

EPFL

■ **IPESÉ**
Industrial Process
and Energy Systems
Engineering

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WALLIS

■ **School of Engineering**

CIRAIG

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ENV-421

Introduction to Energy Systems

Week 2

■ **École
polytechnique
fédérale
de Lausanne**

- 24'004 YEARS

- 24'004 YEARS

- 1809 M

BRIG

- 1502 M

SION

- 1199 M

Lausanne



2024

+7.8°C
in 24'004 years



2024

+7.8°C

in 24'024 years



2050

+1.5°C - +2.5°C






in 60 years?!

+7.8°C

in 24'004 years

Energy Systems

Agenda

	Week 2 	Week 4 	Week 7 	Week 9 
Lectures	Energy System Fundamentals	Energy Conversion Technologies	Technologies' Impacts	Climate Impact on Energies
Applications & Exercises	The Swiss Energy System Evolution & Perspectives	Efficiencies & Classification	Conference <i>Is it all about renewable energies?</i> Closing the Balance & Defining Compromises	Powerplay Game
Project: Addressing Contemporary Challenges to the Swiss system Energy-independent and carbon-neutral Switzerland 2050 				



Week 2



Lectures

Energy System
Fundamentals

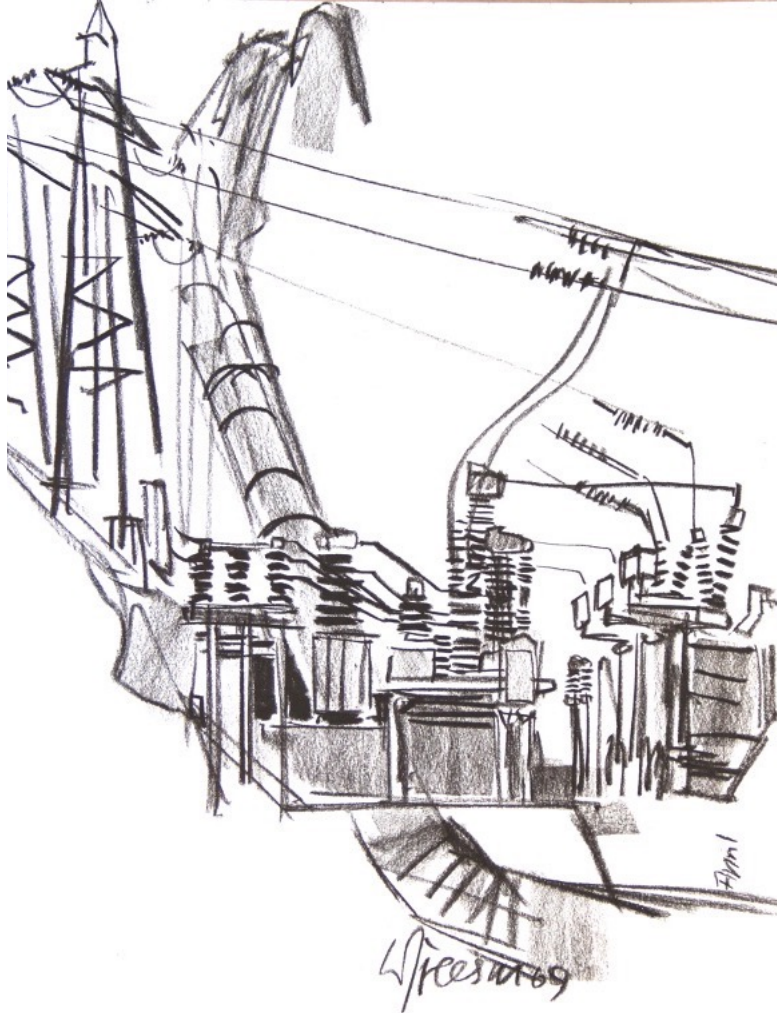
- Introduction to Energy Systems and Key Concepts
- Energy Balance Fundamentals
- Analysis and Evaluation of Energy Systems

Applications & Exercises

The Swiss Energy
System

Evolution
&
Perspectives





A G E N D A

Introduction to Energy Systems

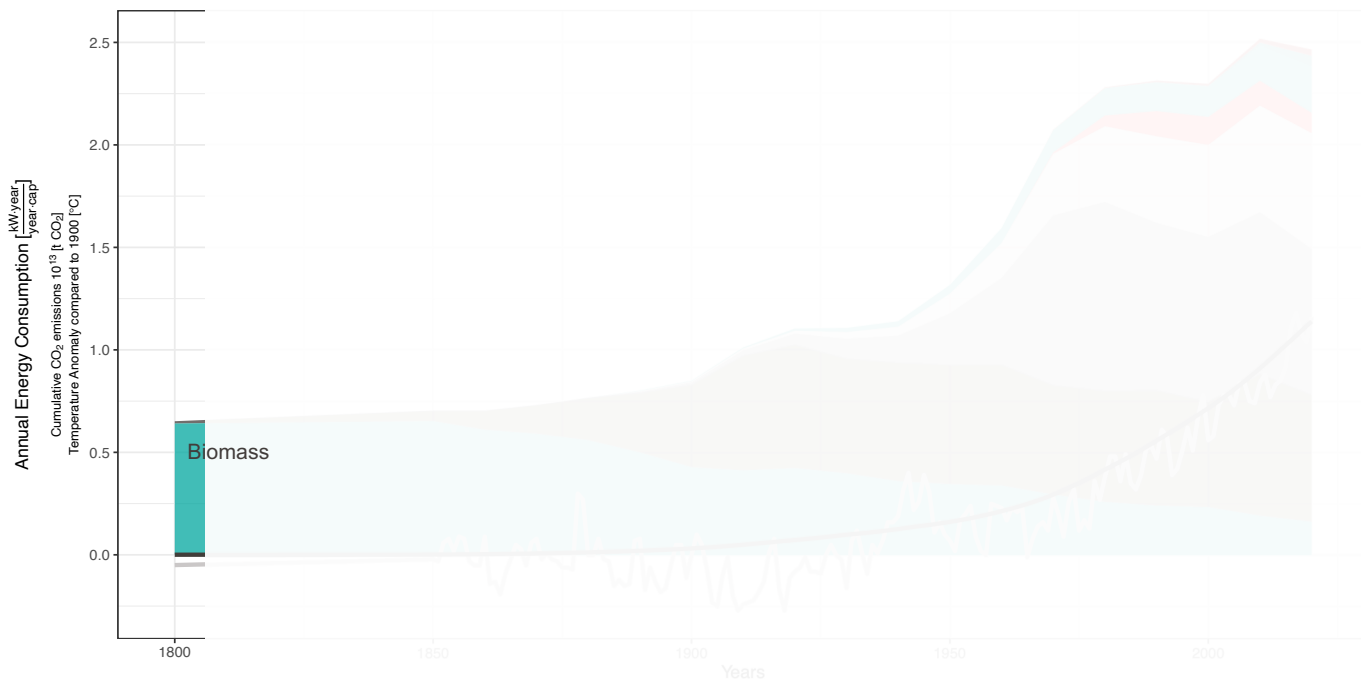
Energy Balance Fundamentals

Analysis and Evaluation of Energy Systems



The Foundation of Ingenuity and Survival

- Mastery of **fire** improved **warmth, protection, and cooking**, altering human interaction with nature [2–5].
- Fire use enhanced living conditions and enabled **migration** [2–5].



Population	0.8 billion
Energy $\left[\frac{\text{W} \cdot \text{year}}{\text{year cap}} \right]$	400
CO ₂ emissions $[10^9 \text{ t}]$	0.12
$\Delta T_{1800} [^{\circ}\text{C}]$	0



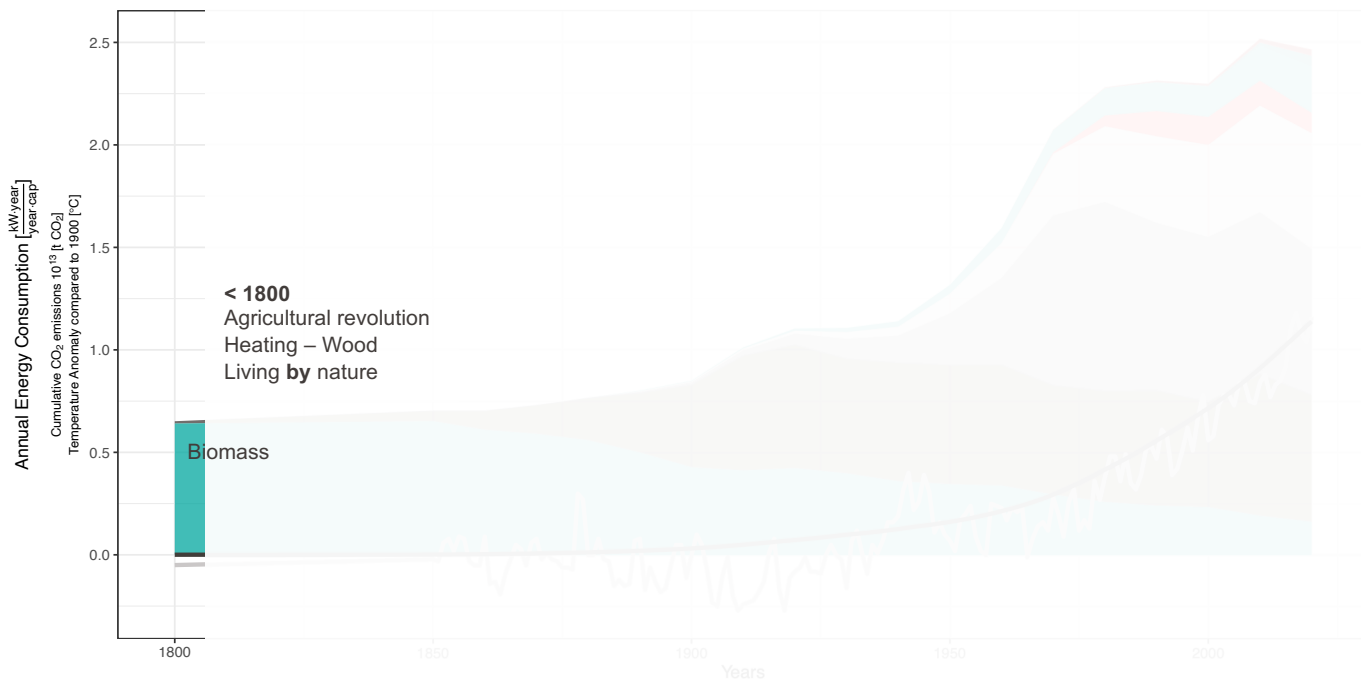
Global energy consumption per capita and temperature evolution.

The temperature anomaly was calculated using the reference year 1900 by [49]. The specific energy use is determined as the ratio between annual energy consumption [50] [W·year] and the respective population [51]. The CO₂ emissions are calculated as the cumulative sum of year emissions since 1800 [52].



Symbiosis with Nature

- Agricultural Revolution began with **glacier retreat**, changing human-nature relations. [6–9]
- **Wood biomass** dominated energy use, meeting demands of 600 $\left[\frac{\text{W}\cdot\text{year}}{\text{year cap}}\right]$. [10,11]
- **Crop cultivation and animal domestication** improved efficiency and understanding of nature. [12, 13]



Population **1 billion**

Energy $\left[\frac{\text{W}\cdot\text{year}}{\text{year cap}}\right]$ **656**

CO₂ emissions $[10^9 \text{ t}]$ **0.19**

ΔT_{1800} [°C] **0**



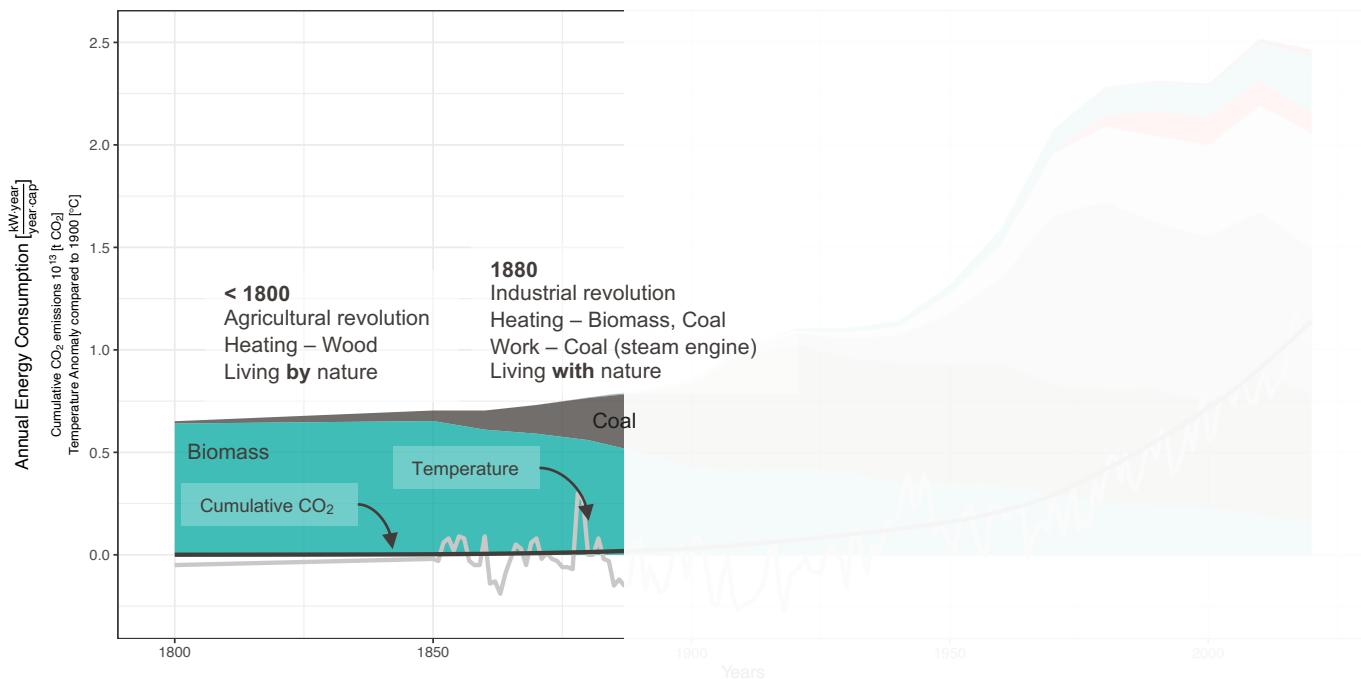
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Harnessing Power

- **Industrial Revolution** increased energy use per capita, raising CO₂ levels. [14–17]
- **Water and steam power** innovations drove technological progress and urbanization. [18–20]
- **Coal** became a major energy source, fueling steam engines. [21]
- Industrialization (1850) doubled the **population** to 2.5 billion; energy consumption reached 27.2 GJ/year per capita. [13,22]



Population	1.4 billion
Energy $\left[\frac{\text{W} \cdot \text{year}}{\text{year cap}} \right]$	766
CO₂ emissions $[10^9 \text{ t}]$	6.41
ΔT_{1800} $[\text{°C}]$	0.05



Global energy consumption per capita and temperature evolution.

