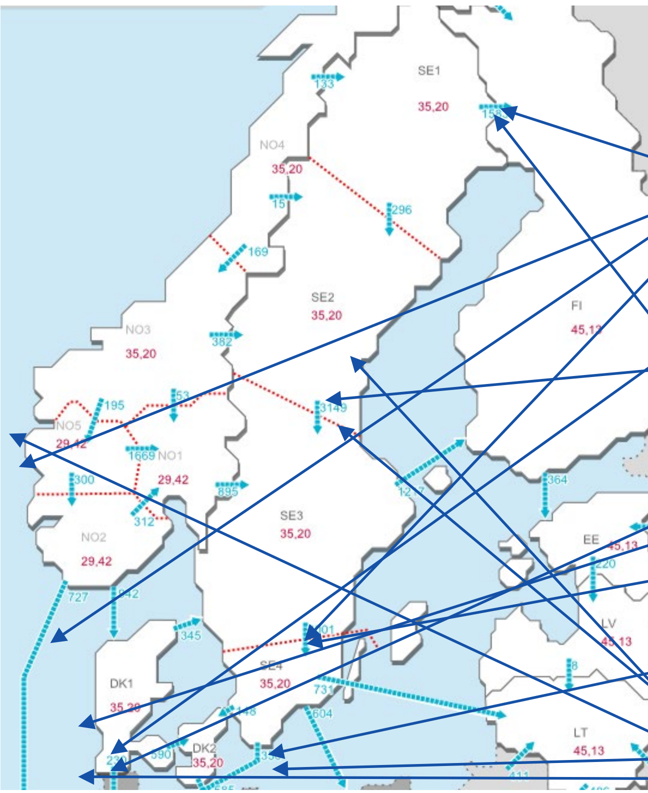
Production Consumption



"Long Term market analysis", from May 2021



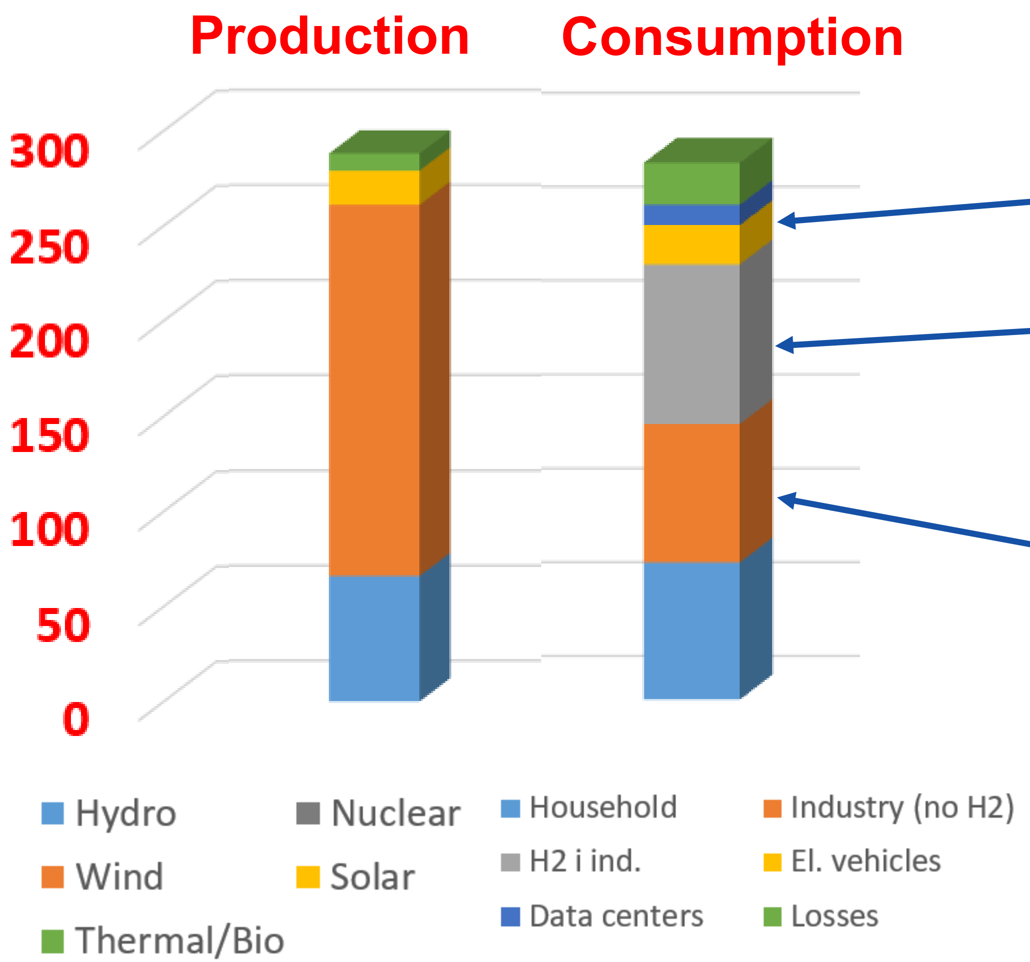
Considered Nordic System Extensions
In total 2020-2040: + 15 GW (same for all cases)



Year		+ MW	MW	
2021	SE3→SE4 SE4→SE3	+800 +800	6 200 2 800	SydVäst-länken
	NO2↔DE	+1400	1 400	NordLink
	NO2↔UK	+1400	1 400	North Sea Link
	DK1→DE DE→DK1	+720 +1000	2 500 2 500	Steg 1 Jylland-Tyskland
2022	SE1→FI	-300	1 200	I och med idrifttagning Olkiluoto 3
2024	SE2↔SE3	+800	8 100	Förstärkning Snitt 2
	DK1↔DE	+1 000	3 500	Steg 2 Jylland-Tyskland
	DK1↔UK	+1400	1 400	Viking Link
2026	SE3→SE4 SE4→SE3	+600 +400	6 800 3 200	Ekhyddan-Nybro-Hemsjö
	SE4↔DE	+700	1 315	Hansa PowerBridge
	SE1→FI FI→SE1	+800 +900	2 000 2 000	Messaure - Keminmaa
2029	DK2↔PL DK1↔NL	+1000 +1500	1000 2200	Förbindelser via "energiöar". OBS! enbart i Elektrifiering förnybart
2035	NO↔UK	+1400	2 800	NorthConnect eller liknande
2040*	SE2↔SE3	+2400	10 500	Förstärkning Snitt 2
>2040	SE2/SE3↔FI	+400 (netto)	3 600 tot SE-FI	Avveckling Fenno-Skan1 (-400 MW SE3↔FI) Ny HVDC (+800 MW SE2↔FI)

