Energy planning and EROI

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2022-10-14 ENVT3065

Plan

Introduction

Power and energy

Introduction: an e-bike

- Hints: the size of the battery, and the power of the motor.
- What does the battery store?
  - Some energy measured in joules (J) or watt-hours (Wh): 1Wh = 3600J.
- How fast is the energy delivered?
  - It depends on the power of the motor, measured in watts (W)
- Good to know: an e-bike has a typical battery size of 500Wh, and the power of the motor is 250W.

You want to buy an electric bike. You already decided on the type, the color, etc. How do you decide on the electrical part? What are the typical options you could have?

Power definition

Power = rate of use of Energy = time derivative of Energy

Power = "effort" × "flow"

Examples:

Mechanical power	$=$	Force	$\times$	speed
Mechanical power	$=$	Torque	$\times$	angular velocity
Mechanical power	$\approx$	Pressure[1]	$\times$	flow
Accoustic power	$\approx$	Sound pressure	$\times$	particle velocity
Electrical power	$=$	Electric tension (voltage)	$\times$	current

[1] Actually, pressure × surface

Units of power and energy in energy systems

- Power typically ranges from
  - kW e.g. PV panels
  - to GW e.g. nuclear power plant
- Energy typically ranges from
  - Several kWh: daily production of a residential PV plant, or 1l of oil
  - To thousands of TWh: consumption of a country over a year
  - One ExaJoule (EJ) = 277,78 TWh
  - "The ton of oil equivalent (toe) represents the quantity of energy contained in a ton of crude oil, that is gigajoules 41.868. This unit is used to express and compare energies of different sources. According to the international conventions, one ton of oil equivalent amounts for example in 1 616 kg of coal, 1 069 m3 of gas from Algeria or 954 kg of gasoline. For electricity, 1 toe is worth 11.6 MWh (caution here) ." (from https://www.insee.fr/en/metadonnees/definition/c1355)

Robert and the toaster: https://youtu.be/S4O5voOCqAQ

Renewable energy sources

Definition

- Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed.
  - Sunlight and wind, for example, are such sources that are constantly being replenished. Renewable energy sources are plentiful and all around us.
- Fossil fuels - coal, oil, and gas - on the other hand, are non-renewable resources that take hundreds of millions of years to form. Fossil fuels, when burned to produce energy, cause harmful greenhouse gas emissions, such as carbon dioxide.

Source:
https://www.un.org/en/climatechange/what-is-renewable-energy

Solar energy

Solar energy is the most abundant of all energy resources (. . .).

The rate at which solar energy is intercepted by the Earth is about 10,000 times greater than the rate at which humankind consumes energy.

Solar technologies can deliver heat, natural lighting, electricity, . . .

Electrical energy either through photovoltaic panels or through mirrors that concentrate solar radiation.

(. . .) A significant contribution to the energy mix from direct solar energy is possible for every country.

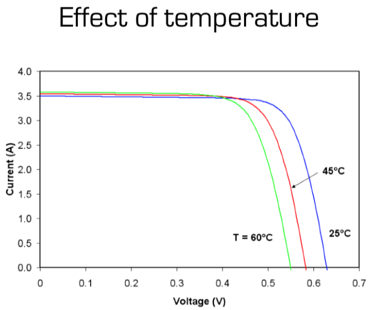
The cost of manufacturing solar panels has plummeted dramatically in the last decade, making them affordable and often the cheapest form of electricity. Solar panels have a lifespan of roughly 30 years, ...

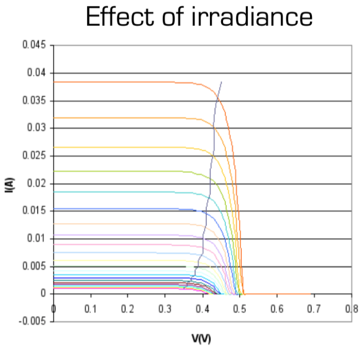
Source:
https://www.un.org/en/climatechange/what-is-renewable-energy

Photovoltaic generation

- A PV cell is composed of semiconductor material. Photons emitted by the sun interact with the semiconducting material in two ways:
  - photons directly transmit energy to electrons and allow them to move into the conduction band.
  - a thermally generated current as in a p-n junction (diode).
- See https://youtu.be/L_q6LRgKpTw