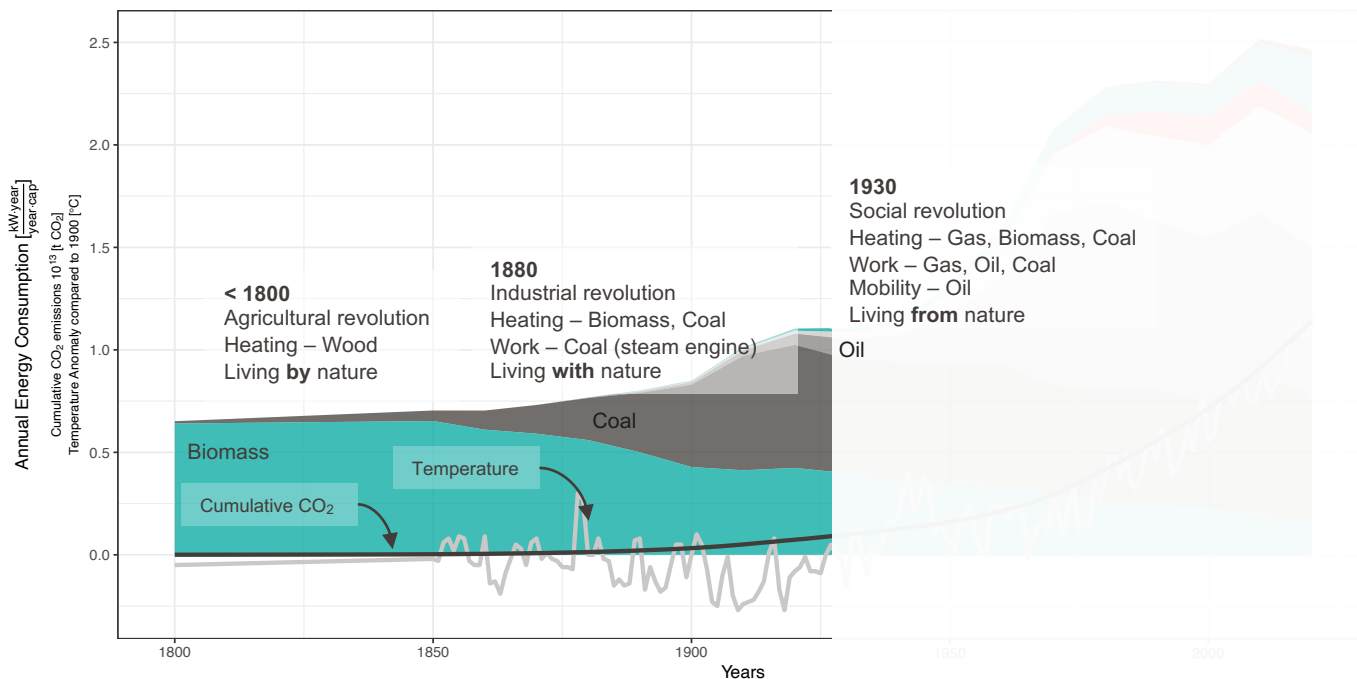
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A brief history of time

Growth and Consequences

- **Oil and electricity** discovery enabled **technological** advancements. [10,23,24]
- **Energy services diversified**: coal for electricity, oil for mobility, natural gas for heating. [25–27]
- Fossil fuels raised CO₂ levels to 415 ppm and temperatures by 0.9°C post-1950. [13,28,29]
- **Oil crises** and conflicts influenced energy patterns. [25–27]



Population	2.1 billion
Energy $\left[\frac{\text{W} \cdot \text{year}}{\text{year cap}} \right]$	1086
CO₂ emissions $[10^9 \text{ t}]$	27.3
ΔT_{1800} $^{\circ}\text{C}$	0.12

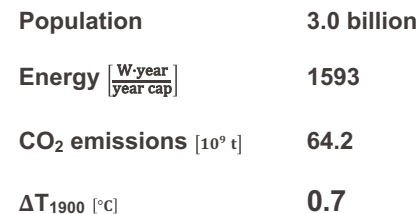


Global energy consumption per capita and temperature evolution.

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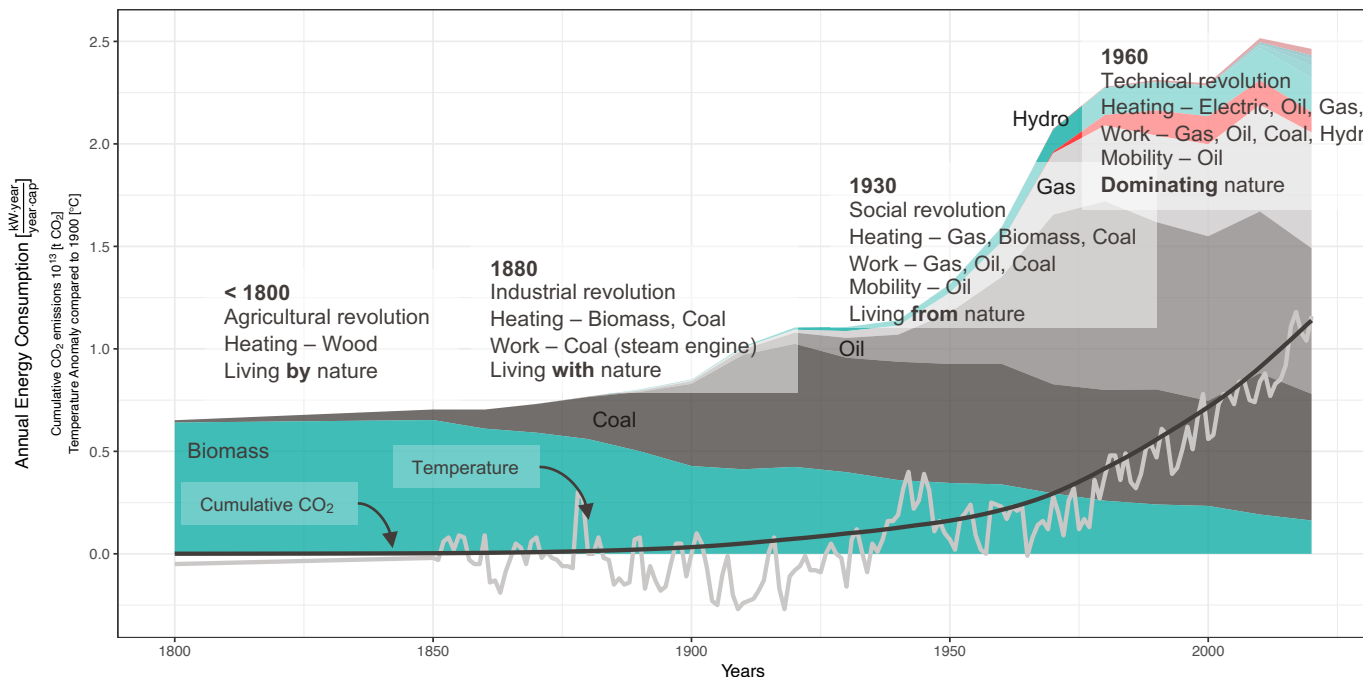


- **Nuclear energy** exploration driven by Cold War and physics advances. [30–34]
- Incidents highlighted **environmental and safety** concerns. [35–39]



The environmental turning point

- By 2015, population reached 7.4 billion, energy consumption marked departure from **Holocene**. [13,27,40,41]
- Environmental awakening emphasized balancing energy development with ecological preservation. [42–47]



Population	7.8 billion
Energy $\left[\frac{\text{W} \cdot \text{year}}{\text{year cap}} \right]$	2463
CO ₂ emissions $[10^9 \text{ t}]$	224.5
$\Delta T_{1900} [\text{°C}]$	1.23



Global energy consumption per capita and temperature evolution.

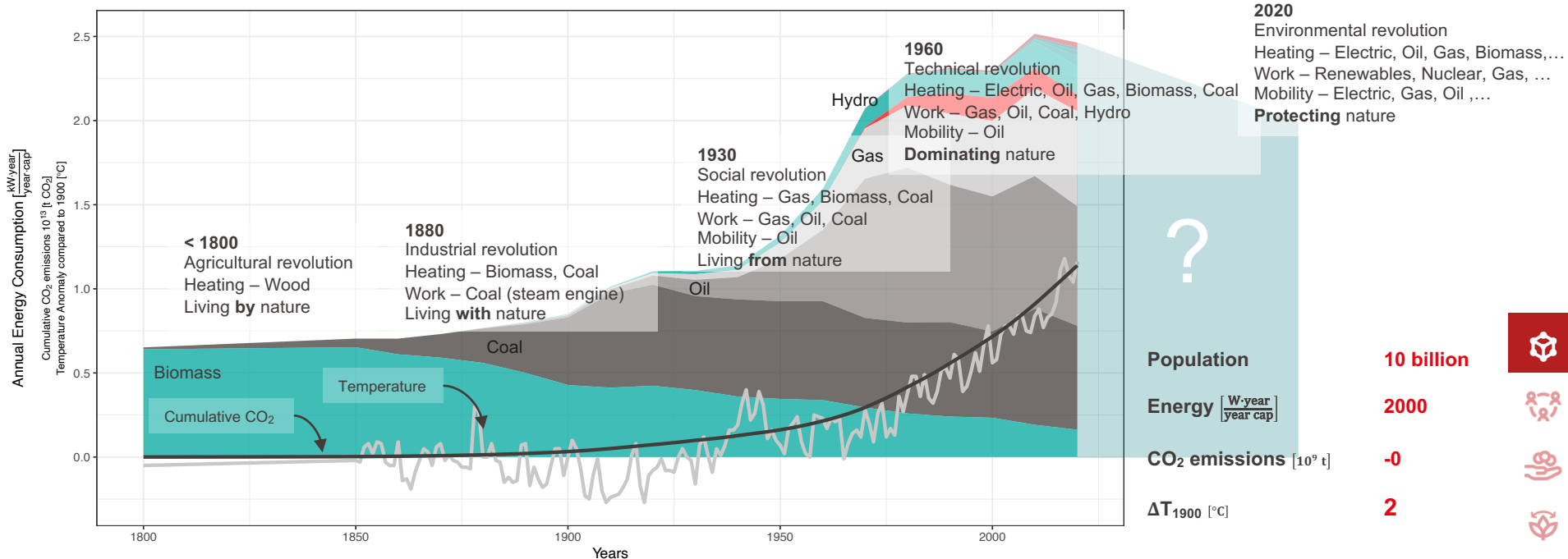
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The big question of the future

And now → 2050?

- Crossroad is both an **opportunity** and a **challenge**, requiring courage to abandon old patterns and enter a new era. [55,56]
- **Multiple sustainable pathways** exist, necessitating comprehensive modeling and quantification. [53,54]
- Equip **decision-makers with tools** to address the greatest challenge of the 21st century. [53,54]



■ Global energy consumption per capita and temperature evolution.
The temperature anomaly was calculated using the reference year 1900 by [49]. The specific energy use is determined as the ratio between annual energy consumption [50] [$\text{W}\cdot\text{year}$] and the respective population [51]. The CO₂ emissions are calculated as the cumulative sum of year emissions since 1800 [52].



What is an energy system

A question of balance

“The energy system comprises all components related to the production, conversion, delivery, and use of energy” (where energy is defined as “the power of ‘doing work’ possessed at any instant by a body or system of bodies”)

O. Edenhofer, Climate change 2014: mitigation of climate change, volume 3, Cambridge University Press, 2015.

“It is important to realize that the use of energy is no end but is always directed to satisfy human needs and desires. Energy services are the ends for which the energy system provides the means.”

H. Groscurth, T. Bruckner, R. Kümmel, Modeling of energy-services supply systems, Energy 20 (1995) 941–958.

“The combined processes of acquiring and using energy in a given society or economy”

J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, Renewable and Sustainable Energy Reviews 16 (2012) 3847–3866.

“energy systems are usually defined as technical and economic systems meeting the energy demand”

T. B. Johansson, A. P. Patwardhan, N. Nakicenovic, L. Gomez-Echeverri, Global energy assessment: toward a sustainable future, Cambridge University Press, 2012.