	2020	2040
Sweden ⬄ neighbours	10,5 GW	12,4 GW

Details of scenario
Electrification - renewable



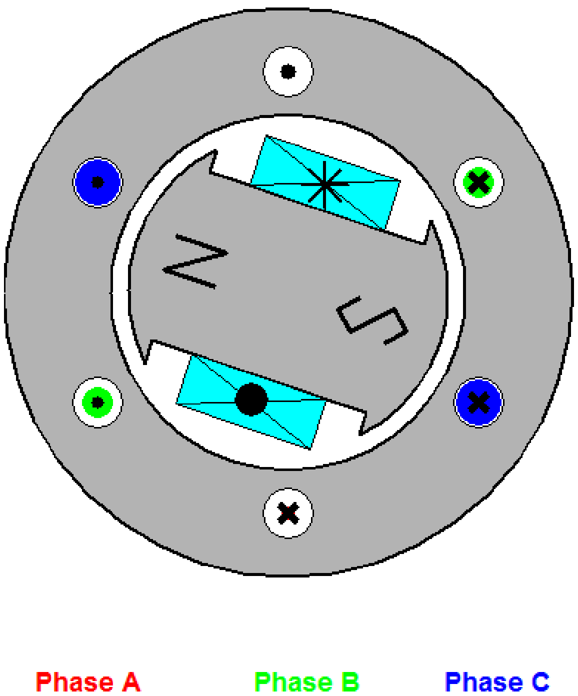
Assumed basic flexibility

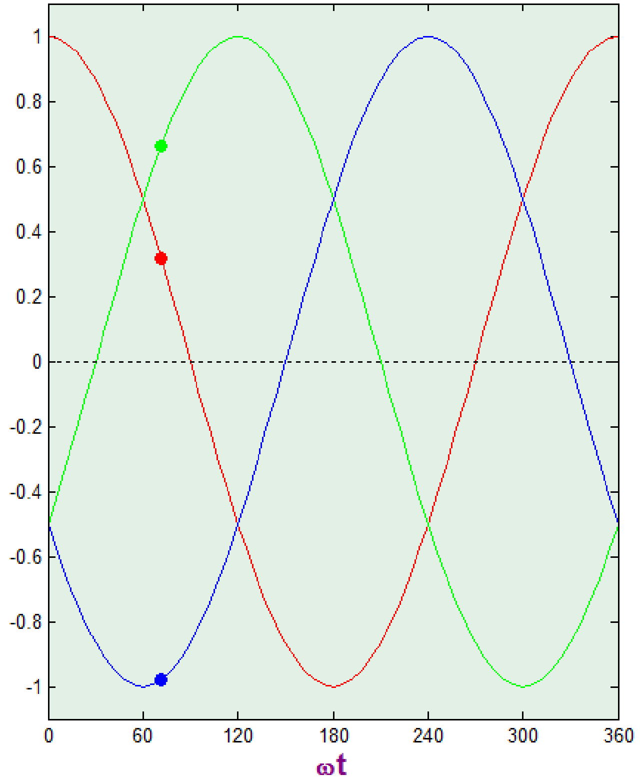
- **EV:s**: 40% is flexible
- **H2**: 7 days storage + 100% extra MW for electrolyzers
- **Current industry**: Use is price dependent (2100 MW)

How to keep short term balance in a power system?

Lennart Söder
Professor in Electric Power Systems

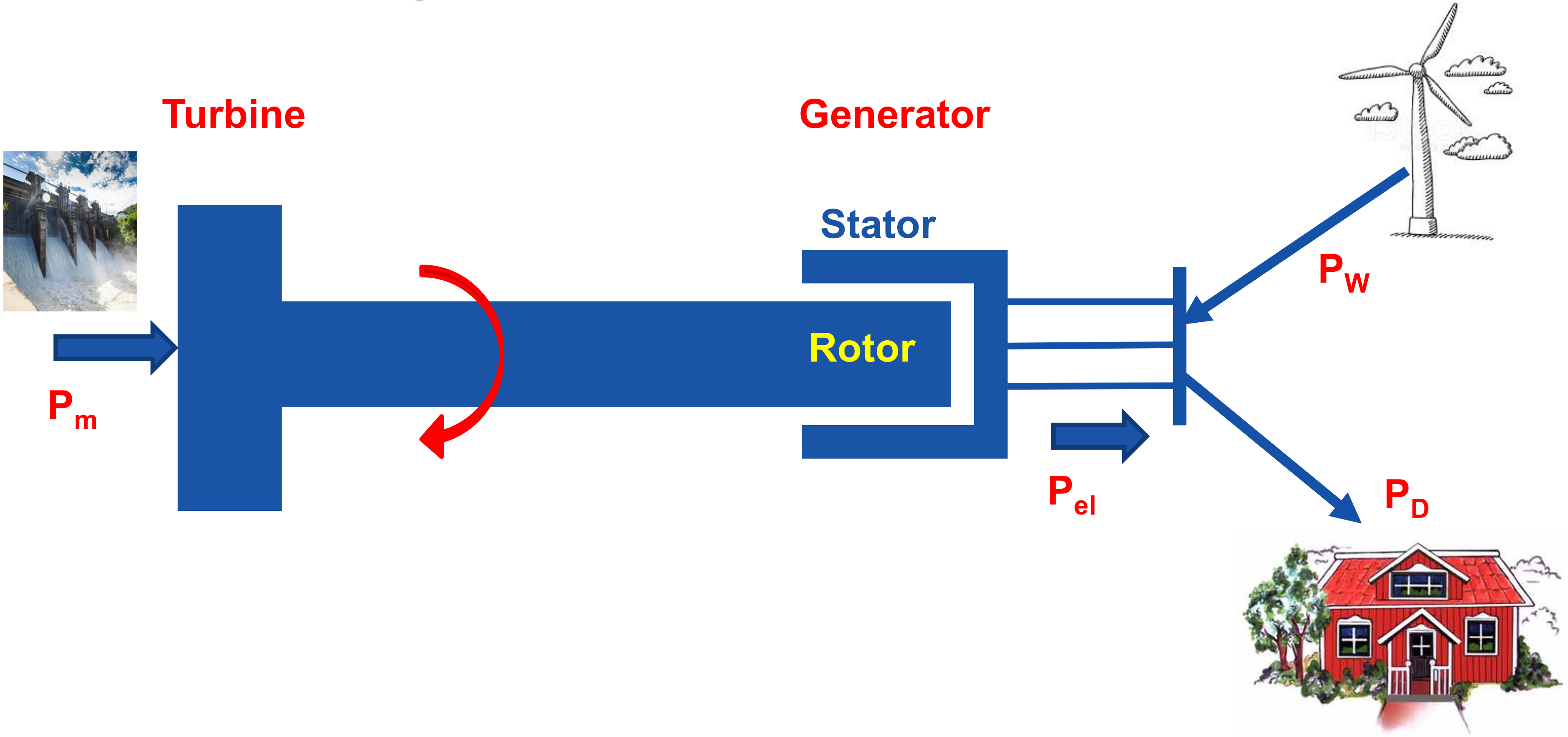
Rotating magnetic field in a generator.
➔ Creation of sinus voltage



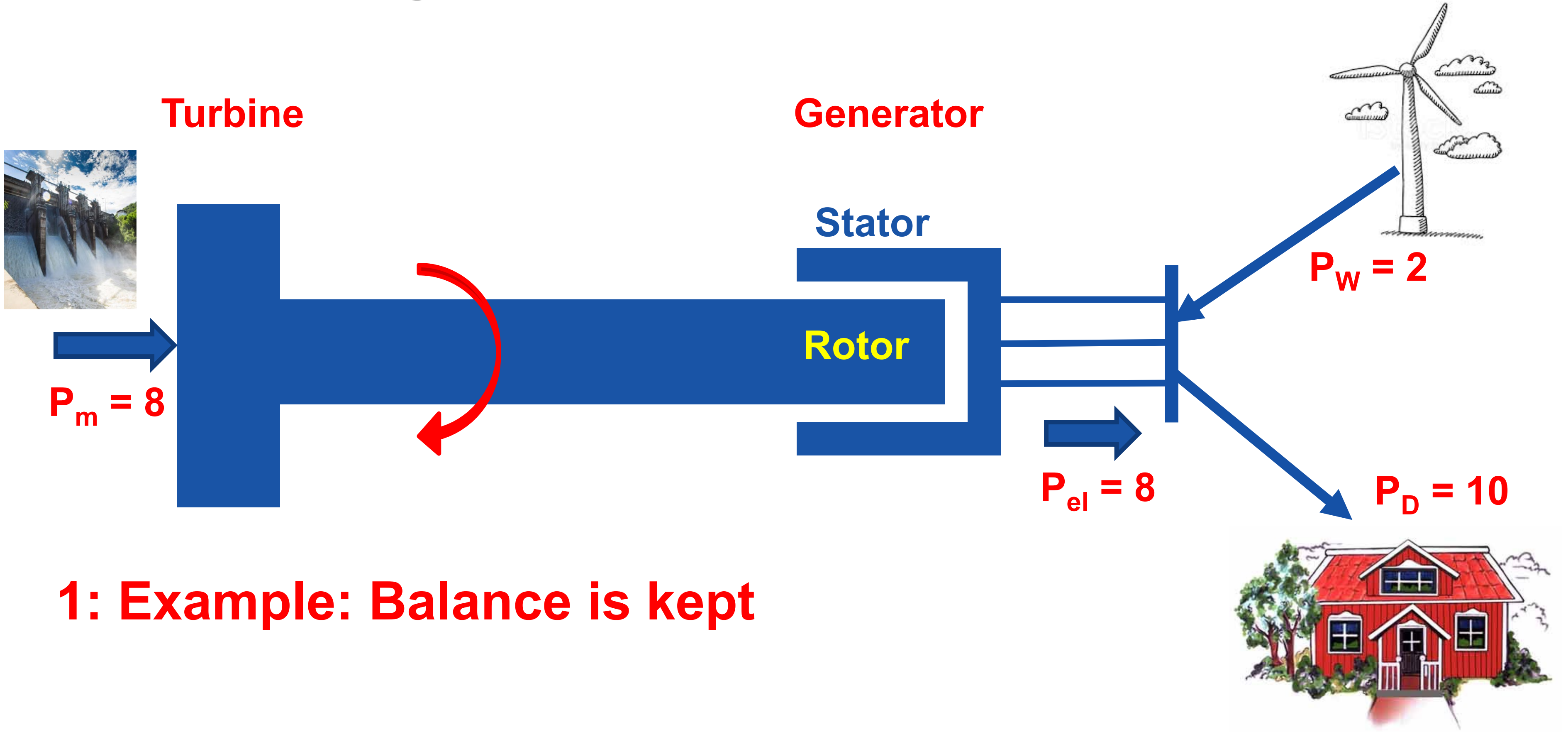


Rotating magnetic field induces
electromotive forces (E) in stator windings
(Faraday's law of induction –> generalisation -> Maxwell-Faraday's law)