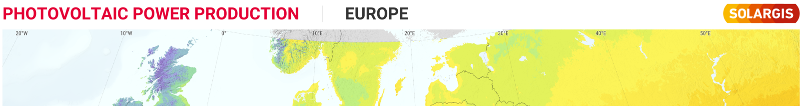
Effect of irradiance and temperature





Sources:

https://en.wikipedia.org/wiki/Theory_of_solar_cells
https://en.wikipedia.org/wiki/Maximum_power_point_tracking



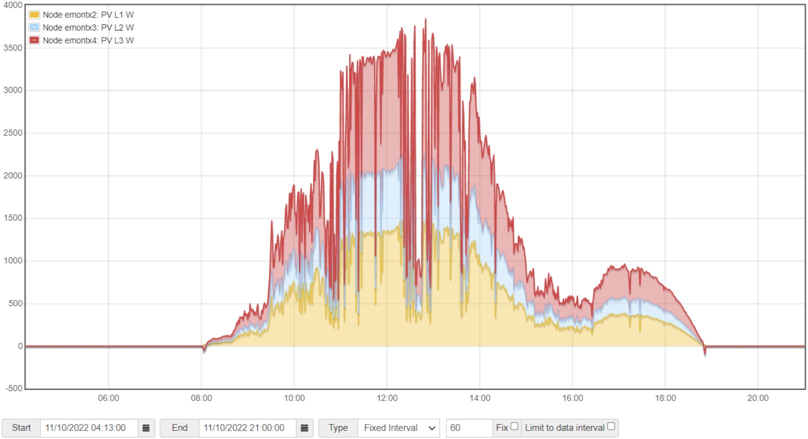
Photovoltaic power production potential

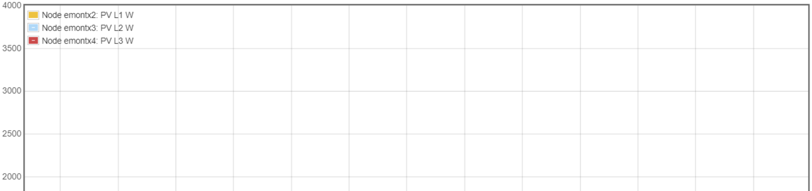
Source: https://solargis.com/maps-and-gis-data/download/europe

How many kWh per kWP in Belgium?

Note: also depends on the orientation of PV panels and other factors

PV variability





Wind energy

Wind energy harnesses the kinetic energy of moving air by using large wind turbines located on land (onshore) or in sea- or freshwater (offshore). Wind energy has been used for millennia, but onshore and offshore wind energy technologies have evolved over the last few years to maximize the electricity produced - with taller turbines and larger rotor diameters.

Though average wind speeds vary considerably by location, the world's technical potential for wind energy exceeds global electricity production, and ample potential exists in most regions of the world to enable significant wind energy deployment.

Many parts of the world have strong wind speeds, but the best locations for generating wind power are sometimes remote ones. Offshore wind power offers tremendous potential.

Wind turbines

- Wind turbines convert the mechanical power of wind into electrical power.
- The power of the wind can be derived from its kinetic energy

Power conversion

Power conversion

Only a fraction of the wind power is harvested by the blades. Actually, the energy harvested is function of the speed of the air that enters the blades, v_u, and speed of the air that leaves the blades, v_d:

$$P_b = \frac{1}{2}\frac{dm}{dt}(v_u^2 - v_d^2)$$

Approximating $\frac{dm}{dt}$ by $\rho A \frac{v_u - v_d}{2}$ and defining the coeffitient λ_w as

