Demography
Energy
Climate

Preamble

This report is an attempt to address some foreseeable challenges regarding climate change and energy production over the world.

Because of the depth of these two themes, this report does also cover a wider range of topics. This report presents how these problems can be defined and proposes solutions.

Many of these problems and solutions can be interpreted in multiple ways. The views on these subjects may differ based on culture, experience, position in society, beliefs etc.
This report does not intend to impose one particular viewpoint.

The solutions proposed in this report, and the way the problems are defined, should not be perceived as the only or best way to address these issues. Proposed solutions depend on parameters, many of which can be estimated but without a guarantee.

Choices made in this report are intended to **increase awareness of the extent of the problem**, and to seek how an **effective strategy** can be built to address climate change and energy challenges.

February 2023

The
Demography Energy Climate
model

Summary

This report presents the situation regarding climate change, energy consumption, and population growth throughout the world. A task is conceived to fulfill the ambitions of the Paris Agreement while considering these topics. Multiple constraints are introduced to represent this task, which partly includes the constraint of preserving an energy system without fossil fuels. A model is built to find an optimal solution to the task, while complying with the specified constraints, and with settings configured by the user. **No solution which would respect the Paris Agreement has been found**. Results include the evolution of multiple sources of energy: wind, solar, nuclear, hydroelectricity, geothermal, fossils, etc., and multiple gases that impact climate: CO_2, CH_4, N_2O, F-gases and SO_2.
Further work is encouraged to improve results and solve the task. The report also addresses economic and social considerations related to energy and climate change.

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Glossary

CH_4 Methane, contributes to global warming.

CMIP Coupled Model Intercomparison Project.

CO Carbon Monoxide.

CO_2 Carbon Dioxide, contributes to global warming.

CO_2eq CO_2 equivalent, unit used to compare the impact of GHGs as an equivalent in CO_2.

DEC Demography Energy Climate, the main constraints studied in the model.

EOL-RR End-of-life recycling rate: Share of a material in waste flows that is recycled.

EROI Energy Return on Investment: Ratio between usable energy and energy used to get that usable energy.

ET Energy Transition.

EV / HEV / PHEV / BEV / FCEV (H)ybrid / (P)lug-in (H)ybrid / (B)attery / (F)uel (C)ell, Electric Vehicles.

F-Gases Fluorinated gases, contribute to global warming.

Fossil fuels Coal, oil, natural gas, fuel formed naturally in the Earth's crust from the remains of dead plants and animals.

GHG Greenhouse Gas, a gas that absorbs and emits radiant energy within the thermal infrared range.

GTP Global Temperature Potential, estimates impact of a gas on climate.

GWP Global Warming Potential, estimates impact of a gas on climate.

IPCC Intergovernmental Panel on Climate Change.

LFP Battery Lithium Ferro-Phosphate battery, does not use Cobalt.

LTO Battery Lithium-Titanium-Oxide battery, does not use Cobalt.

LULUCF Land-Use, Land-Use Change, and Forestry.

N2O Nitrous oxide, contributes to global warming.

NCA Battery Nickel Cobalt Aluminium + Lithium battery.

NDCs Nationally Determined Contributions, climate action plan to cut emissions and adapt to climate impacts.

NMC Battery Nickel Manganese Cobalt + Lithium battery.

NPP Nuclear Power Plant.

PM2.5 Particulate Matter with a diameter of 2.5 μm or less.

PSH Pumped-Storage Hydroelectricity.

SLCF Short-Lived Climate Forcer, a gas with a short-term impact on climate.

SO2 Sulfur Dioxide, aerosol pollutant that contributes to atmospheric cooling.

SSPs Shared Socioeconomic Pathways.

Chapter 1 The DEC task

In this first chapter, the DEC task is introduced.
The way the task is formulated adds important context for **interpreting solutions**.

1.1 The Limits to Growth

In 1972, a report named "The Limits to Growth" [1] was made for the Club of Rome. The report used the World3 model [2] to simulate interactions between multiple systems: food, industries, demography, non-renewable resources and pollution. Researchers from the MIT team concluded this way:

> If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, **the limits to growth on this planet will be reached sometime within the next one hundred years**. The most probable result will be a rather sudden and **uncontrollable decline** in both population and industrial capacity.

