Green Computing - Introduction

Quentin Perez
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4INFO
2023-2024

Who I am ?

- Associate Professor in Software Engineering at INSA Rennes, France - Research in the [DiverSE team]
- Research topics
  - **Software metrics**
  - **Empirical software engineering**
  - IA for software quality
  - **DevOps**
  - **GreenIT** (since january 2023)
- Main research topic : **energy consumption in CI/CD pipelines**

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Green Computing
CM 1

Rappels des notions de physiques / GES / mix électrique / énergie pour l'ICT

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Petit QCM/QRU Wooclap

1 Allez sur wooclap.com

2 Entrez le code d'événement dans le bandeau supérieur

Code d'événement
LLAUKX

1 Envoyez @LLAUKX au 06 44 60 96 62

2 Vous pouvez participer

Physics basics

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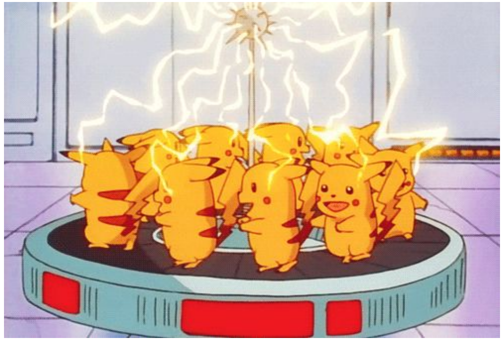
Energy

Wikipedia Definition

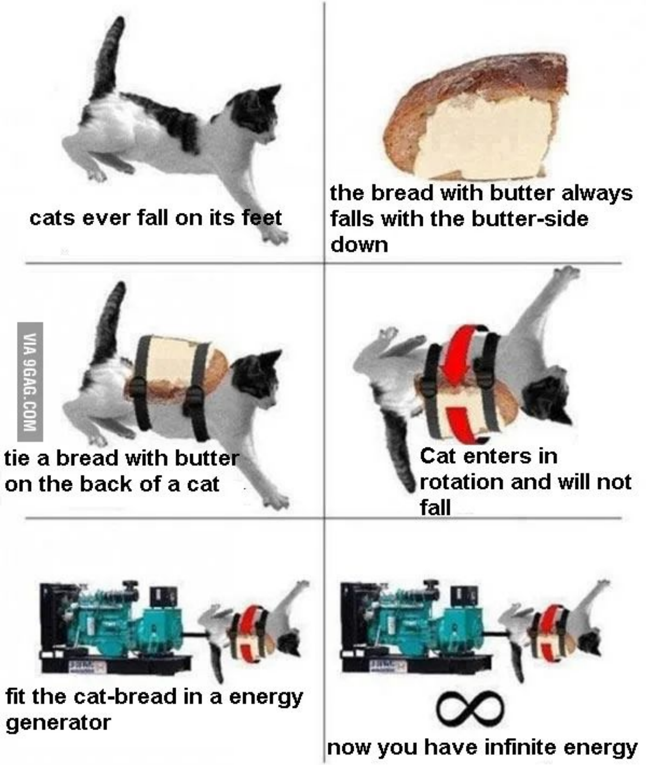
“In physics, energy is the quantitative property that is transferred to a body or to a physical system”

Energy forms :

- Mechanical
- Potential
- Radiant
- **Chimical**
- **Electrical**
- ...



Energy - Free and infinite !!!!... (spoiler: nope)



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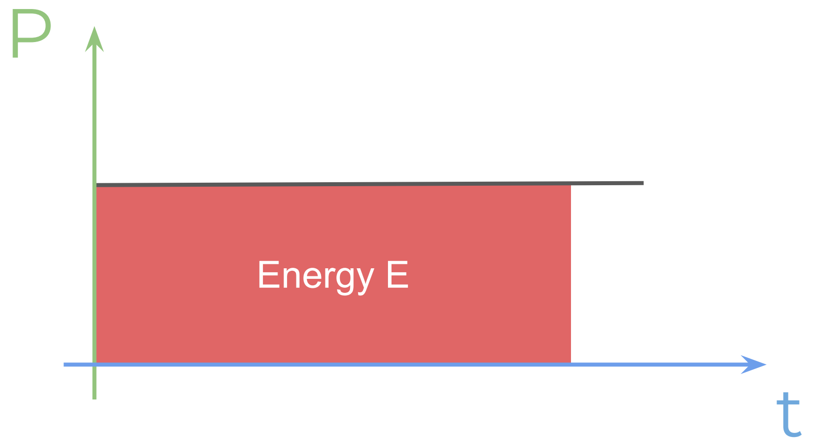
Energy

Physical formula (electrical domain) :

$$E = P \times t$$



Energy (E)
In Joules (J)
International System of Units (SI)

Also expressed in Watt.hour (Wh)

Power (P)
In Watt (W)

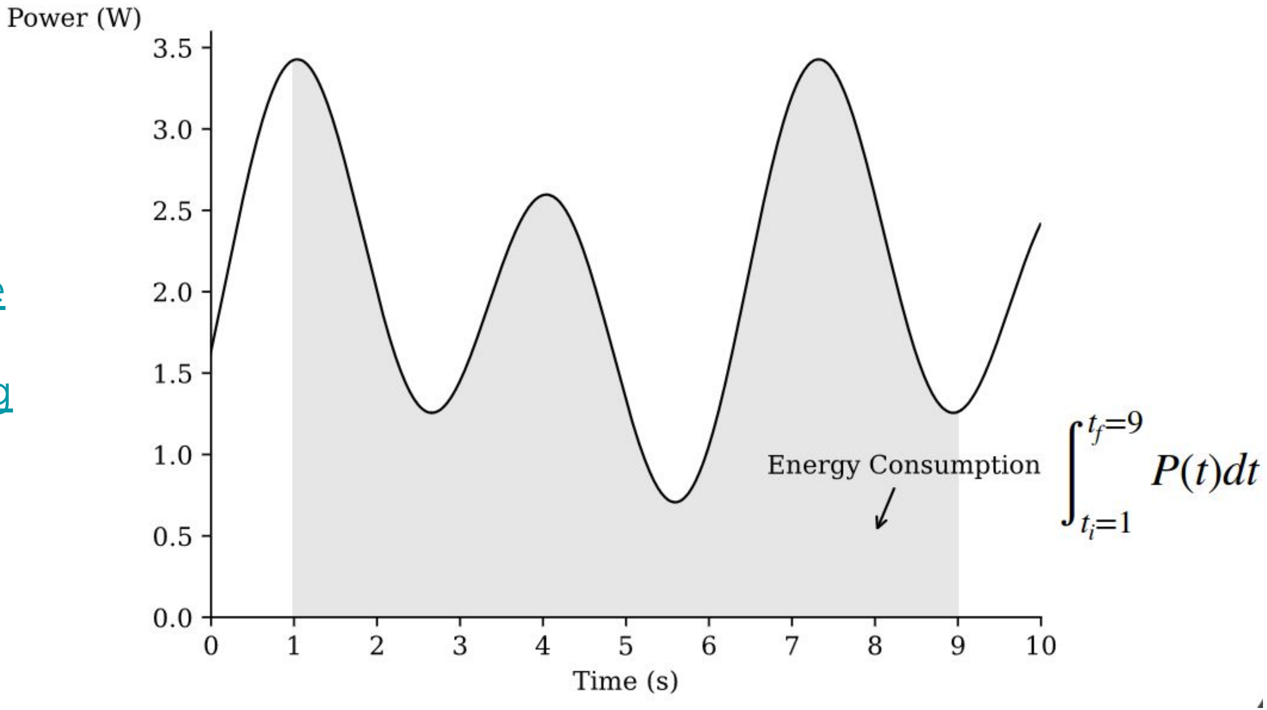
1Wh = 3600J

Time (t)
In Joules (J)
International System of Units (SI)

In hour (h) to have E in Wh

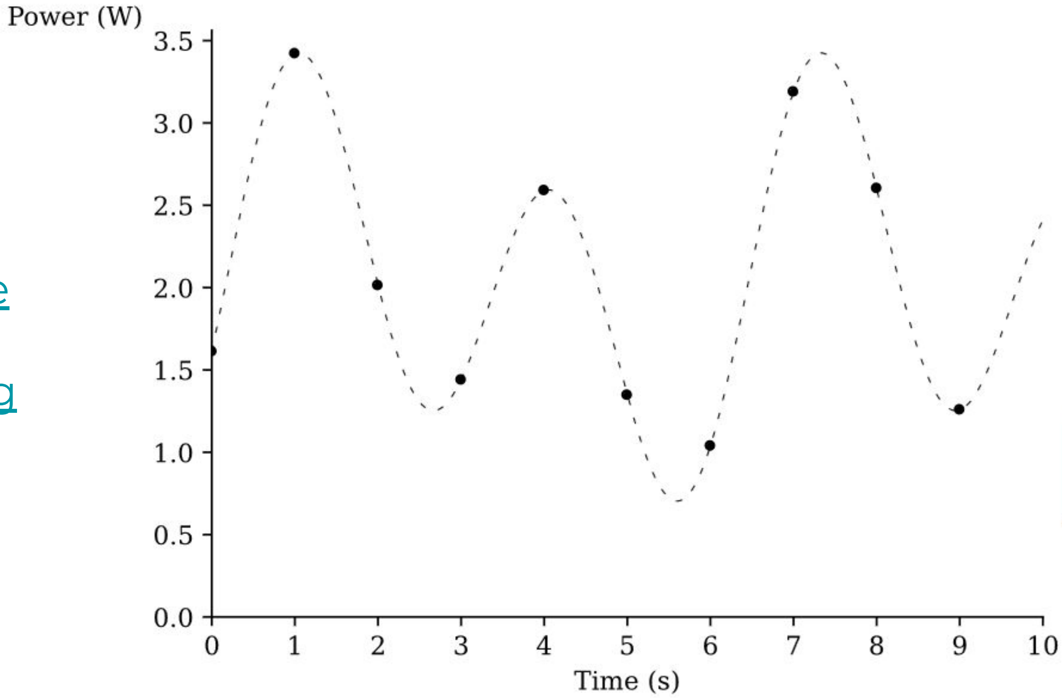
Energy

[Luís Cruz, Sustainable Software Engineering Course]



Energy

[Luís Cruz, Sustainable Software Engineering Course]



$$\int_{t_i=1}^{t_f=9} P(t)dt$$

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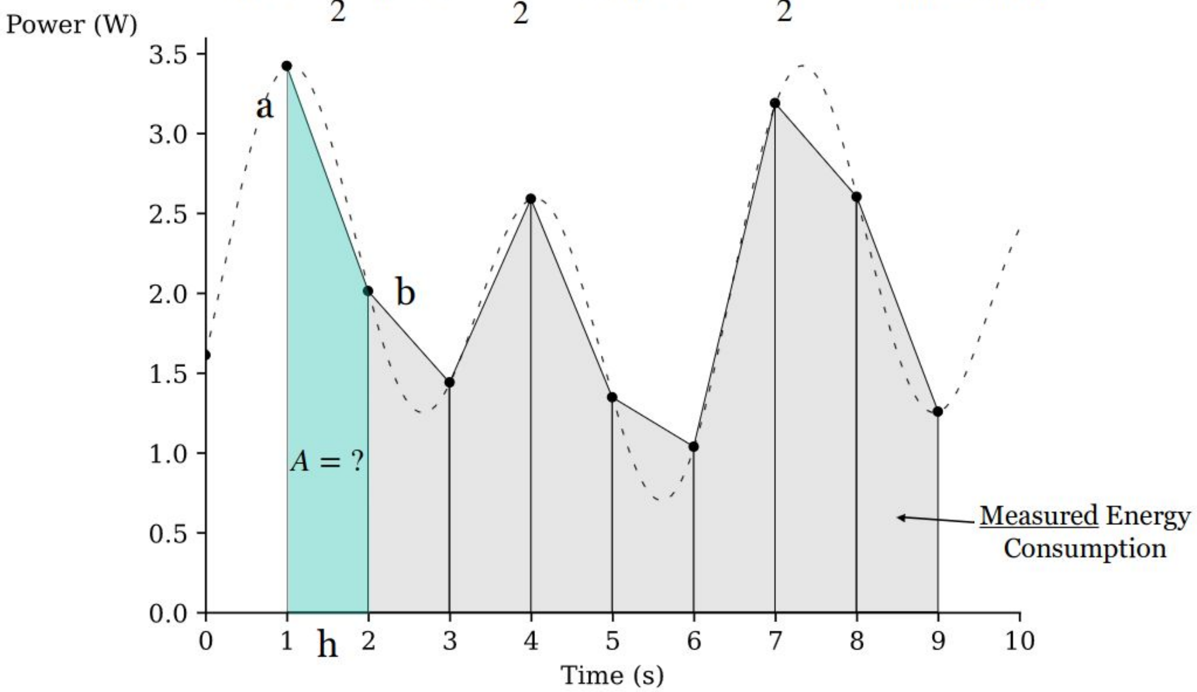
Energy

