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EU4ENERGY PHASE II

Cross-cutting Water and Energy Needs of Human Activities

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EU4Environment Water and Data programme

Contents

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Session objectives

- Introduce basic vocabulary for studying water and energy flows
- Give orders of magnitude for water and energy consumption on a European scale
- Identify the main interdependencies between water and energy uses

Representing the challenges of the water-energy nexus:

the water-energy matrix

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Building a quantified water-energy coupling matrix for a given region

- **A matrix for what?**

  - Visualize in a synthetic document the distribution of the **main water and energy flows** between the different sectors of activity.

  - Identify the **interdependencies** between water and energy flows

  - Identify and describe **competing uses**

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Main stages

- **Main stages in drawing up a country's water/energy matrix**
  1. Determine the perimeter of the matrix
  2. Precise vocabulary
  3. Choice of units to represent physical flows of water and energy
  4. Identify sectors of activity
  5. Determine and represent water flows by sector
  6. Determine energy flows by sector
  7. Determine energy requirements for various water uses
  8. Determine water requirements for energy production

Period and scope

- **Data presentation period**
  - one year

- **Scope of the matrix**
  - **For water**
    - The relevant scale is that of the **watershed** (**river basin**)
    - We can also use the national scale, but the analysis of water-related issues is less relevant at this scale (it hides spatial distribution problems)
  - **For energy**
    - The relevant scale is the **national scale**
    - Energy consumption data is not available at the watershed level

- **Choice :** presentations of the **water-energy nexus are made on a national scale**, keeping in mind that water management takes place on a watershed scale.

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Vocabulary

- **Energy**
  - Transformation chain from primary energy to service provision
    - **Primary** : raw, unprocessed energy (solar, wind, hydro, biomass, fossil, nuclear)
    - **Final** : energy delivered to the user (comercial energy)
    - **Useful** : energy that provides the service
  - Different types of energy
    - Heat / mechanical / mechanical hydraulic / electrical

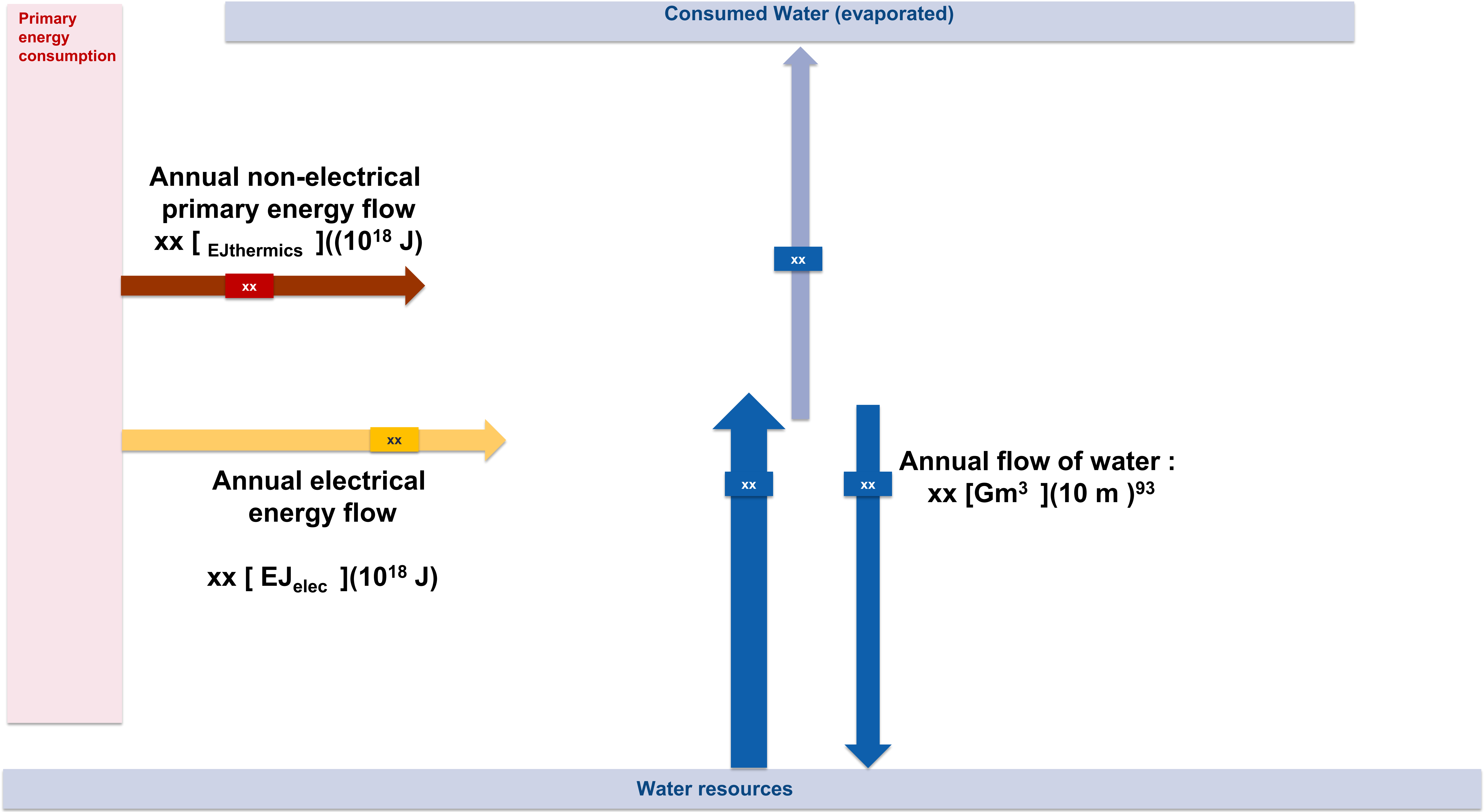
- **Water**
  - Withdrawn (abstracted) : volumes of water withdrawn from water resources
  - Consumed : volumes of water evaporated or discharged into the sea
  - Usage in stream : the water is used in its environment without withdrawal (e.g. navigation)

Units of measurement and orders of magnitude

- **For water**
  - The basic unit of measurement for volume in the International System (IS) is the cubic metre m^3
  - The order of magnitude of flows on a national scale is **Gm^3** ($10^9 .m^3$) (equivalent to $(km)^3$)

- **For energy**
  - the joule (J) is the unit of energy used in the international system
  - The order of magnitude of flows on a national scale is **the EJ (Exa Joule: 10^{18} J)**
    - **1 EJ heat = 23,8 Ton Oil Equivalent (toe) heat**
    - **1 EJ electric = 278 TWh electric**

- When speaking of energy, it is advisable to **specify the nature of the energy** (e.g. for one J of heat, we note: 1 J_{heat}).

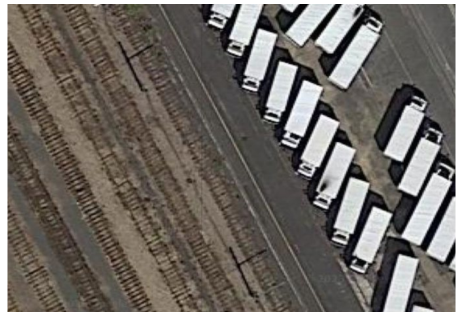


Primary energy consumption
Consumed Water (evaporated)
Annual non-electrical primary energy flow
xx [EJthermics]((10^{18} J)
xx
xx
Annual electrical energy flow
xx [EJ$_{elec}$](10^{18} J)
xx
xx
Annual flow of water :
xx [Gm^3](10 m)^{93}
Water resources

Classification of human activities by sector

- **Sectors of activity**
  - Residential
  - Services (which can be merged with the residential sector)
  - Industrial
  - Agricultural
  - Transport
- **Not forgetting**
  - Power generation
  - Water production for domestic use
  - Wastewater treatment







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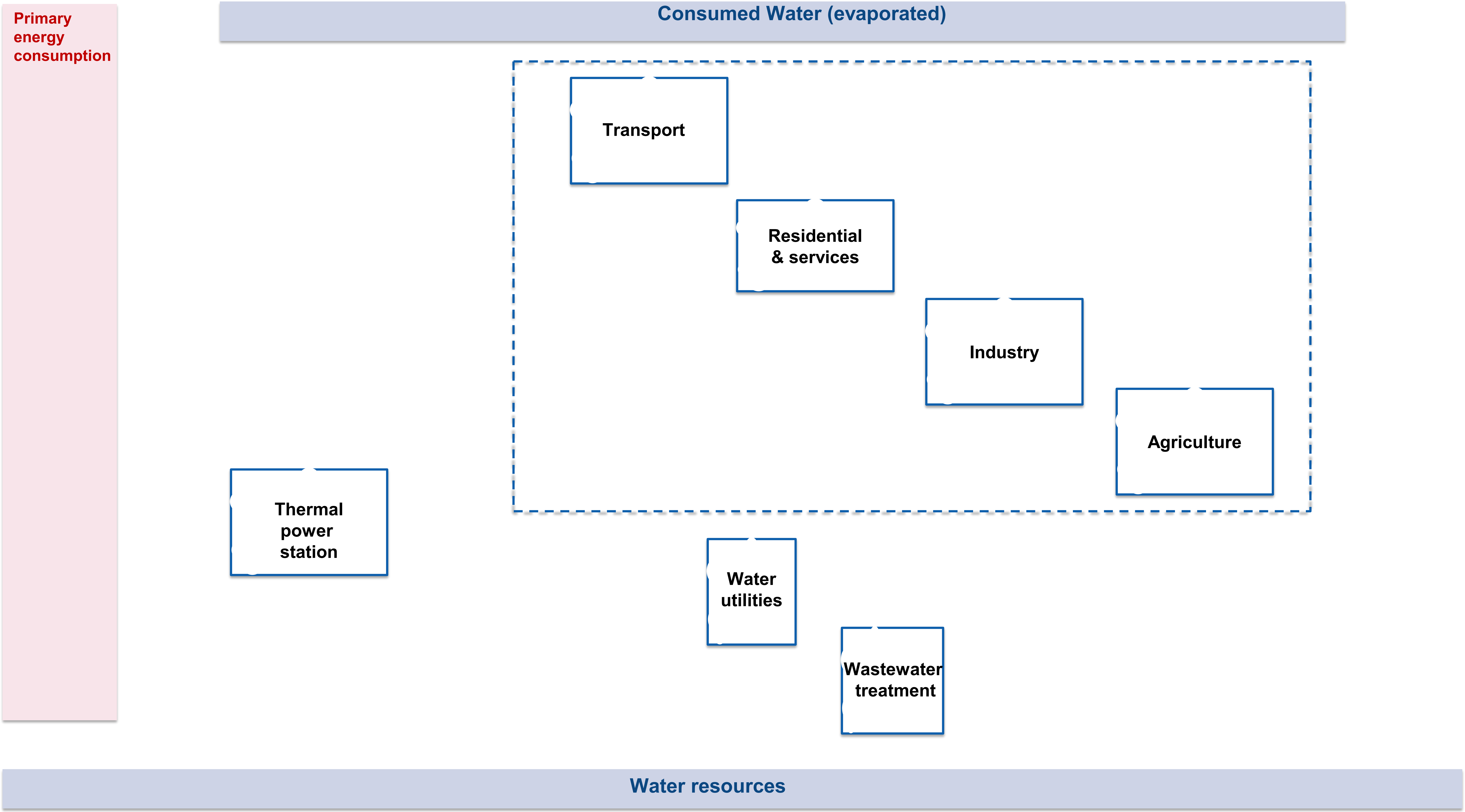
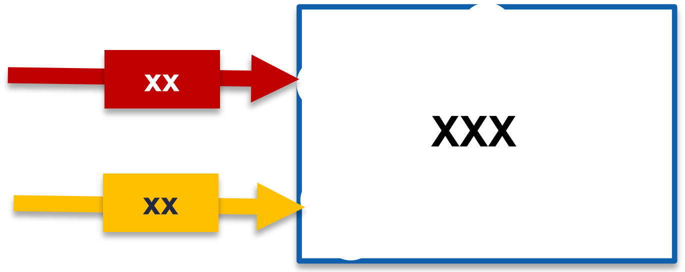