The report emphasized the need for **a more in-depth work on these constraints**.

Between 1972 and now, fifty years have passed. These fifty years allowed access to a much larger, more accurate and usable set of data on human activities than what was available at the time.
Regarding physical phenomena, the MIT team **already included CO2 concentrations** in their model. The comprehension of the different limits and constraints benefits from another 50 years of research, which can change the perceived priority for action and methodology on multiple topics, including energy and climate change.

1.2 Basics on climate change and energy

In 2018, Antonio Guterres, Secretary-General of the United Nations, said:

> "None of the world's challenges loom as large as climate change" [3]

This statement is in line with the work of the IPCC [4] indicating that with further global warming:

> Every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. [...] **Extreme heat thresholds relevant to agriculture and health are projected to be exceeded more frequently** [...] Heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions [...] It is very likely to virtually certain that **regional mean relative sea level rise will continue** throughout the 21st century [...] Cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes **will increase the severity of heatwaves**. Concurrent extremes at multiple locations, including in crop-producing areas, become **more frequent at 2°C and above** compared to 1.5°C global warming.

1.2.1 What is causing observed global warming?

> It is very likely that well-mixed GHGs were **the main driver of tropospheric warming** since 1979 [4]

1.2.2 What is the main source of changes in GHG concentrations?

> Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are **unequivocally caused by human activities**. [4]

GHGs absorb and emit energy within the thermal infrared range: they prevent a part of the light from escaping Earth which heats up the atmosphere.
They cause the greenhouse effect on Earth. This phenomenon existed before human activities, but **it is amplified due to GHGs emitted by human activities**.

1.2.3 Empirical data on global warming

The average world temperature since 1850 is presented in fig. 1.1.
An increase in the average temperature can be observed. According to IPCC:

> The likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is **0.8°C to 1.3°C**, with a best estimate of 1.07°C. **It is likely that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C**, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. [4]

Following the current trend, the average world temperature can go beyond 2°C of warming.

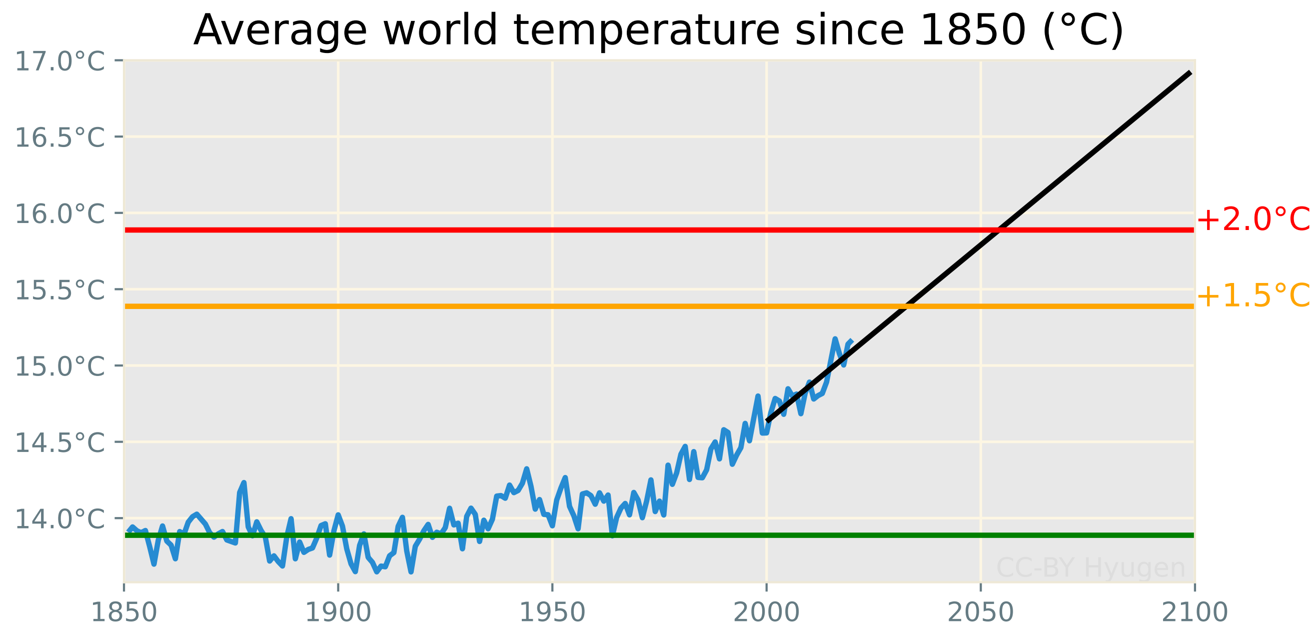


Fig. 1.1: Average world temperature on Earth since 1850 [5], green bar indicates world average between 1850 and 1900, orange bar indicates 1.5°C above the green bar, red bar indicates 2°C above the green bar, black bar indicates 2000-2019 trend