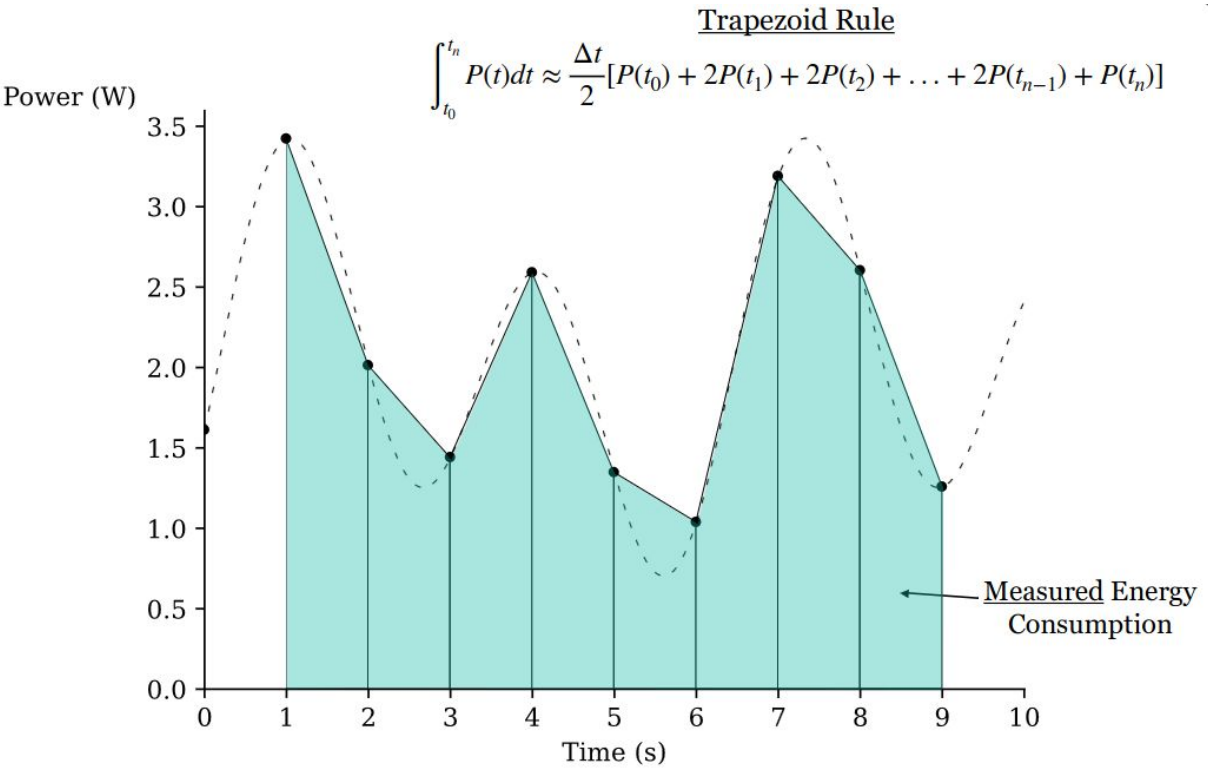
$$A = \frac{a+b}{2}h \quad = \frac{P_{t_n} + P_{t_{n+1}}}{2} \cdot \Delta t \ = \frac{3.5\text{W} + 2.0\text{W}}{2} \cdot 1\text{s} = 2.75\text{J}$$



[Luís Cruz, Sustainable Software Engineering Course]

Energy

[Luís Cruz, Sustainable Software Engineering Course]



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Electrical Power

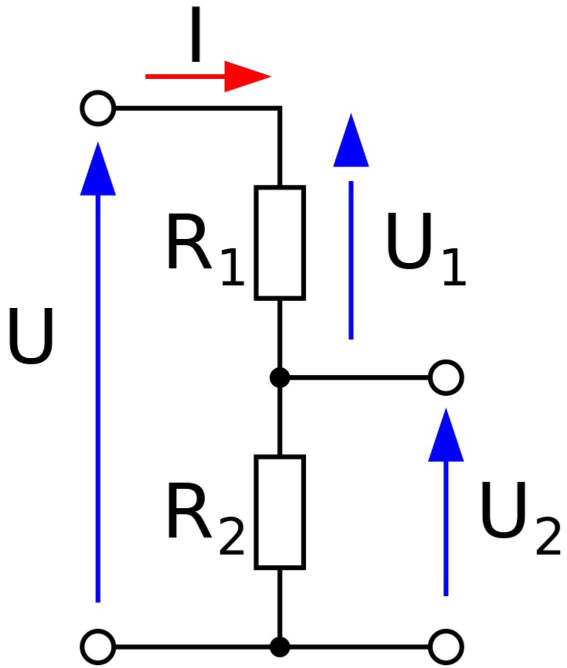
Physical definition:

$$P = U \times I$$

Power (P)
In Watt (W)

Voltage (U)
In volt (V)

Current (I)
In ampere (A)



Electric charge - Battery

Physical definition:

$$Cap = t \times I$$

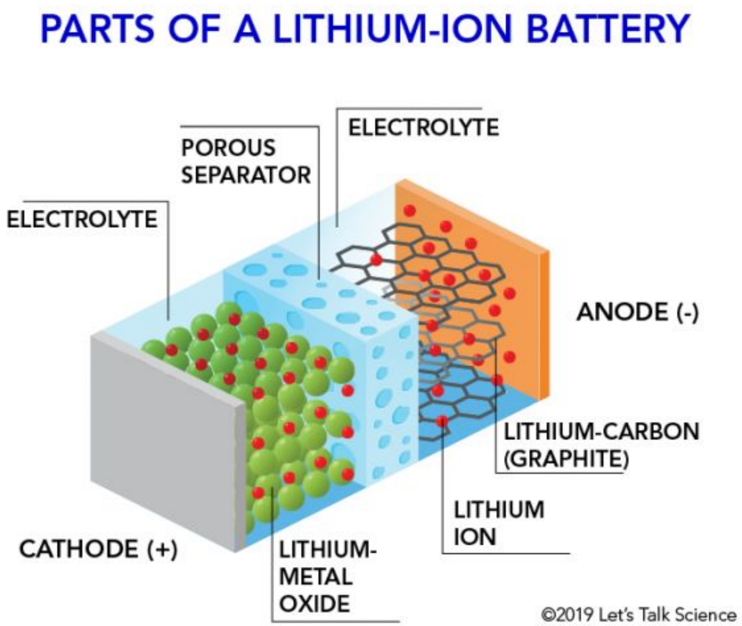
Capacity (Cap)
In Coulomb © International System of Units (SI)

Also expressed in Ampere.hour (Ah)

Time of charge/discharge (t) in second or hour

Current (I)
In ampere (A)

1Ah = 3600C



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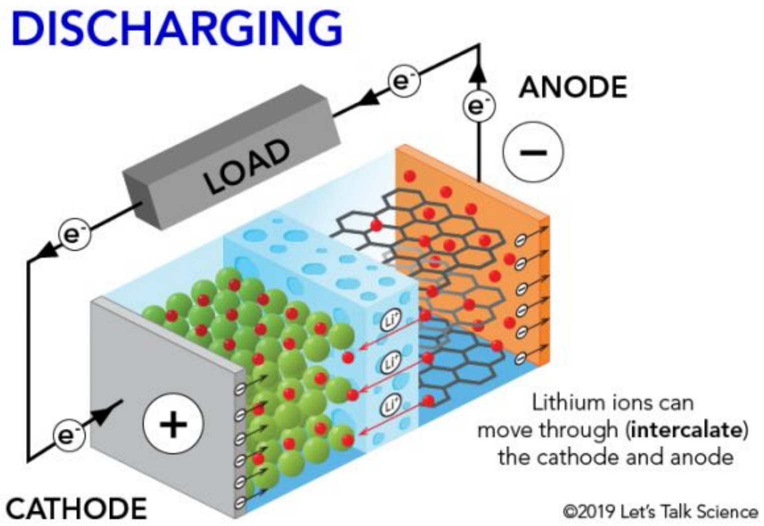


Electrical energy - Battery

Physical definition:

$$E = Cap \times U$$

Energy (E) Capacity (Cap) Voltage (U)
Battery Voltage

Nintendo Switch battery: 3.7V and 4310mAh

E = 3.7V x 4.31Ah = 16Wh = 16Wh x 3600 = 57600J

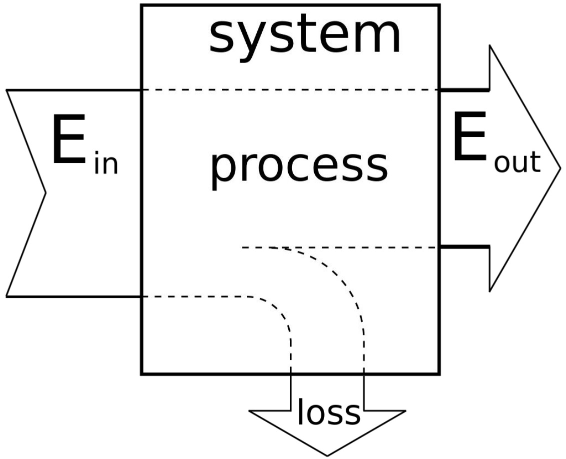
Energy Efficiency

Ratio of **energy input** to **useful energy output**

Number without dimension, nor unit and noted :

η = **Useful energy output** / **Energy input**

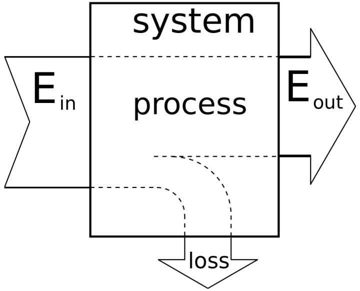
= (**Energy input** - **Losses**) / **Energy input**



Energy Efficiency

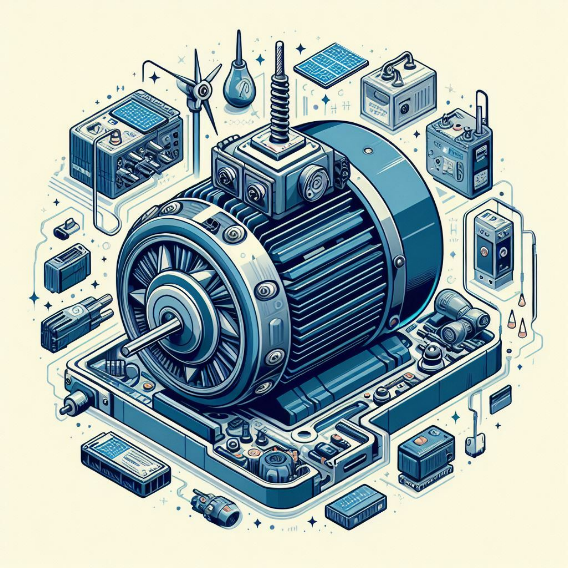
Example: an ATX power supply of 500W loaded at 100% will have a power efficiency of η = 0.82

η = **500W Useful power output** / **610W power input** = **0.82**



Energy / Power — a few points of comparison

- Tesla Model Y electric induction motor: 148kW
- Electrical hoven : 2500W
- Annual consumption of an Internet box (in France) : 97kWh
- Annual consumption of a dishwasher (188 duty cycles in France) : 197kWh
- Nintendo Switch Battery : 4310mAh
- LED light bulb energy efficiency : 0.85 - 0.90