Frequency control = how to balance a change in production/consumption - 1

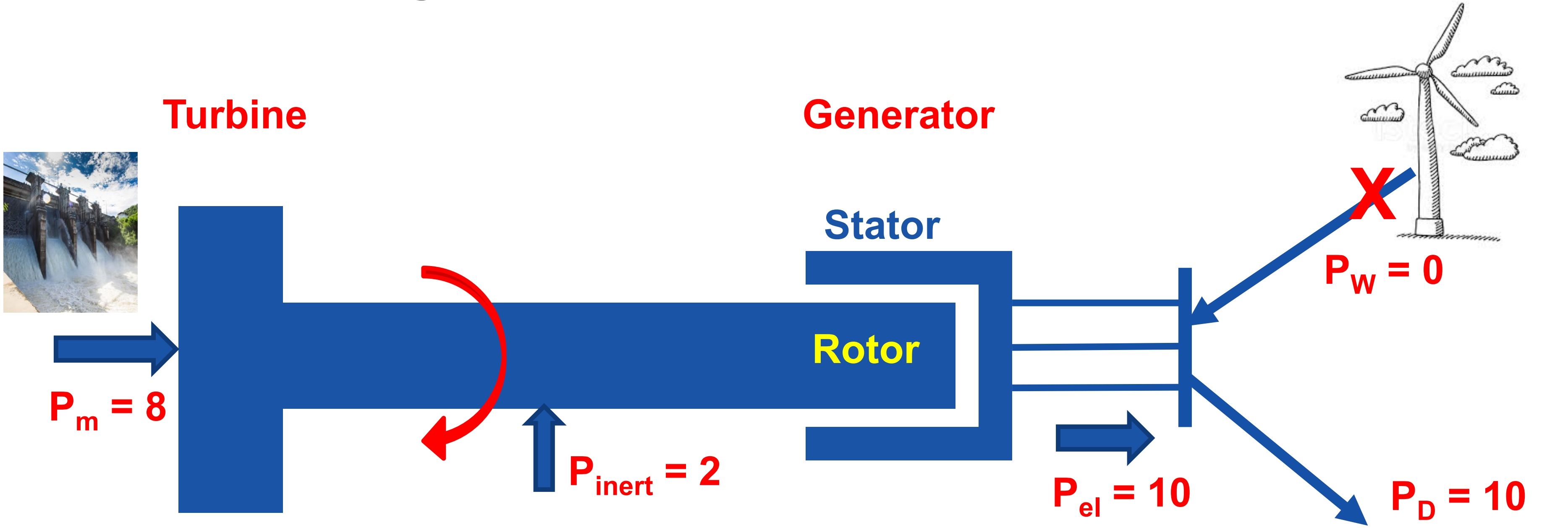


Frequency control = how to balance a change in production/consumption - 2



1: Example: Balance is kept

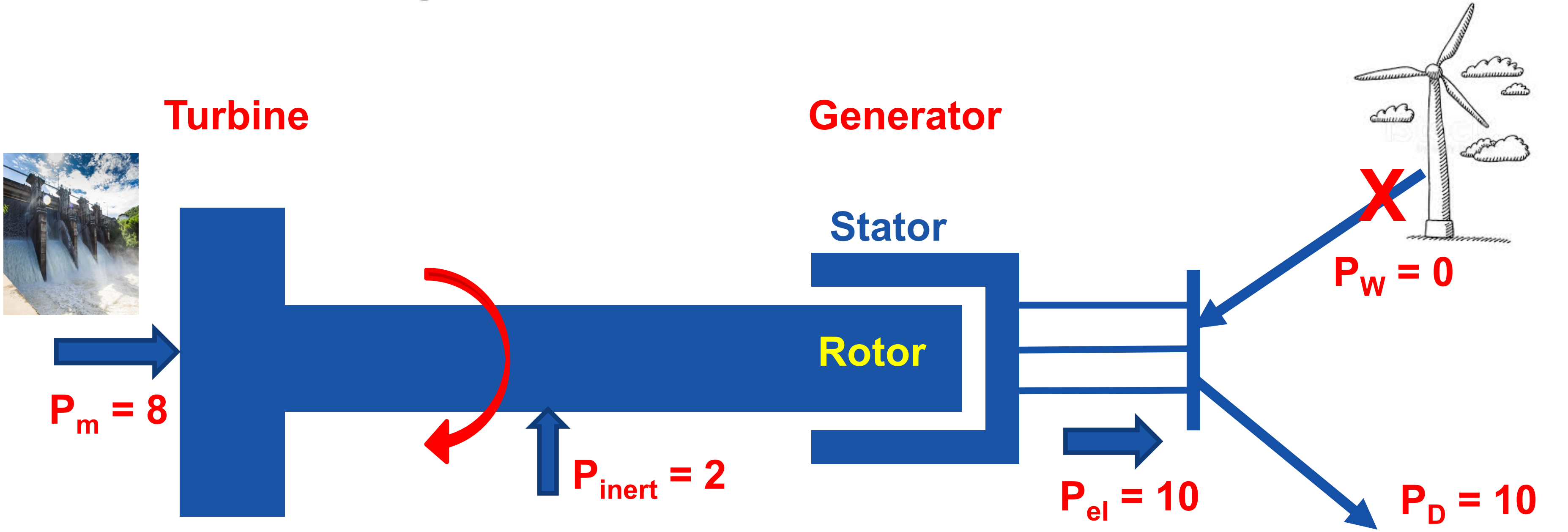
Frequency control = how to balance a change in production/consumption - 3



2: Example: Balance is kept

- Outage in wind power.
- Compensated by turbine/rotor inertia

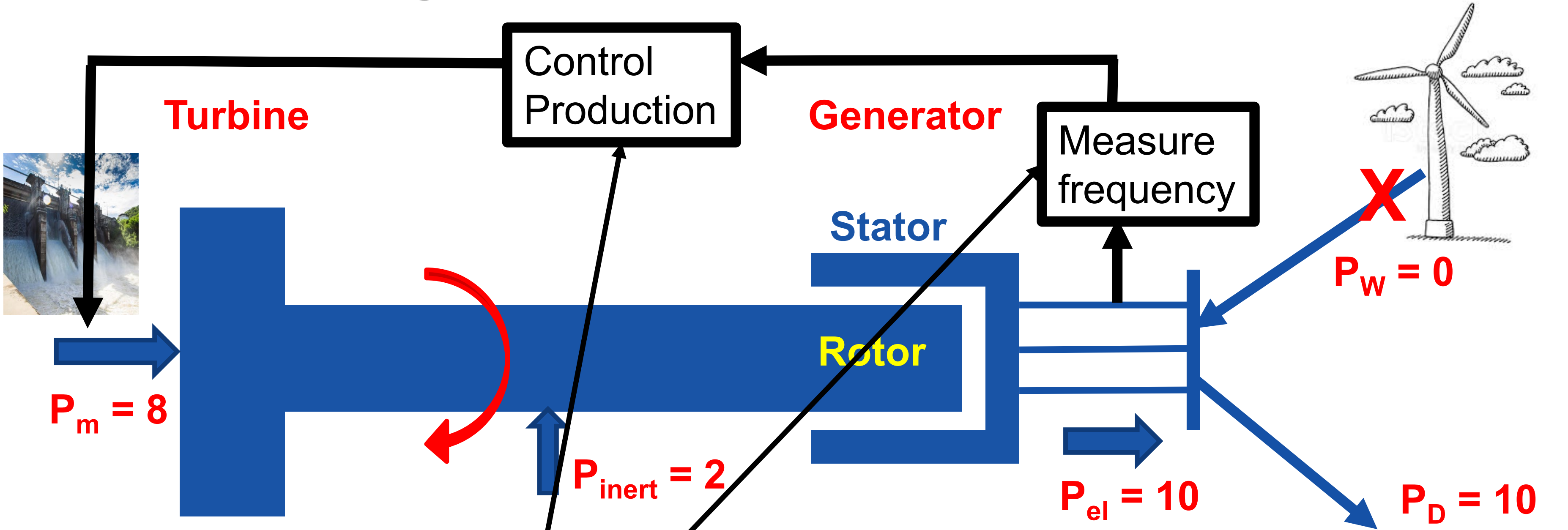
Frequency control = how to balance a change in production/consumption - 4