What is an energy system

A question of balance

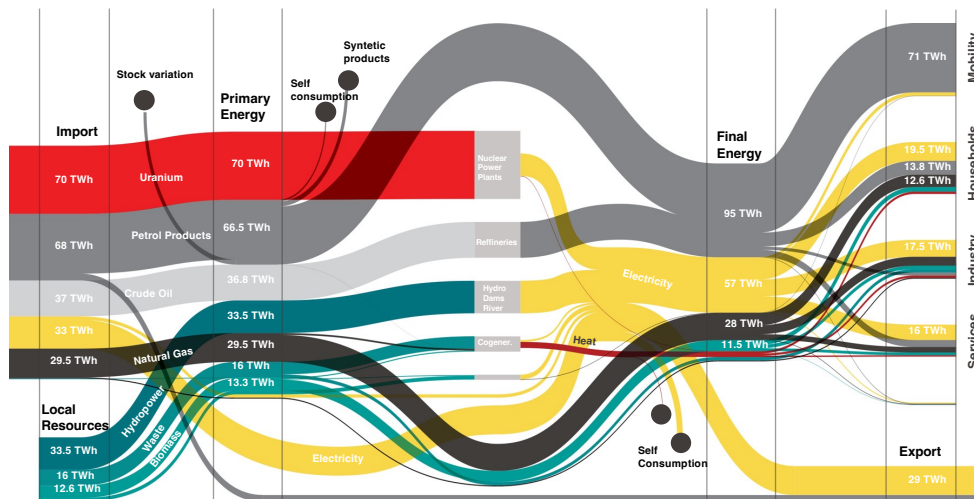
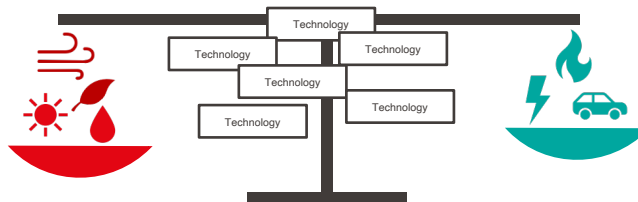
Resources

Costs & Emissions
Annual availability

Technology

Fossils & Renewables
Investments & O&M
Efficiencies & Emissions
Storage

Energy demands



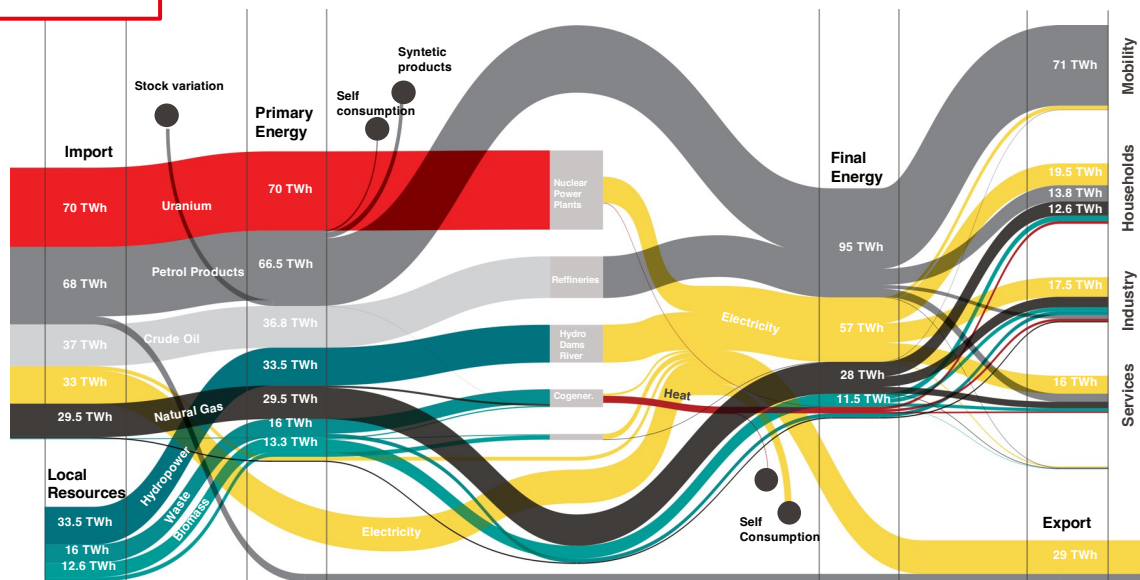
The energy system

Definitions

Primary energy is any extraction of energy products in a useable form from natural sources. This occurs either when natural sources are exploited (for example, in coal mines, crude oil fields, hydro power plants) or in the fabrication of biofuels.

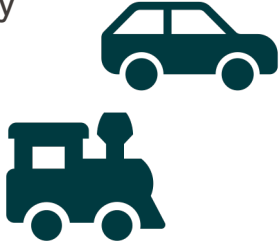
Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.

End-use energy demand, or useful energy, is the last measurable energy flow before the delivery of energy services.



Demands

Mobility



Housing



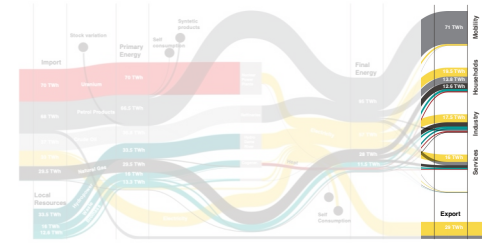
Sectors



Industry
&
Agriculture



Services



Low Temperature



Heat



Process Heat

End-Uses

Electricity



Passenger [pkm/year]

Transportation

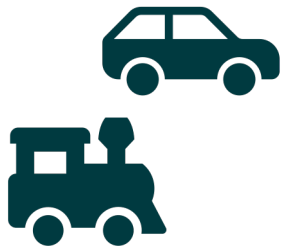


Freight [tkm/year]



Demands

Mobility



14030 p km



3970 t km



41 W



101 W



147 W



Industry



10 W



135 W



523 W



139 W



199 W

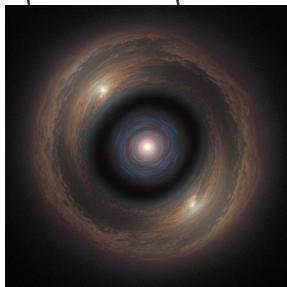
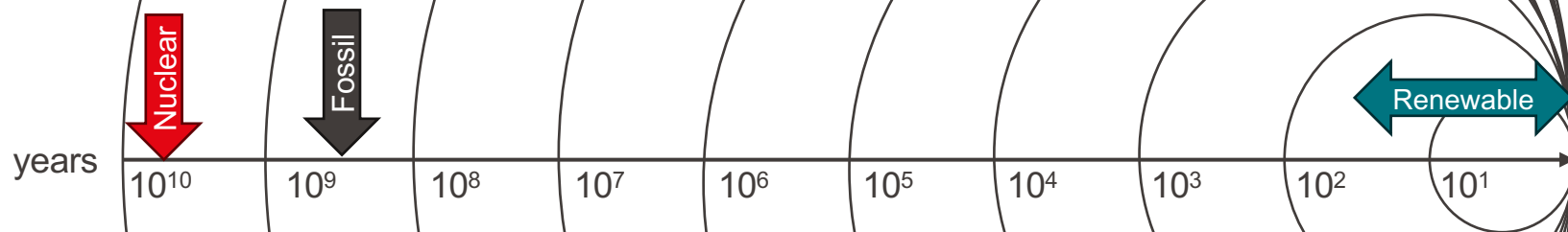


Services



Resources

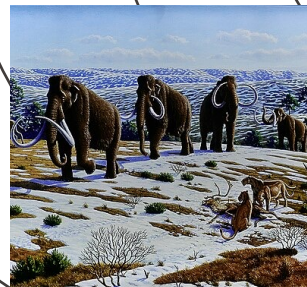
Renewable vs non-renewable



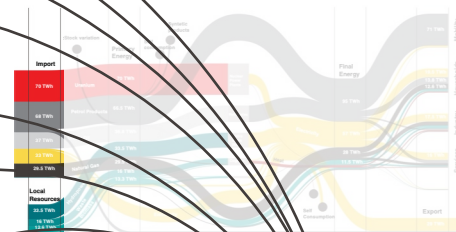
An Impression of the Big Bang Exploding from Nothing.
©Wikimedia commons, Author unknown, 2024



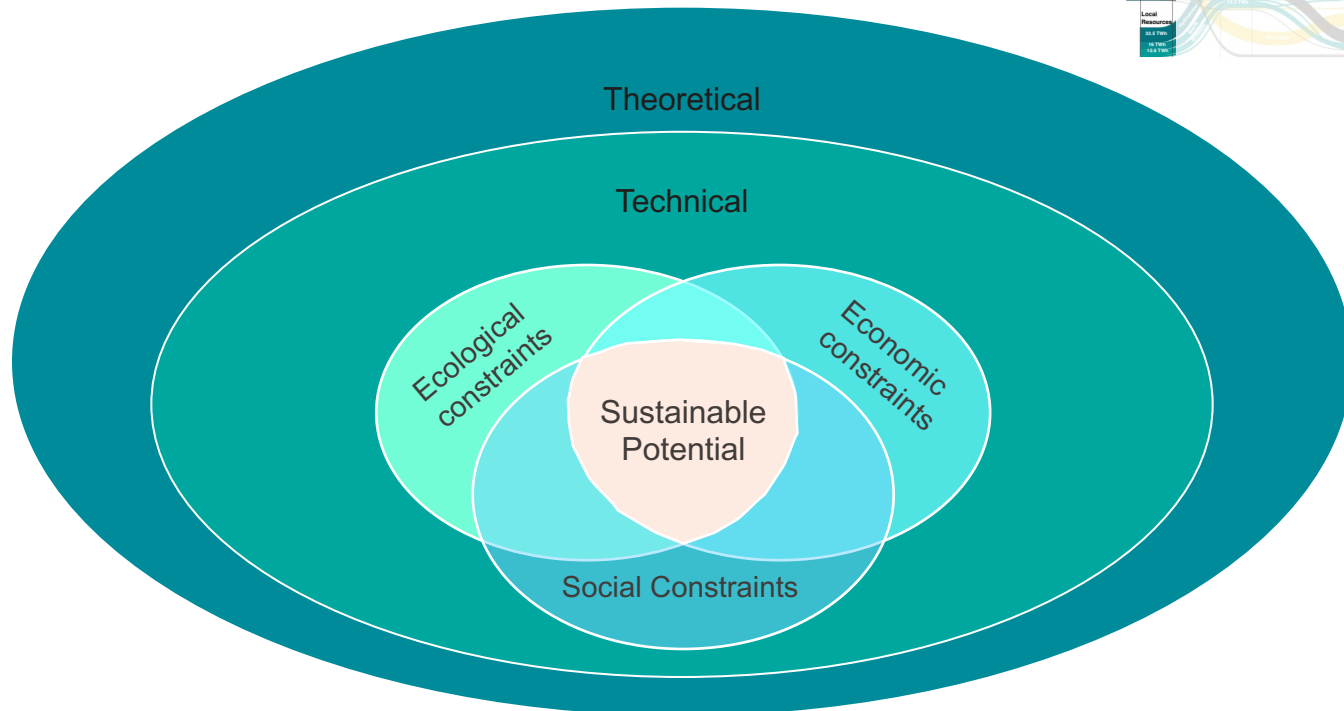
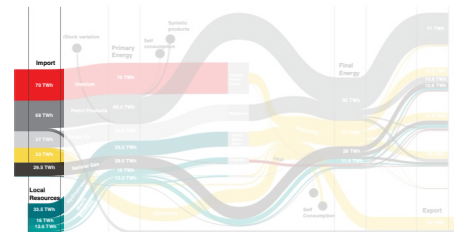
Life restoration of Barosaurus lentus defending itself from a pair of Tyrannosaurus fragilis.
© Wikimedia commons, Fred W. W. 2016



Una representación del hábitat del mammothus primigenius en el pleistoceno.
© Wikimedia commons, JI FilipoC, 2021