Greenhouse effect - Greenhouse gases

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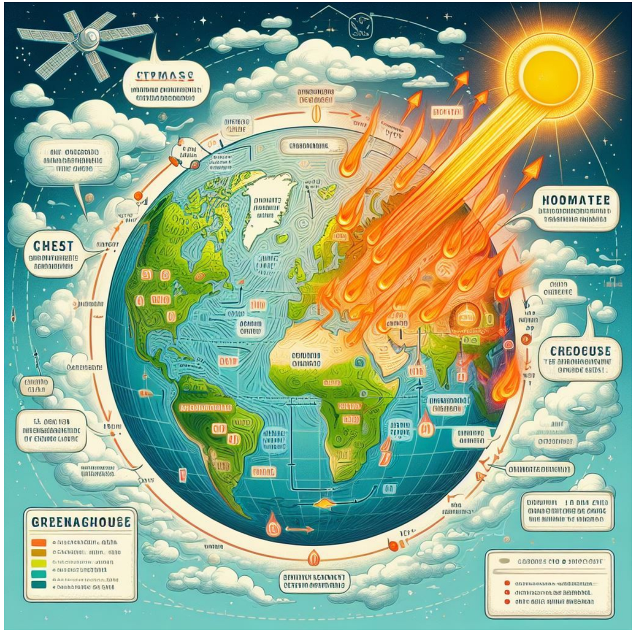
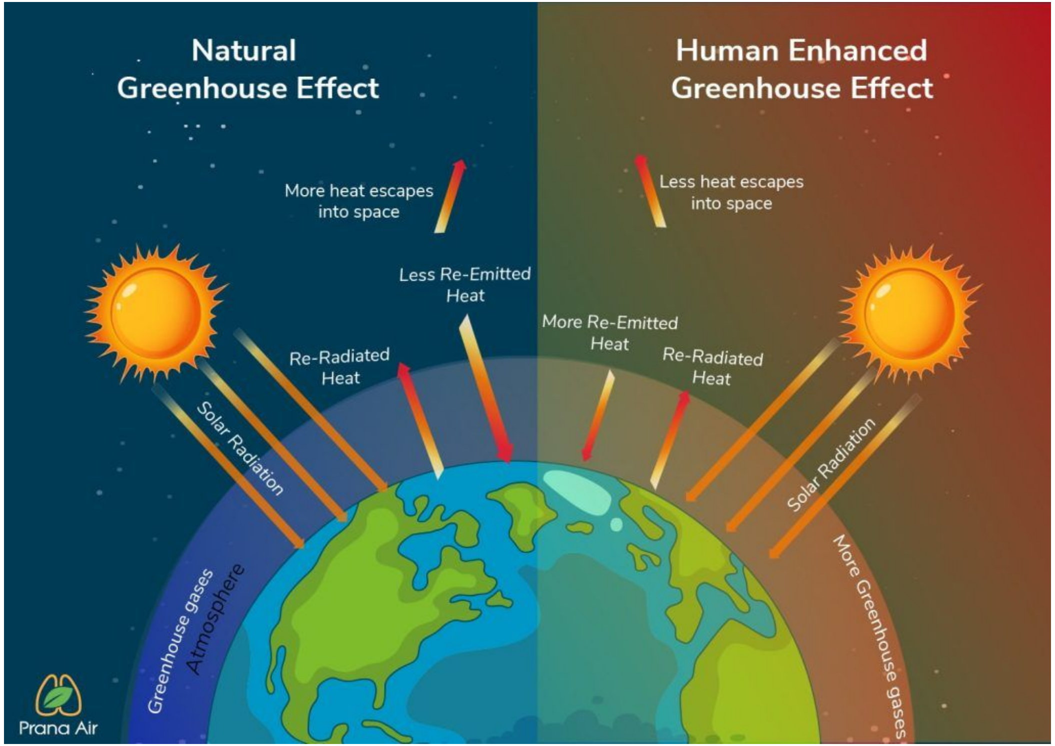
Greenhouse effect - Greenhouse gases (by Dall-E)



Greenhouse effect



Greenhouse effect - types de gaz

7 Types of greenhouse gases defined by the **Kyoto Protocol, signed in 1997**

How can we compare these gases and their effects on global warming?

<table>
<tr><th colspan="2">Gaz</th><th>Source</th></tr>
<tr><td colspan="2">Carbon Dioxide (CO2)</td><td>Fossil fuel combustion, industrial production and deforestation/fires</td></tr>
<tr><td colspan="2">Methane (CH4)</td><td>Landfills, agriculture, livestock farming and industrial processes</td></tr>
<tr><td colspan="2">Nitrous oxide (NO2)</td><td>Agriculture, industrial processes, fertilizer use</td></tr>
<tr><td rowspan="4">Fluorinated gases</td><td>HFCs (hydrofluorocarbons, a family of different molecules)</td><td rowspan="3">Sprays, refrigeration, industrial processes, electrical transformers</td></tr>
<tr><td>PFCs (perfluorocarbons, a family of different molecules)</td></tr>
<tr><td>SF6 (sulfur hexafluoride)</td></tr>
<tr><td>NF3 (nitrogen trifluoride)</td><td>Cleaning silicon electronic components</td></tr>
</table>

Carbon Dioxide Equivalent Unit (CO_2-eq)

Convert greenhouse gases into a single unit of comparison by calculating their weight of CO2

1kg of Methane (CH4) is estimated **21 time more "impacting"** than **1kg of carbon dioxyde (CO2)** over a 100-year period (100-global-warming potential (**GWP-100**))

CO2-eq is expressed in kgCO2-eq

Gas	GWP-100
Carbon Dioxide (CO2)	1
Methane (CH4)	21
Nitrous oxide (NO2)	310
Nitrogen trifluoride (NF3)	17200
Sulfur hexafluoride (SF6)	23900

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Carbon Dioxide Equivalent Unit (CO_2-eq)

Example : using a software system requires: 1000Kg of CO_2, 20Kg of CH_4 and 5Kg of N_2O

CO2eq = 1x1000 + 21x20 + 5x310

= 2970 kgCO2eq

Gas	GWP-100
Carbon Dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (NO_2)	310
Nitrogen trifluoride (NF_3)	17200
Sulfur hexafluoride (SF_6)	23900

Carbon Dioxide Equivalent Unit (CO2-eq)

Please note that GWP-100 is only an estimate!

GWP-20 and GWP-500 are also available.

Values given here come from the study by Foster *et al.*, Changes in Atmospheric Constituents and in Radiative Forcing, 2007

https://archive.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

World energy consumption and electricity mix

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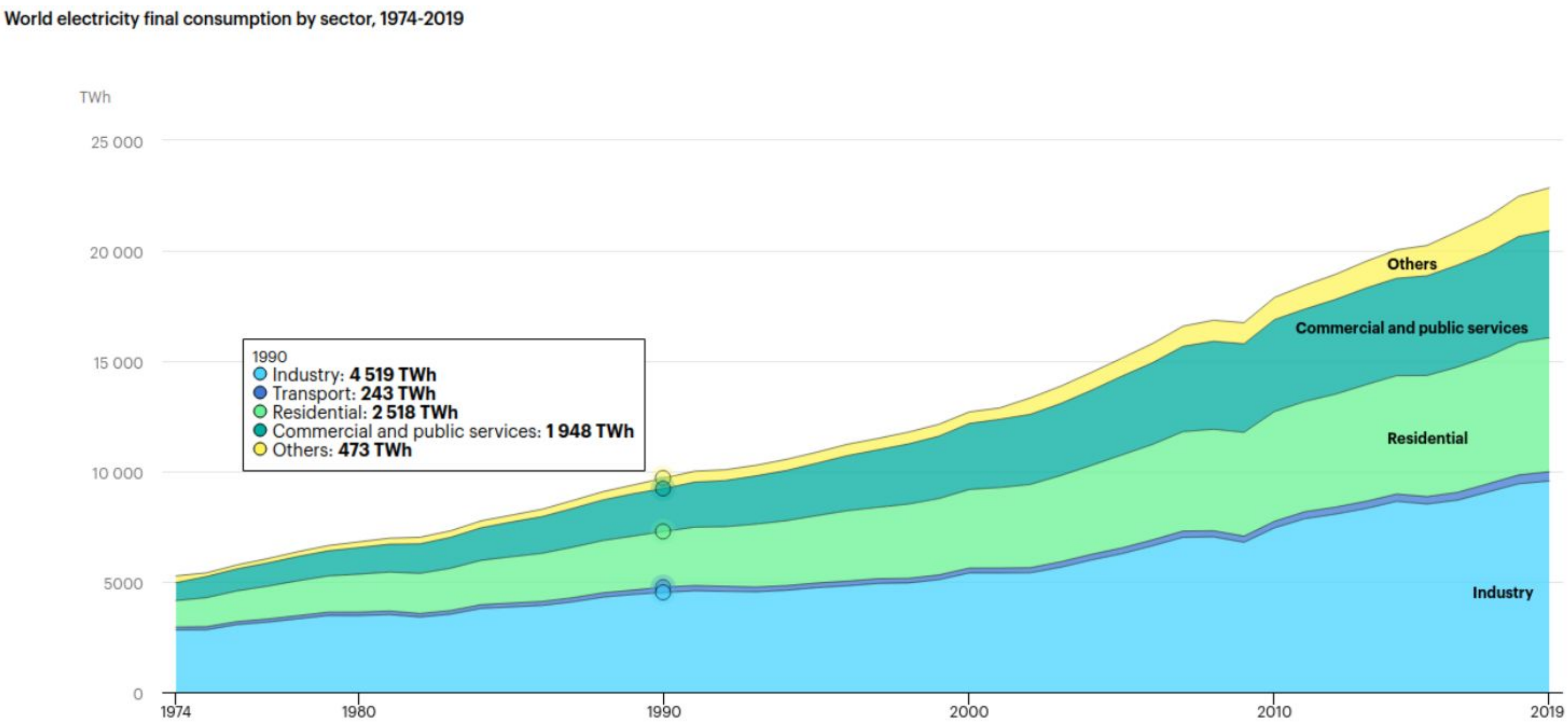
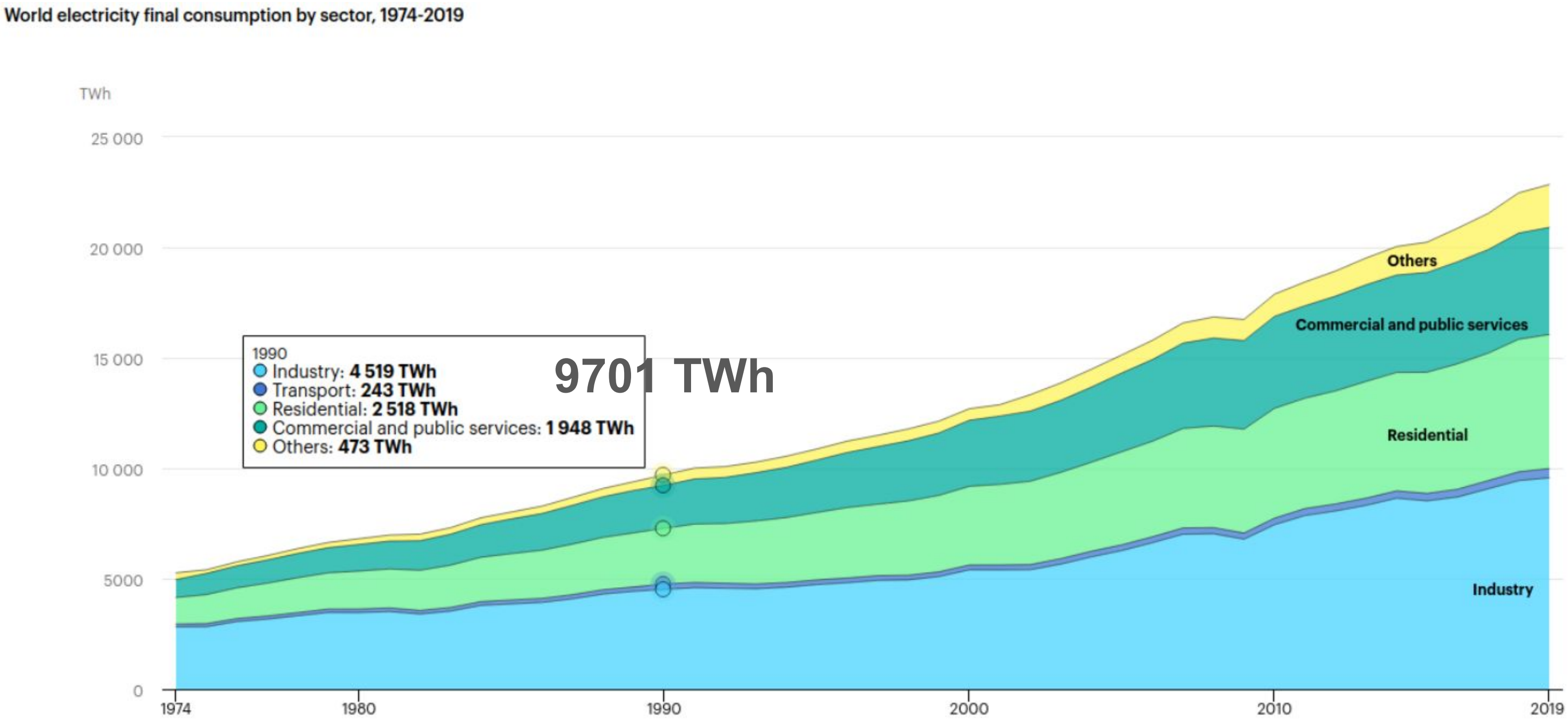
World energy consumption



https://www.iea.org/reports/electricity-information-overview/electricity-consumption