Primary energy consumption
Consumed Water (evaporated)
Transport
Residential & services
Industry
Agriculture
Thermal power station
Water utilities
Wastewater treatment
Water resources

Determine energy flows

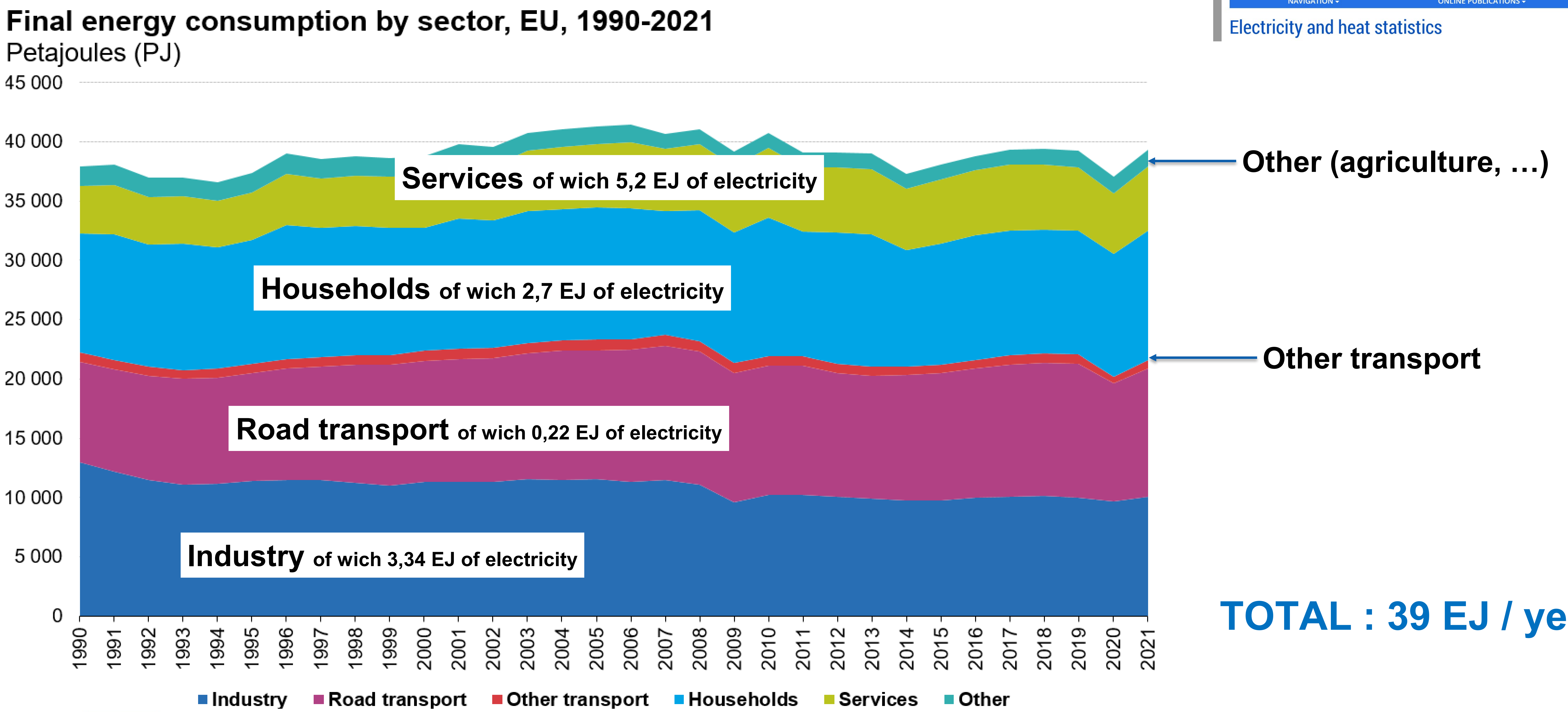
- **Energy flows consumed by sector**
  - Data sources: European or national statistics (pay attention to units)
  - For simplicity, avoid specifying the type of energy used for each sector
  - Differentiate between electrical energy and other final energy sources



- **Energy flows consumed in electricity generation**
  - Electricity generated by **thermal power** plants (oil, gas, coal, other fuels, nuclear)
  - **Hydropower**
  - Electricity generated from non-combustion renewable energy sources

Requires large quantities of water

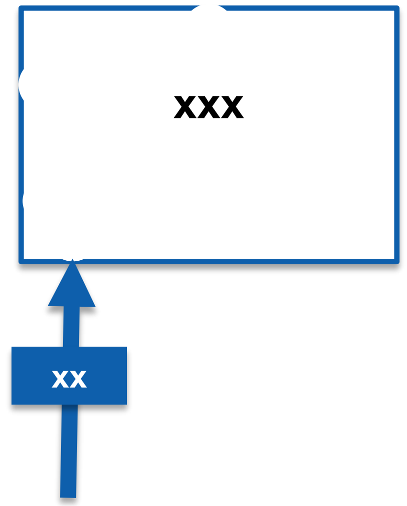
Final energy consumption



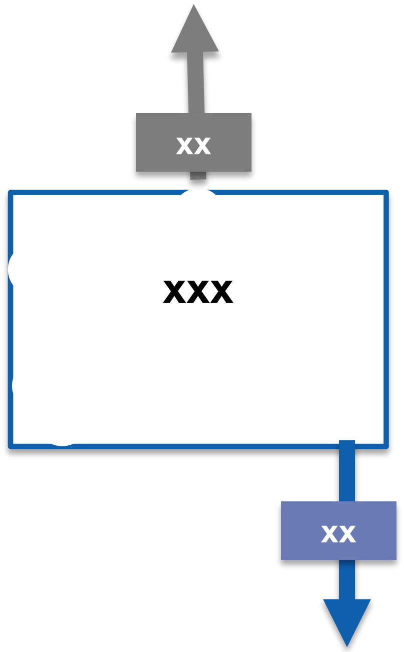
TOTAL : 39 EJ / year

Water flows by sector of activity

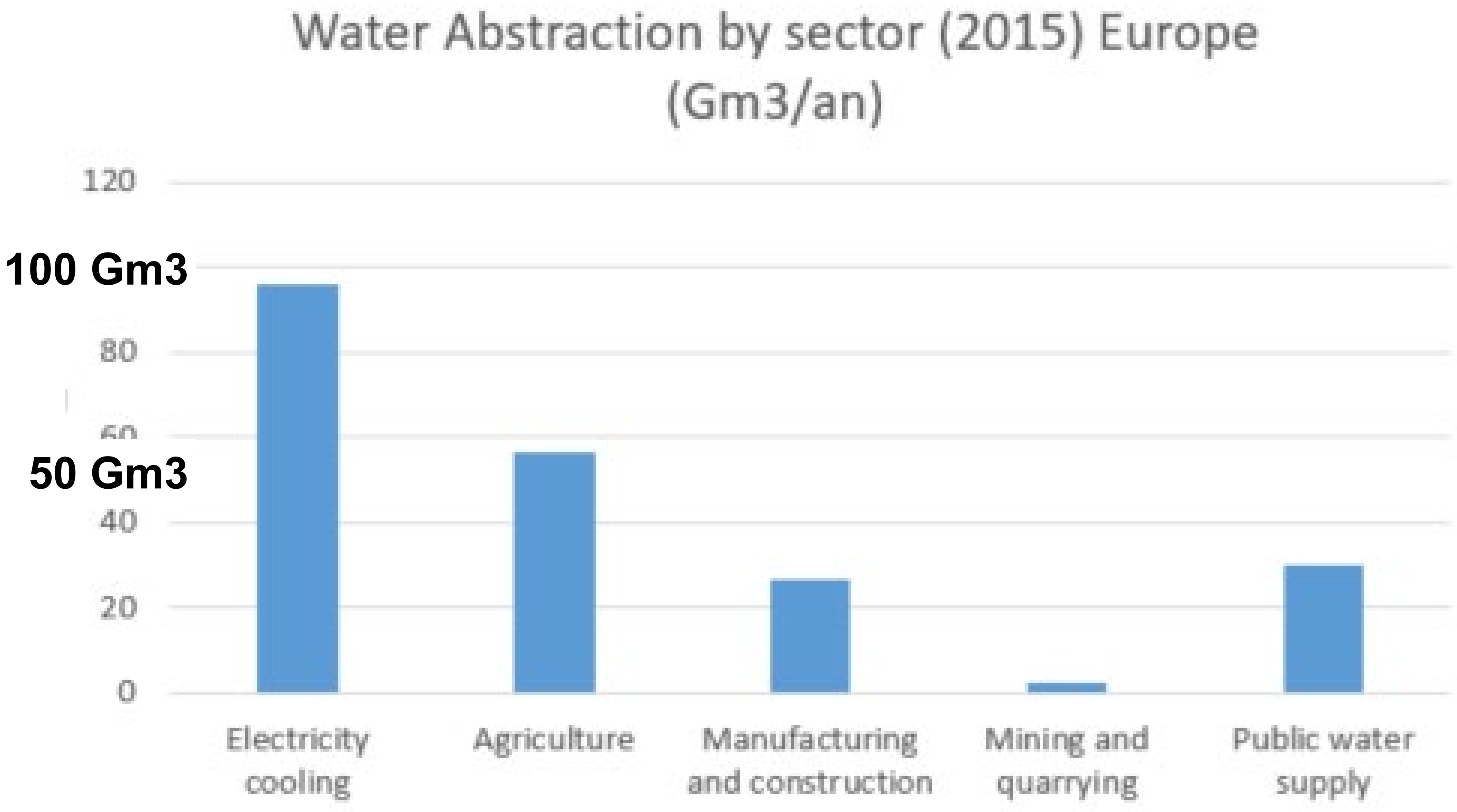
- **Incoming water flow**
  - Water abstraction volumes (withdrawal)
  - Possibility of specifying the nature of the resource mobilized (surface or groundwater. Seawater is not taken into account)