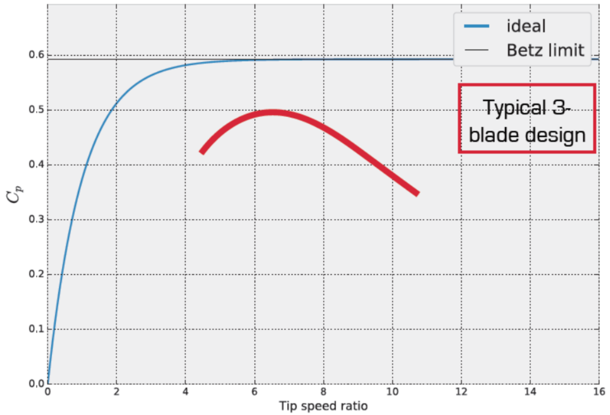
$$\lambda_w = \frac{v_d}{v_u}$$

Then the power harvested by the turbine can be written as

$$P_b = \frac{1}{2}\rho A \frac{v_u - \lambda_w v_u}{2}(v_u^2 - \lambda_w^2 v_u^2)$$

Turbine efficiency

Efficiency of different technologies as a function of tip-speed ratio (TSR)

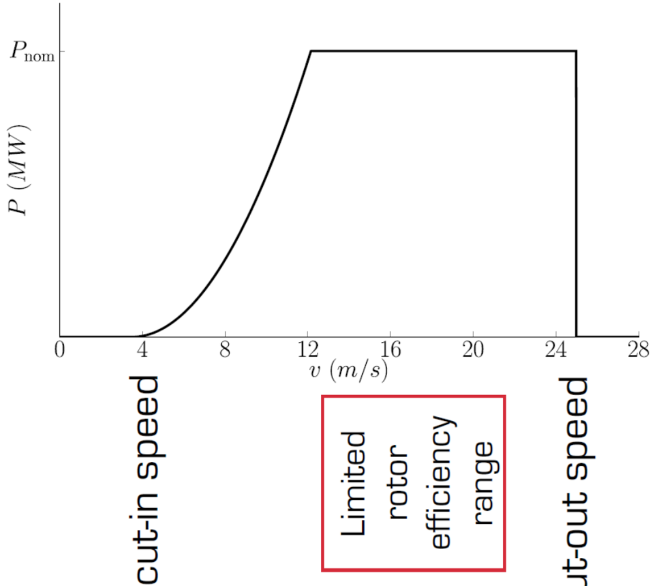


TSR = rotor tip speed / wind speed.

If we define the coefficient

Wind generator operating characteristic

Wind generator operating characteristic



Wind atlas

Source: https://globalwindatlas.info/en

How many MWh per MWP in Belgium?

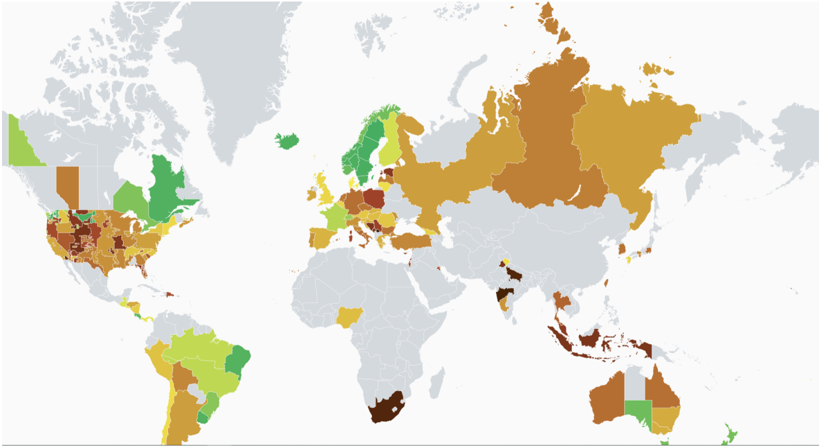
Offshore vs. onshore?