World energy consumption



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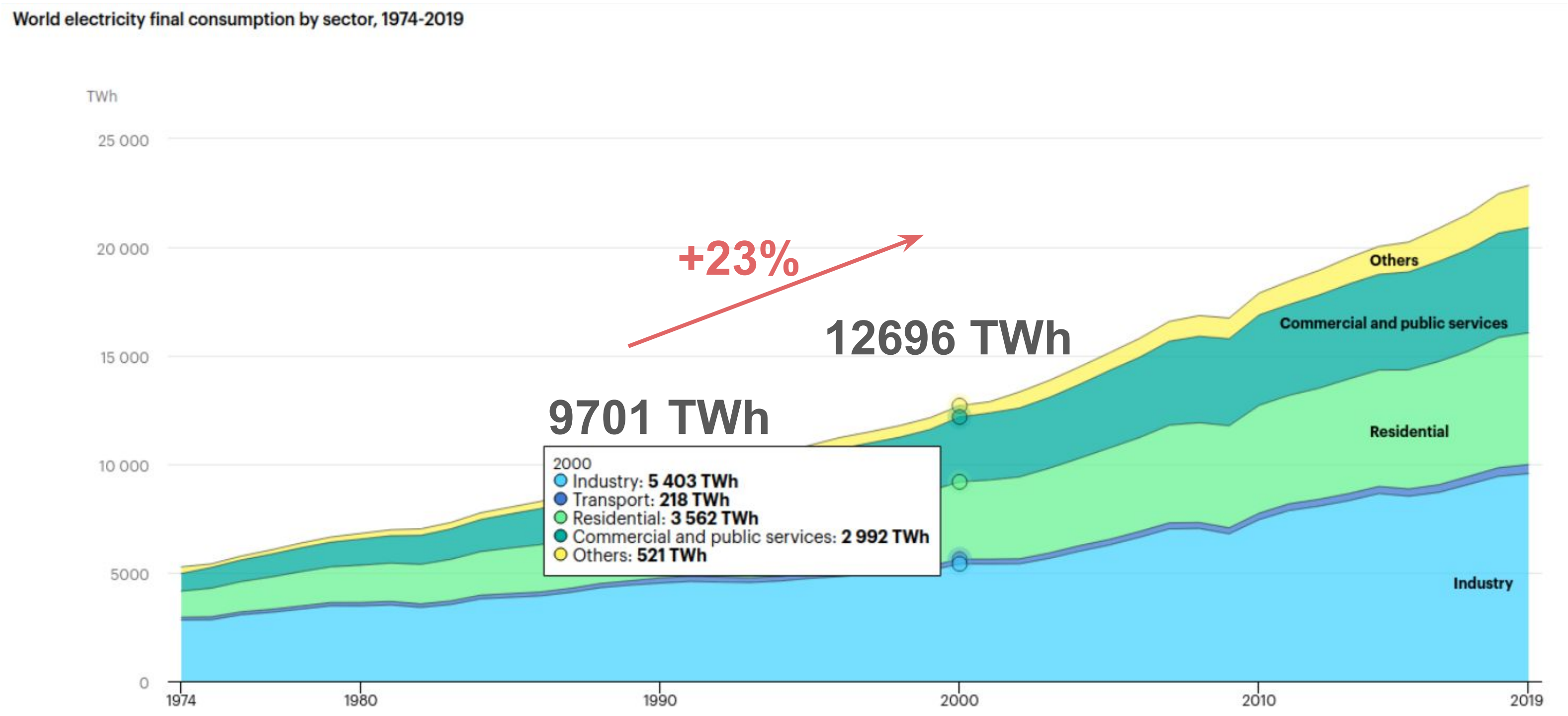
World energy consumption



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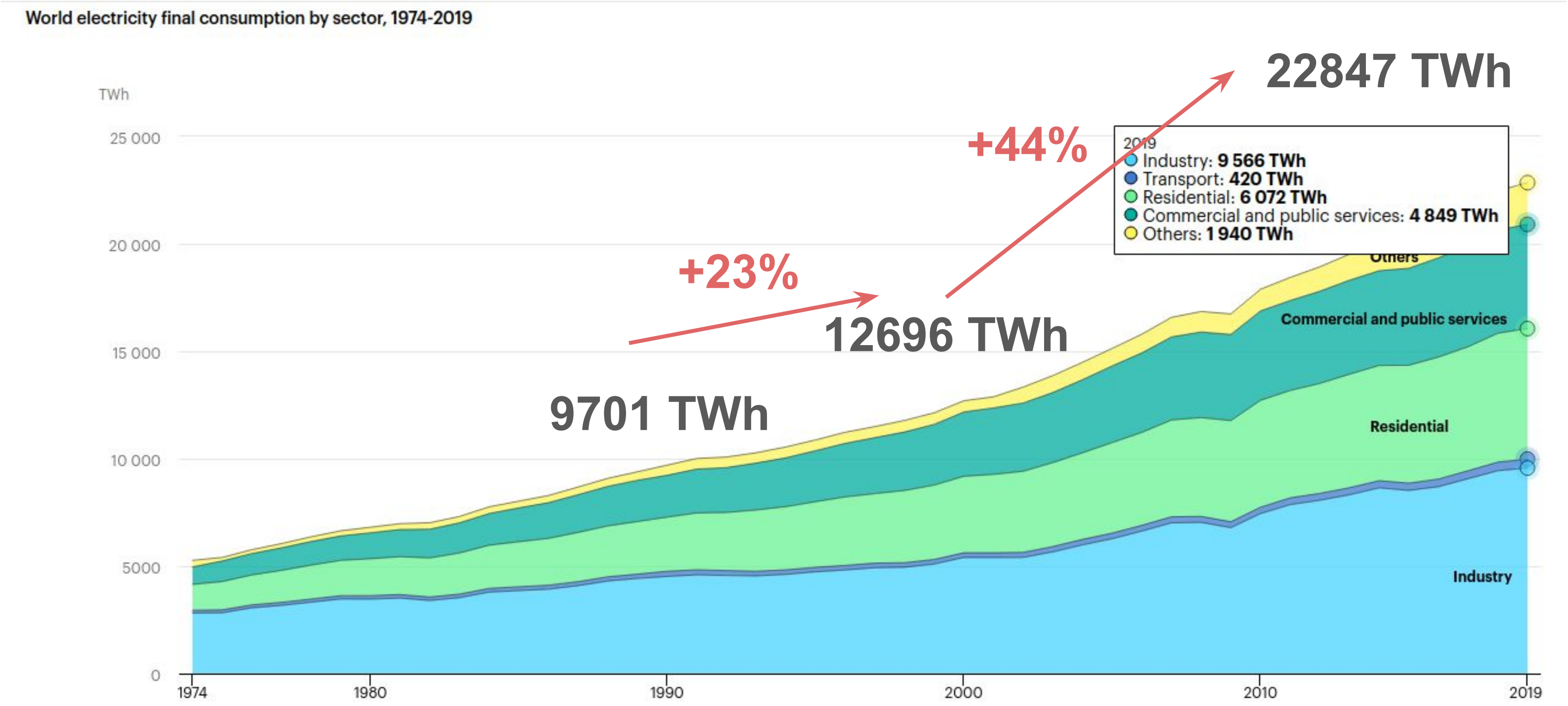
World energy consumption



https://www.iea.org/reports/electricity-information-overview/electricity-consumption

CO2 equivalents for electricity generation

France ☢️👍 : 68 gCO2-eq/kWh [Source]

Europe : 251 gCO2-eq/kWh [Source]

USA : 192 gCO2-eq/kWh [Source]

World average : 475gCO2-eq/kWh [Source]

CO2 equivalents for electricity generation

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World average : **475gCO_2-eq/kWh** [Source]

Here we see great disparities between regions of the world ⇒ **Electricity Mix**

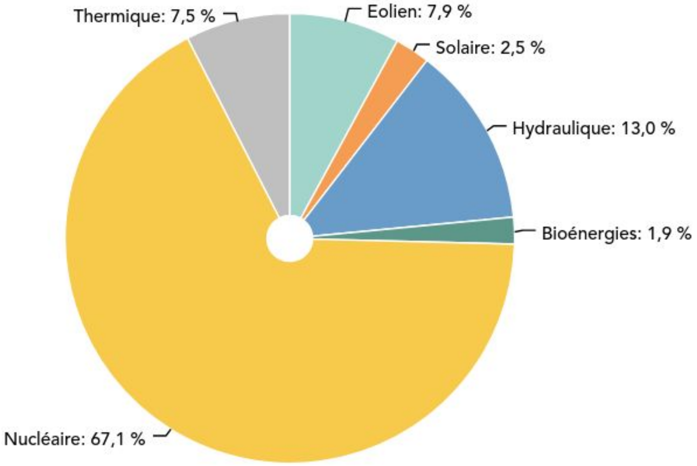
Electricity Mix

Electricity mix = all the means of electricity production in a given geographical area.

≠

Energetic Mix = all primary energy sources used in a geographical area (electricity production, transport, industry, etc.).

Electric mix in France in 2020



[2020 RTE Electricity Report in France]

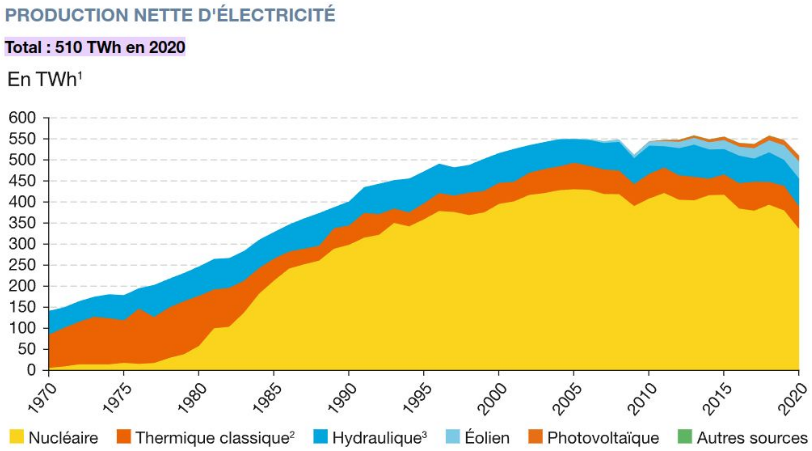
Primary energy used in France VS electricity production

Primary energy consumption in France in 2020:

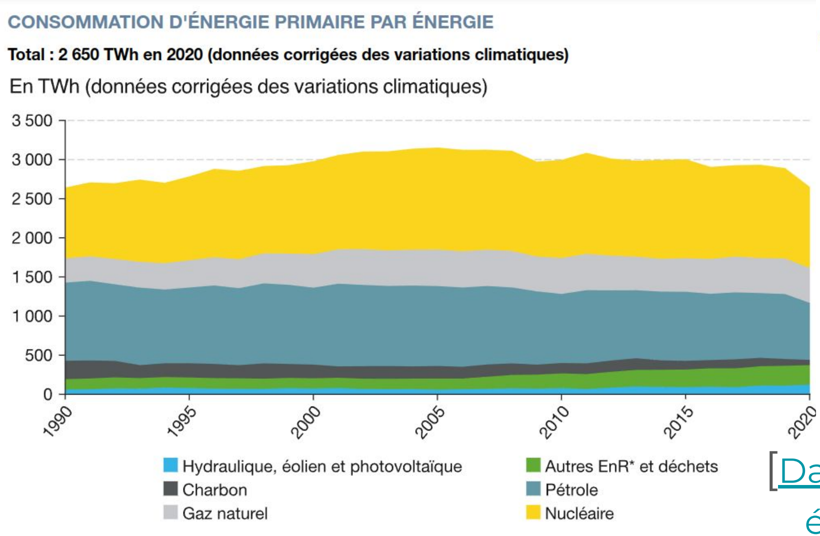
2650 TWh

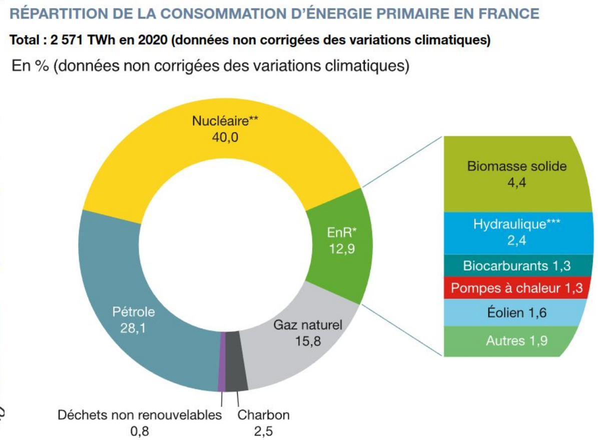
Electrical production in France in 2020:

510 TWh



[Data from "ministère de la transition écologique - Production d'électricité"]





[Data from "ministère de la transition écologique - Bilan énergétique"]

Electricity Mix - Types of Energy

Renewable energies: non-limited energies whose renewal is sufficiently rapid on a human timescale.

Non-renewable energies: energies that renew themselves less quickly than we consume them on a human timescale.

Electricity Mix - Types of Energy

Renewable energies ⇒ **Intermittent energies:** the availability of the energy flow varies over time without any possibility of control (wind, sunshine, tide, etc.).