- **Outgoing water flow**
  - Volumes consumed (evaporated)
  - Volumes of degraded quality passing through a treatment system
  - Volumes returned to the natural environment (surface or groundwater)



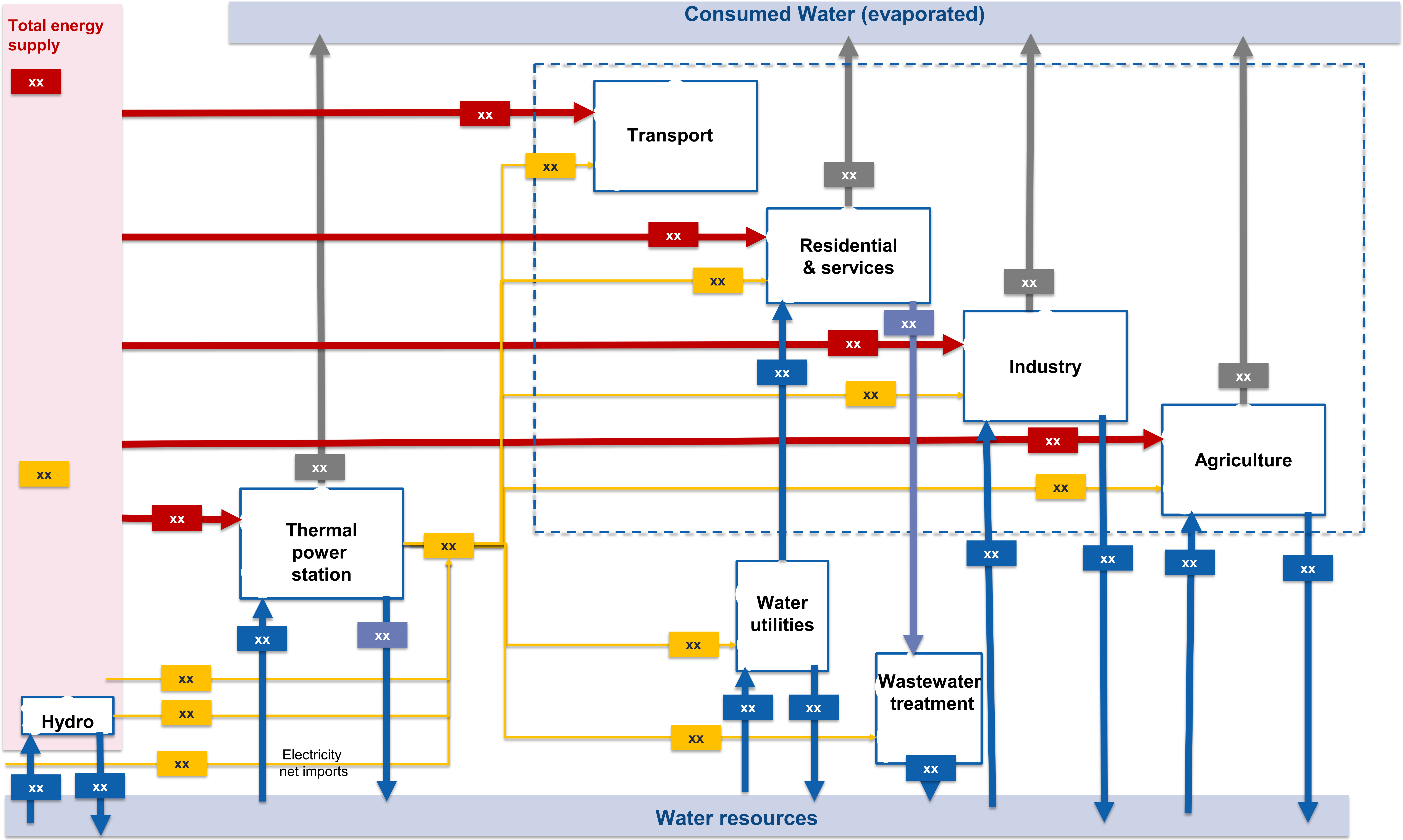
Water abstraction by sector (EUROPE)



Total Europe :

224 Gm3 /year

https://www.eea.europa.eu/data-and-maps/daviz/water-abstraction-by-sector-eu-2/#tab-chart_1


Consumed Water (evaporated)
Total energy supply
xx
Transport
Residential & services
Industry
Agriculture
Thermal power station
Water utilities
Wastewater treatment
Hydro
Electricity net imports
Water resources

Definition of the two nexuses

- **Energy for water (section 2)**
  - Energy requirements for water services
    - Water distribution services
    - Collective sanitation service
  - Energy requirements for irrigation

- **Water for energy (section 3)**
  - Water requirements for cooling thermal power plants
    - Water abstraction (withdrawal)
    - Water consumption
  - Water turbined in hydroelectric power plants

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Energy needs for water mobilization in human activities

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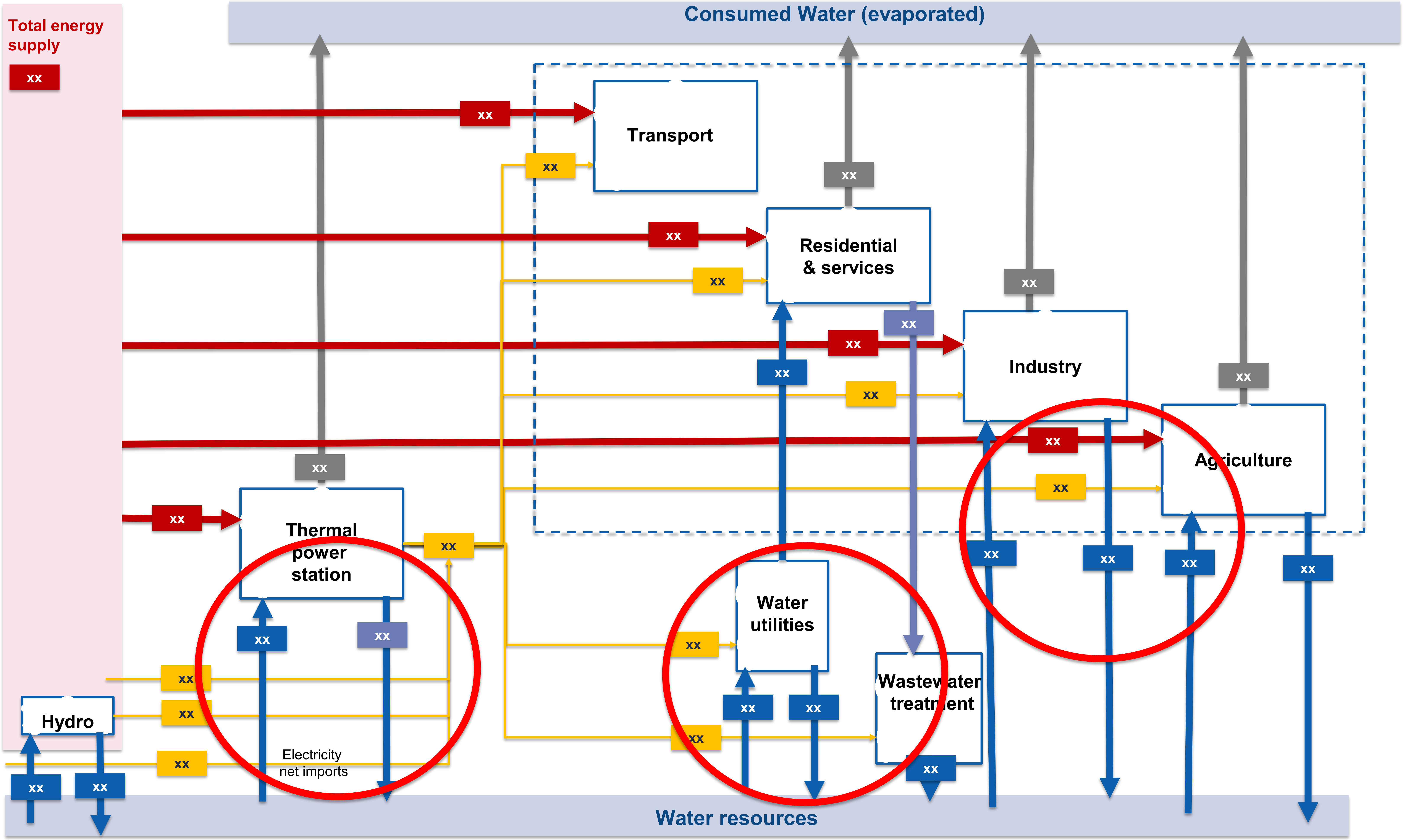
Energy for water

- **Why are we interested in energy requirements for water mobilization in human activities? Because it's:**

  - A share of national energy consumption that is usually small (<5%), but potentially significant in certain contexts

  - A factor of vulnerability for essential services (drinking water, sanitation)

  - A production cost that can be significant in a budget


Consumed Water (evaporated)
Total energy supply
xx
Transport
Residential & services
Industry
Agriculture
Thermal power station
Water utilities
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Hydro
Electricity net imports
Water resources

Calculation of the energy required to perform water mobilization functions

- **Calculate "useful energy" requirements for each function**

Work = Force . Displacement

Work [expressed in joule or Watt.second]

Force (weight) [Newton] = Mass [kg] . g [$N.kg^{-1}$] = ρ . V [m^3] . g [N.kg] $^{-1}$

V : volume of water to move [m] ^{3}

ρ = density of water = 1000 kg / m^3

g : gravitational acceleration on earth = 9,81 [$m.s^{-2}$ or N.kg]$^{-1}$

Displacement [meter in the direction of the Force] = Head [meter]

Work [W expressed in joule or Watt.second] = ρ . g [N.kg-1] . **V** [m3] . **Head** [meter of water column]

Work [J] = 9810 . VOLUME [m^3] . HEAD [m]

Work [kWh $_{mecanics}$] = **2,725.10^{-3} [kWh.m^{-4}] . VOLUME [m^3] . HEAD [m]**

1 J = 1 W.s
1 kWh = 3,6 MJ = 3,6.10^6 J

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Energy requirements for water resource mobilization

- **Some basic functions (HMT (total head) and useful energy in $_{\text{mechanical}}$ kWh for 1 m^3)**
  - Abstraction (withdrawal)
    - Head: altitude difference from 0 to 300 m / Useful energy: from 0 to 0.83 kWh
  - Filtration
    - Head: pressure drop from 2 to 10 m / Useful energy: from 0.005 to 0.03 kWh
  - Desalination (reverse osmosis technique for seawater 35g salt/l)
    - Head: pressure 700 m / Useful energy: 1.93 kWh
  - Transport and distribution (for 1km of pipe). *Determining factors (flow rate, diameter, roughness)*
    - Head losses: pressure drop from 20 m to 100 m / Useful energy: from 0.06 to 0.3 kWh
  - Spreading over an irrigated field
    - Gravity irrigation / Head: 0 m to 5 m / Useful energy: 0 to 0.015 kWh
    - Localized irrigation / Head: 5 m to 30 m / Useful energy: 0.015 to 0.083 kWh
    - Sprinkler irrigation / Head: 20 to 80 m / Useful energy: 0.06 to 0.22 kWh