The influence of different greenhouse gases varies over time. Because of that, **in a hypothetical scenario**, temperatures could also partly decrease after having increased ([6], ch1, fig1.5, p65). Carbon dioxide has a long-term impact on temperatures; while methane has a short-term impact, it's a short-lived climate forcer (SLCF) [6]. In theory, it is possible to go to +2.2°C in 2060, then back to +2°C in 2100 by reducing CH4 emissions.

In order to reduce climate change, human activities need to be altered so that they don't result in an increase of GHG concentrations around the world.
The scope of the challenge is on all human activities that raise the concentration of gases that impact the climate.

1.2.4 What are these gases?

The main gases considered in this report are the ones with the largest effects on temperature and / or the longest impact on climate. All gases have different lifespans in the atmosphere, they may contribute to warming even beyond their atmospheric lifetime [7].

- Main contributors to observed global warming ([4], fig SPM.2) include
  - Carbon Dioxide (CO2), approx. +0.8°C
  - Methane (CH4), approx. +0.5°C
  - Nitrous Oxide (N2O), approx. +0.1°C
  - Halogenated Gases (including F-gases), approx. +0.1°C
  - Volatile organic compounds and carbon monoxide (CO) approx. +0.2°C

- Main contributors to cooling ([4], fig SPM.2) include
  - Sulphur Dioxide (SO2), approx. -0.5°C
  - Nitrogen Oxides (NOs), approx. -0.15°C

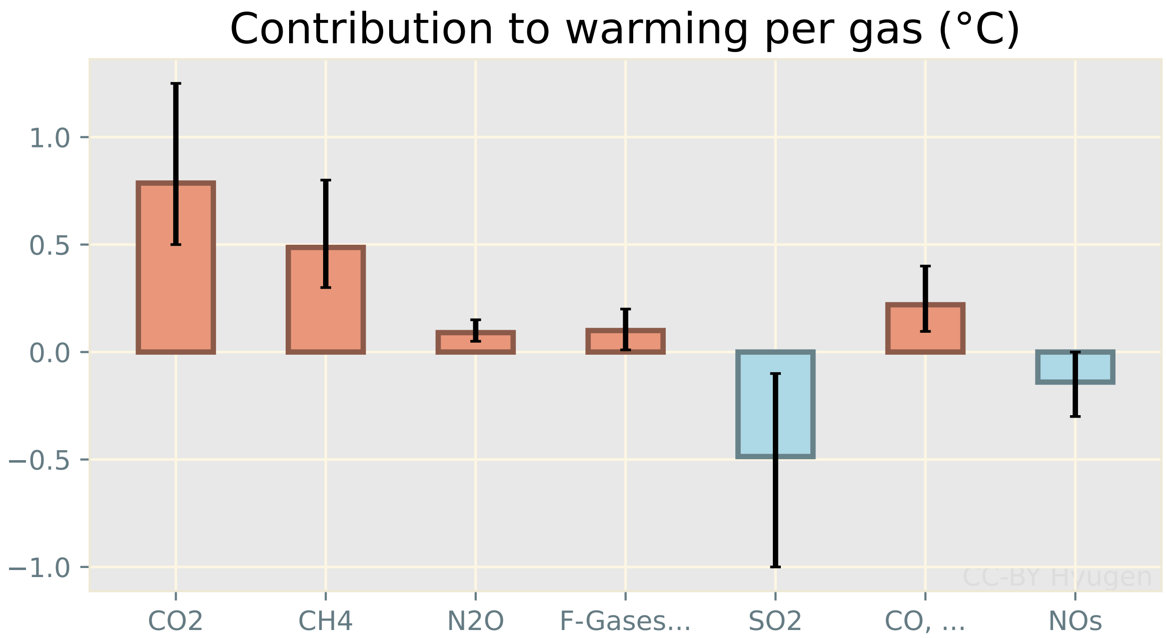


Fig. 1.2: Contribution to warming per gas ([4], fig SPM.2), CO2, CH4, N2O, F-Gases and SO2 are the main gases considered in the model