Non CO2 emitting (in production) and renewable, but high impact on grid management due to **intermittency** ⇒ **Need for storage or adaptation of other means of production ⇒ STEP**

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Electricity Mix - Types of Energy

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Non CO2 emitting (in production) and renewable, but high impact on grid management due to **intermittency** ⇒ **Need for storage or adaptation of other means of production**

⚠️ **EXCEPTION: hydropower (dams) and geothermal energy ⇒ renewable, non-intermittent and controllable production tools**

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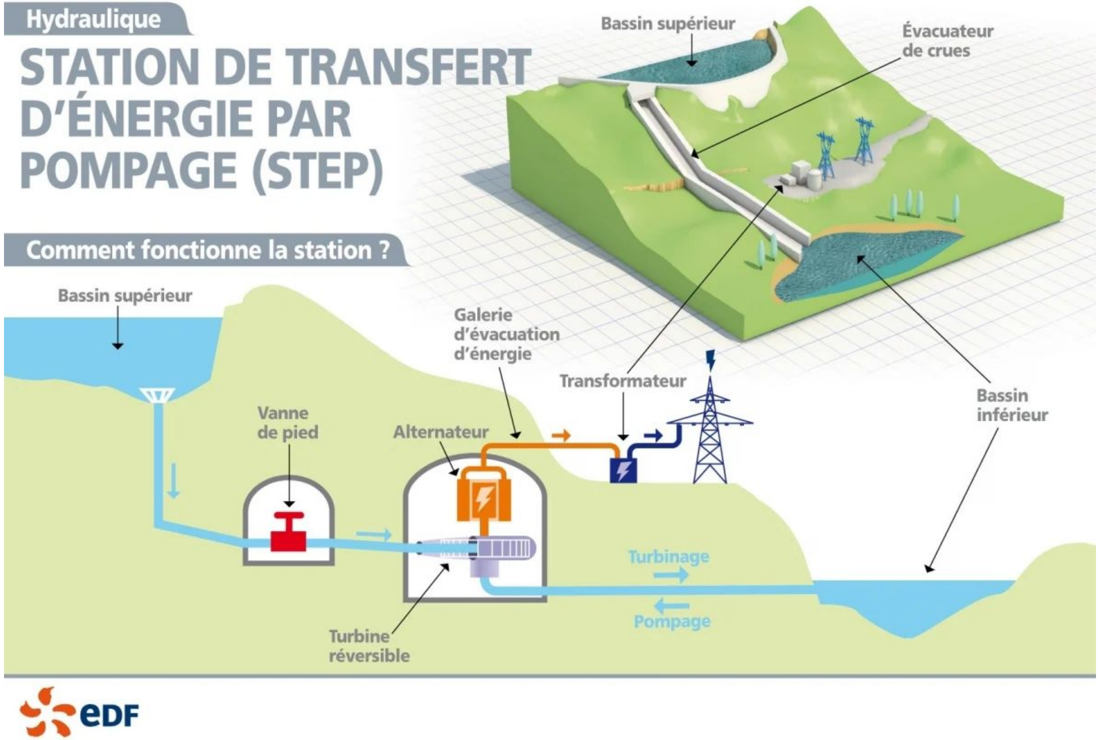
Electricity Mix - Types of Energy

Renewable energies ⇒

Non CO2 emitting (in production) and renewable, but high impact on grid management due to **intermittency ⇒ Need for storage or adaptation of other means of production ⇒ Pumped-storage power transfer station (in french: “Station de Transfert d’Énergie par Pompage-Turbinage (STEP)”**



Electricity Mix - Types of Energy

Non CO2 emitting (in production) and renewable, but high impact on grid management due to **intermittency** ⇒ **Need for storage or adaptation of other means of production ⇒ Pumped-storage power transfer station (in french: “Station de Transfert d’ Énergie par Pompage-Turbinage (STEP)”**

Pumped-storage power transfer station of Revin in France

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Electricity Mix - Types of Energy

Non-renewable energies: controllable energies: ⇒ energy flow availability is fixed and can be controlled according to demand

CO2-emitting (in production) and **non-renewable,** but **enabling controllable and adaptable management** of electrical production.

Natural gas/coal power plant in Saint-Avold, France

Nuclear power plant of Penly in France

Electricity Mix - Types of Energy

Non-renewable energies: controllable energies: ⇒ energy flow availability is fixed and can be controlled according to demand

CO2-emitting (in production) and **non-renewable,** but **enabling controllable and adaptable management** of electrical production.

⚠️ **EXCEPTION: nuclear energy ☢️ ⇒ a non-renewable production tool, but with large quantities of dense, controllable, and decarbonized uranium stocks. It produces waste related to fission, but some of it can be recycled into MOX.**

Natural gas/coal power plant in Saint-Avold, France

Nuclear power plant of Penly in France

Electricity Mix - Capacity Factor

"The net **capacity factor** is the unitless ratio of actual electrical energy output over a given period of time to the theoretical maximum electrical energy output over that period." Wikipedia

Capacity factor = Cf

Energy effectively produced = Efp

Energy theoretically produced at nominal power = Enp

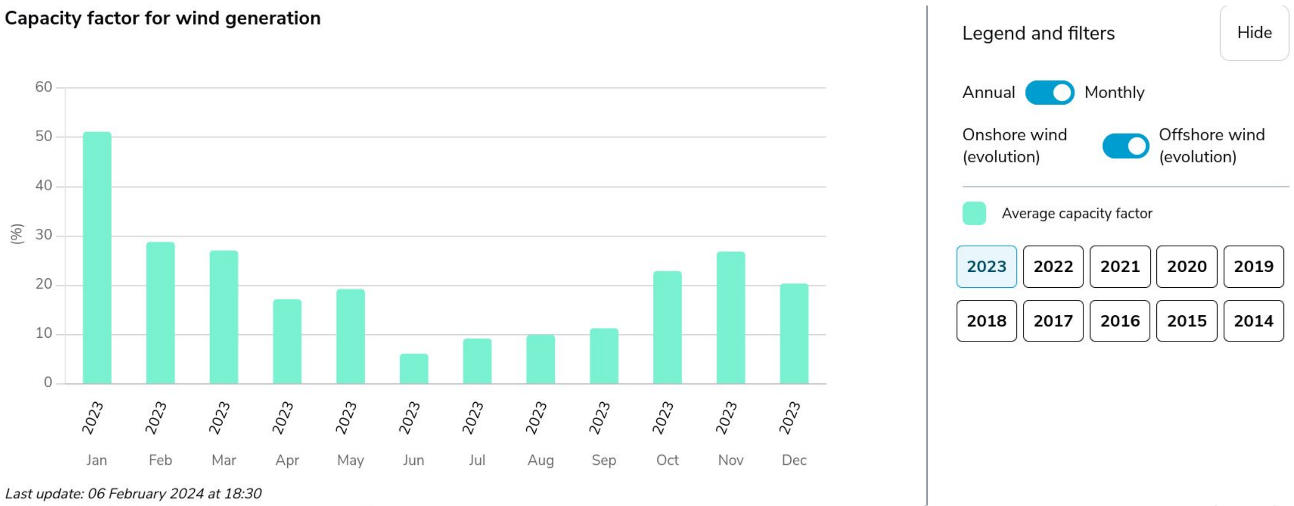
Cf = Efp / Enp

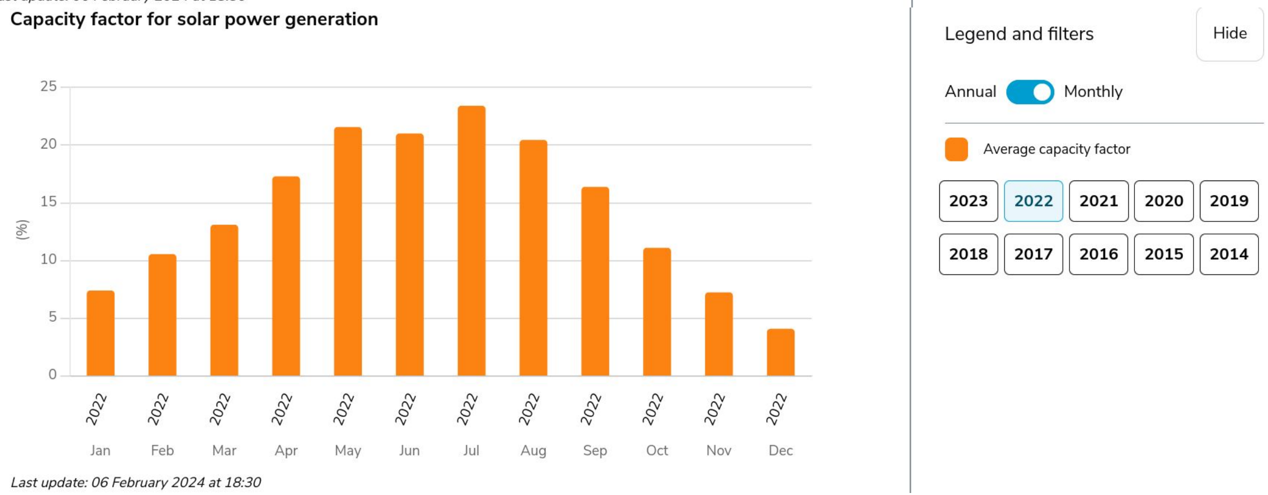
Natural gas/coal power plant in Saint-Avold, France

Nuclear power plant of Penly in France

Electricity Mix - Capacity Factor

[[Electricity Report RTE]]





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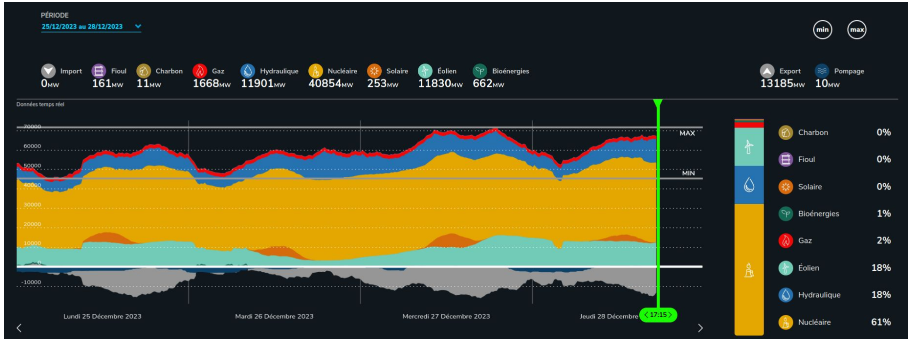
Electricity production management

Generating electricity on a large scale is not simple, as production must closely follow the energy demand, and this, under the following constraints:

- generate stable 230V / 50Hz
- avoid power grid collapse and minimize outages
- adapt to intermittent renewable energy production
- adapt to irregular consumption during the day

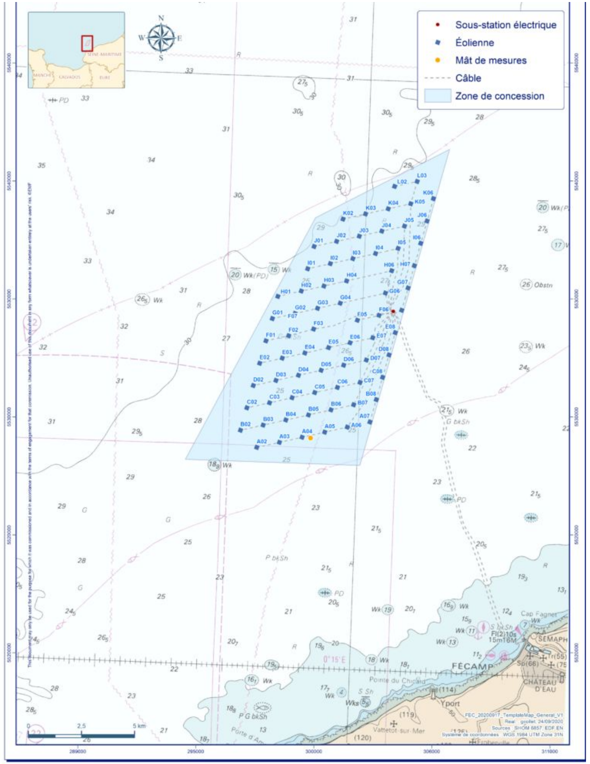
[Demonstration with RTE's éCO2mix website]



100% RE electricity mix a utopia? - Example with Ground Footprint

Fécamp Wind Farm in France 💨 :

- 71 offshore wind turbines
- 7MW Siemens SWT-7.0-154 wind turbine [datasheet]
- Total power 497MW
- Total area 60km² [Wind Farm's Website]



100% RE electricity mix a utopia? - Example with Ground Footprint

Cattenom (France) nuclear power plant ☢️ :

- 4 Réacteurs à eau pressurisée de 1300MW chacun (palier P’4)
- Surface globale de 415 hectares soit 4,15km² [Site EDF]
- Un des plus grands sites de production nucléaire de France

Nuclear power plant of Cattenom in France

100% RE electricity mix a utopia? - Example with Ground Footprint

Cattenom nuclear power plan ☢️ :

- P = 4*1300MW = 5200MW
- S = 4,15km²

[Fécamp Wind Farm]() 💨 :

- P = 497MW
- S = 60km²

100% RE electricity mix a utopia? - Example with Ground Footprint

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Fécamp Wind Farm 💨 :

- P = 497MW
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P_Ground Footprint = P/S

= 5200MW / 4,15 km²

= **1253MW/km²**

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[Fécamp Wind Farm](#) 💨 :

- P = 497MW
- S = 60km²

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= **8,28MW/km²**

100% RE electricity mix a utopia? - Example with Ground Footprint

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Rapport de 151

100% RE electricity mix a utopia? - Example with Ground Footprint

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d Farm 💨 :

W

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Rapport de 151

OOF

100% RE electricity mix a utopia? - Example with Ground Footprint

Cattenom nuclear power plan ☢ … d Farm 💨 :

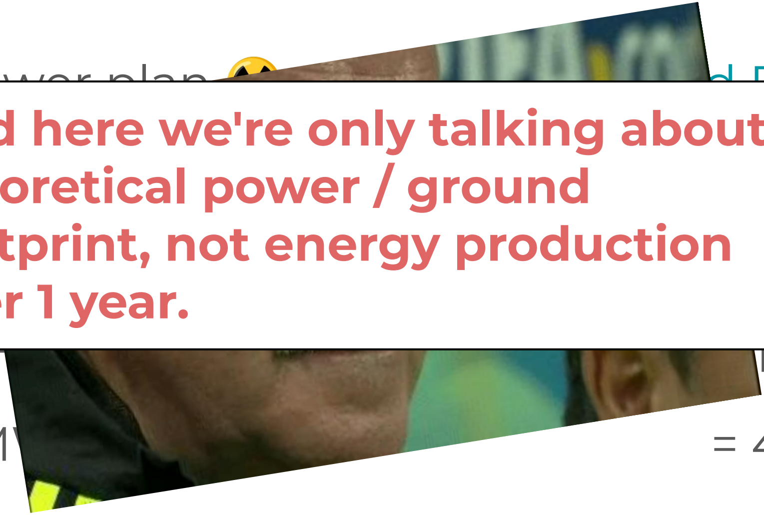
- P = 4*1300MW
- S = 4,15km²

P_Ground Footprint = … print = P/S

= 5200MW … = 497MW / 60km²

= **1253MW/km²** ⟷ = **8,28MW/km²**

Ratio of 151



And here we're only talking about theoretical power / ground footprint, not energy production over 1 year.