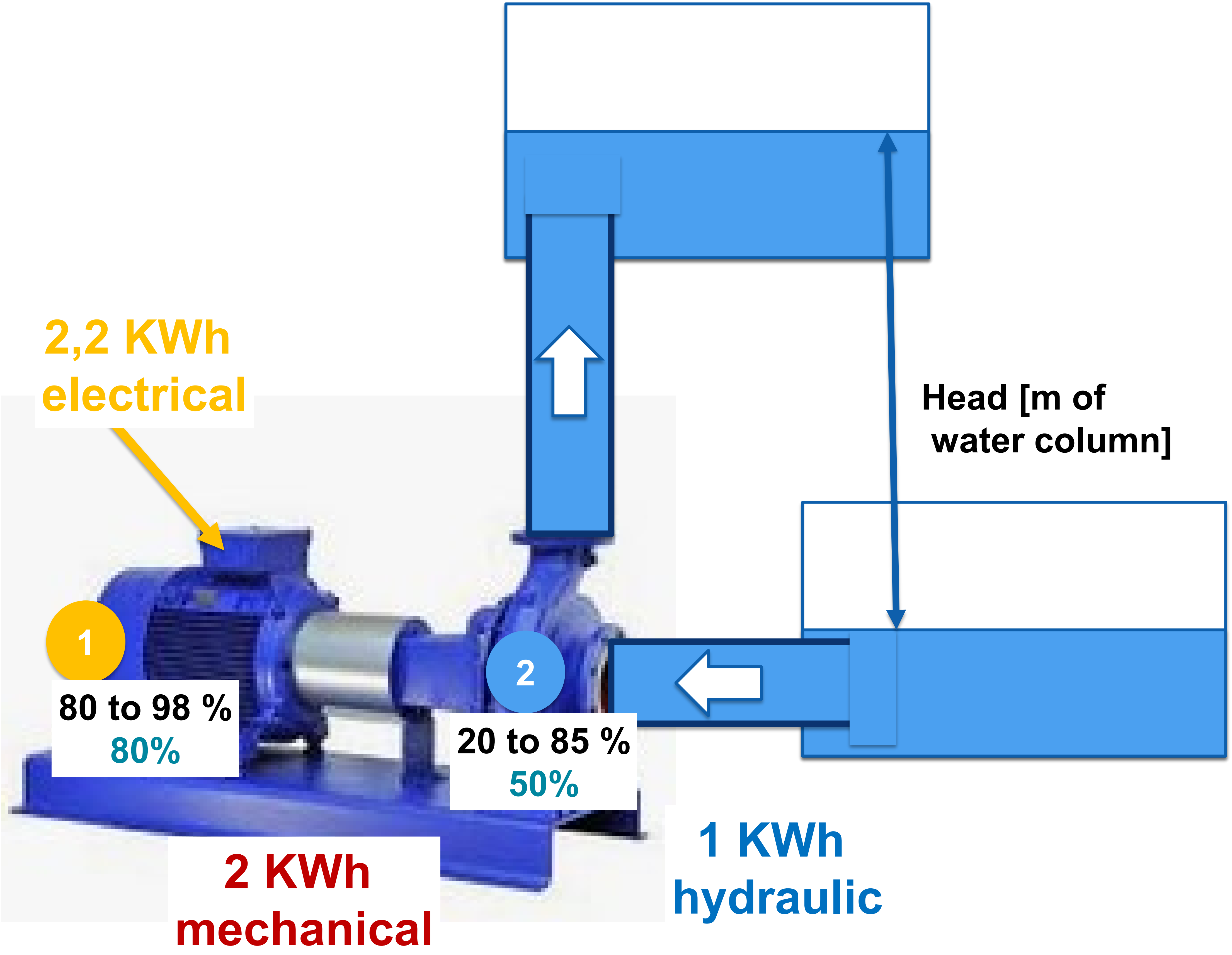
Please note that the above indicative values are given in kWh of hydraulic power (mechanical). Several conversion efficiencies need to be taken into account

Generating hydropower

- **Producing "useful energy" from "final energy "**

1 Mechanical Power generation: converting **final energy** (kWh of electricity or liter of fuel) **into mechanical energy**

2 **Pumping**: converting a **motor's mechanical energy** (torque and number of revolutions) into **hydraulic mechanical energy**



Generating hydropower

- **Producing "useful energy" from "final energy "**
  - **Pumping**: converting a motor's mechanical energy (torque and number of revolutions) into hydraulic mechanical energy (volume and pressure).
    - Pumping efficiency = hydraulic energy produced / mechanical energy input (from 20 to 85%)

    It takes between **1.2 and 5** $_{\text{mechanical}}$ **kWh to produce 1** $_{\text{hydraulic}}$ **kWh.**

  - **Méchanical Power generation**: converting final energy (kWh of electricity or liter of fuel) into mechanical energy
    - Electric motor efficiency = mechanical energy / incoming electrical energy (80 to 98%)

    It takes between **1.02 and 1.2 kWh of** $_{\text{electricity}}$ **to produce 1 kWh of** $_{\text{mechanical energy}}$**.**

    - The efficiency of a combustion engine is a thermodynamic machine that can produce around 3 kWh of $_{\text{mechanical energy}}$ from 1 liter of gasoline (38 MJ $_{\text{thermal}}$ or 10.5 kWh $_{\text{thermal}}$).

    It takes about **0.33 liters (3 kWh heat) of fuel to produce 1** $_{\text{mechanical}}$ **kWh.**

1 kWh $_{\text{mechanical hydraulic}}$ **≠ 1 kWh** $_{\text{mechanical}}$ **≠ 1 kWh** $_{\text{electrical}}$ **≠ 1 kWh** $_{\text{thermal}}$

Order of magnitude: Drinking water

- **Delivery of 1 m^3 to the water meter**

  - Total head for service functions: 170 m
    - Withdrawal from the resource: 25 m
    - Transport : xx0 m
      - 3 km of pipe (head loss 30 m/km x 3 = 90 m)
      - 30 m vertical drop
    - Provide pressurized water to the customer's water meter: 25 m
  - Conversions: 63%
    - Pumping: 70%
    - Motorization (electric): 90%
  - Distribution network water efficiency: 80% (1.25 m^3 of water must be put in the distribution network to deliver 1 m^3 to the user)

Water services Orders of magnitude :

0.5 to 1.5 kWh / m3

→ Useful energy required = 0.00275 x (1 / 0.8) x 170 = 0.584 $kWh_{hydraulic}$

→ **Final energy consumption** = (0.00275 x (1 / 0.8) x 170) / (0.63) = **0.927 $kWh_{electricity}$ / m^3**

Economic interpretation: energy represents 2 to 10% of the price of 1 m3 billed to domestic users.

The economic equilibrium of water utilities is sensitive to variations in the price of electricity

Order of magnitude: Irrigation

- **Example: sprinkler irrigation with a pivot**

  - Total head for service functions: 69 m
    - Withdrawal from surface water resources: 4 m
    - Transport water from the canal: 30 m head loss
      - 2 km of pipe (head loss 15 m/km x 2 = 30 m)
    - Distribution of water over the plot (pressure required, e.g. pivot-type sprinkler irrigation: 35 m)
  - Conversions: 72%
    - Pumping: 80%
    - Motorization (electric): 90%
  - Distribution network water efficiency: 98% (1.02 m^3 of water must be put in the distribution network to deliver 1 m^3 to the plot)

→ Useful energy required = 0.00275 x (1 / 0.98) x 69 = 0.191 $kWh_{hydraulic}$

→ **Final energy consumed** = (0.00275 x (1 / 0.98) x 69) / (0.72) = **0.270 $kWh_{electricity}/m^3$**

e.g. 66 kWh for an irrigation dose of 25 mm over a surface area of 1 ha (250 m3)

Approximately 800 kWh / year / ha => **order of magnitude 0.8 MWh / ha**

1 ha = 100 m x 100 m = 10,000 m²

Irrigation
Orders of magnitude :
1000 to 3000 m3/ha

0.3 kWh / m3

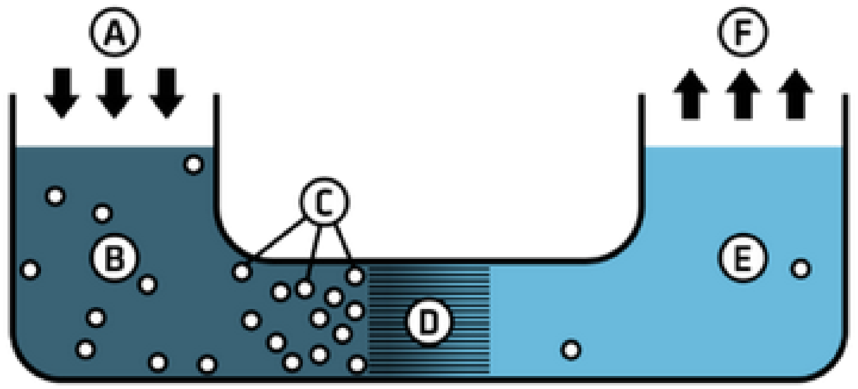
0,4 to 0,8 MWh / ha / year

Order of magnitude: desalination

- **Production of 1 m^3 of water with a reverse osmosis desalination plant.**
  - Seawater supply and brine removal functions
    - Withdraw seawater: 10 m difference in height (volume x 2)
    - Transport seawater (over 1 km): head loss 20 m (volume x 2)
    - Transport brine (over 1 km): pressure drop 20 m (volume x 1)
    - Volume of seawater required for 1 m3 of fresh water produced: 2 m^3

    →Useful energy required = 0.00275 x (2x(10+20) + 1x(20-10)) = 0.19 $_{\text{hydraulic}}$ kWh

  - Reverse osmosis desalination function: 700 m for 1m3 of fresh water produced
    - Desalination (reverse osmosis technique for seawater 35g salt/l): pressure 700 m
    - Part of the pressure transmitted to the seawater can be recovered when the brine is evacuated.
  - Conversions: 74%
    - Pumping: 80%
    - Motorization (electric): 92%



Desalination Orders of magnitude :

3 to 6 kWh / m3

→Useful energy required (without pressure recovery) = 0.00275 x (2 x 700) = 3.85 kWh hydraulics

→Useful energy required (100% pressure recovery) = 0.00275 x (1 x 700) = 1.925 $_{\text{hydraulic}}$ kWh

→**Final energy consumed min=** (0.19 + 1.92) / 0.74 = **2.88 kWh** $_{\textbf{electricity}}$

→**Final energy consumption max** = (0.19 + 3.85) / 0.74 = **5.49 kWh** $_{\textbf{electricity}}$

Order of magnitude: Wastewater treatment

- **Wastewater treatment**
  - a domestic user
    - Consumes approximately 0.15 m^3 of drinking water per day
    - Generates wastewater with a biological oxygen demand of around 0.06 kg/d
    - Under these conditions, the biological oxygen demand $(BOD)_5$ for 1 m^3 of wastewater is of the order of 0.4 kg BOD_5
  - Electricity consumption for wastewater treatment (excluding collection and sludge management)
    - Activated sludge plant: 2 to 5 kWh / kg BOD_5
    - Biological reactor station: 4.6 kWh / kg BOD_5
    - Fluidized fixed-culture reactor plant: 6.5 kWh / kg BOD_5
  - Possibility of producing biomethane (activated sludge + digester)
    - Reduced electrical energy consumption for processing <1KWh /m3
    - Production of bio methane by bio digester 0.6 kWh thermal / m^3 of wastewater
    - Only feasible for large units

Wastewater treatment Orders of magnitude :

1 to 5 kWh / m3 (excluding collection)

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Energy for water: key points

- Energy requirements for water use are relatively modest compared to other sectors.
- The share of energy can be significant in the operating costs of water services, wastewater treatment, or irrigation systems.
- A deterioration in the quality and accessibility of water resources always leads to an increase in energy requirements and operating costs.