3: Example: Balance is kept

- Energy supply from inertia
- Consequence: Lower speed ➔ lower frequency

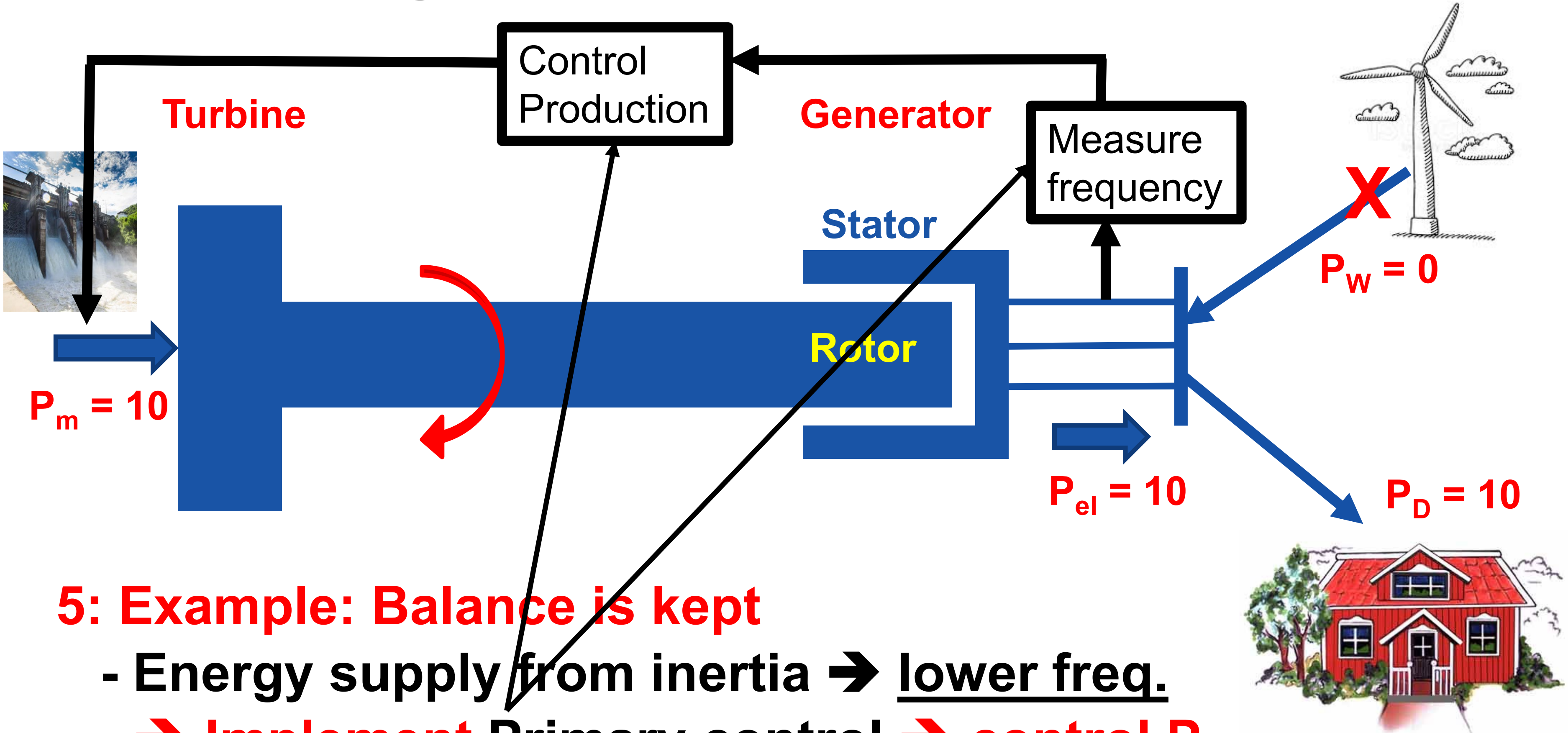
Frequency control = how to balance a change in production/consumption - 5



4: Example: Balance is kept

- Energy supply from inertia ➔ <u>lower freq.</u>
- ➔ Implement <u>Primary control</u> ➔ control P_m

Frequency control = how to balance a change in production/consumption - 6



5: Example: Balance is kept

- Energy supply from inertia ➔ lower freq.
- ➔ Implement Primary control ➔ control P_m

Keep the balance in the power system

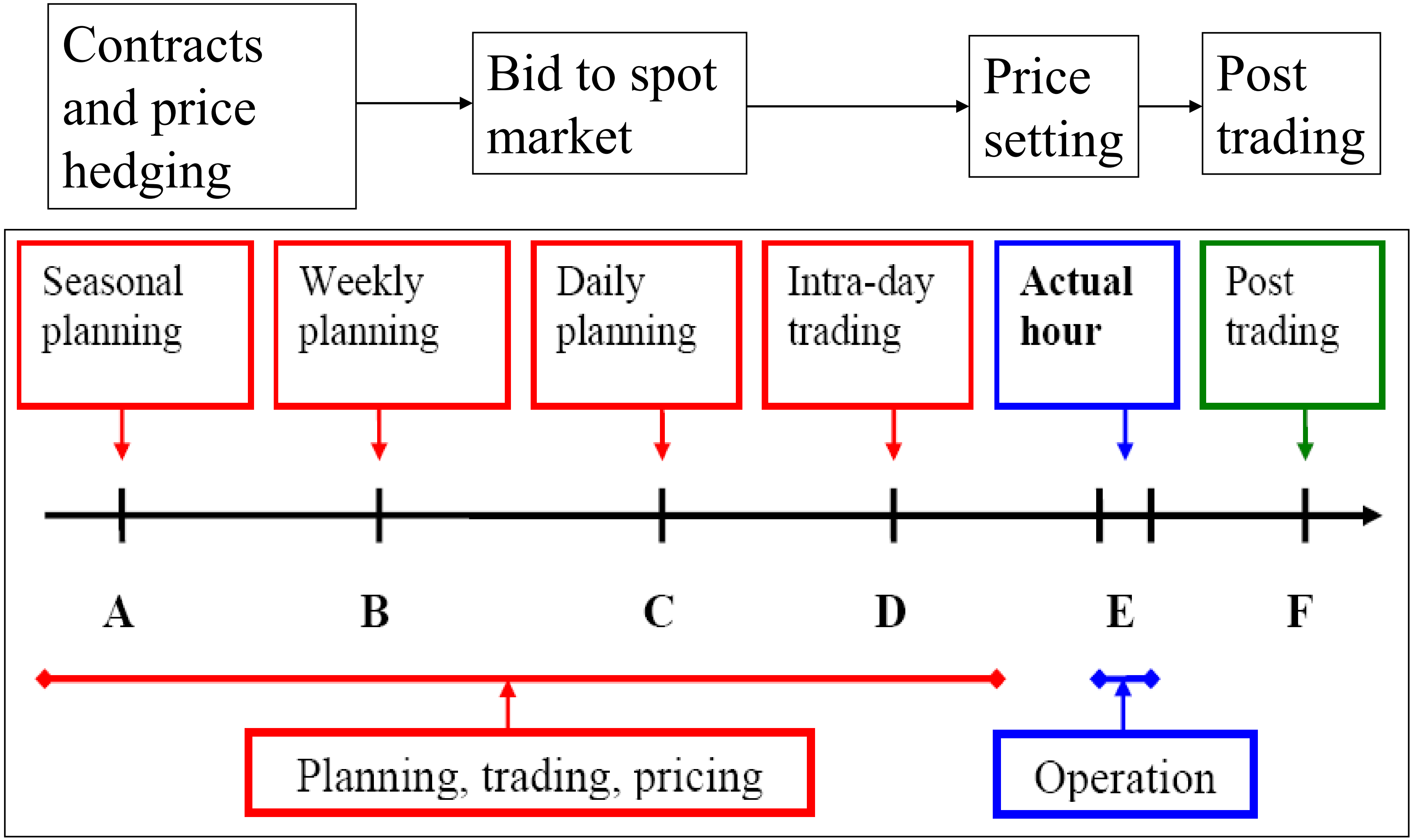
Different time steps:

1. Inertia (seconds)
2. Primary control (minutes)
3. Secondary control(quarter)
4. Tertiery control (quarter)
5. Intra-day-trade (hours)
6. Day-ahead-trade (day)
7. Weekly planning (week)
8. Yearly planning (year)

Security ↕ **Uncertianty**

Technology ↕ **Economy**

Power operation planning



The power system = a long bike

Keep active power balance

Bike

- Pedal forces = breaking forces
- Otherwise changed speed
- Break bike => lower speed

Power System

- Total generation = total load
- Otherwise changed electric frequency
- Increase load => lower frequency

Speed control

Bike

- Keep a constant speed
- Measure the speed (same on the whole bike)
- Reduced speed=> increase the force on the pedals.

Frequency control

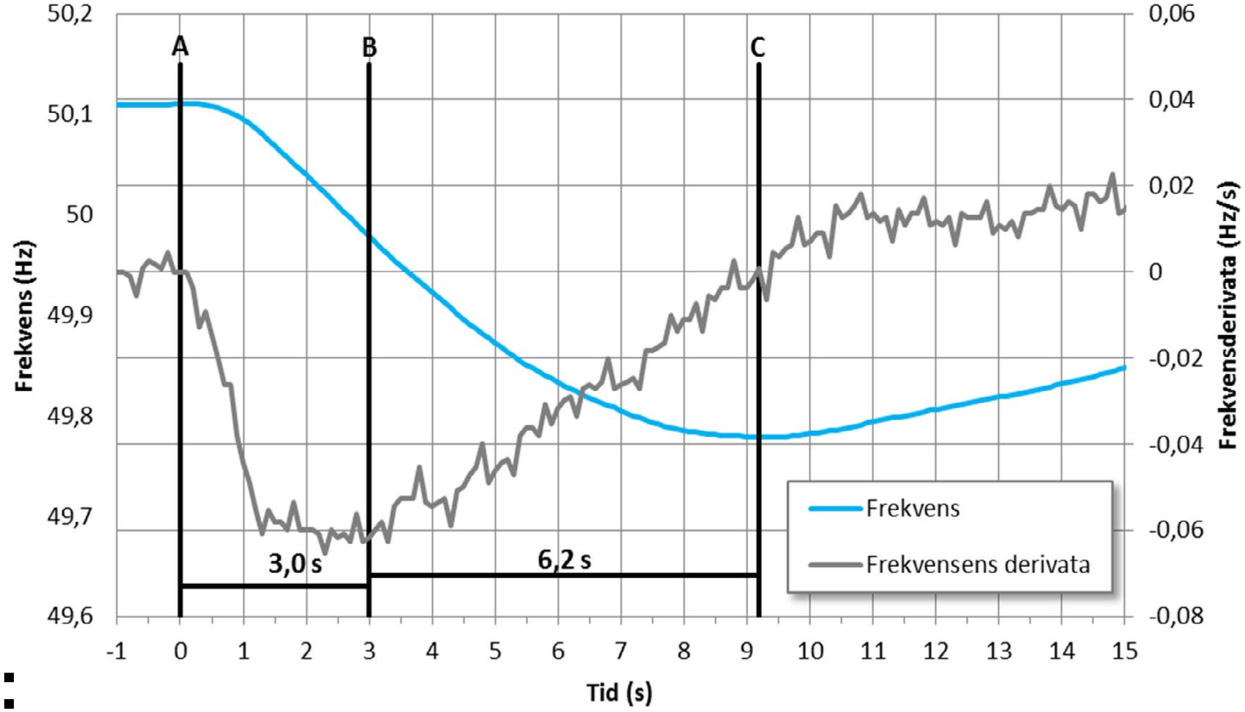
Bike

- Keep constant speed
- Measure speed (same on whole bike)
- Decreased speed => increase pedal force

Power System

- Keep constant frequency
- Measure frequency (same in whole system)
- Decreased frequency => increase generation

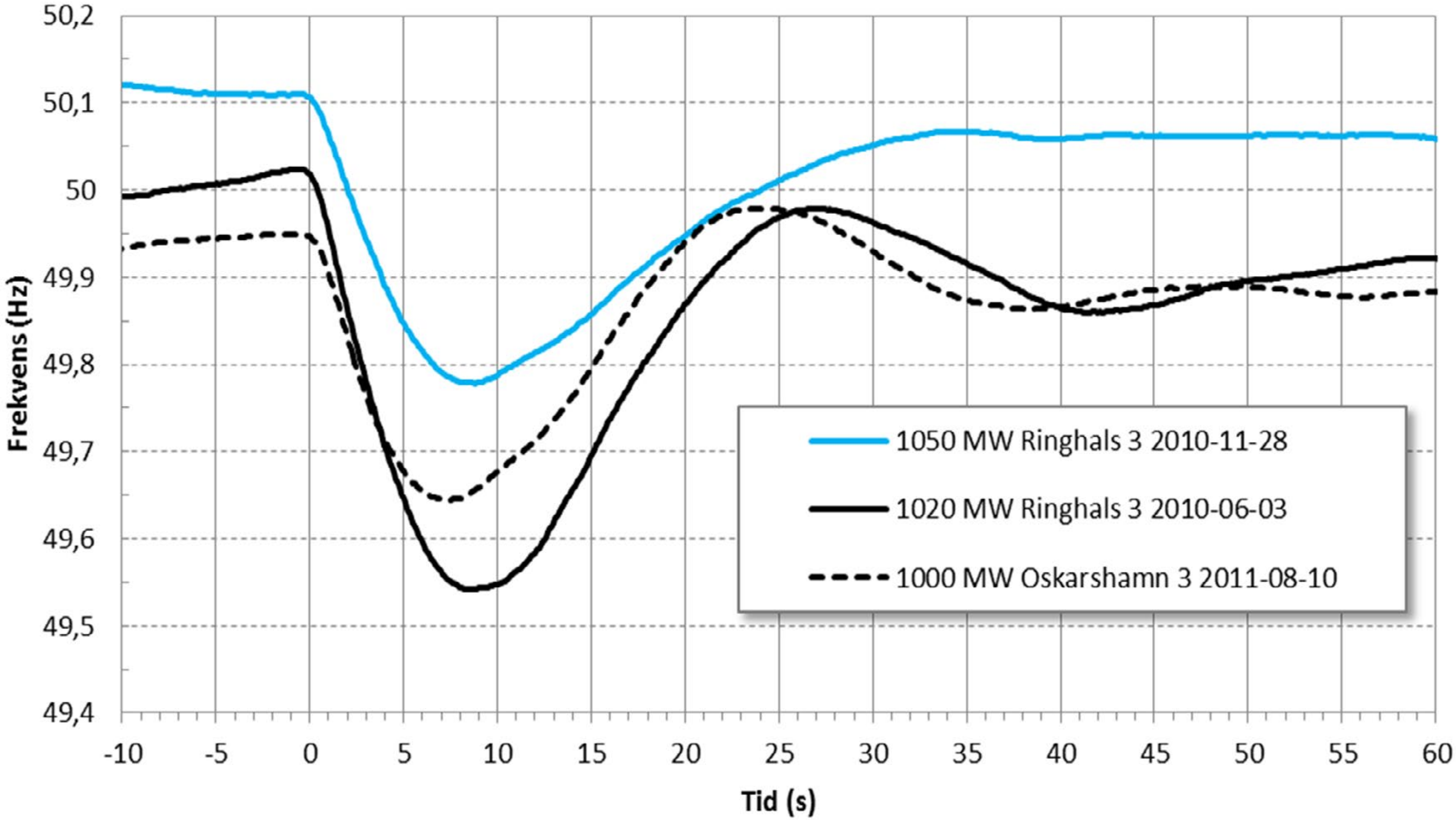
Real initial phase of a power system outage