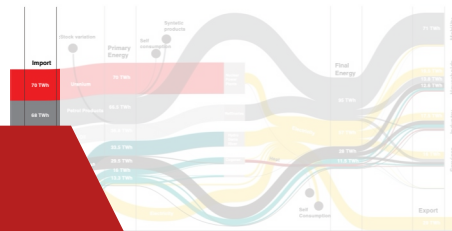
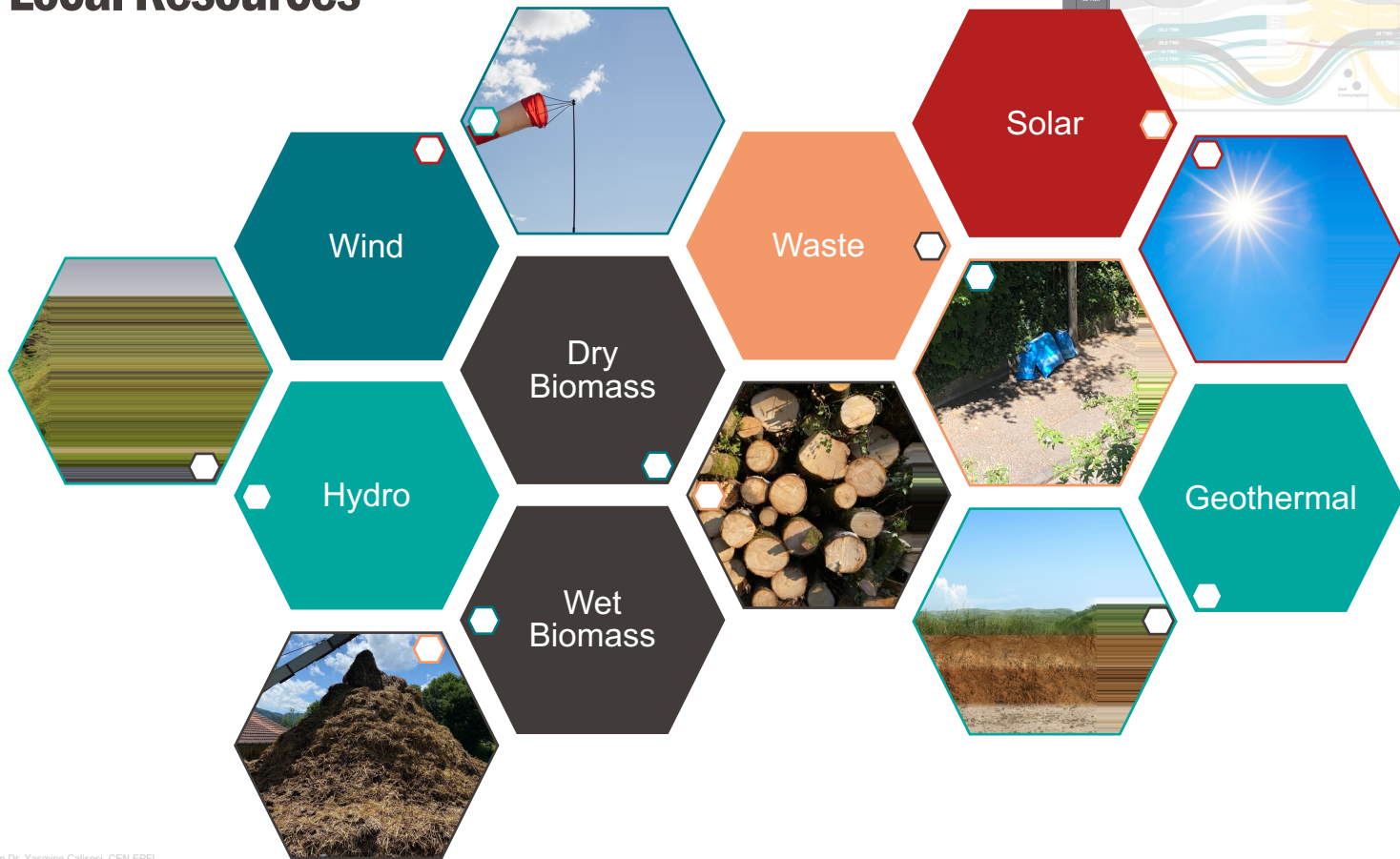


Resources Potentials



Resources

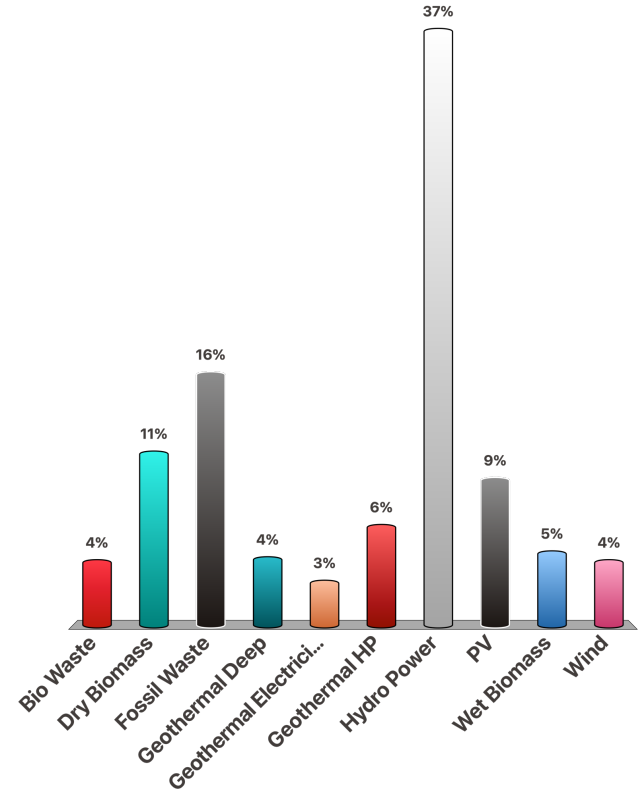
Local Resources



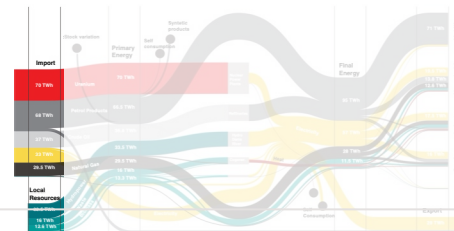
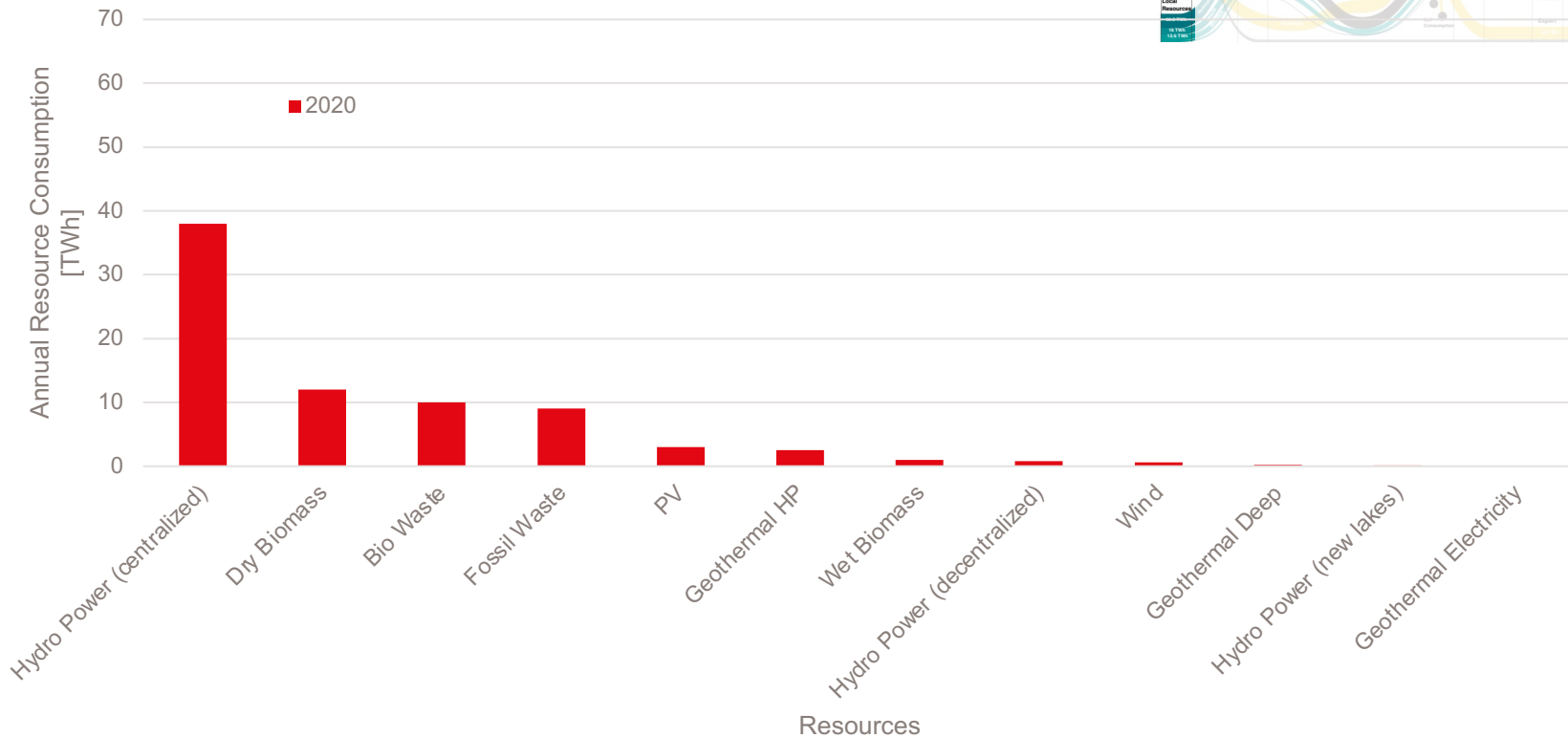
Resources Potential & Used

Class the following resources by
Used Energy in 2020 in Switzerland

- A. Bio Waste
- B. Dry Biomass
- C. Fossil Waste
- D. Geothermal Deep
- E. Geothermal Electricity
- F. Geothermal HP
- G. Hydro Power
- H. PV
- I. Wet Biomass
- J. Wind



Resources Potential & Used



Resources Potential & Used

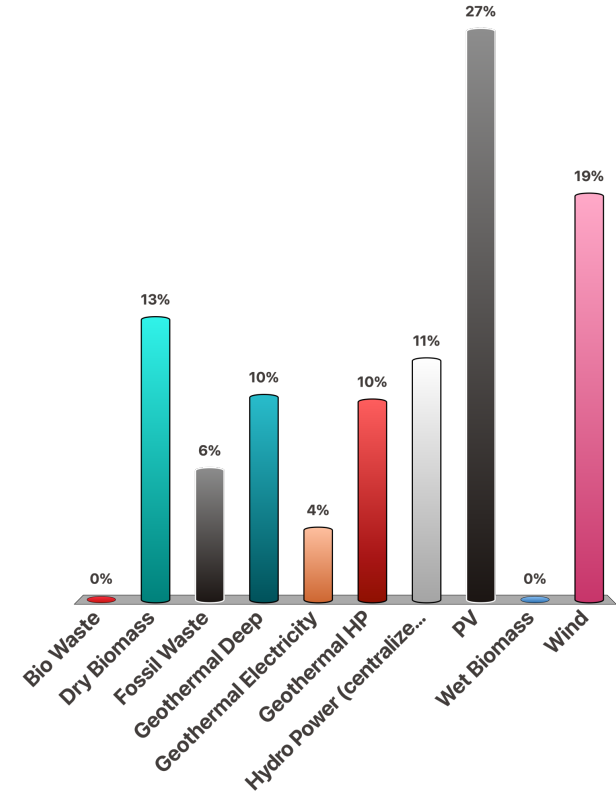
- Class the following resources by
 - Technical Potential in Switzerland
-
- | | | |
|-------------------|-------------------------------|---------------------------|
| ▪ Bio Waste | ▪ Geothermal Electricity | ▪ Hydro Power (new lakes) |
| ▪ Dry Biomass | ▪ Geothermal HP | ▪ PV |
| ▪ Fossil Waste | ▪ Hydro Power (centralized) | ▪ Wet Biomass |
| ▪ Geothermal Deep | ▪ Hydro Power (decentralized) | ▪ Wind |



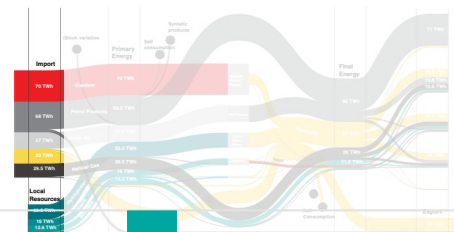
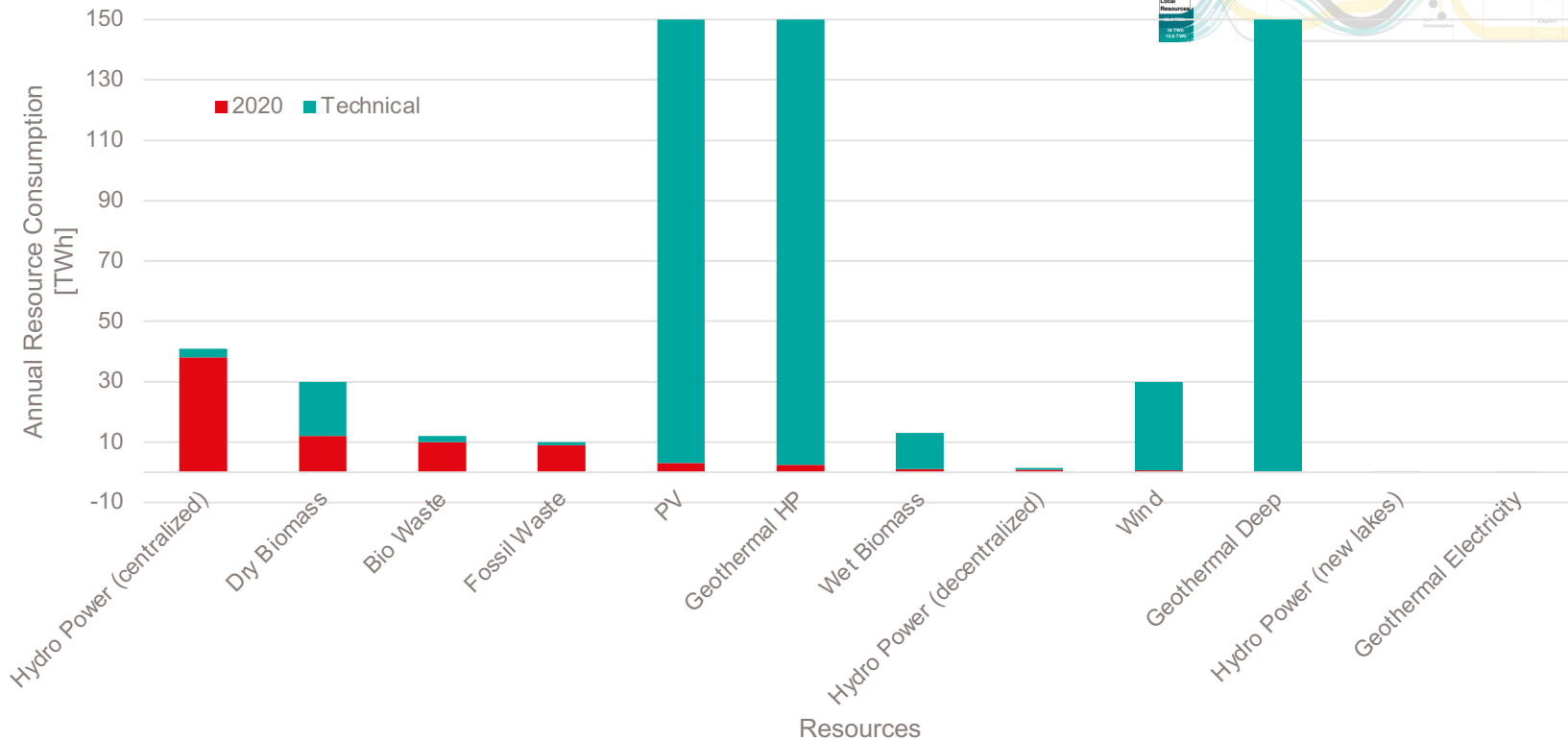
Resources Potential & Used