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Energy for water: recommendations

- **To reduce energy consumption**
  - Control **water consumption**
    - Supply water at levels as close as possible to the needs
    - Sectorize networks to be able to locate and repair leaks
  - Favour technical choices that require **little pressure**
    - Give priority to local resources
    - Longer pumping time => lower flow rate => reduced head losses
  - Choosing the right pumps for your flow and pressure requirements
    - Determine the point of operation (intersection of pump and network)
    - Avoid oversizing a pump in terms of flow or pressure
    - Adapt pumping solutions to different network operating conditions

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Water for energy production and conversion

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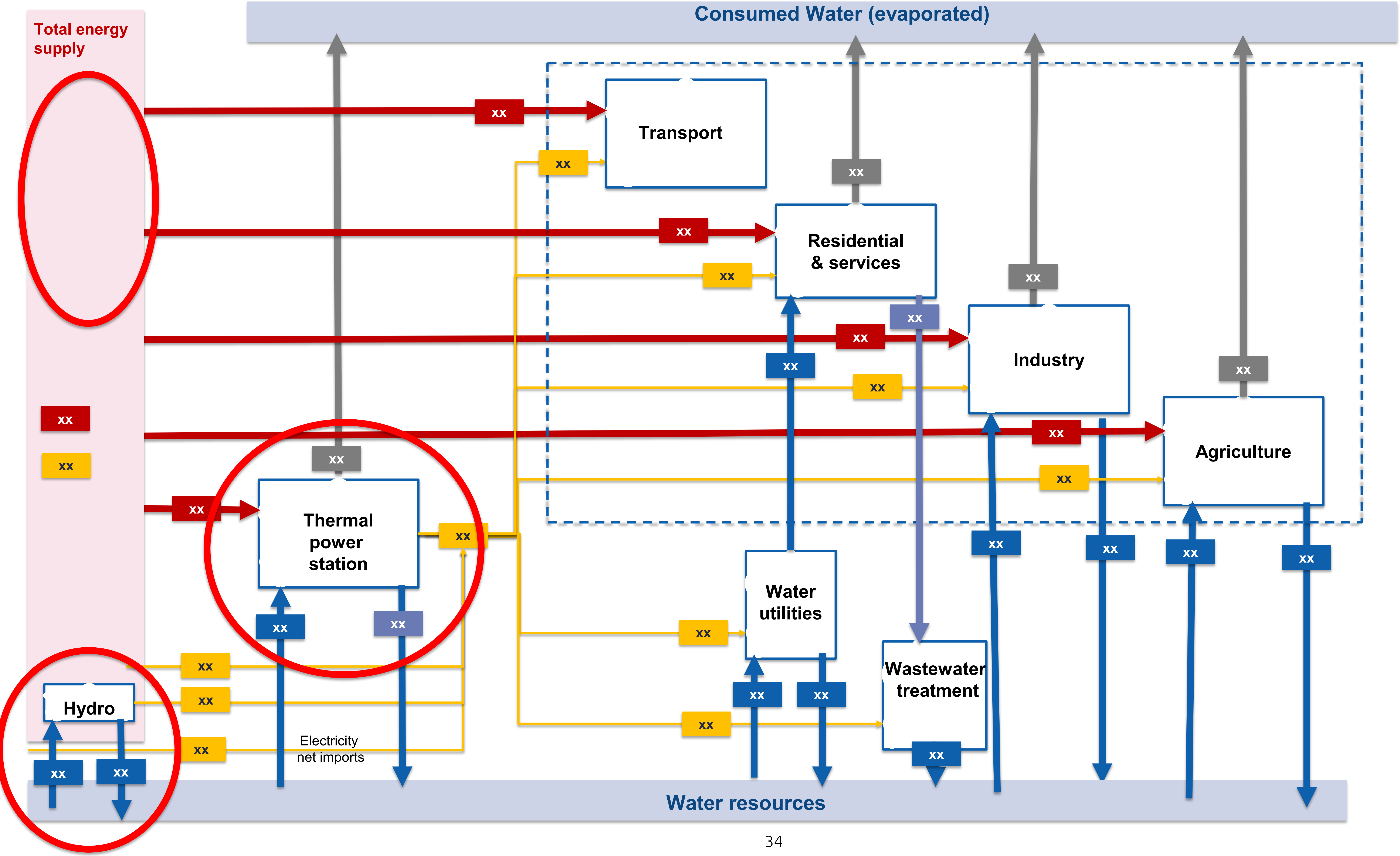
Water for energy

▪ Why focus on water mobilization in the energy sector?

- Water is a massive and essential input for power generation in **thermal power plants**
  - A quantitative management issue: reserved flows for power generation, some of which can be consumed
  - Water is a key input for cooling shut-down nuclear power plants
- Hydropower is a significant primary energy source
  - Structures with multiple functions (river flow regulation, etc.)
- Other specific aspects or couplings
  - Water may be needed to extract or transform fossil fuels
  - Some processes can lead to degradation of water resources


Consumed Water (evaporated)
Total energy supply
Transport
Residential & services
Industry
Agriculture
Thermal power station
Water utilities
Wastewater treatment
Hydro
Electricity net imports
Water resources
xx

Hydropower

- **An energy production function**
  - Assement of the amont of energy that can be produced : Take into account flow variations, head variations and the main characteristics of the facilities (equipment flow rate and reservoir volume)
  - **Energy output [kWh] = efficiency . 0,00275 . Turbined volume [m3] . Height [m from upstream to downstream]**

- **An energy storage function (pumping/turbining process)**
  - Pumping process when energy production is surplus / turbining during peak periods
  - Sites suitable for storage: steep gradients over a short distance, upstream and downstream storage volume, proximity to the power grid
  - Energy efficiency of a storage/retrieval cycle > 65%

- **Environmental issues**
  - Flooded surfaces
  - Breach of river continuity
  - Modification of flow and sediment transport regimes

Evacuating heat

- **Two technical choices for cooling thermal power plants**

  - **Open circuit (One Through)** heats liquid water
    - Requires reserving large flows that cannot be used for other purposes upstream of the plant
    - **Heat dissipated for a 1 K rise in** 1 m3 of water (Kelvin equivalent to °C Celsius) : 4.18 $MJ.m^{-3}.K^{-1}.m^{-3}$
    - to remove 1kWh of heat, 86 liters of water need to be heated by 10 K

  - **Closed circuit (Tower)** : heat is removed by increasing the temperature and water content of the air. Part of the water extracted is consumed (evaporation) (37%)
    - Reduced withdrawal volume: 3 to 4 l/kWh th to be evacuated or 6 to 8 l/kWh elec produced
    - Some water is consumed (evaporation): 1.2 l/kWh th to be evacuated or 2.5 l/kWh elec produced

Water for energy production and conversion

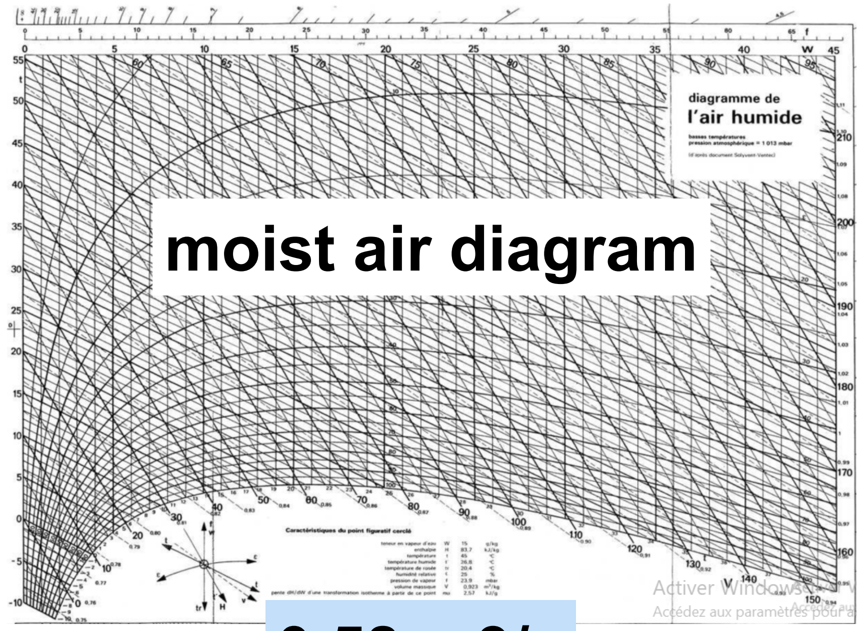
Bibliography :

- *Morten Andreas Dahl Larsen ⁎, Martin Drews, 2019 - Water use in electricity generation for water-energy nexus analyses: The European case*
- *Eurostat, Electricity and heat statistics*
- *https://www.energyinst.org/statistical-review*

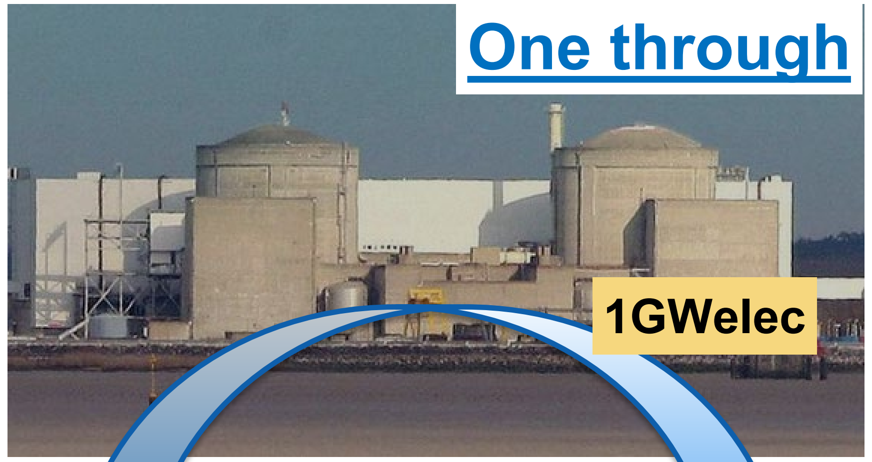
Thermal energy: 1 GWh thermal

Thermal power plant

Electricity 0.33 GWh elec



Heat to be evacuated 0.67 GWh heat



4.18 MJ.k^{-1} .m^{-3}

45 m3/s

45 m3/s +10°C

Option 1 cooling
Open circuit

For 1 GWh electricity

Volume drawn: 162 000 m3
Discharge volume (+10°C): 162 000 m3

Volume consumed: low? (changes in evaporation of the watercourse)