Other sources

Geothermal energy

Hydropower

Bioenergy

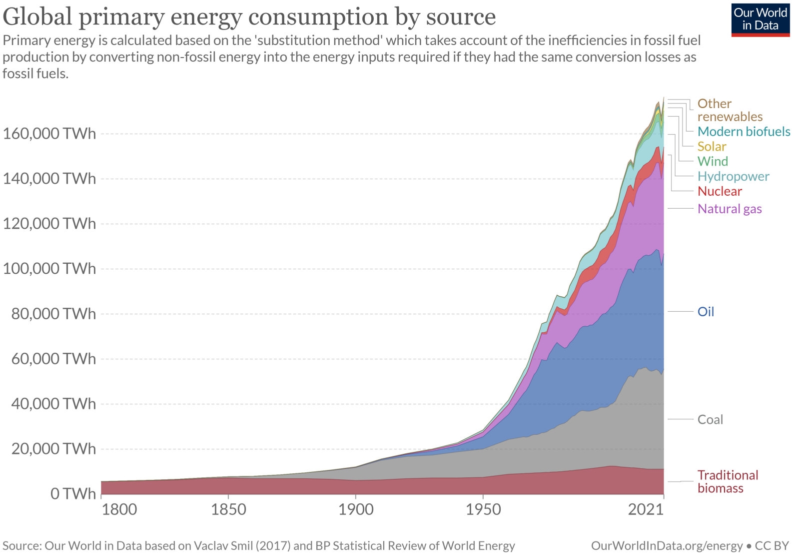


CHG emissions related to electricity consumption

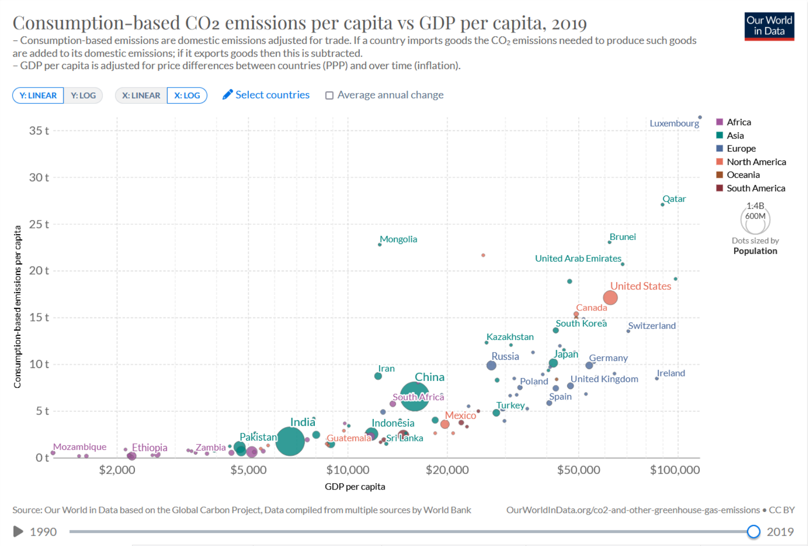
https://app.electricitymaps.com/map

World energy outlook

World energy consumption

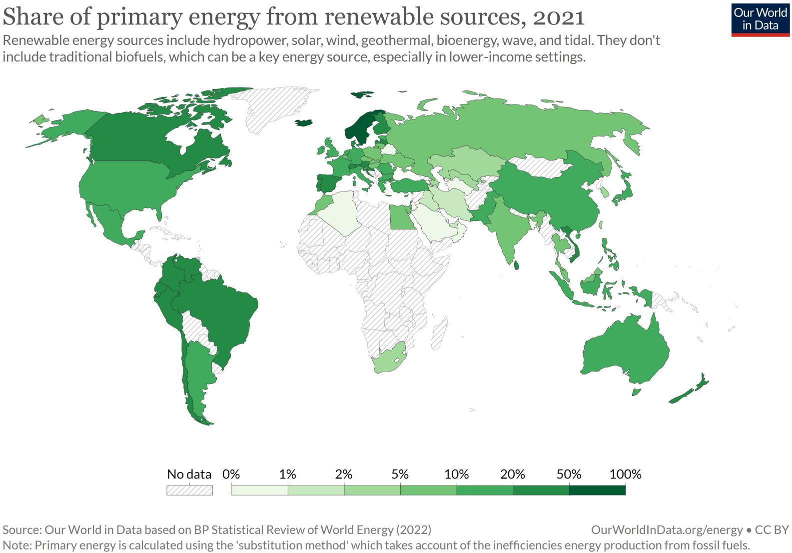


Consumption-based CO2 emissions per capita vs GDP per capita, 2019

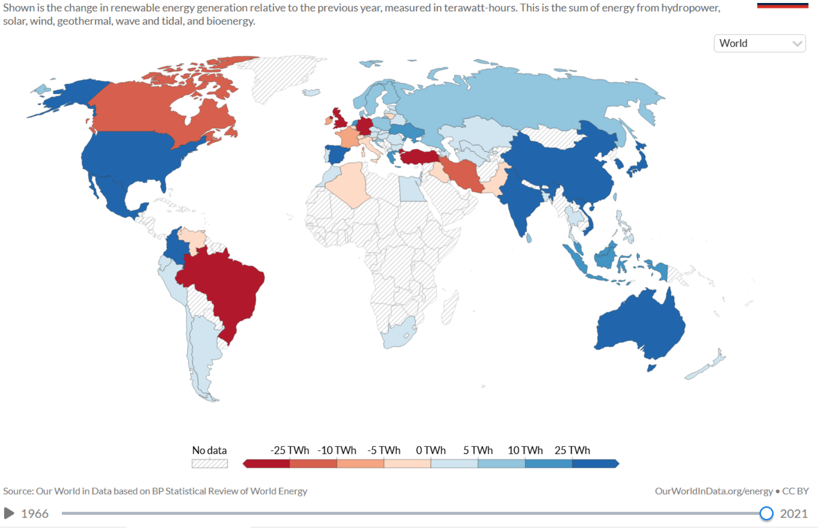


CO2 emissions are directly related to our consumption / production

Share of primary energy from renewable sources, 2021



Annual change in renewable energy generation, 2021



Source:
https://ourworldindata.org/grapher/annual-change-renewables

See also

A great references to dig: is IEA's, World Energy Outlook. The latest one: https://www.iea.org/reports/world-energy-outlook-2021