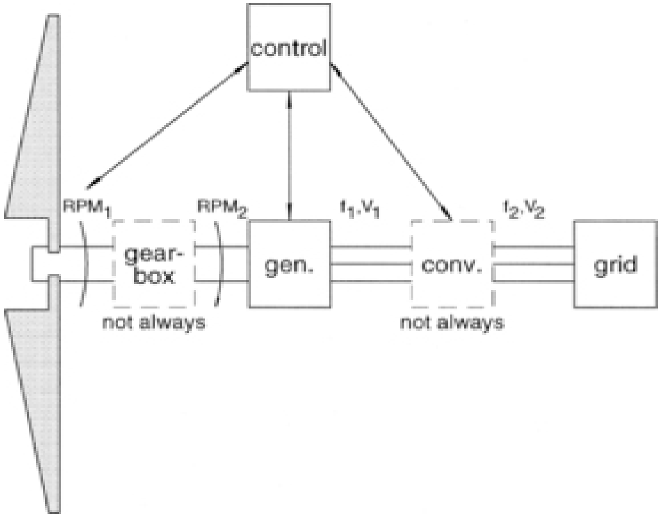
Time steps:

A. Disconnection of Swedish 1050 MW nuclear station
B. Primary control starts
C. Primary control has increased with 1050 MW

Frequency drop after 3 real outages in Sweden



Inertia: for wind power



Contribution:

- Wind power stations use converters between generator and grid. This means that advanced control is needed in order to make them contribute.

Challenges:

- A challenge in power systems with, e.g. large amounts (80-90% of production) of solar power, wind power or HVDC infeed, which may not contribute with inertia. If not, then there are stability challenges

2. Primary control: For wind power

Contribution:

- Primary control means that one in some units has to change the production fast (within seconds). Both increase and decrease is needed. This means that one has to keep margins. Wind power is a possible contributor, but normally not economically efficient

Challenges:

- To be able to increase production it is necessary to spill energy ➔ not so efficient.
- At winds that are high enough, it is possible to decrease production. But this means spillage ➔ not so efficient

Three challenges at large amount of variable renewables (solar/wind)

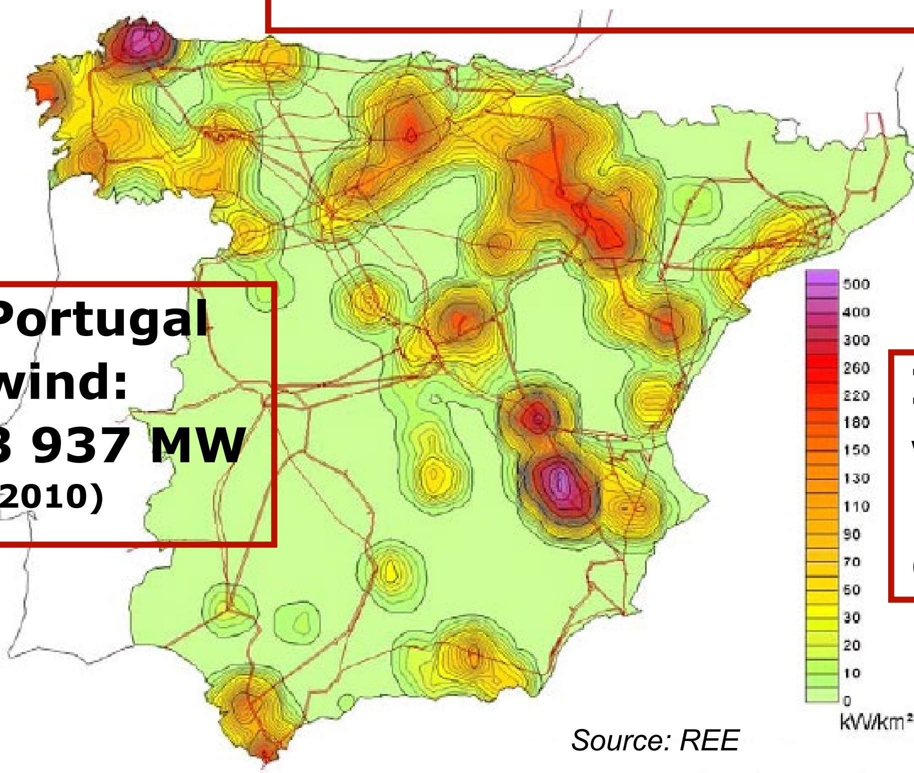
C1: Handling of the continuous balance.

C2: Low wind and solar power production and high power consumption. This issue is called ”capacity adequacy issue”.

C3: High wind and solar power production and low power consumption.

Wind power in some European countries

Spain wind: 20 733 MW



Source: REE

Portugal wind: 3 937 MW (2010)

Ireland wind: 1539 MW (2010)

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

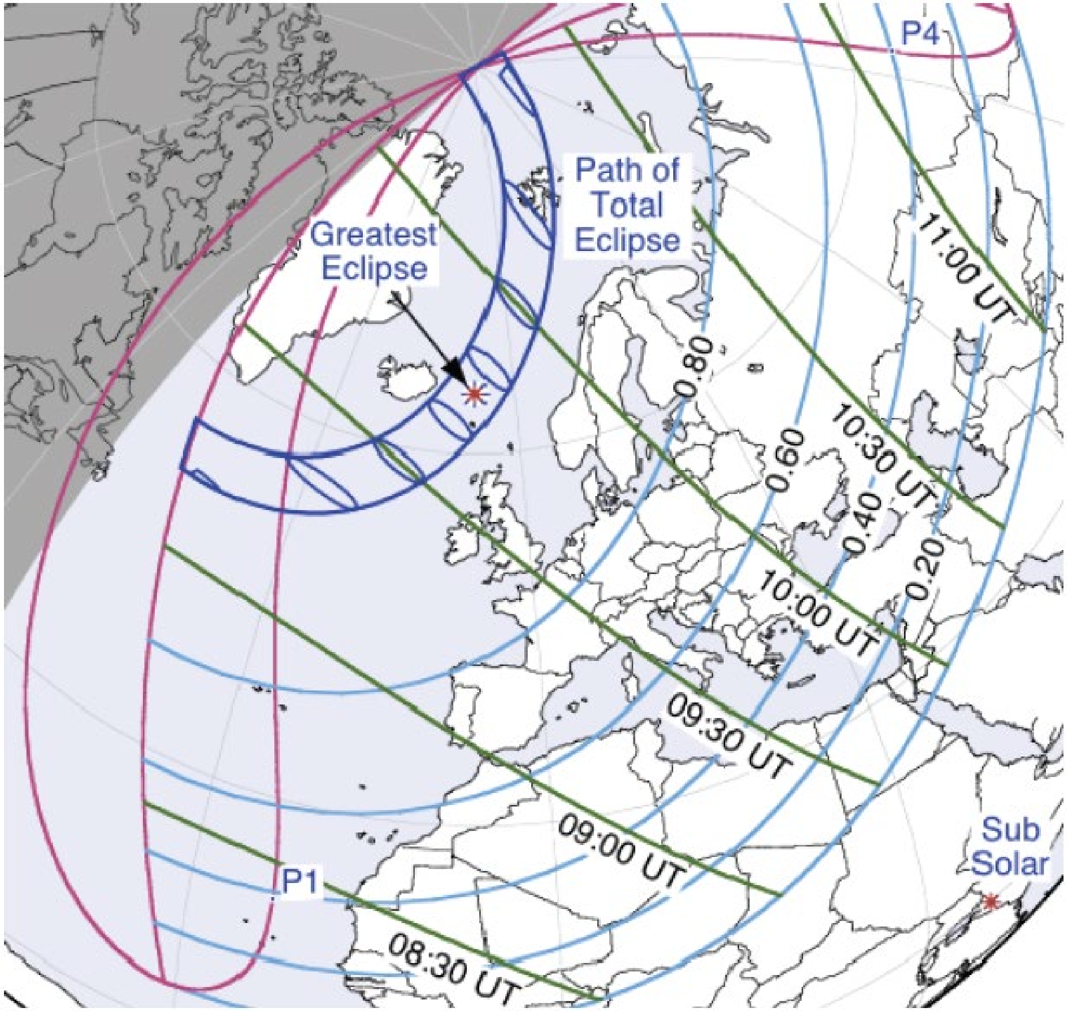
Portugal –Spain: 1200 MW
Spanien – France: 1200 MW
Spanien – Morocko: 650 MW