Option 2 cooling
Closed circuit

For 1 GWh electricity

Volume drawn: 5 500 m3
Discharge volume (+10°C): 3400 m3

Volume consumed: 2 100 m3

0.58 m3/s

2 m3/s

0.96 m3/s +10°C

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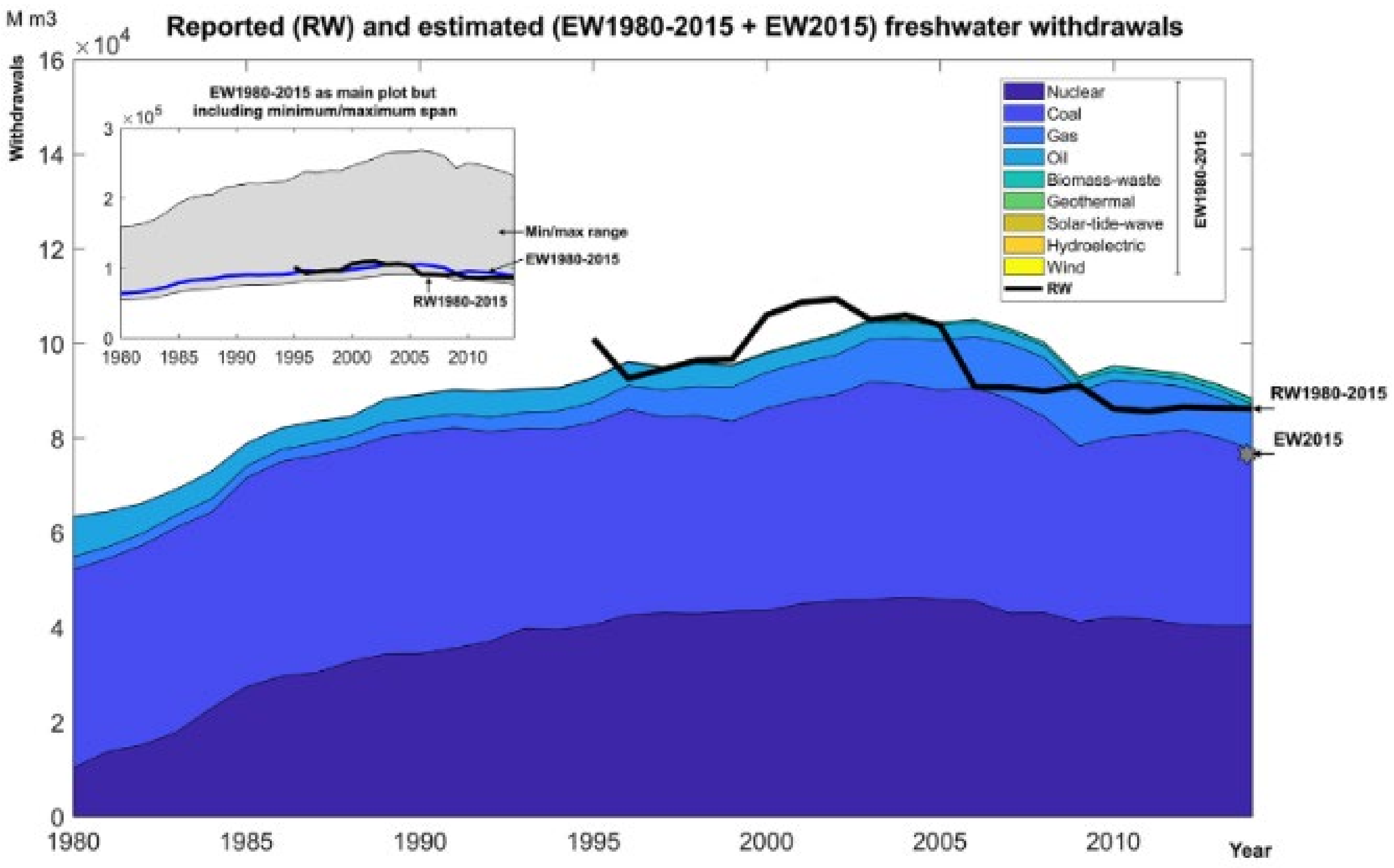
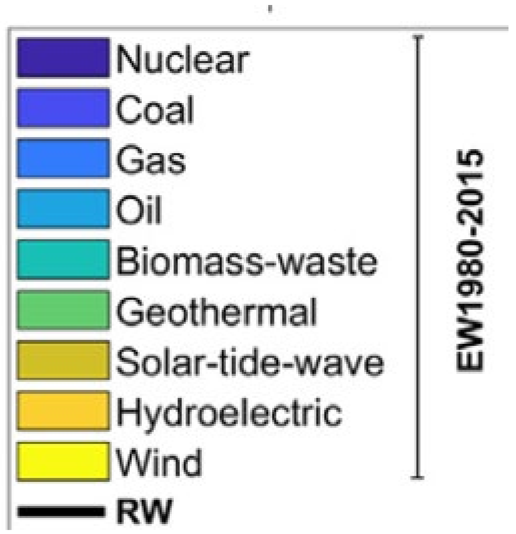
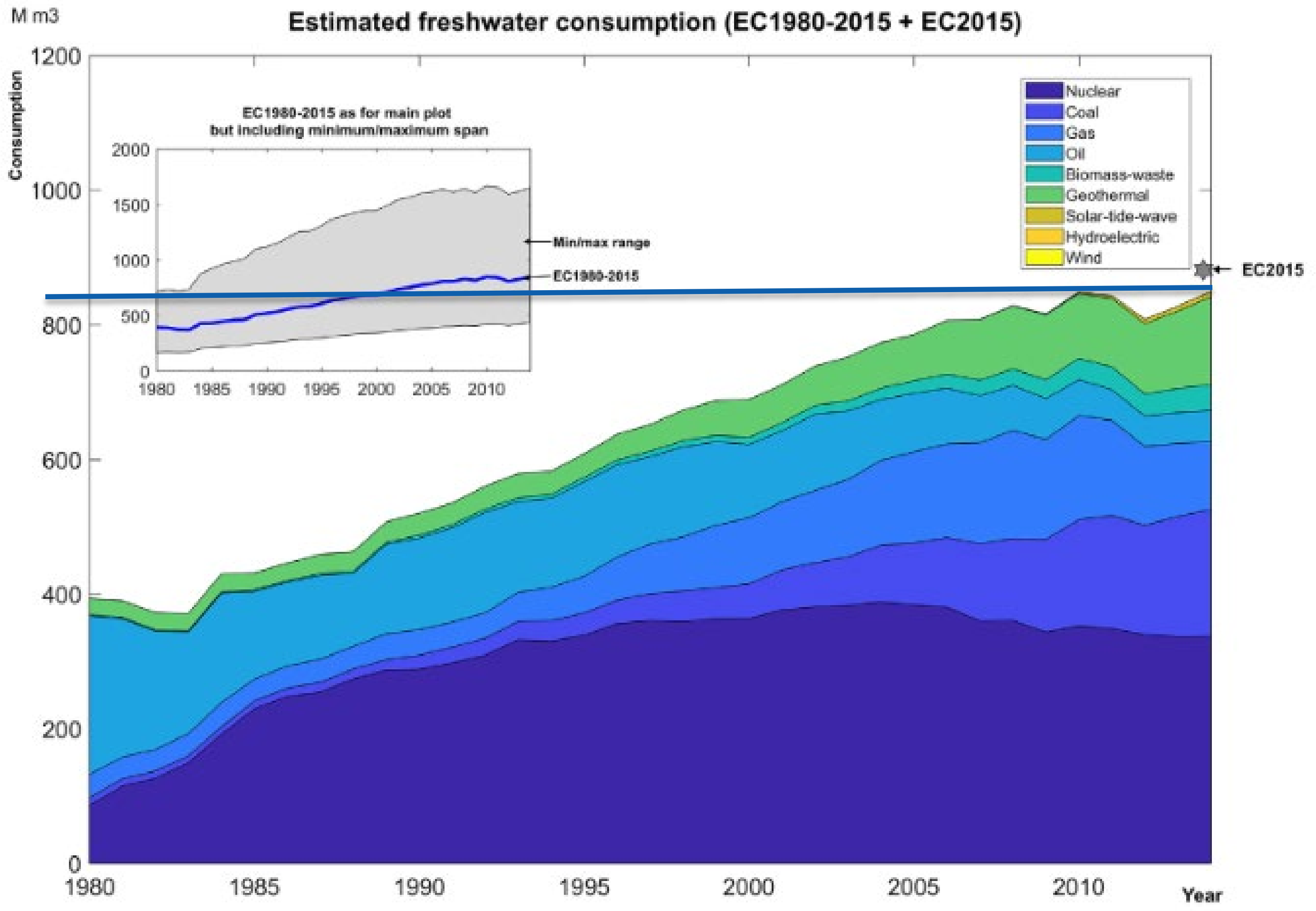
Order of magnitude: cooling in Europe

***Source**: Morten Andreas Dahl Larsen ⁎, Martin Drews, 2019 - Water use in electricity generation for water-energy nexus analyses: The European case*







<u>Withdrawals for cooling</u> power plant : 90 Gm3 / year

<u>Water consumption</u> for cooling power plant : 0,85 Gm3 / an

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How to present results : Matrix of water and energy flows for human activities