Energy planning

Definition of energy planning

- Energy planning aims at determining in which types of energy sources, transmission and conversion systems we want to invest to satisfy some needs for
  - Mobility
  - Industry
  - Heating
  - Agriculture
  - Etc.
- The plan should be sustainable and in line with CO2 emission targets

Energy sources

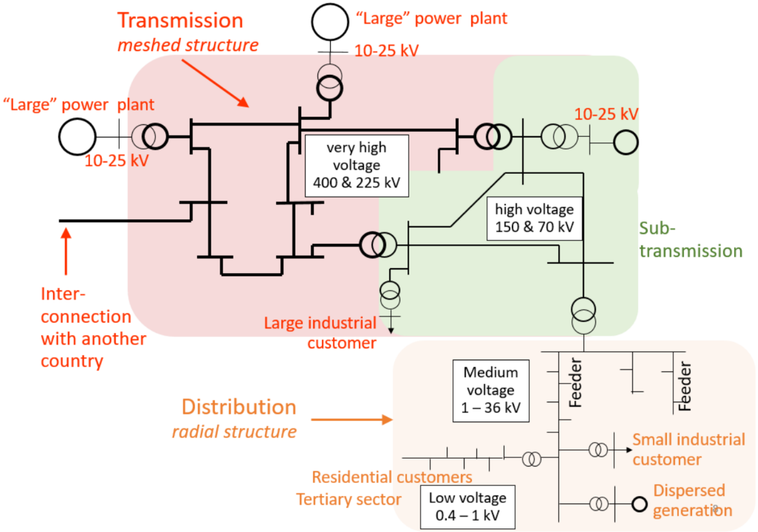
Renewable energy sources

Nuclear energy

Fossil fuels

Transmission and distribution systems - electricity

Structure of electric network (case of Belgium)



Transmission and distribution systems - gas

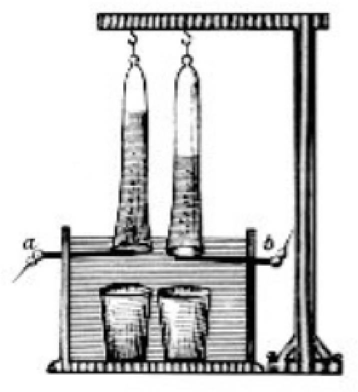
https://www.entsog.eu/sites/default/files/2018-10/ENTSOG_CAP_MAY2015_A0FORMAT.pdf

See also https://www.fluxys.com/en/company/fluxys-belgium/infrastructure

Other networks: oil, wood, etc.