Class the following resources by
Technical Potential in Switzerland

- A. Bio Waste
- B. Dry Biomass
- C. Fossil Waste
- D. Geothermal Deep
- E. Geothermal Electricity
- F. Geothermal HP
- G. Hydro Power (centralized)
- H. PV
- I. Wet Biomass
- J. Wind



Resources Potential & Used





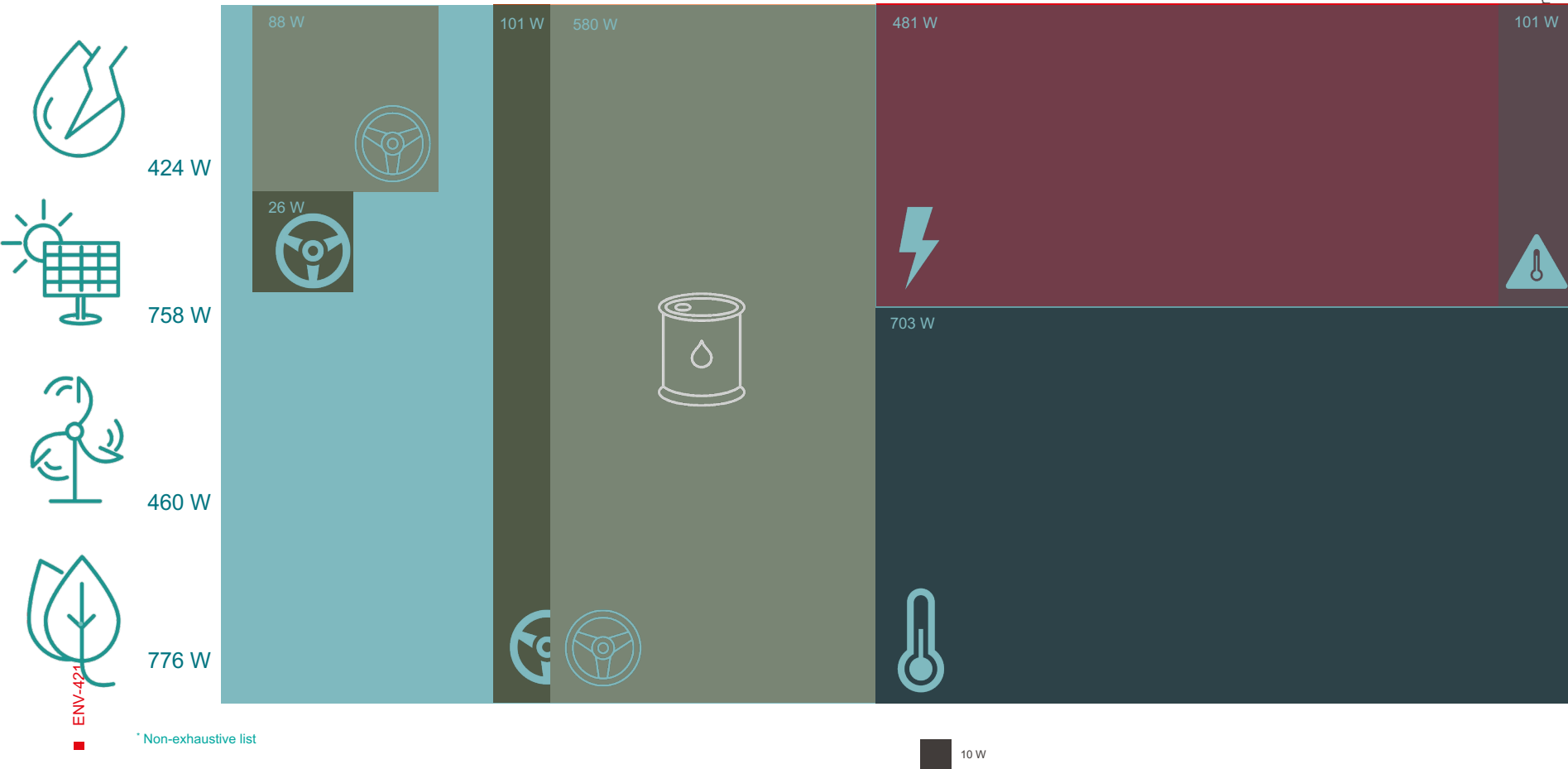
A G E N D A

Introduction to Energy Systems

Energy Balance Fundamentals

Analysis and Evaluation of Energy Systems





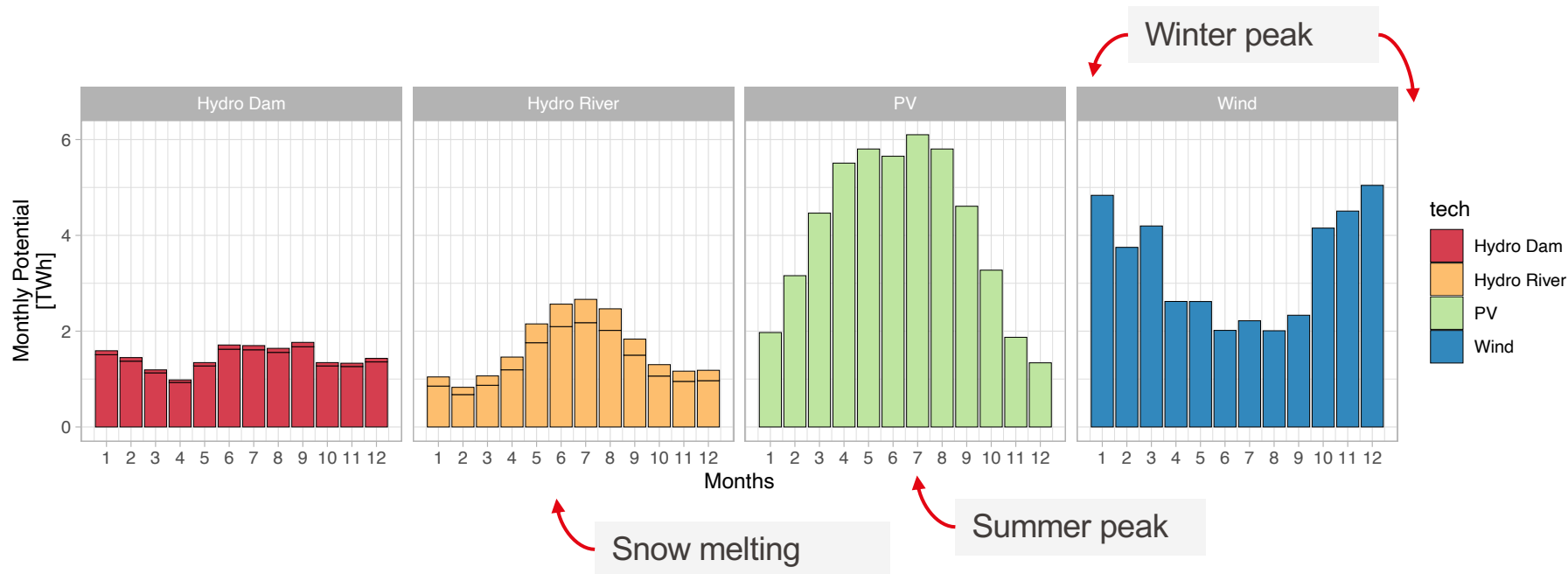
The Systemic Approach

The intermittency Challenge



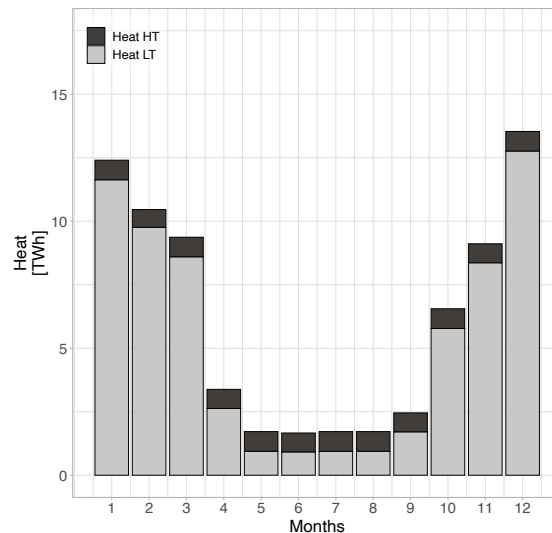
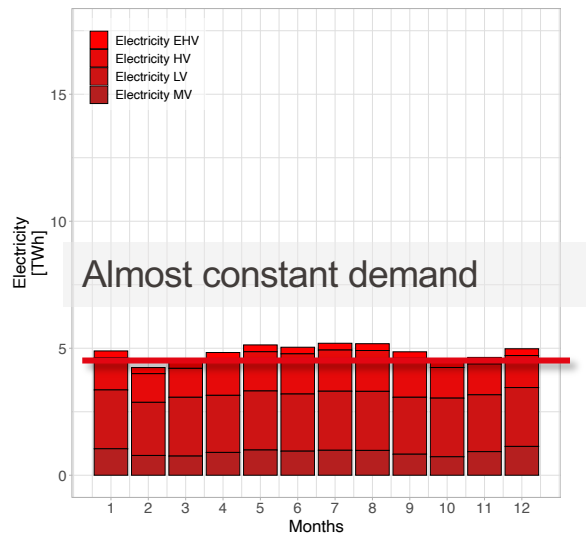
The Systemic approach

Intermittency of Resources

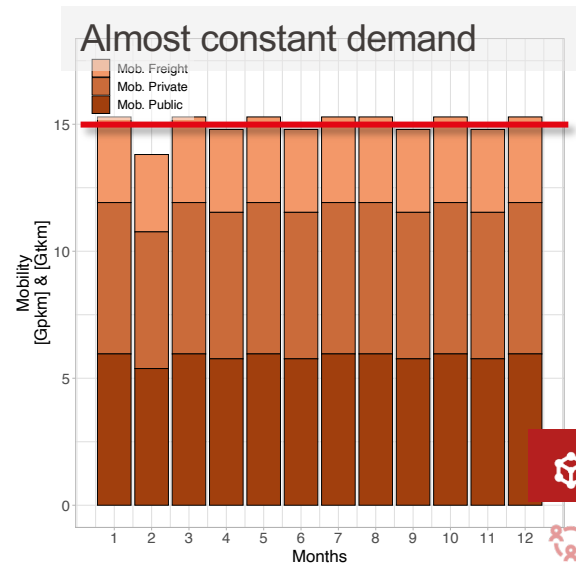


The Systemic approach

Intermittency of demands

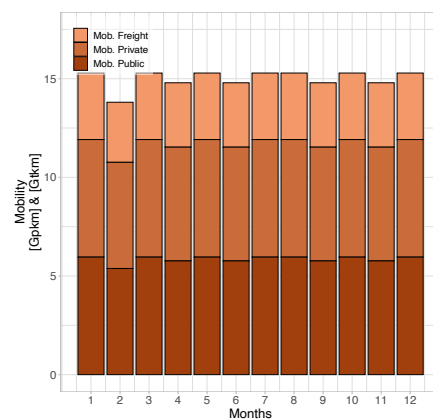
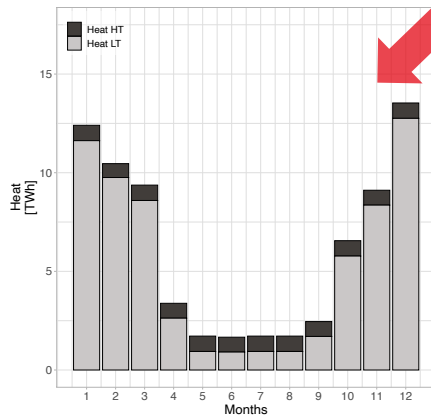
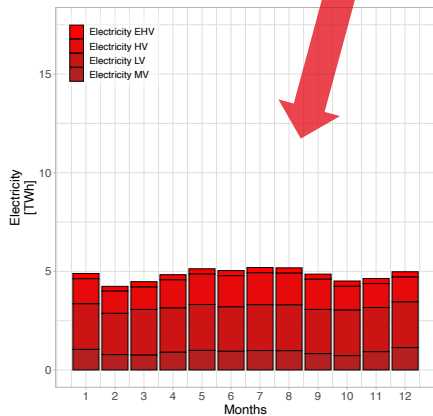
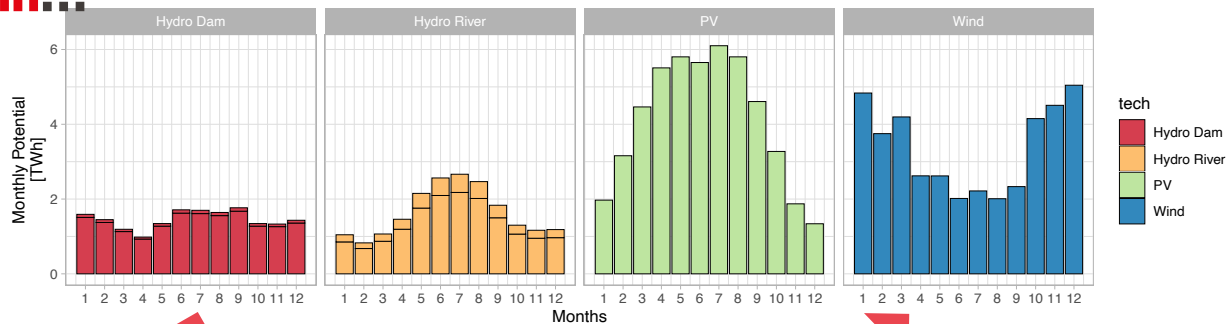