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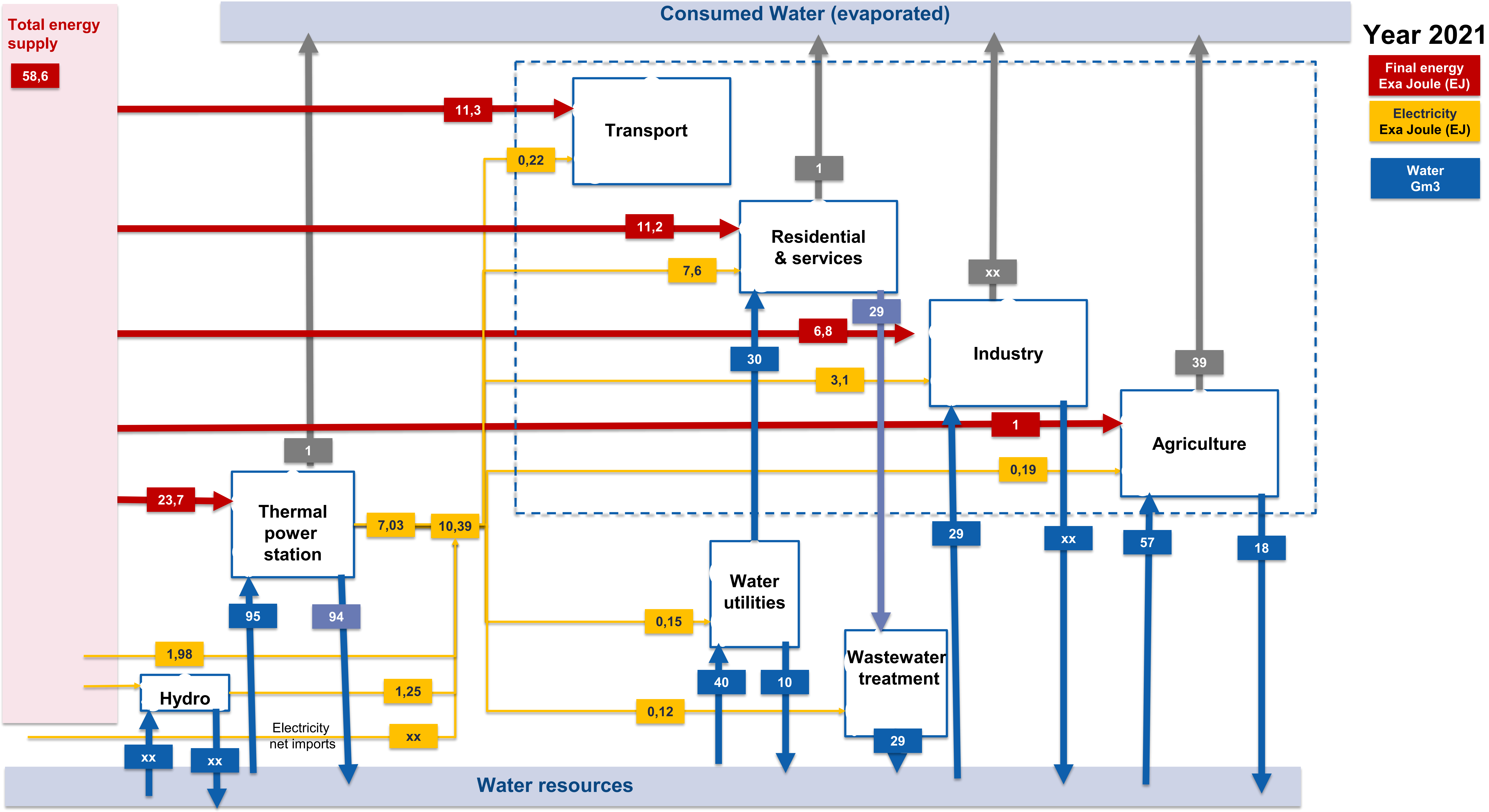
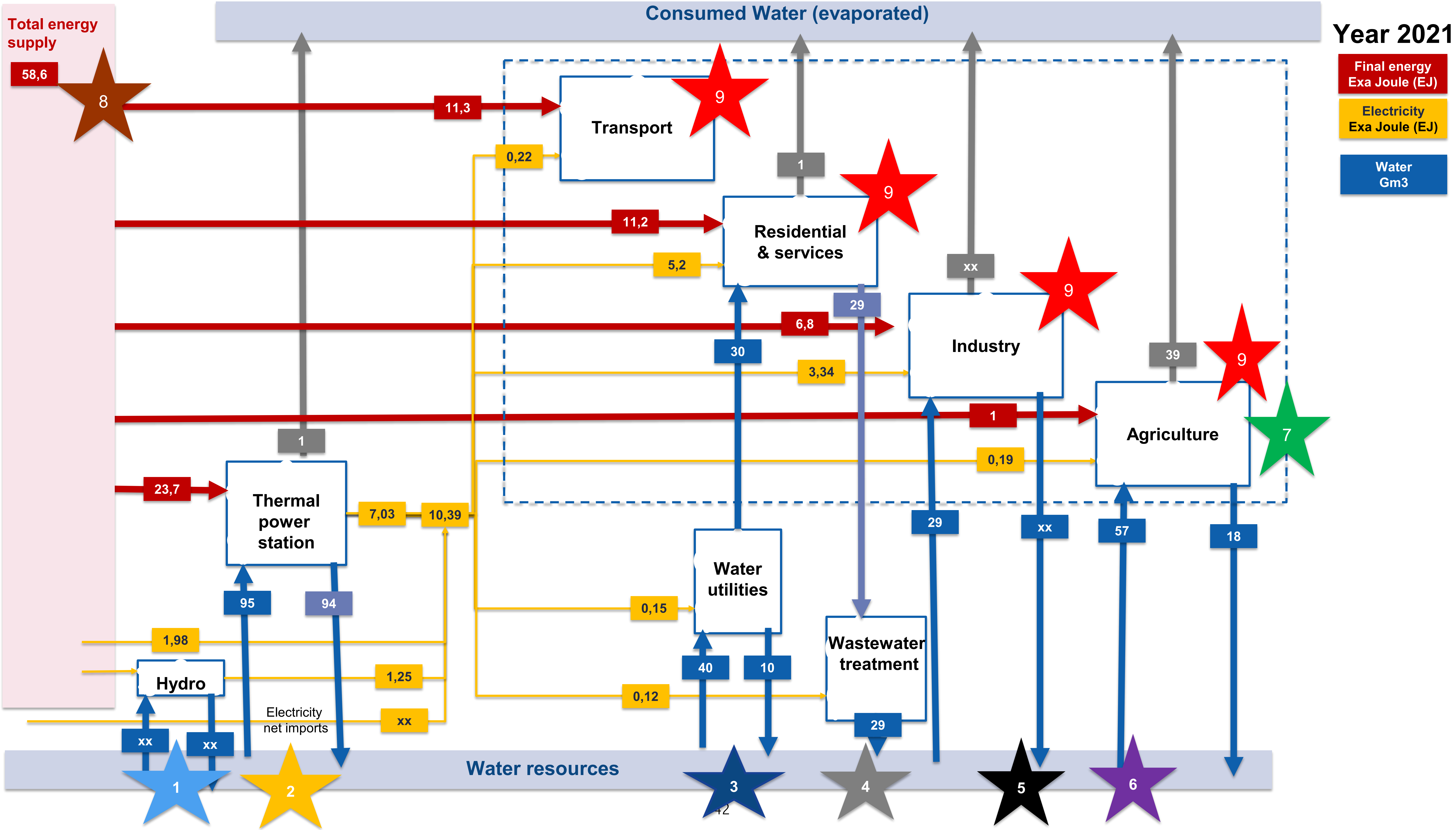

Total energy supply
58,6
Consumed Water (evaporated)
Year 2021
Final energy Exa Joule (EJ)
Electricity Exa Joule (EJ)
Water Gm3
Transport
11,3
0,22
Residential & services
11,2
7,6
1
Industry
6,8
3,1
xx
Agriculture
1
0,19
39
Thermal power station
23,7
1
7,03
10,39
95
94
29
30
Water utilities
0,15
40
10
Wastewater treatment
0,12
29
29
xx
57
18
1,98
Hydro
1,25
Electricity net imports
xx
xx
xx
Water resources

Highlight environmental damage

- **Impact on water resources and aquatic ecosystems**
  - 1 altered river morphology, flow regimes and ecological continuity
  - 2 Quantitative and thermal impact
  - 3 Modification of quantitative balances
  - 4 Qualitative degradation of domestic origin (untreated pollution)
  - 5 Qualitative and/or thermal degradation of industrial origin
  - 6 Modification of quantitative balances
  - 7 Modification of land use, ecosystems and quantitative balances
  - 8 Degradation of aquifer quality (fossil fuel extraction techniques)
  - 9 Climate change modification of the water cycle


Consumed Water (evaporated)
Total energy supply
58,6
8
Year 2021
Final energy Exa Joule (EJ)
Electricity Exa Joule (EJ)
Water Gm3
11,3
Transport
9
0,22
1
11,2
Residential & services
9
5,2
29
xx
6,8
30
Industry
9
3,34
39
9
1
Agriculture
7
0,19
1
23,7
Thermal power station
7,03
10,39
29
xx
57
18
Water utilities
0,15
95
94
1,98
Wastewater treatment
1,25
40
10
Hydro
0,12
Electricity net imports
xx
xx
xx
29
Water resources
1
2
3
4
5
6

Appendices

Units for energy

- 1 metric tonne = 2204.62 lb. = 1.1023 short tons
- 1 kiloliter = 1 cubic meter = 6.2898 barrels
- 1 kilocalorie (kcal) = 4.1868 kJ = 3.968 Btu
- 1 kilojoule (kJ) = 1,000 joules = 0.239 kcal = 0.948 Btu
- 1 petajoule (PJ) = 1 quadrillion joules (1 x 10)^{15}
- 1 exajoule (EJ) = 1 quintillion joules (1 x 10)^{18}
- 1 British thermal unit (Btu) = 0.252 kcal = 1.055 kJ
- 1 barrel of oil equivalent (boe) = 5.8 million Btu = 6.119 million kJ
- 1 kilowatt-hour (kWh) = 860 kcal = 3600 kJ = 34xx Btu

Transformation chain from primary energy to service provision

- Primary energy: raw, unprocessed energy (solar, wind, hydro, biomass, fossil, nuclear).
- Secondary energy: energy transformed before transmission
  - Electricity, fuels, ... leaving the transformation site
- Final energy: energy delivered to the user
  - Electricity, fuels and combustibles delivered to the user (oil, gas, coal, wood energy)
- Useful energy: energy that provides the service
  - Mechanics (displacement, distribution, collection, processing, etc.)
  - Thermal (heating, cooling, cooking, etc.)
  - Specific electricity (communication, lighting, chemical transformations, etc.)
- Services broken down into functions (e.g. water)
  - Drinking water delivered to the tap / Functions: withdrawal, treatment, storage, transport, distribution
  - Irrigation water / Functions: withdraw, transport, distribute to plot