Conversion systems – clean hydrogen

- Hydrogen is necessary for industry, and can be a solution for long term storage of renewable energy (e.g. to cope with seasonal variation of PV generation)
- Hydrogen currently mostly generated from fossiel fuels
  - Need to move towards clean hydrogen. What is it?



Device invented by Johann

What about the efficiency of clean hydrogen production?

Considering the industrial production of hydrogen, and using current best processes for water electrolysis (PEM or alkaline electrolysis)

which have an effective electrical efficiency of 70–80%,[46][47][48]

producing 1 kg of hydrogen (which has a specific energy of 143 MJ/kg) requires 50–55 kWh (180–200 MJ) of electricity.

As of 2022, different analysts predict annual manufacture of equipment by 2030 as 47 GW, 104 GW and 180 GW, respectively.[50]

Source: https://en.m.wikipedia.org/wiki/Electrolysis_of_water

Note on clean hydrogen

- *Green hydrogen has been hailed as a clean energy source for the future.*
- *But the gas itself is invisible – so why are so many colourful descriptions used when referring to it?*
    - *It all comes down to the way it is produced. Hydrogen emits only water when burned. But creating it can be carbon intensive.*
    - *So various ways to lessen this impact have been developed – and scientists assign colours to the different types to distinguish between them.*
- *Depending on production methods, hydrogen can be grey, blue or green – and sometimes even pink, yellow or turquoise – although naming conventions can vary across countries and over time.*
- *But green hydrogen is the only type produced in a climate-neutral manner, meaning it could play a vital role in global efforts to reduce emissions to net zero by 2050 .*

Source: https://www.weforum.org/agenda/2021/07/clean-energy-

Conversion systems –Synthetic fuels

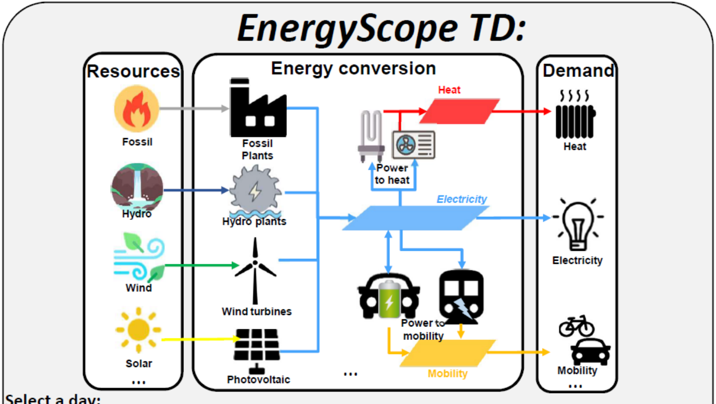
Energy planning is a very complex problem

- Energy impacts all aspects of life
- There is much uncertainty on technologies, efficiencies, availability of resources
- Networks must be built to transmit energy in various forms
- We must work on the demand side as well
- We inherit from the current situation
- State budgets are limited
- Transition should be fast
- Many actors make decisions => huge need for coordination
- . . . There is no easy solution

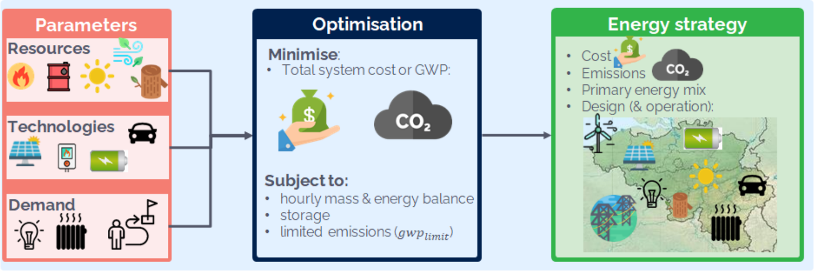
The energy scope model

The EnergyScope project is an open-source whole-energy system for regional energy system. The model optimises the design and hourly operation over a year for a target year.

EnergyScope is mainly developped by EPFL (Switzerland) and UCLouvain (Belgium). See Releases section for acknowledgment, versions and publications.