Winter heating

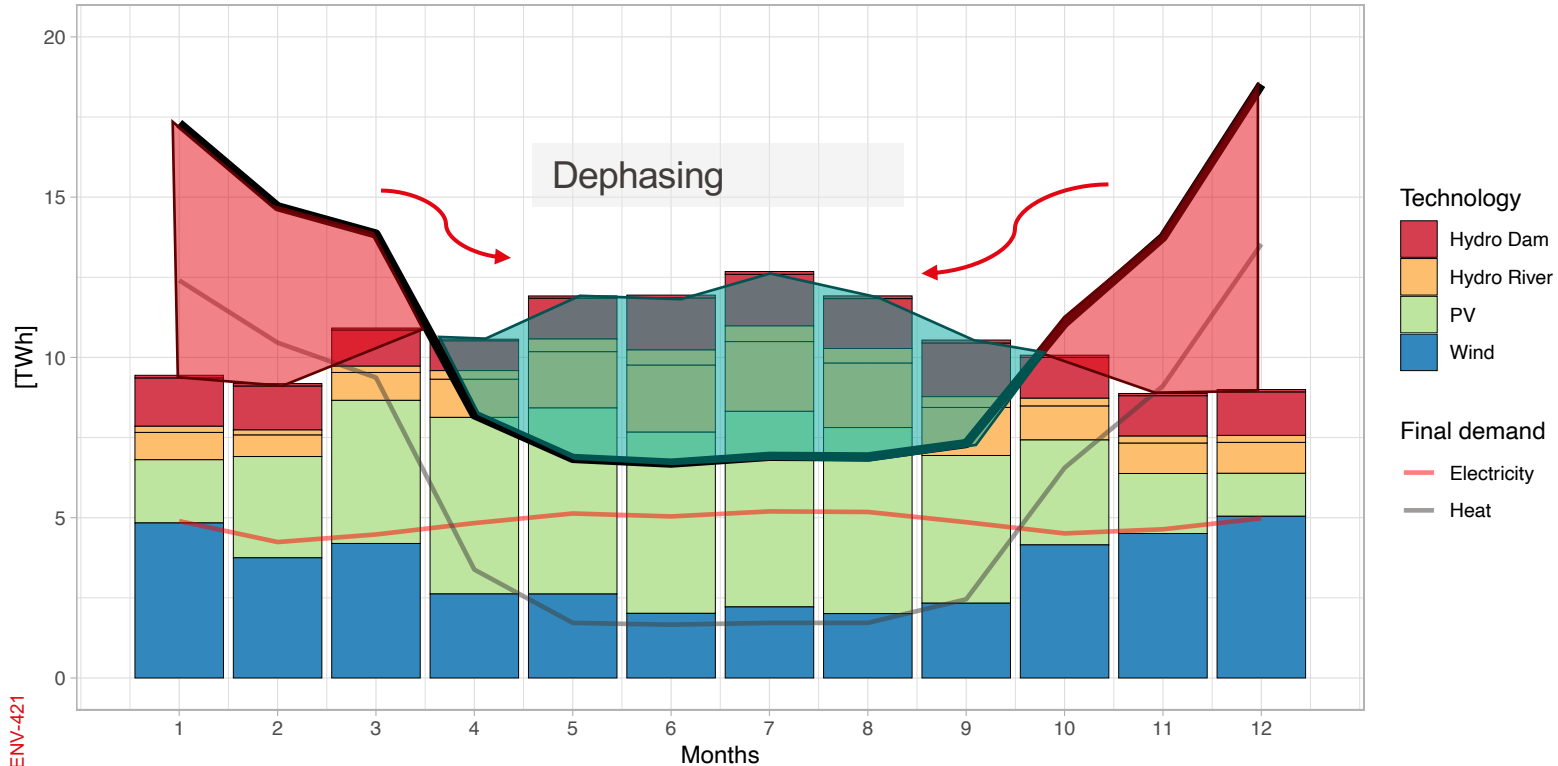


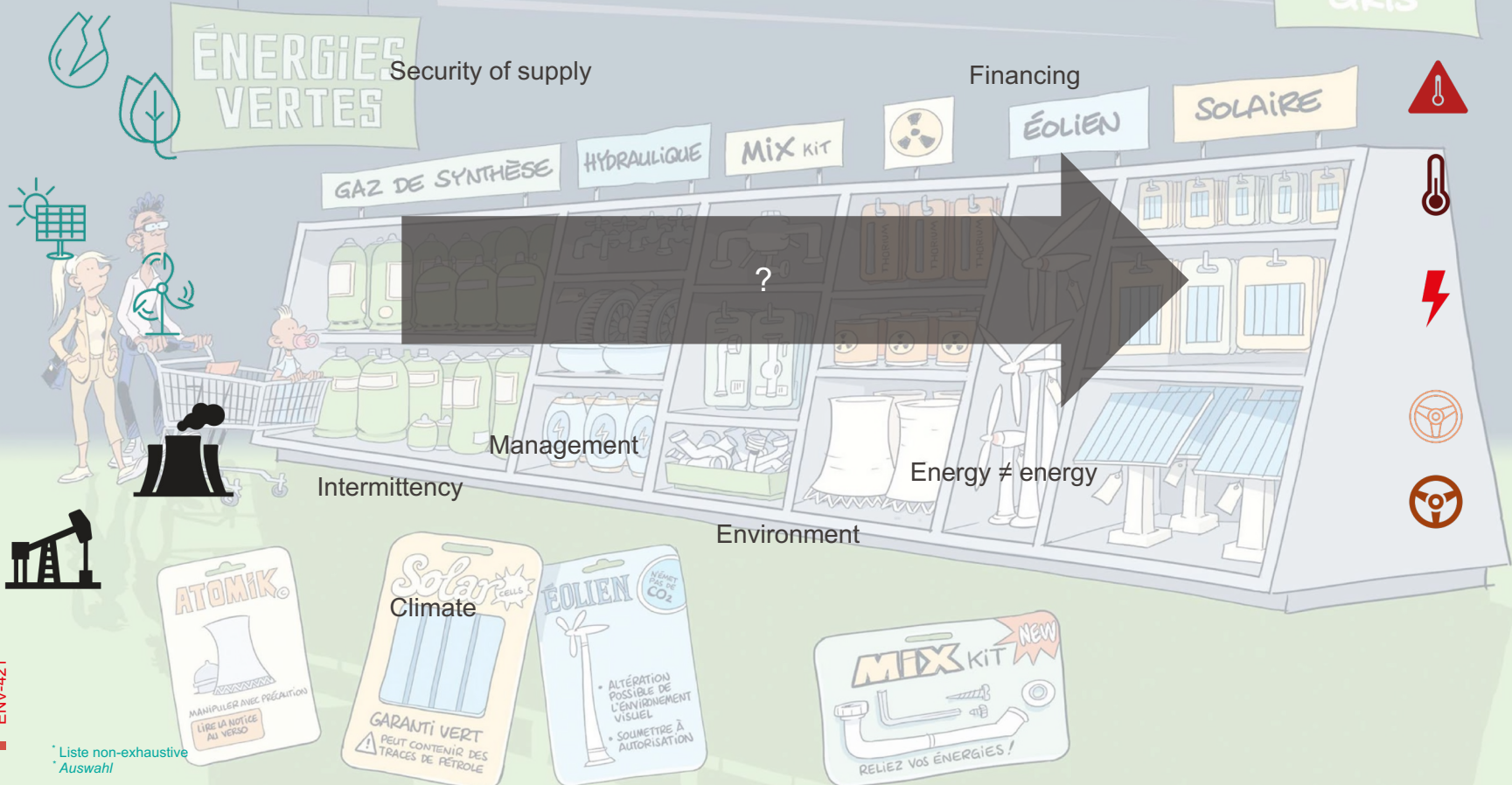
The Systemic approach

A question of equilibrium – again...

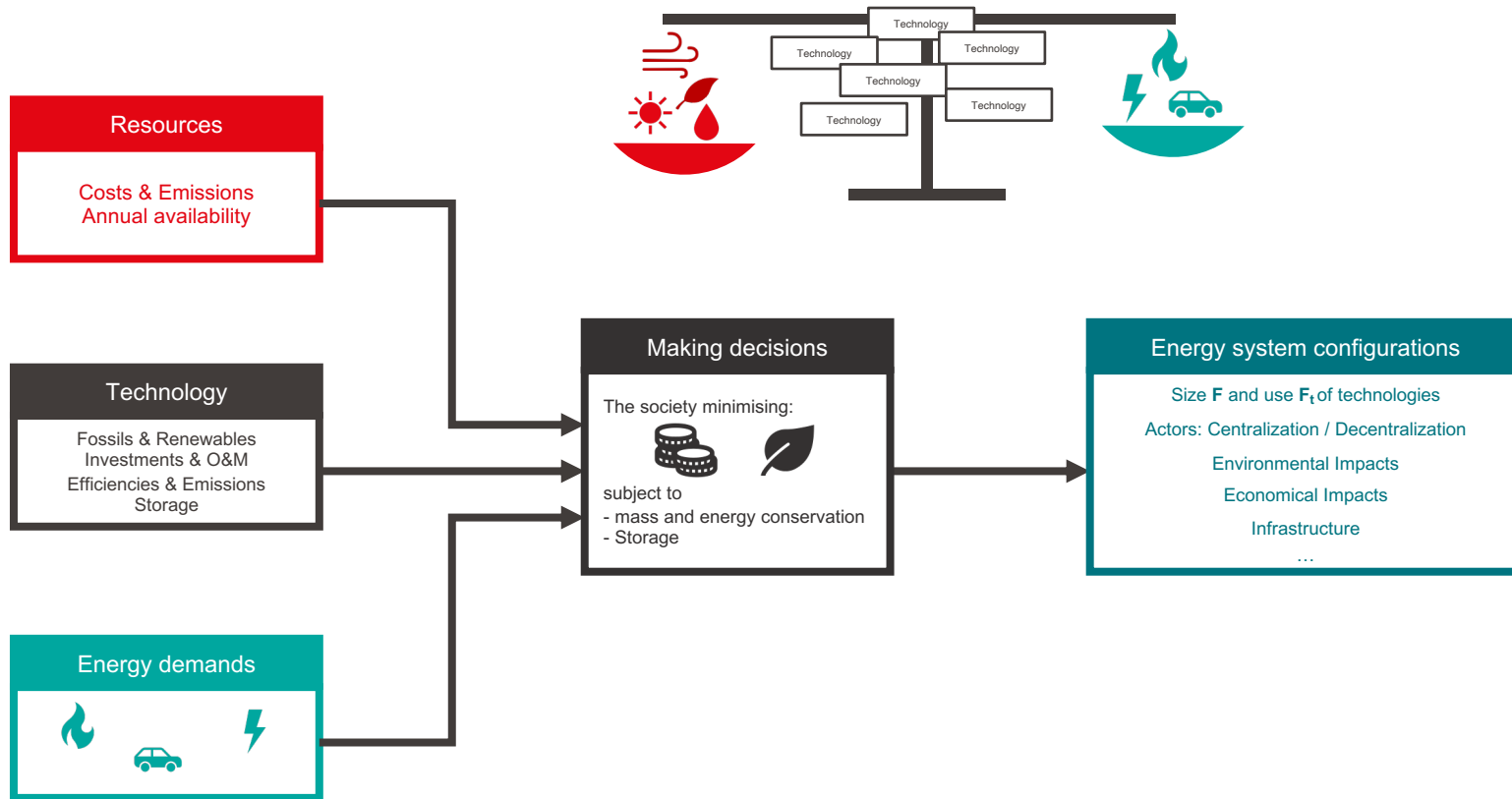


A question of management



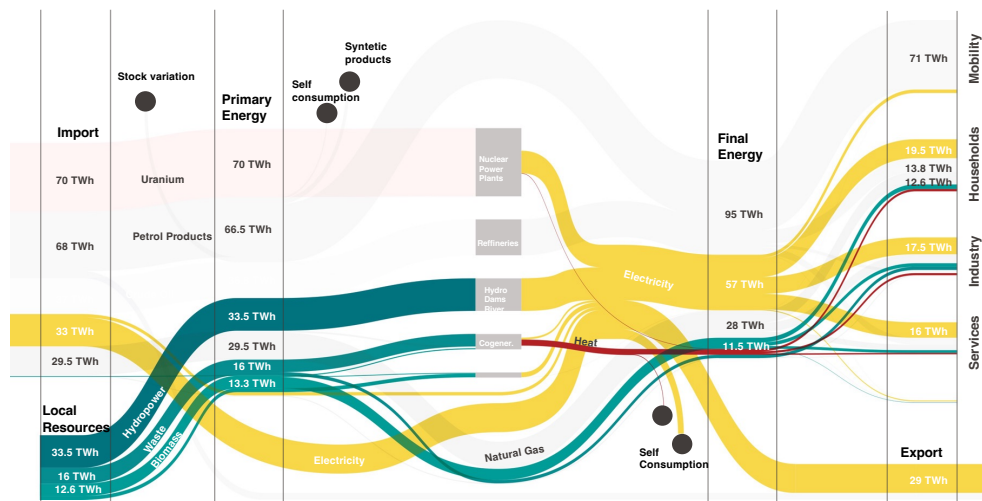


Energy system modeling - EnergyScope



The Swiss Challenge

In the Heart of Europe



Sankey Diagram Global Swiss Energy System Statistic 2022 [63]. Switzerland imports 79 % of its PE, of which 57 % is of fossil origin. The electricity share in the final energy amounts to 30 %: with 33 TWh of electricity import and 29 TWh export due to seasonal intermittency and transit. Local resources are dominated by hydropower, while waste incineration is used in cogeneration units to generate heat and electricity. The remaining renewable energy shares are negligible (1.2 %). Illustration adapted from Sébastien Fasel (Emphase Sàrl) [79].