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100% RE electricity mix a utopia? - Example with energy over 1 year, taking load factor into account

Cattenom nuclear power plan ☢️ :

- P = 4*1300MW = 5200MW
- S = 4,15km²
- Lf = 68,3% [Wikipedia]

E = P*365*24*Lf

= 5200MW * 365 * 24 * 0,683

= **31,1 TWh**

Fécamp Wind Farm 💨 :

- P = 497MW
- S = 60km²
- Lf = 21,9% (Average offshore load factor in France) [RTE]

E = P*365*24*Lf

= 497MW * 365 * 24 * 0,219

= **0.95 TWh**

Ratio of 33

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100% RE electricity mix a utopia? - Example with energy over 1 year, taking load factor into account

Cattenom nuclear power plan ☢️ :

- P = 4*1300M
- S = 4,15km²
- Lf = 68,3% [

[Fécamp Wind Farm](#) 💨 :

verage offshore
n France) [[RTE](#)]

To produce the same amount of energy as 4.15km² produced in 1 year, you need 1980km² of wind turbines (33*60km²).

E = P*365*24*Lf

= 5200MW * 365 * 24 * 0,683

= **31,1 TWh**

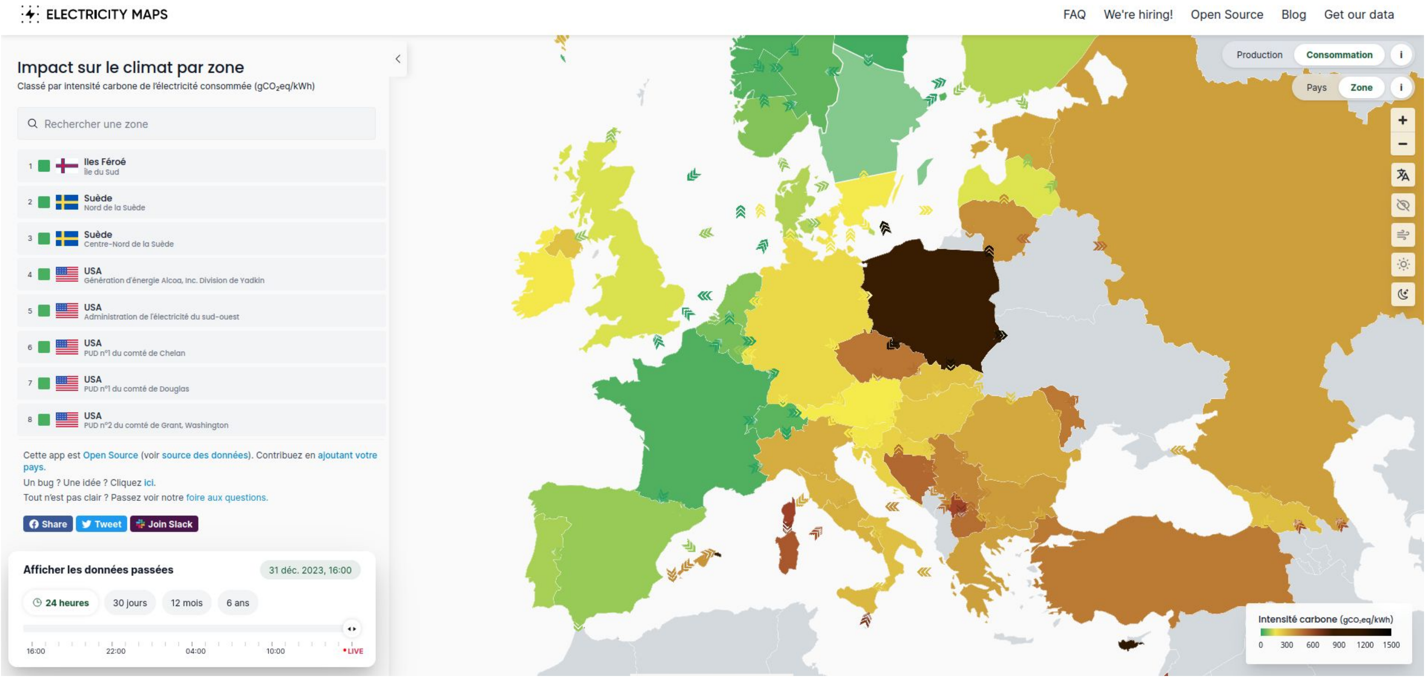
E = P*365*24*Lf

= 497MW * 365 * 24 * 0,219

= **0.95 TWh**

Ratio of 33

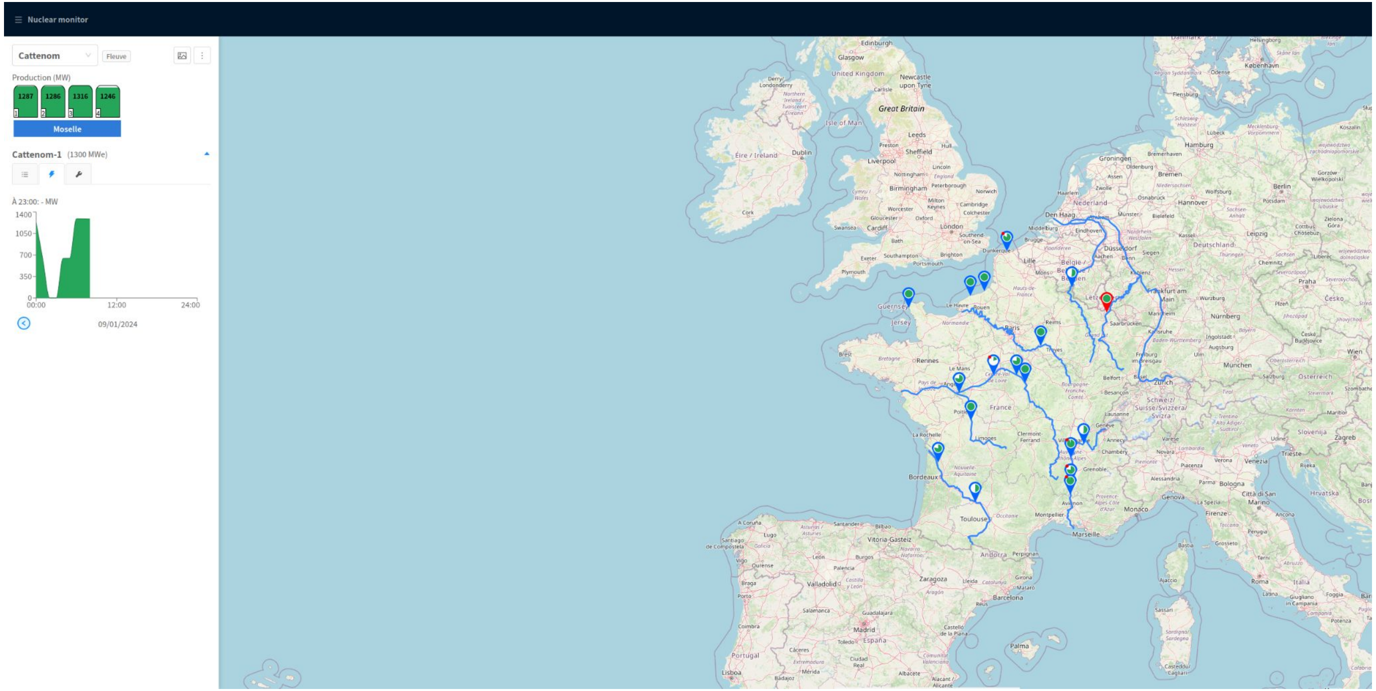
Visualizing the world's electricity mix and CO2 emissions: Electricity Map



https://app.electricitymaps.com/map

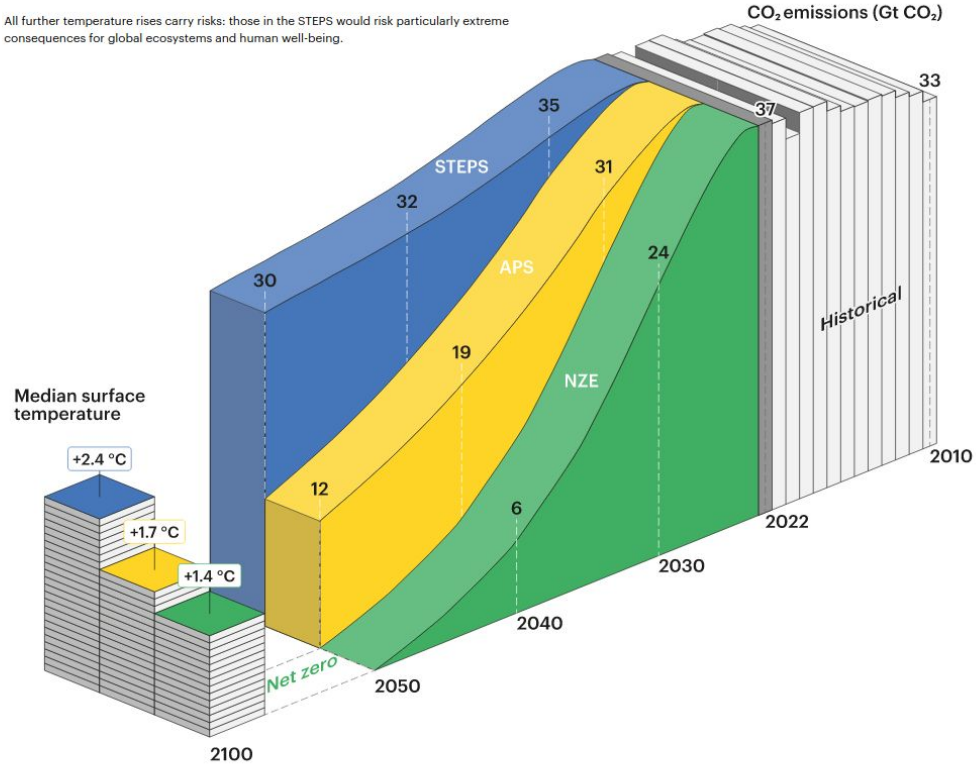
API available (for a fee)