The planning problem is modeled as a large linear optimisation problem



Overview of the LP modeling framework

Source: https://energyscope-td.readthedocs.io/en/master/sections/Model%20formulation.html

What is an optimisation problem?

Mathematical **programming** is a field of applied mathematics that deals with solving optimization problems.

It provides a framework and solution methods for computing the decisions of an optimization problem, given an *objective function to minimize or maximize* and *constraints* on the *decision variables* .

Mathematical programming relies on a model of the problem.

There is a large variety of mathematical programming problem types, depending on the characteristics of the objective function and of the constraints, and the restrictions that apply to variables.

Linear program, mathematical formulation

If the objective is linear and the constraints are linear, we talk about linear programming (LP) or linear optimization.

These problems are nowadays easy to solve, even for large problems (millions of decision variables), with standard computers.

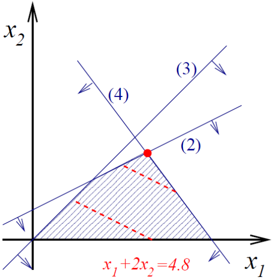
LP in standard form

$$\begin{aligned} \min\ & c^T x \\ \text{s.t. } & Ax = b \\ & x \in \mathbb{R}^n_+ \end{aligned}$$

Graphic representation

Graphic representation

$$\max\ x_1 + 2x_2 \quad (1)$$
$$-x_1 + 2x_2 \leq 1 \quad (2)$$
$$-x_1 + x_2 \leq 0 \quad (3)$$
$$4x_1 + 3x_2 \leq 12 \quad (4)$$
$$x_1,\ x_2 \geq 0 \quad (5)$$



Details of the energy scope model

- satisfy the system end-use demand (EUD) instead of final energy consumption
  - The system end-use demand comprises electricity, heat, transport, and non-energy demands. For instance, passenger mobility is defined in passenger kilometers per year rather than in a certain amount of gasoline to fuel cars or electricity to power trains;
- optimizing the system design and operation by minimizing its overall cost;
- using an hourly resolution which makes the model suitable for analyzing the integration of intermittent renewable energy resources and storage;
- modeling the country as a single node where transmissions constraints within the country are not considered
- For details, see https://energyscope-td.readthedocs.io/en/master/sections/Model%20formulation.html

Energy planning and EROI

Summary of

Dumas, Jonathan, Antoine Dubois, Paolo Thiran, Pierre Jacques, Francesco Contino , Bertrand Cornélusse, and Gauthier Limpens . “The energy return on investment of whole energy systems : application to Belgium .“ *arXiv _ _ preprint _* arXiv:2205.06727_ (2022). To appear in *Biophysical Economics and Sustainability* .

Motivation

Planning the defossilization of energy systems while maintaining access to abundant primary energy resources is a nontrivial multi-objective problem encompassing economic, technical, environmental, and social aspects.

However, most long-term policies consider the cost of the system as the leading indicator in the energy system models to decrease the carbon footprint.

What is the EROI: Energy return on energy invested

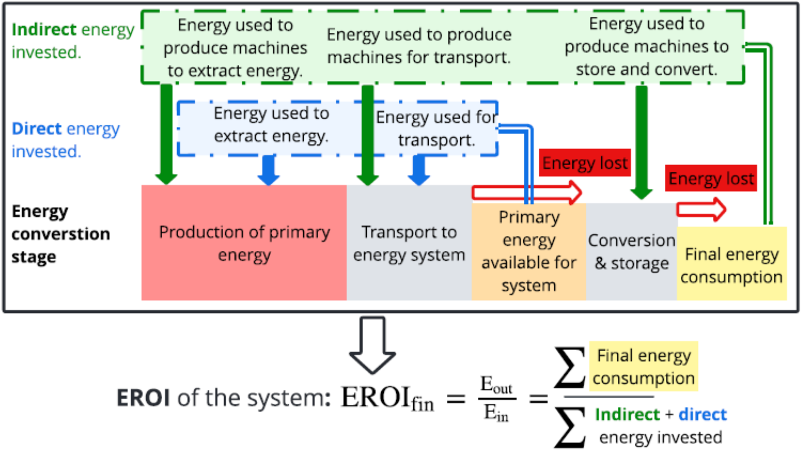


Fig. 2: The energy cascade illustrates the EROI of the system at the final stage ($\mathrm{EROI}_{\mathrm{fin}}$), considered in this study, with the direct and indirect energy invested at each step of the energy conversion required to produce final energy and satisfy the final energy consumption. This Figure was adapted from Brockway et al (2019).