Strategic Geographic Position



- Bridge of European energy network^[57].
- linking diverse energy systems, including Austria's, France's nuclear energy, Germany's renewable and fossil-based power, and Italy's energy imports from North Africa^[58-60].

Pioneering Renewable Energy Integration



- Historical reliance on hydroelectric power^[63-65]
- play with market fluctuations foundation for expanding renewable energy capacity^[63,66,87].

Decentralized Energy Potential



- Potential for decentralized renewable energy sources, such as photovoltaics, small hydropower, and wind^[64,66,67].
- Existing centralized renewable energy as opportunity for energy management and distribution^[69,70-73].

Economic and Environmental Synergy



- Environmental imperatives and economic goals, aiming for sustainability, efficiency, and reliability^[61,78].
- Imperatives on sustainability for unique landscape and tourism reasons.^[68,70-73, 84-86]





A G E N D A

Introduction to Energy Systems

Energy Balance Fundamentals

Analysis and Evaluation of Energy Systems

The systemic perspective

Conversion – some formulas

- Energy conversion efficiency

$$\eta = \frac{\text{useful Energy}}{\text{required Energy}} = \frac{\text{useful Power}}{\text{required Power}}$$

- Thermal efficiency

$$\eta_{th} = \frac{\text{useful Energy}}{\text{required heat/fuel Energy}} = \frac{\text{useful Power}}{\text{required heat/fuel Power}}$$

- Combination of efficiencies

$$\eta_{tot} = \prod_i \eta_i$$



The systemic perspective

Conversion – some formulas

- Primary Energy

$$E_{primary} = \sum_{r \in Resources} E_r$$

- Secondary Energy

$$E_{secondary} = E_{primary} \cdot \eta_{conversion} = E_{primary} - L_{conversion}$$

- Final Energy

$$E_{Final} = E_{secondary} \cdot \eta_{distribution} = E_{secondary} - L_{distribution}$$

- End-Use Demand

$$E_{demand} = E_{Final} \cdot \eta_{end-uses} = E_{final} - L_{end-use}$$



The systemic perspective

Conversion – some more formulas

Annual perspective

- Conversion efficiency

$$\eta_{conv} = \frac{E_{secondary}}{E_{primary}}$$

- Distribution efficiency

$$\eta_{dist} = \frac{E_{final}}{E_{secondary}}$$

- End-use efficiency

$$\eta_{end-use} = \frac{E_{end-use}}{E_{final}}$$

- Combination of efficiencies

$$\eta_{system} = \eta_{conv} \cdot \eta_{dist} \cdot \eta_{end-use}$$

Seasonality

- Conversion efficiency

$$\eta_{conv}(t) = \frac{E_{secondary}(t)}{E_{primary}(t)}$$

- Distribution efficiency

$$\eta_{dist}(t) = \frac{E_{final}(t)}{E_{secondary}(t)}$$

- End-use efficiency

$$\eta_{end-use}(t) = \frac{E_{end-use}(t)}{E_{final}(t)}$$

- Combination of efficiencies

$$\eta_{system}(t) = \eta_{conv}(t) \cdot \eta_{dist}(t) \cdot \eta_{end-use}(t)$$

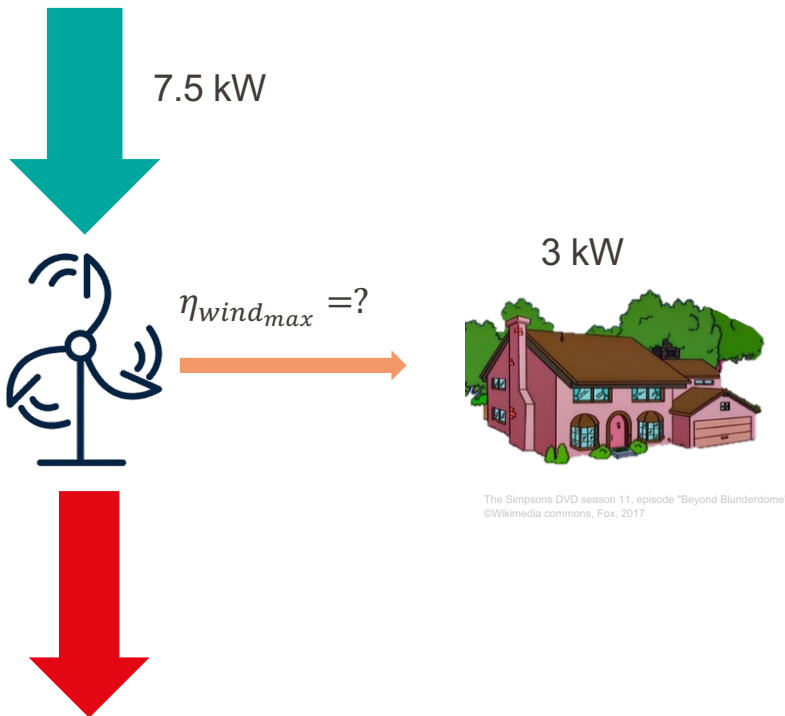


The systemic perspective

Conversion – the Simpsons live intermittently

Case 1: Full Wind

$$\eta_{full-wind} = ?$$

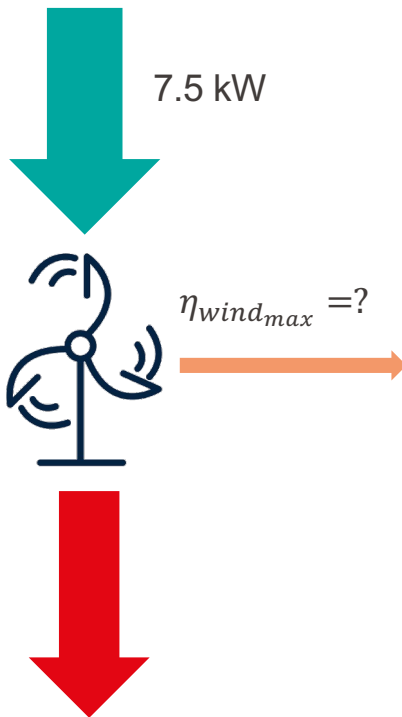
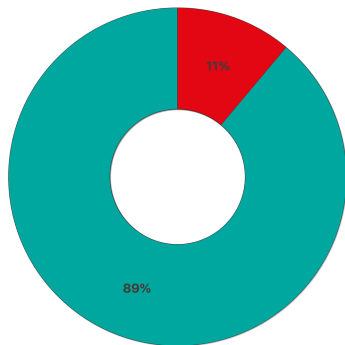


The systemic perspective

Conversion – the Simpsons live intermittently

Case 1: Full Wind

$$\eta_{full-wind} = ?$$



7.5 kW

Calculate the electricity conversion system efficiency $\eta_{full-wind}$ to cover the Simpson's electricity demand

3 kW

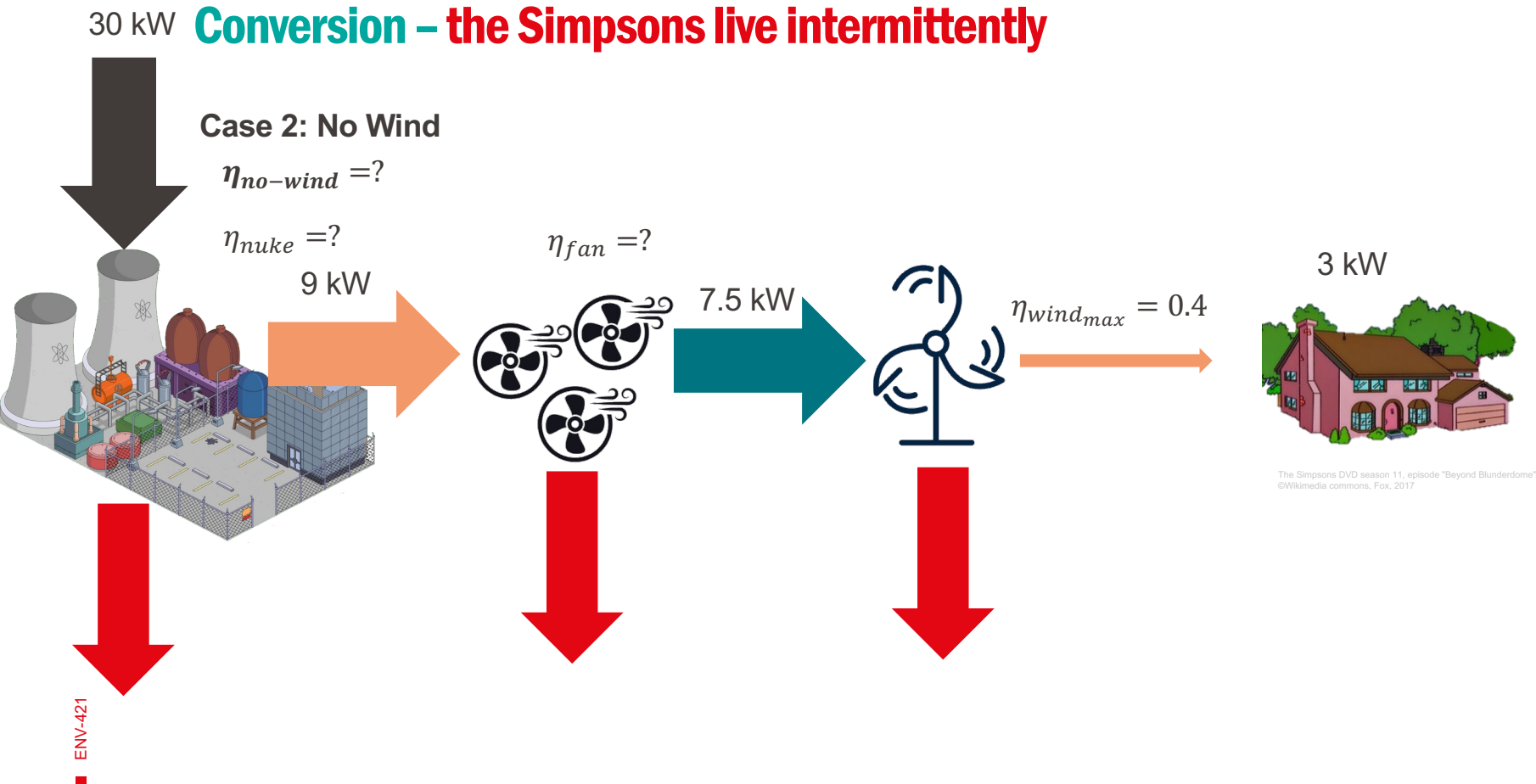


The Simpsons DVD season 11, episode "Beyond Blunderdome"
©Wikimedia commons, Fox, 2017