Visualize nuclear reactors in France and their output: Nuclear Monitor



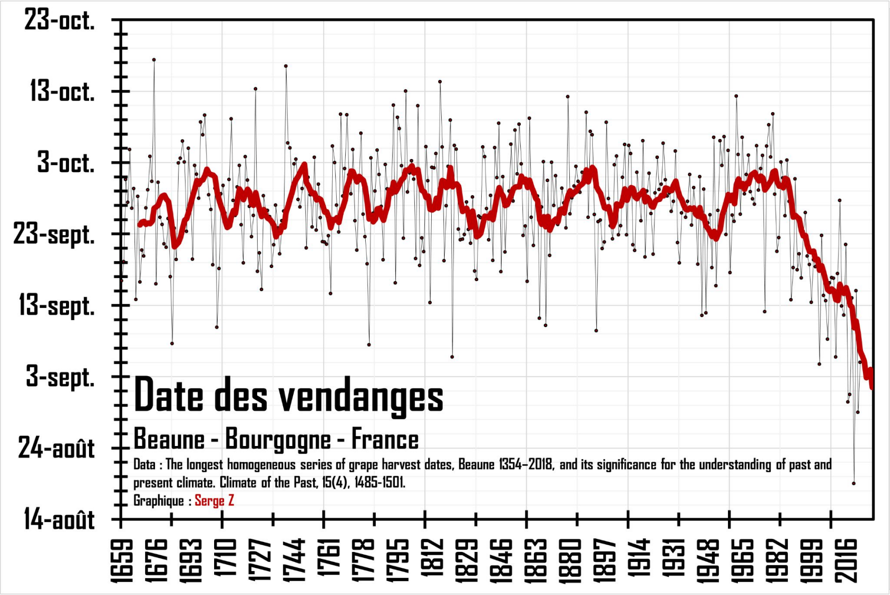
https://nuclear-monitor.fr/

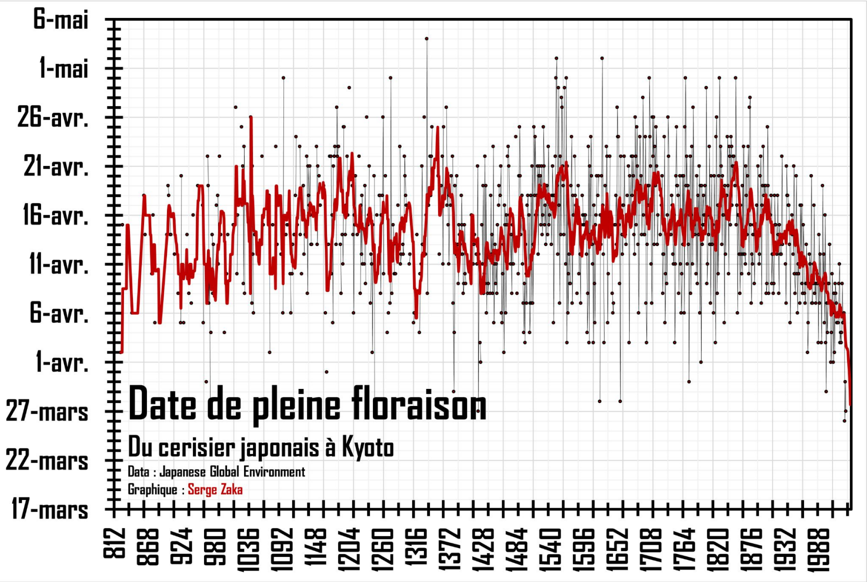
Ecological transition - possible trajectories



[World Energy Outlook 2023, IEA]

Effects of global warming on flowering

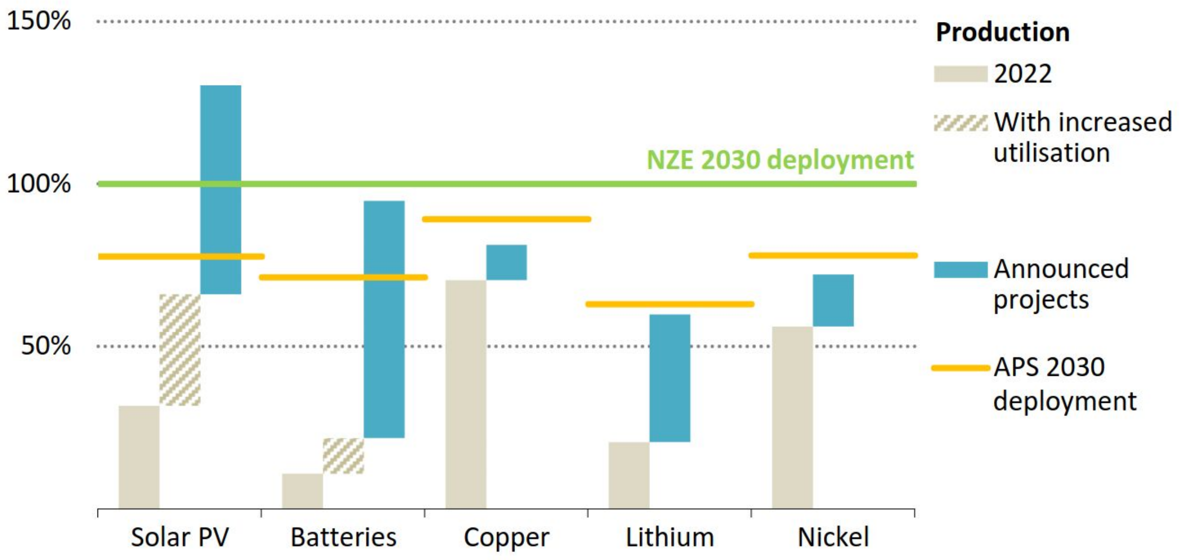




[Charts from Serge Zaka]

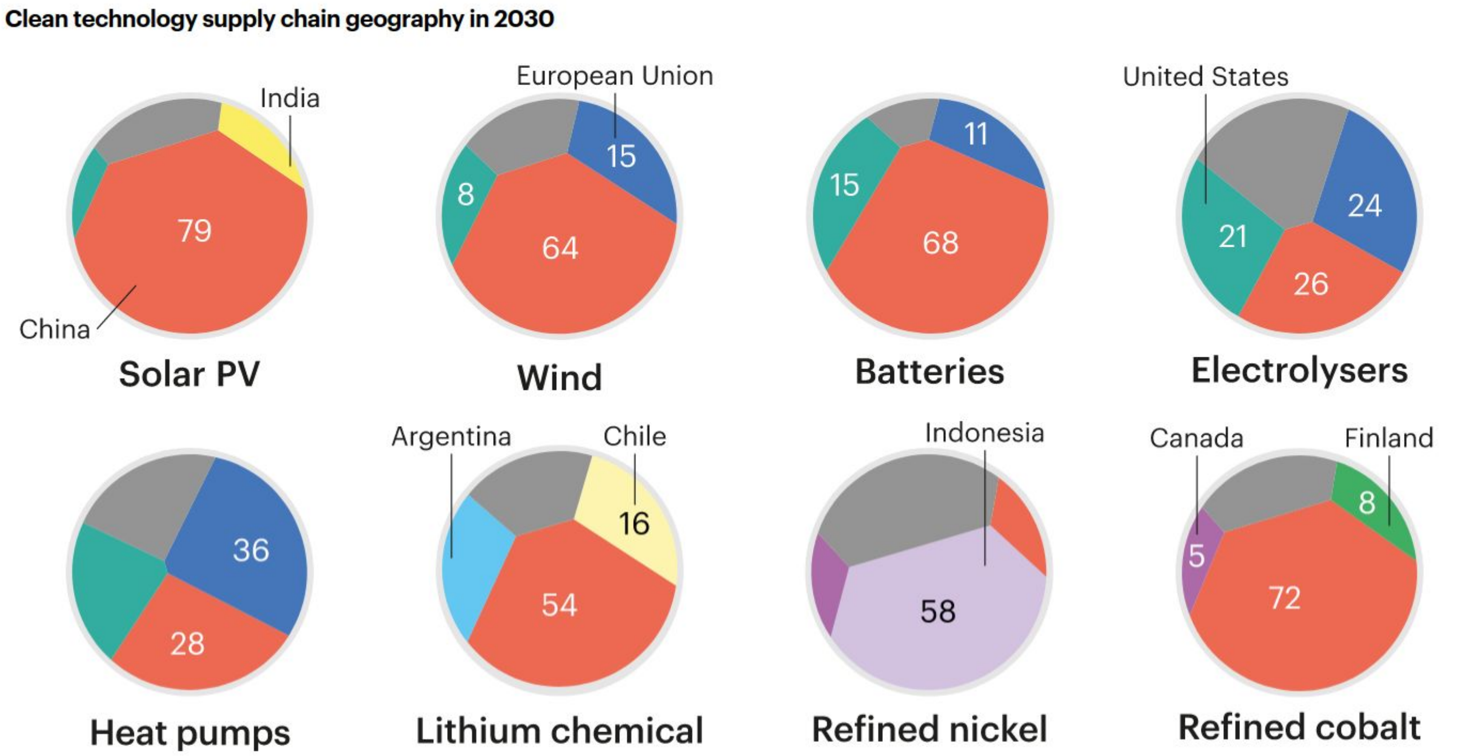
Ecological transition - Geopolitical uncertainties and the supply chain

Figure 4.18 ▷ Announced project throughput, and deployment and supply needs for key clean energy technologies and minerals in 2030



[World Energy Outlook 2023, IEA]

Ecological transition - Geopolitical uncertainties and the supply chain



[World Energy Outlook 2023, IEA]

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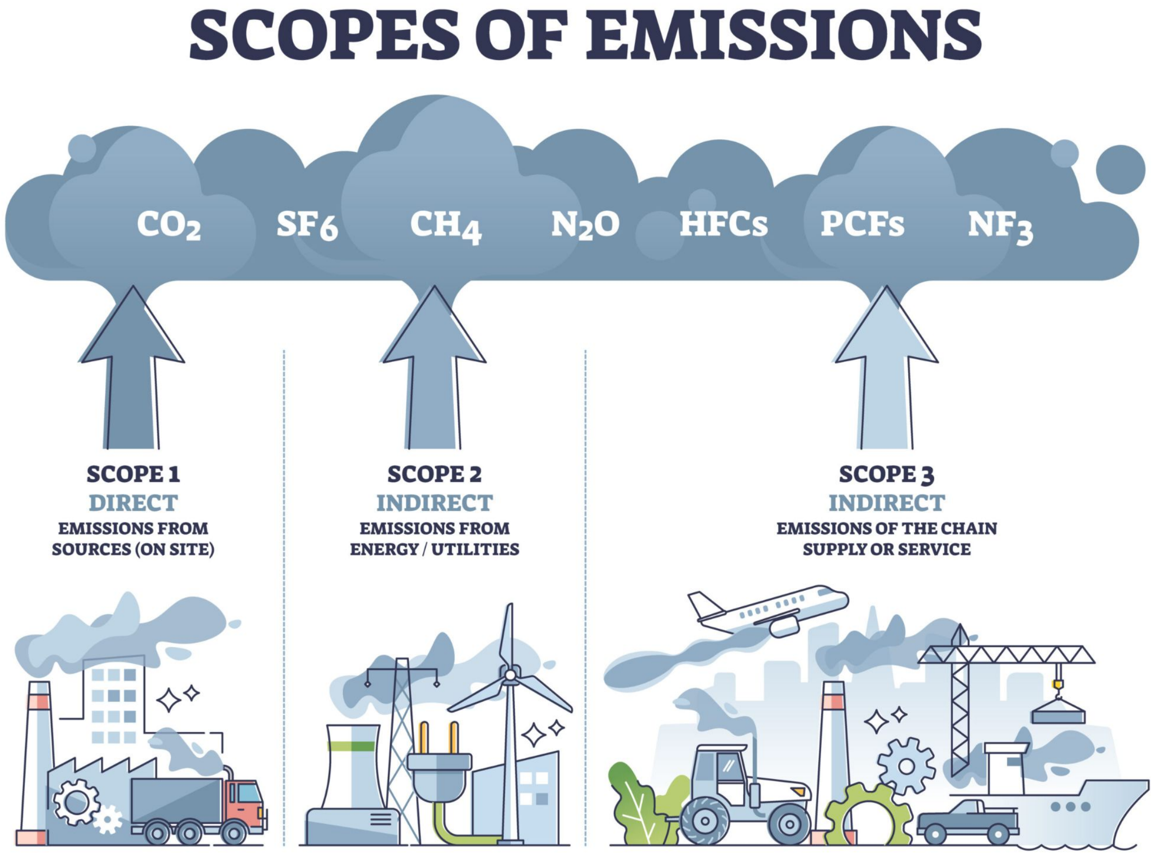
Information and Communication Technologies Energy Consumption

ICT carbon footprint: scopes



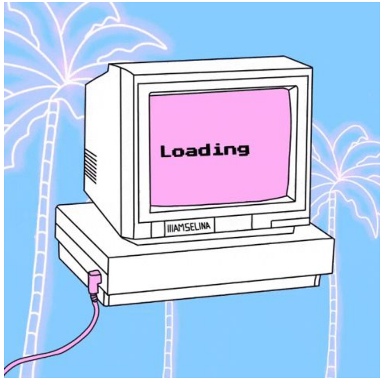
ICTs Energy Consumption

World energy consumption: 2,848 TWh in 2019 (IEA)

⇒ +1.7% compared to 2018

⇒ +44% compared to 2000

ICTs CO_2 emissions: 1,8% to 3,9% of global CO_2 emissions



The figures given here are taken from the publication by Freitag *et al.*, "*The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations*", 2021 [Freitag2021]

ICTs Energy Consumption

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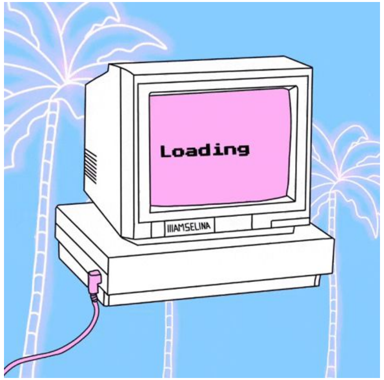

CO2 emissions from aviation in 2018: 2,4%

[*Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", 2018*]