Comments

- The lower the EROI of an energy source, the more input energy is required to produce the output energy, which results in less net energy available for consumption.
- The literature about EROI focuses mainly on three main fields of research:
  - (1) the link between EROI and societal well-being;
  - (2) estimation of the EROI of an energy resource or technology;
  - (3) estimation of the EROI at the level of an economy or a society.

(1) Link between EROI and societal well-being

The estimated societal EROI is correlated with the **Human Development Index** (HDI), which is a standard living indicator.

However, for a few countries with a high level of development, HDI above 0.75, there is a saturation point where increasing the EROI above 20 is not associated with further improvement in society.

In addition, the relationship between EROI and HDI is non-linear as the HDI increases less and less rapidly with societal EROI.

(2) Estimation of the EROI of an energy resource or technology

- The characteristics of the primary energy sources, including the EROI of each fuel, are investigated by Hall et al. [7].
- They conclude that:
  - (i) the EROI of critical fuels, such as oil and gas, is declining;
  - (ii) most renewable and non-conventional energy alternatives have substantially lower EROI values than traditional conventional fossil fuels.
- Another more recent study [8] estimates the EROI of fossil fuels at both primary and final energy stages. However, their results suggest that the current EROIoffossil fuels may not differ from the EROI of renewables, which illustrates the difficulty of adequately assessing the EROI of resources or technologies.

References relate to « Dumas, Jonathan, Antoine Dubois, Paolo Thiran, Pierre Jacques, Francesco Contino, Bertrand Cornélusse, and Gauthier Limpens. "The energy return on investment of whole energy systems: application to Belgium." *arXiv preprint arXiv:2205.06727* (2022). To appear in *Biophysical Economics*

(3) The estimation of the EROI at the level of an economy or a society

This is precisely the topic of the paper. Why?

It is not relevant to compare the EROI of renewable resources or technologies independently. For instance, solar and wind energies are intermittent and stochastic. Gas and nuclear power plants are adjustable and can meet fluctuating demand. Thus, comparing the EROI of solar vs. nuclear without considering storage systems and other assets to balance the system is not pertinent.

Second, a whole energy system comprises several sectors (mobility, heat, electricity, industry) that use several technologies and resources that can be imported or extracted. These resources are transported, stored, and converted by energy conversion technologies to supply end-use demands such as electricity, transport, heating, and the production of goods. Assessing an energy system as a whole opens the opportunity for the full deployment of synergies and generates unexpected results [15]. Thus, the EROI of the system cannot be the sum of the EROI of each of its components.

Results

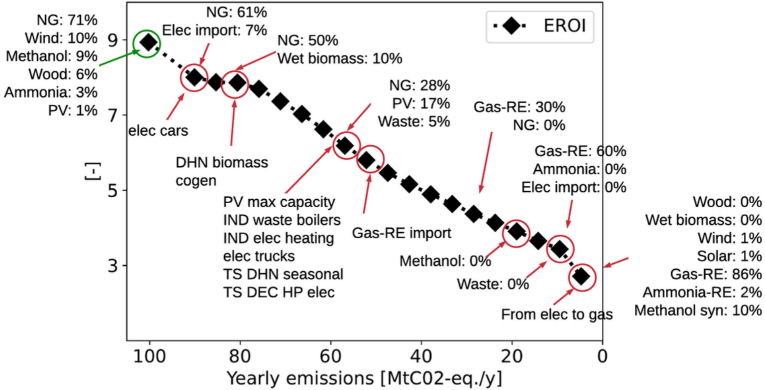


Figure 3: EROI - GHG emissions optima with primary energy mix and technologies implementation. The energy transition is composed of seven main steps illustrated with the red circles. Abbreviations: natural gas (NG), electricity (elec), district heating networks (DHN), decentralized (DEC), heat pump (HP), thermal storage (TS), industrial (IND), maximal (max), renewable gas (Gas-RE).