- Ireland - Skottland: 450 MW
- Ireland – UK: 850 MW

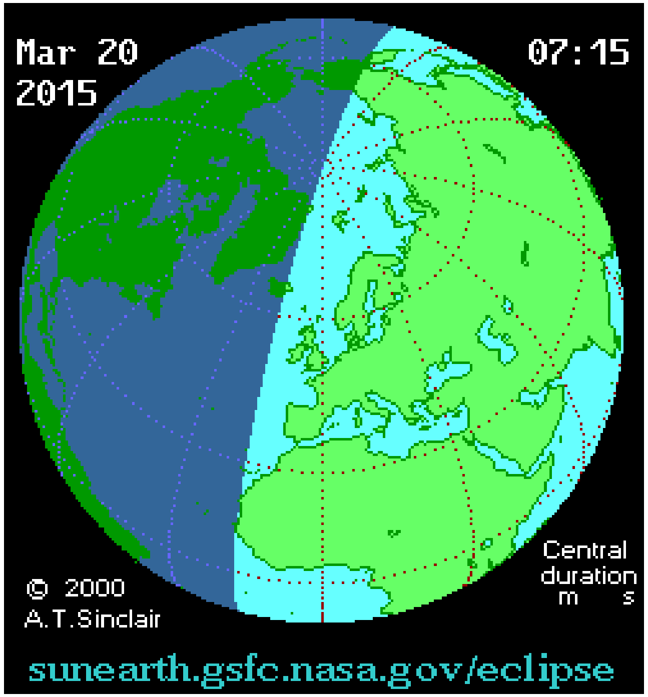
Solar power:

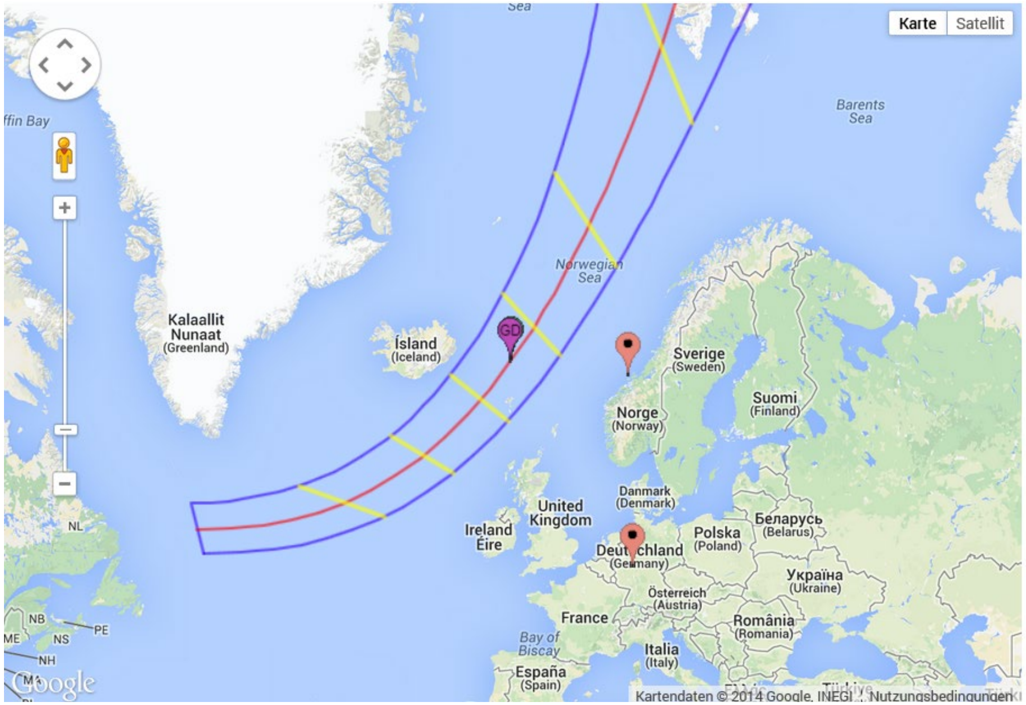
Specific Challenge:

- In the morning on March 20, 2015, a partial solar eclipse covered large areas on North and Central Europé
- Germany had at that time > 35000 MW of solar power



Solar eclipse over Europe on 20 March 2015

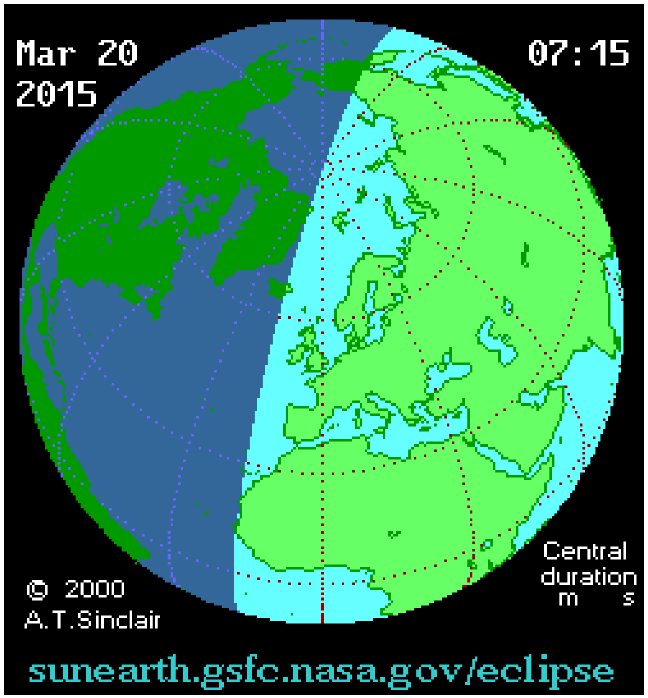


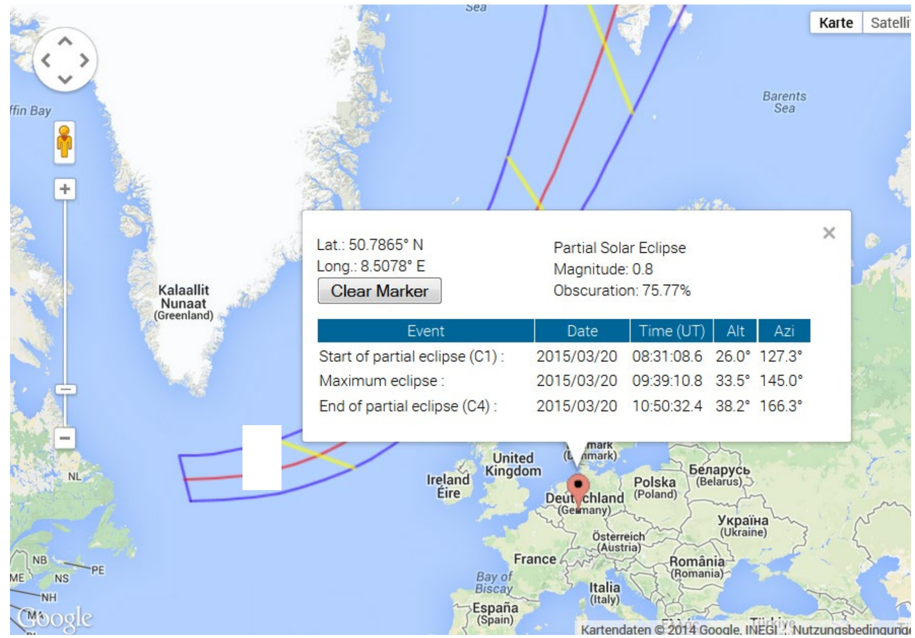


http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2015Mar20Tgoogle.html

Fraunhofer IWES

Solar eclipse over Germany on 20 March 2015

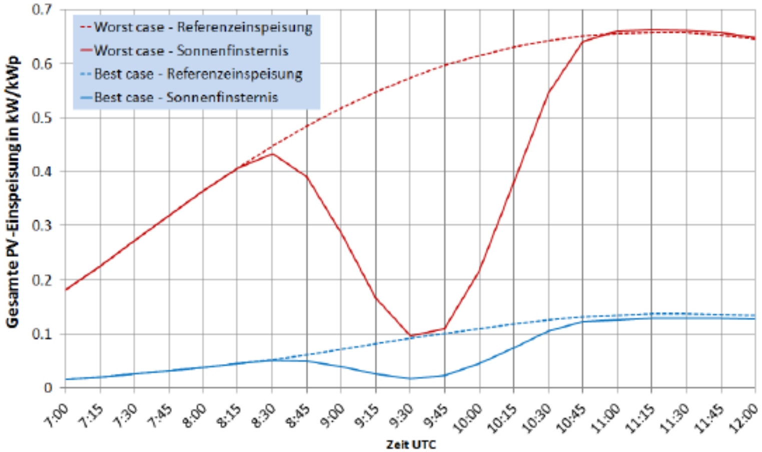


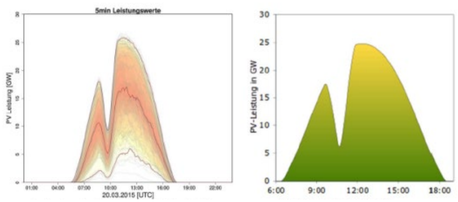


http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2015Mar20Tgoogle.html

[source: HTW Berlin]