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ICTs Energy Consumption

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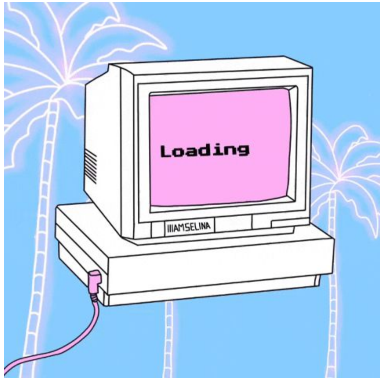

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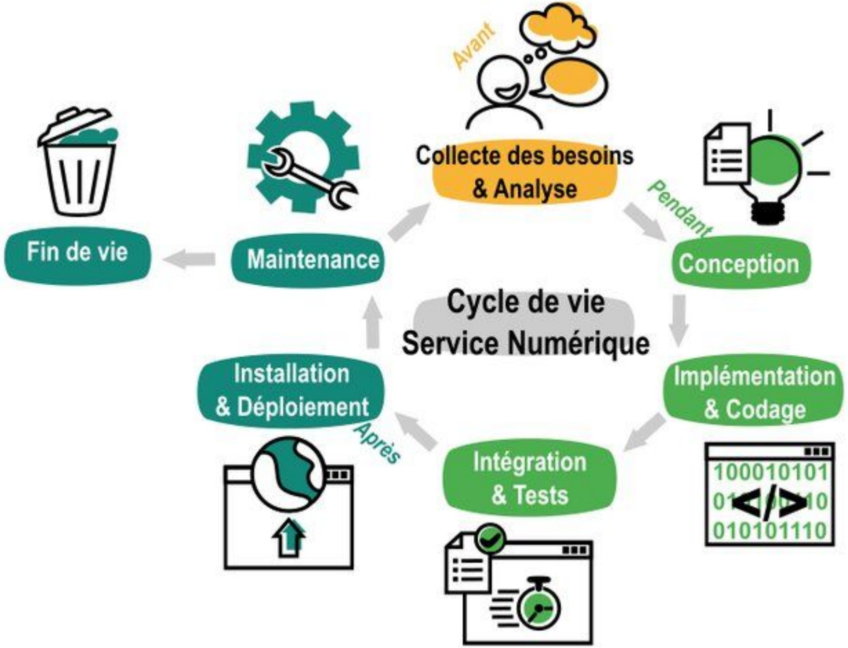
C02 emissions for ICTs are very hard to quantify "precisely"

Quantifying ICTs' energy consumption

C02 emissions for ICTs are veryhard to quantify “precisely”

- Scope: software, peripherals, users, networks, hardware workload, etc.
- Share of the material life cycle considered: manufacture, use, recycling, reuse, etc.
- Share of software life cycle
- Electrical mix



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Quantifying ICTs' energy consumption

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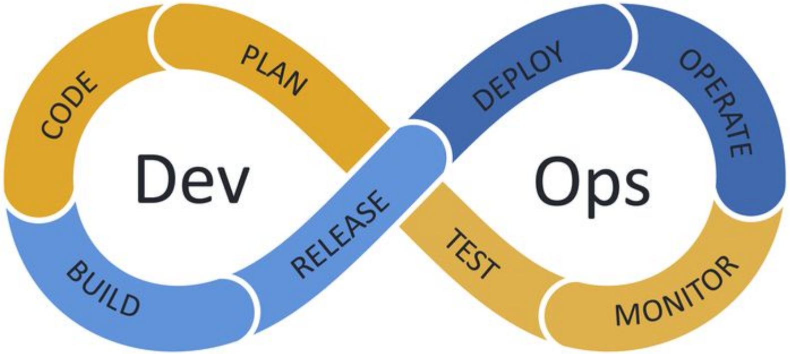
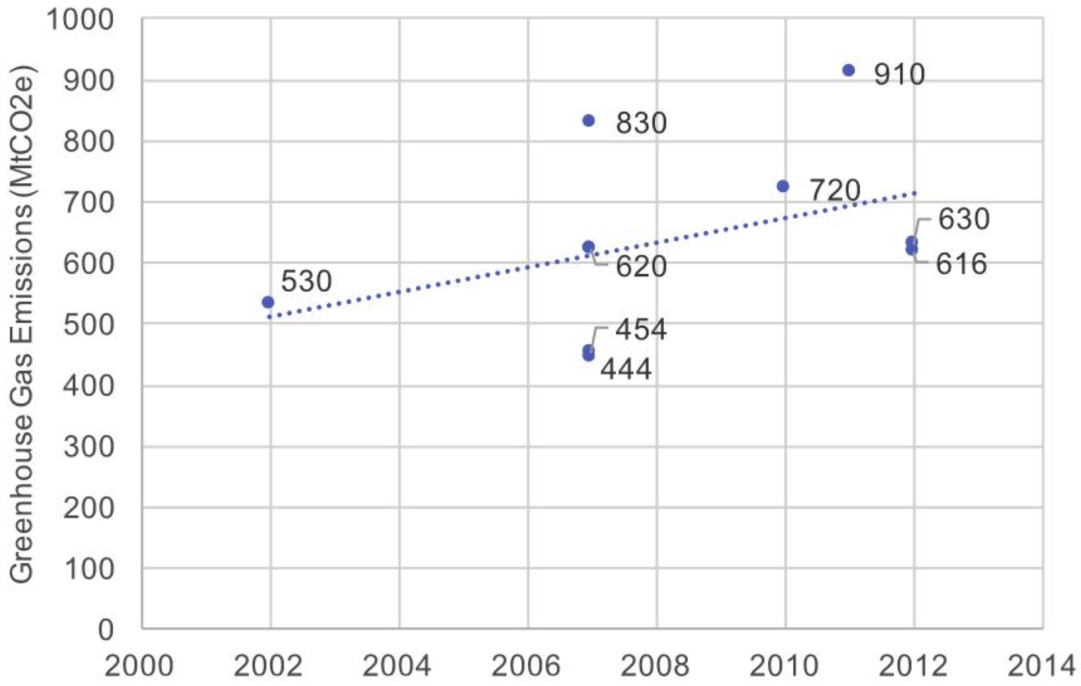
- Scope: software, peripherals, users, networks, hardware workload, etc.
- Share of the material life cycle considered: manufacture, use, recycling, reuse, etc.
- Share of software life cycle
- Electrical mix
- **Iterative and incremental cycle makes calculations more complex**



ICT CO2 emissions, estimates and uncertainties

[Freitag2021]

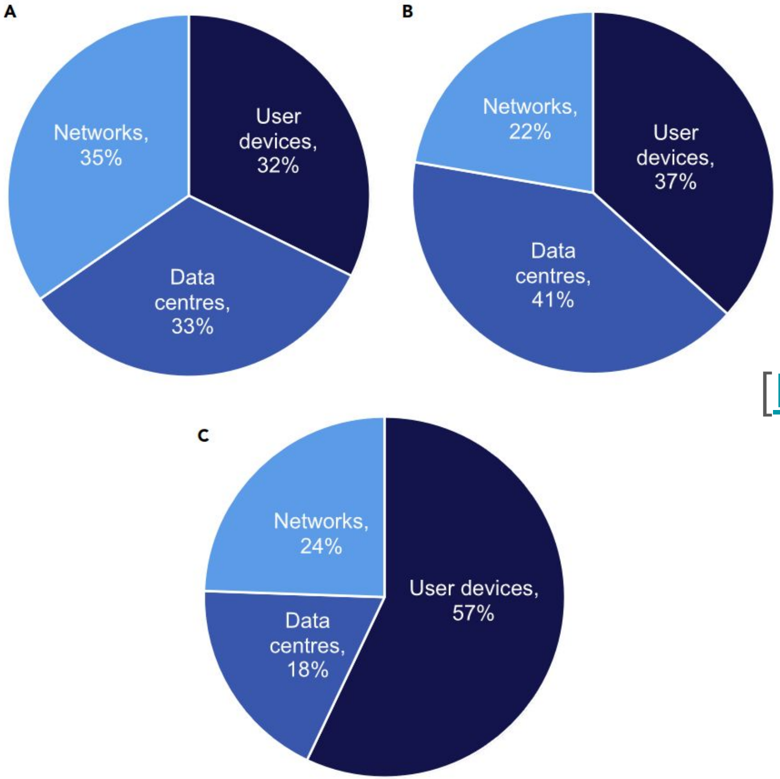


ICTs' impact on CO_2 emissions (excluding TV)

(A) Andrae and Edler (2015): 2020 best case (total of 623 $MtCO_2e$)

(B) Belkhir and Elmeligi (2018): 2020 average (total of 1,207 $MtCO_2e$)

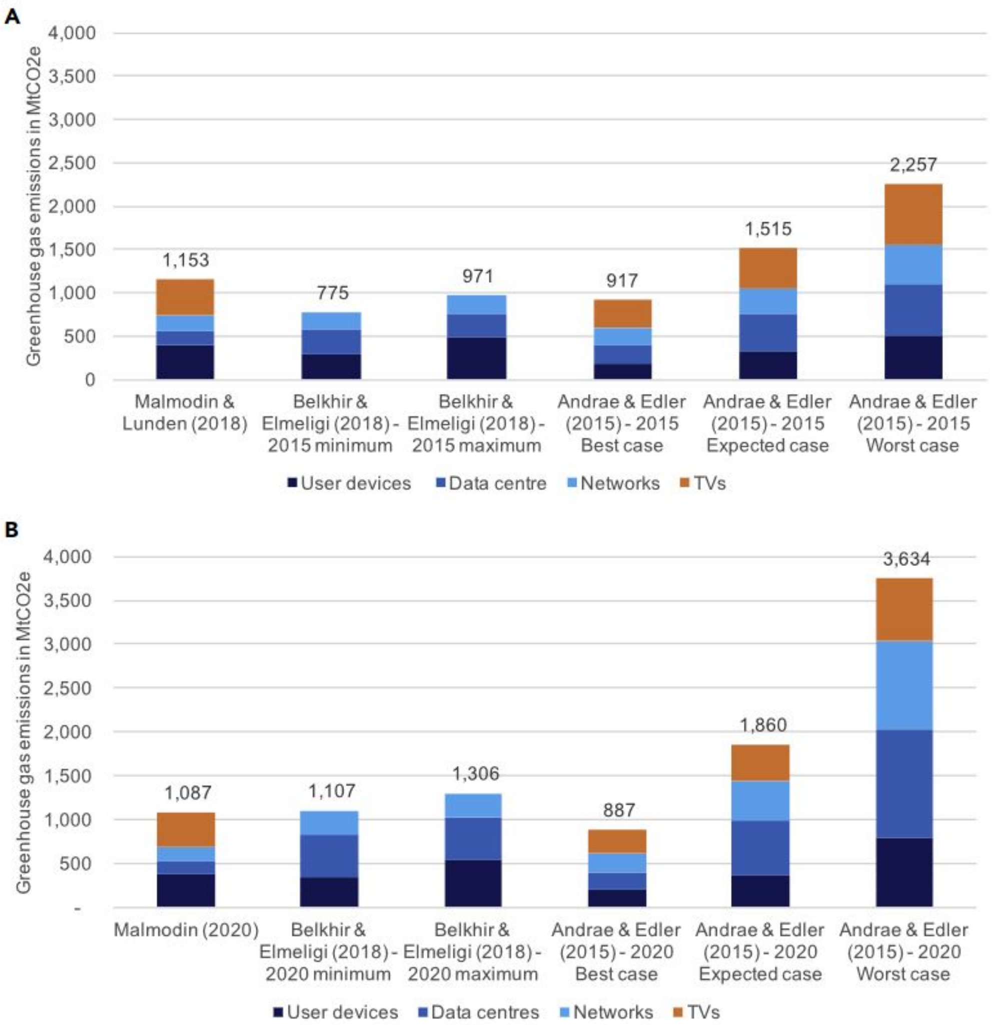
(C) Malmodin (2020): 2020 estimate (total of 690 $MtCO_2e$)



[Freitag2021]

ICT CO2 emissions, estimates and uncertainties

Estimated ICT emissions in 2015 (A) and 2020 (B)



[Freitag2021]

Increasing use of ICTs

[Agence Internationale de l'énergie - Data Centres and Data Transmission Networks]

	2015	2022	Change
Internet users	3 billion	5.3 billion	+78%
Internet traffic	0.6 ZB	4.4 ZB	+600%
Data centre workloads	180 million	800 million	+340%
Data centre energy use (excluding crypto)	200 TWh	240-340 TWh	+20-70%
Crypto mining energy use	4 TWh	100-150 TWh	+2300-3500%
Data transmission network energy use	220 TWh	260-360 TWh	+18-64%

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Conclusion

- **Sharp rise in energy requirements since 1980**
- Need to reduce our emissions in order to achieve the greatest possible reduction in GHGs
- Uncertainty over supply and green transition technologies
- **No single solution for reducing emissions** from power generation ⇒ **mix of decarbonized / controllable and non-controllable sources** to be found
- **Significant increase in the use of ICTs**
- Uncertainties about ICT estimates, and therefore a need to **quantify** and **evaluate** them in order to **identify levers for action**.