- A. 2.5%
- B. 40%
- C. 25%
- D. 0.4%

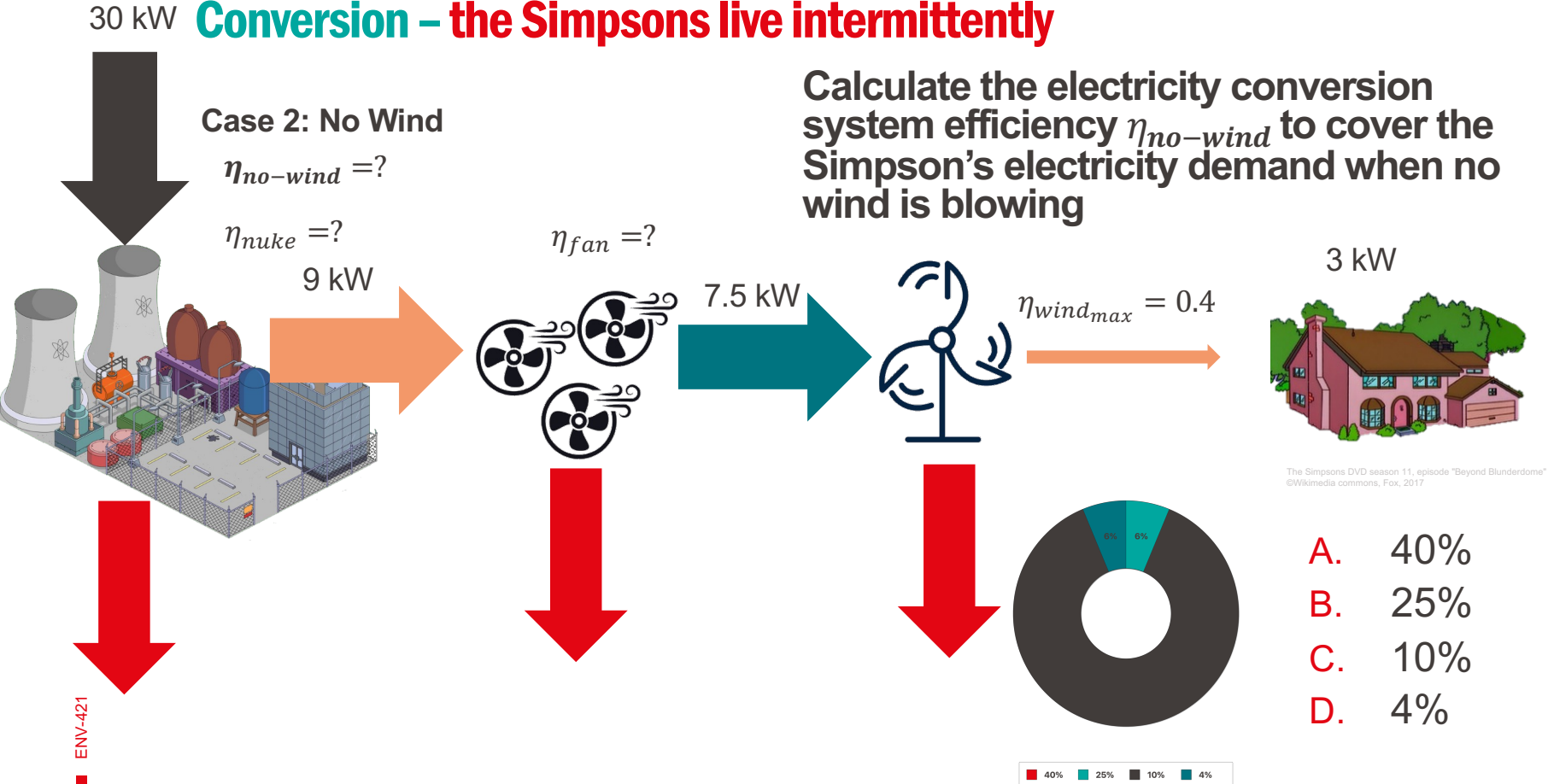
The systemic perspective

Conversion – the Simpsons live intermittently



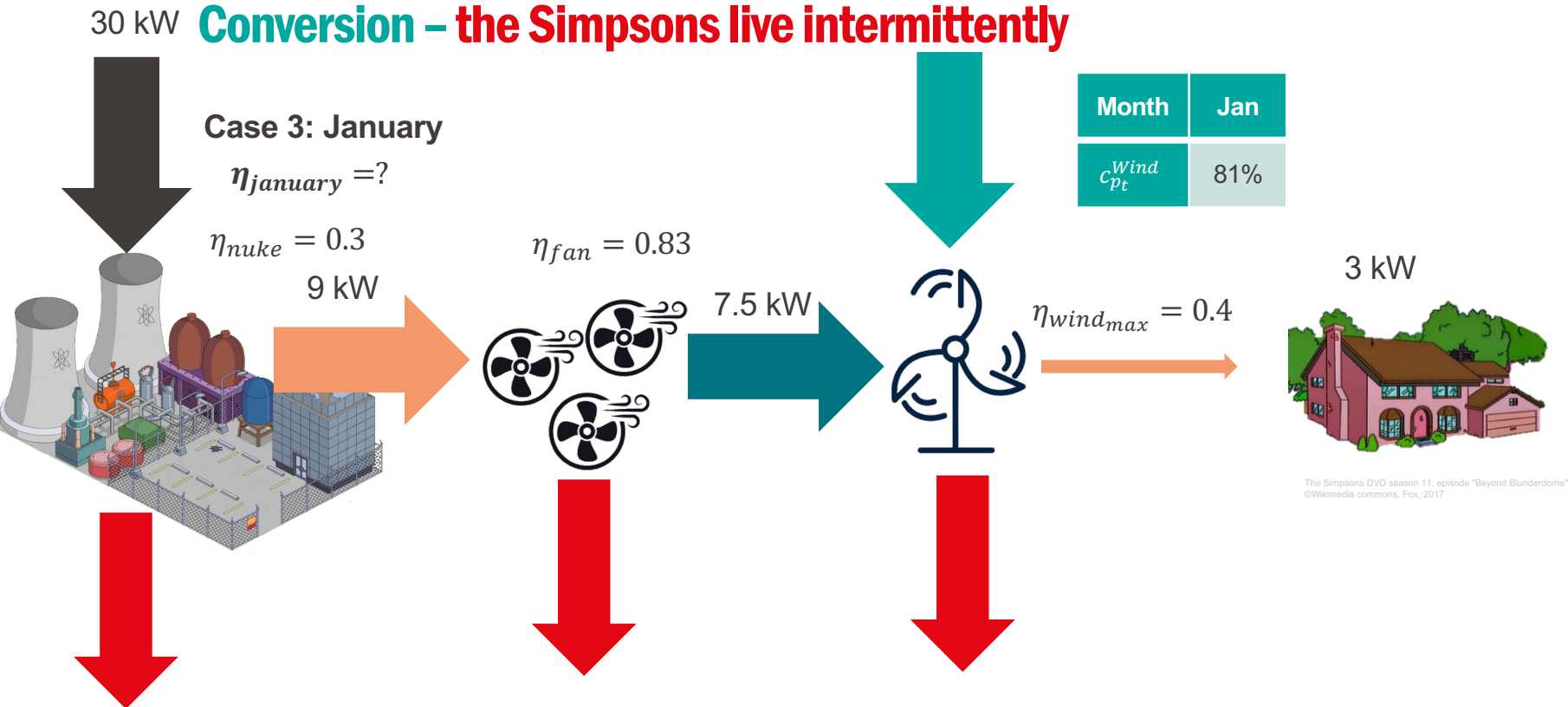
The systemic perspective

Conversion – the Simpsons live intermittently



The systemic perspective

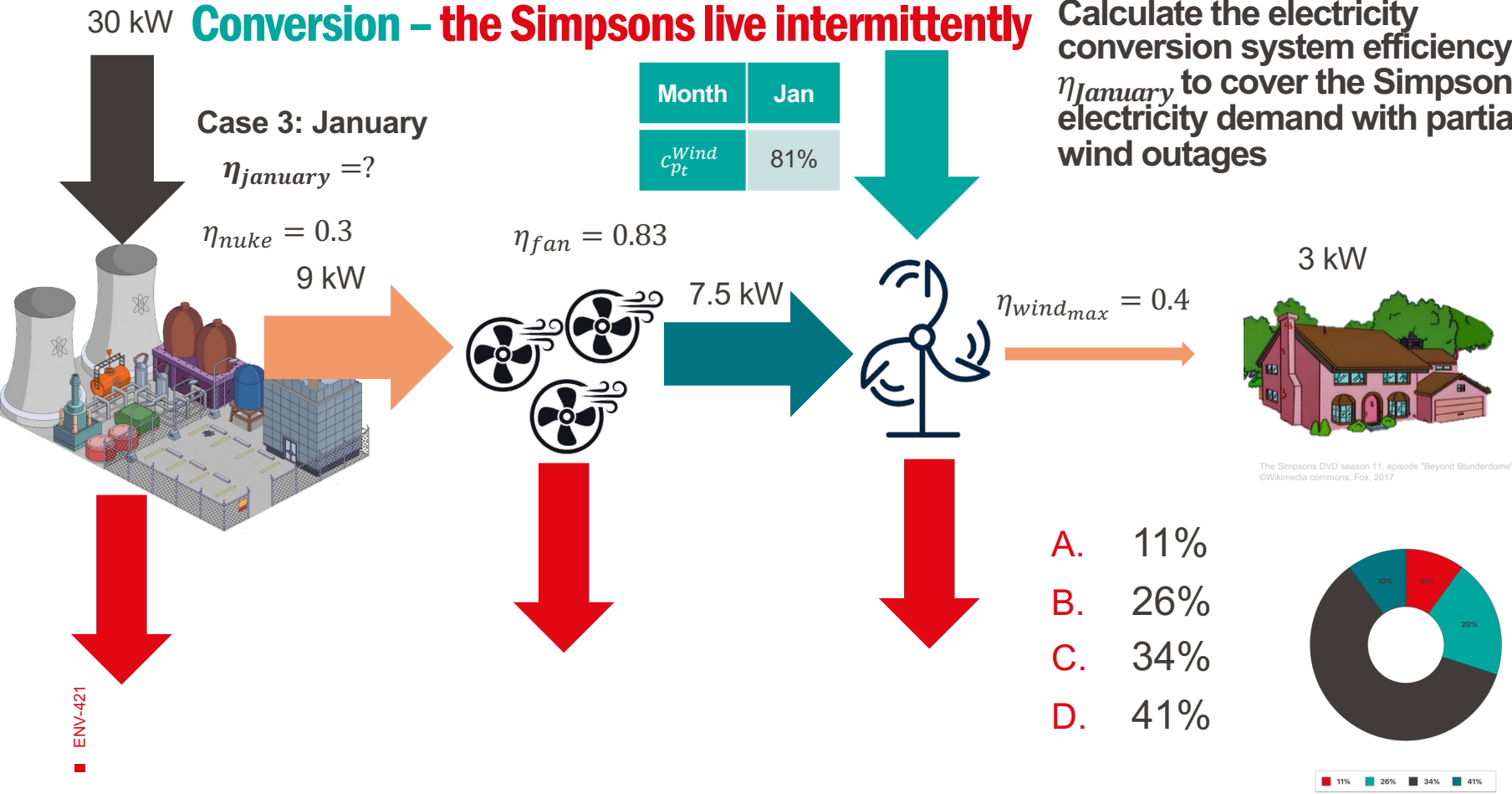
Conversion – the Simpsons live intermittently



The systemic perspective

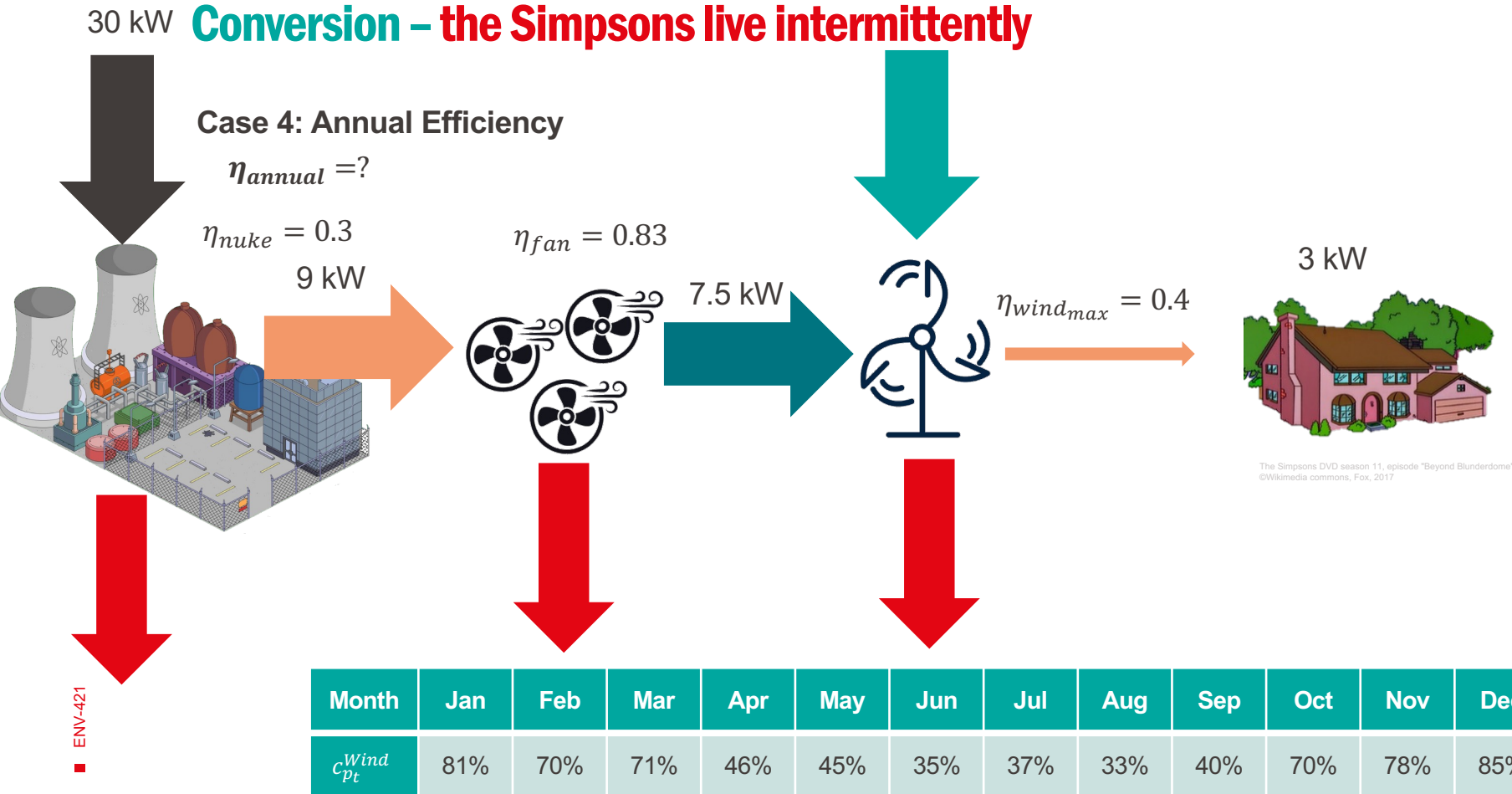
Conversion – the Simpsons live intermittently

Calculate the electricity conversion system efficiency $\eta_{January}$ to cover the Simpson's electricity demand with partial wind outages



The systemic perspective

Conversion – the Simpsons live intermittently



The systemic perspective

Conversion – the Simpsons live intermittently