Some Results





[source: HTW Berlin und Fraunhofer ISE]

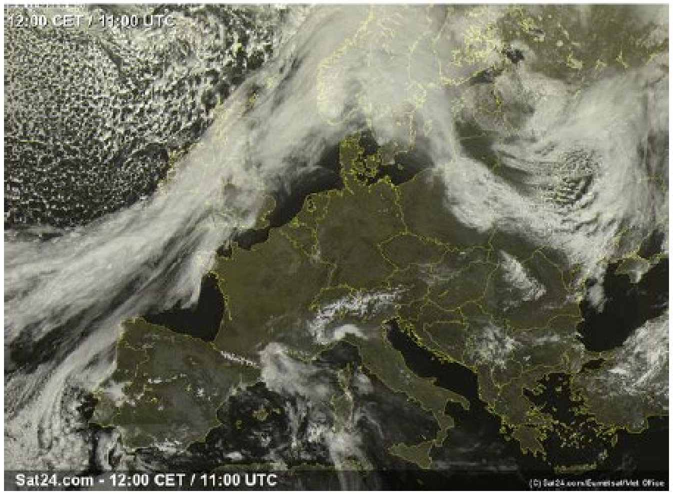


Abbildung 2-1: Satellitenbild vom 20.03.2014 um 11:00 Uhr UTC – der Tag der für das Worst Case Szenario ausgewählt wurde (Quelle: www.Sat24.com).

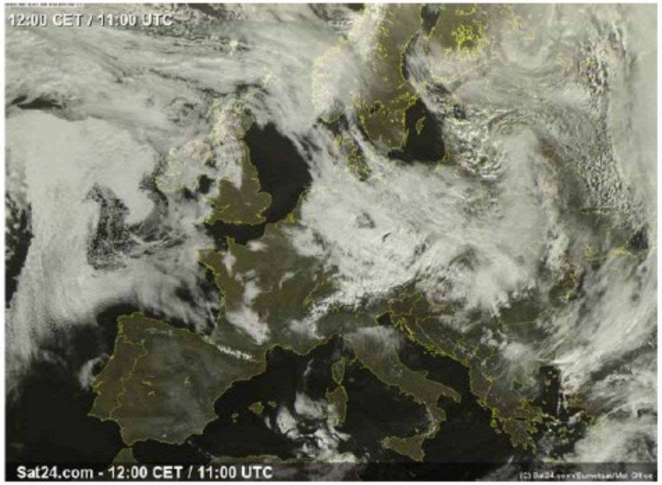


Abbildung 2-2: Satellitenbild vom 16.03.2014 um 11:00 Uhr UTC – der Tag der für das Best Case Szenario ausgewählt wurde (Quelle: www.Sat24.com).

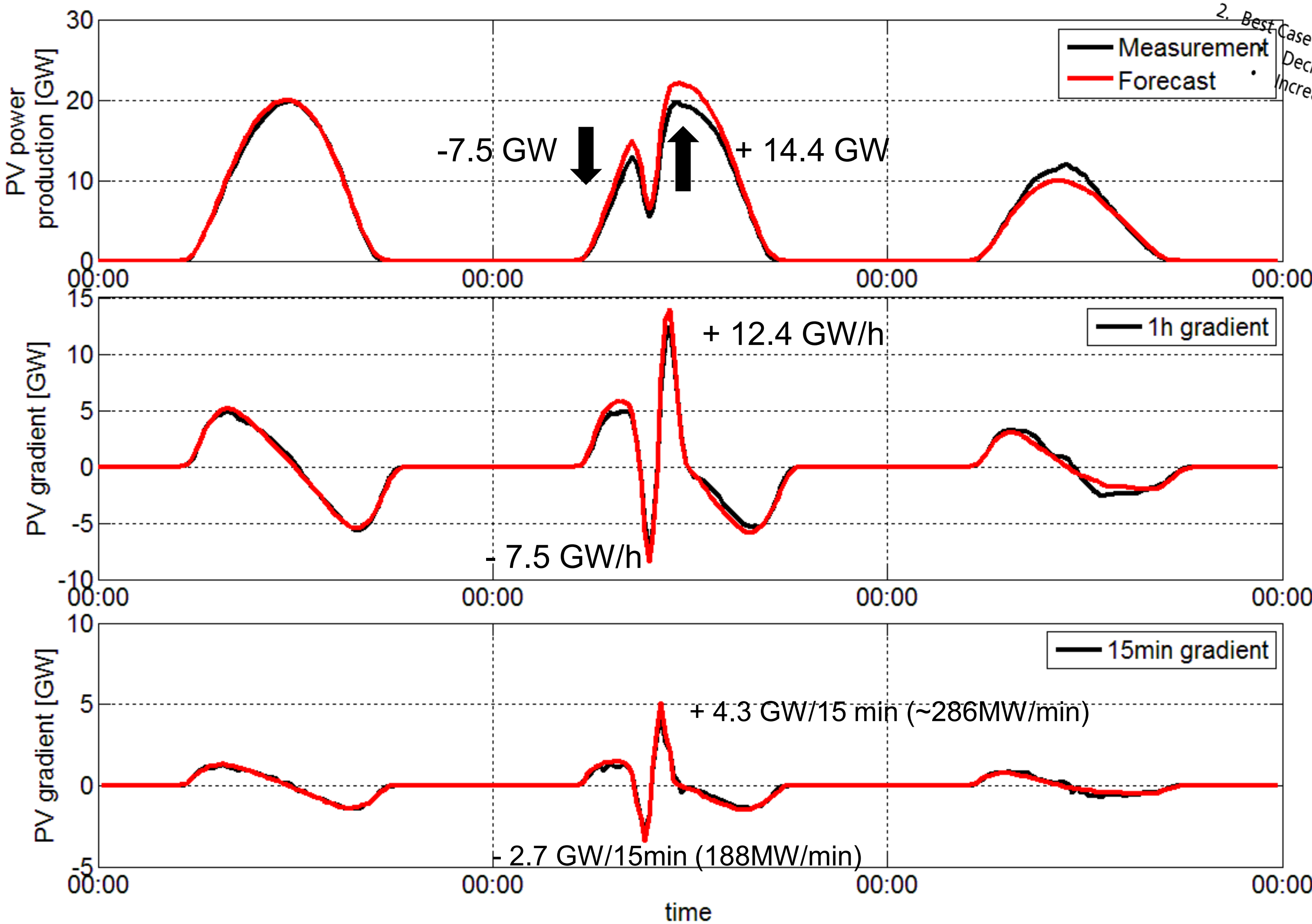
Estimated average maximum values of three studies

1. Worst Case:
   - Decrease 11 GW, -11 GW/h, 250MW/min
   - Increase 19 GW, +15GW/h, 350MW/min
2. Best Case
   - Decrease 1.3 GW, 1.3 GW/h, 25MW/min
   - Increase 4 GW, 3.2GW/h, 65MW/min

PV Measurement & Forecast

Estimated average maximum values of three studi

1. Worst Case:
   - Decrease 11 GW, -11 GW/h, 250MW/min
   - Increase 19 GW, +15GW/h, 350MW/min
2. Best Case
   - Decrease 1.3 GW, 1.3 GW/h, 25MW/min
   - Increase 4 GW, 3.2GW/h, 65MW/min



Fraunhofer IWES