$1\ \text{kWh}_{primary} \neq 1\ \text{kWh}_{final} \neq 1\ \text{kWh}_{utile}$

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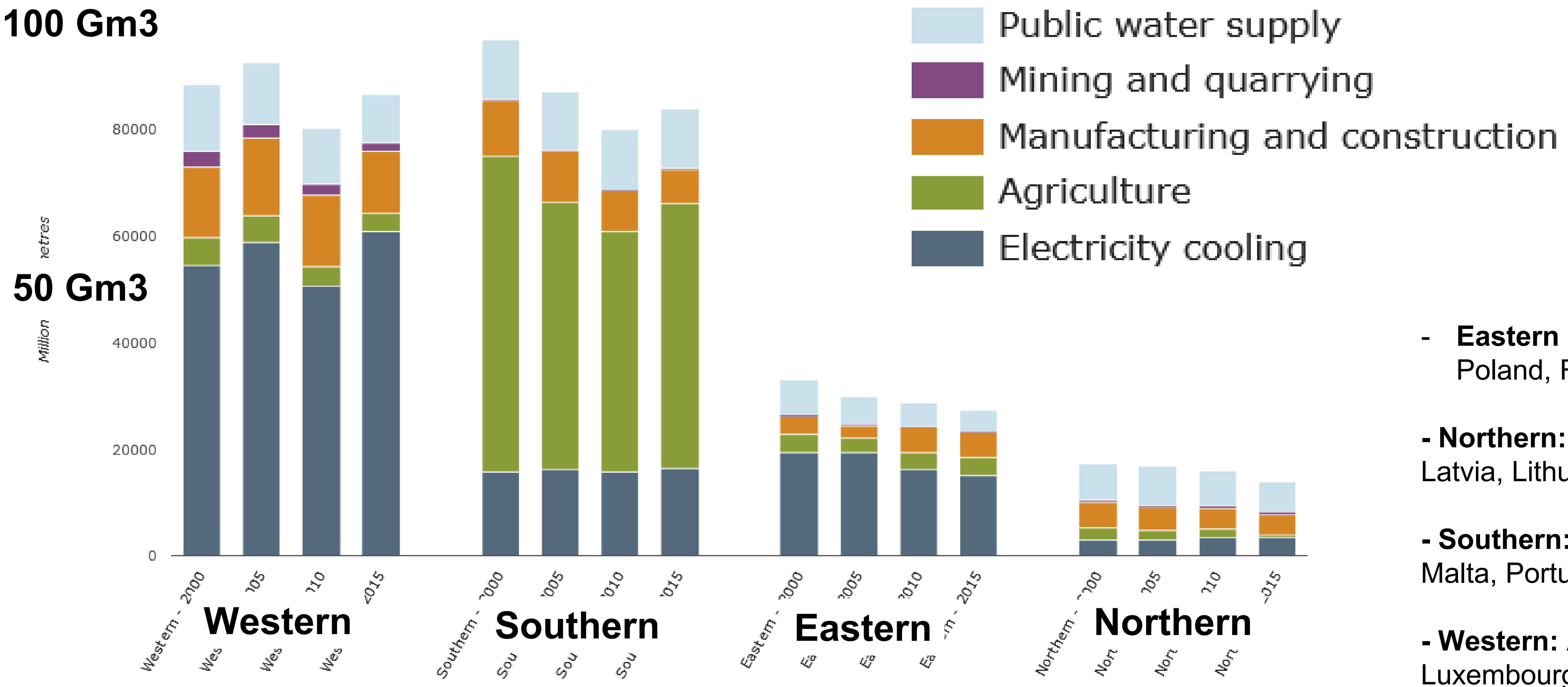
iea
CEER Council of European Energy Regulators
Funded by the European Union
EU4Environment Water and Data in Eastern Partner Countries

Water abstraction by sector (EUROPE)

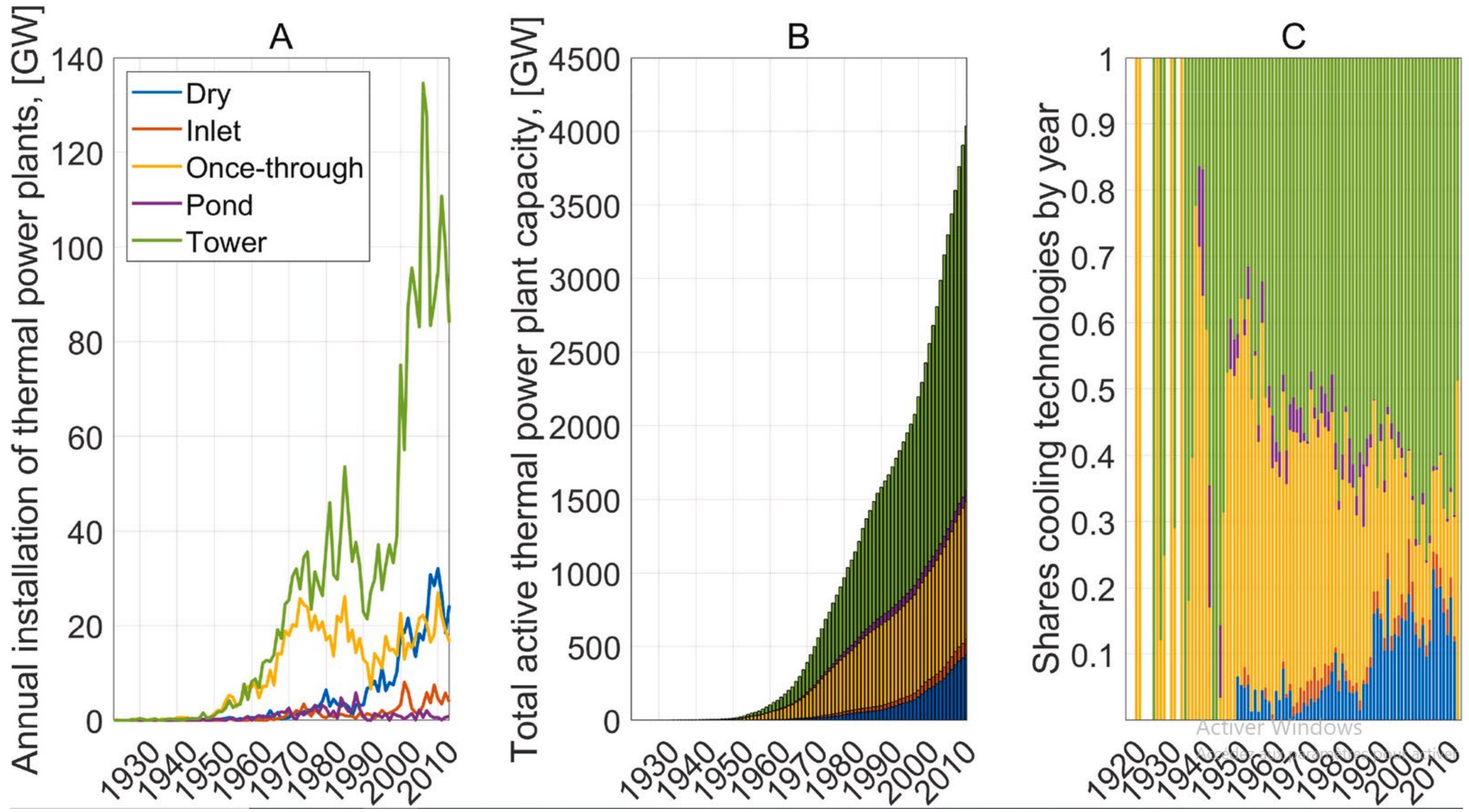


Industry
and energy sector

- **Eastern :** Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia
- **Northern:** Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Sweden, United Kingdom
- **Southern:** Croatia, Cyprus, Greece, Italy, Malta, Portugal, Slovenia, Spain
- **Western:** Austria, Belgium, France, Germany, Luxembourg, the Netherlands

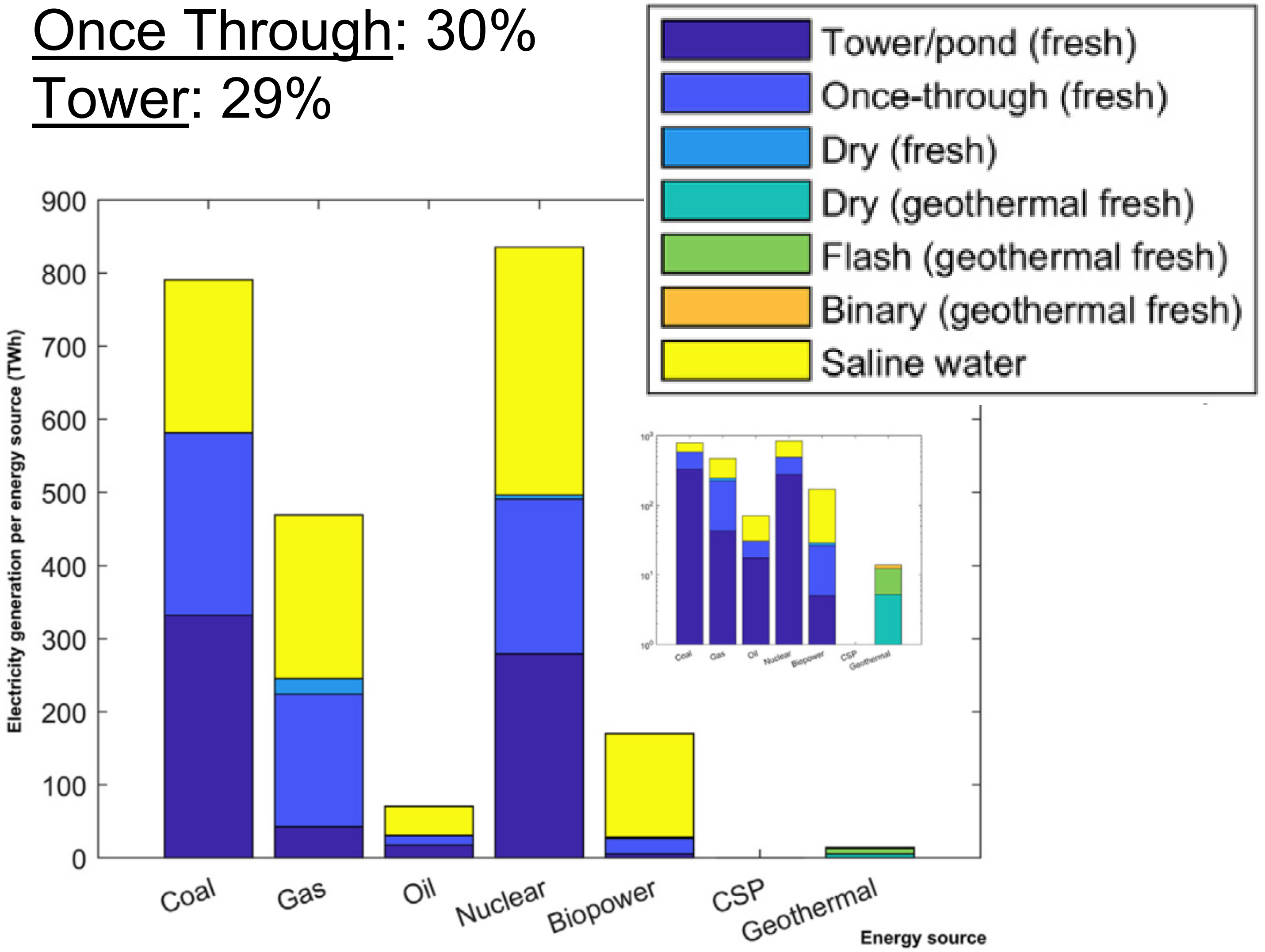
https://www.eea.europa.eu/data-and-maps/daviz/water-abstraction-by-sector-eu-2/#tab-chart_1

Shares cooling technologies



Global study

Saline Water: 41%
Once Through: 30%
Tower: 29%



The European case

Source : *Lohrmann A., Lohrmann C., Luukka P., 2022 - Global and regional models for identification of cooling technology in thermal power generation for water demand estimations in water-energy nexus studies*

Source*: Morten Andreas Dahl Larsen ⁎, Martin Drews, 2019 - Water use in electricity generation for water-energy nexus analyses: The European case*

Example using Sankey diagram (USA)

Energy for Water

Water for energy