Gases that contribute to global warming can often be expressed in CO2 equivalent. This comparison is a simplification because their impact compared to the impact of CO2 may vary **depending on the timing of emissions, on atmospheric composition, emission rates, time horizons etc.** [7, 8]

Gases that contribute to cooling such as SO2 and NOs can have adverse health effects on populations [9, 10].

1.2.5 Which human activities are responsible for increased GHG concentrations?

Human activities can be broken down in multiple ways to attribute GHG emissions, a breakdown is proposed in fig. 1.3.

It is possible to decompose human activities by country, by sector, by fuel. It is possible to decompose them from a production perspective, or from a consumption perspective.

There are different levels of uncertainty which are not represented in this report. Choices made to represent an information here have no normative ambitions.

Apart from the direct impact of human activities, a non-negligible cause of increase in GHG concentrations is how human activities impact the natural ability of the world to absorb some GHGs. A part of this natural absorption comes from LULUCF: Land-Use, Land-Use Change, and Forestry.

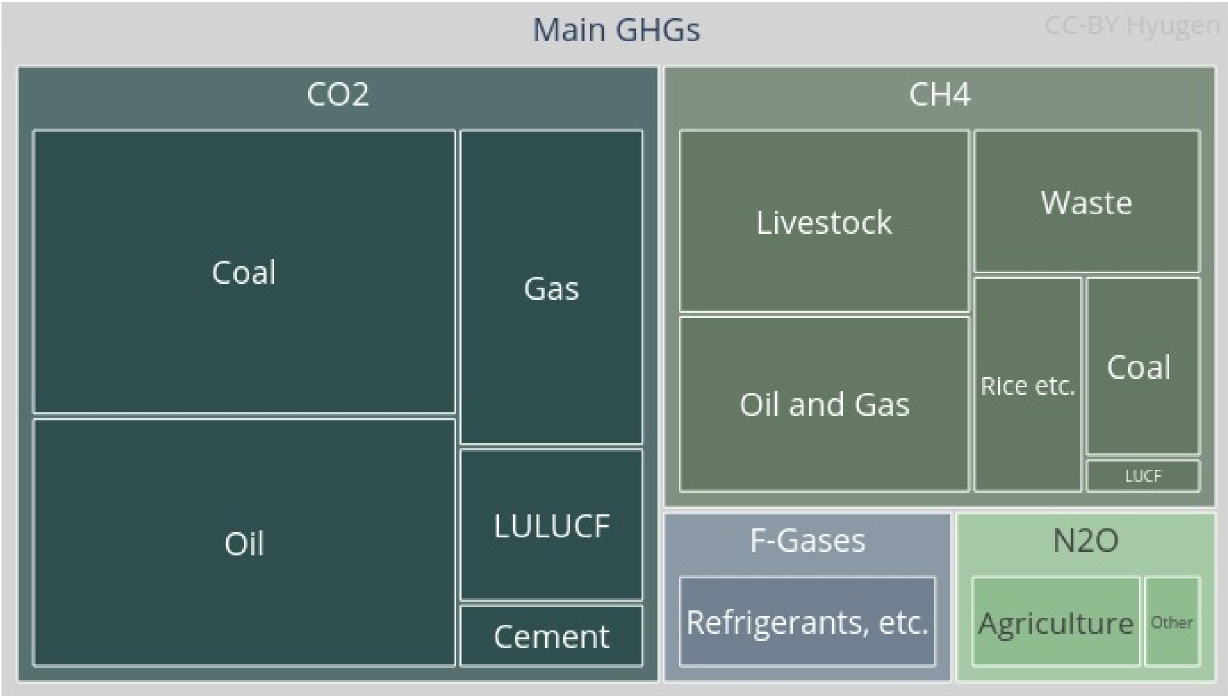


Fig. 1.3: Per-gas per-source decomposition. Sources are represented as a proportion of recent[1] contribution to the gas emissions. Gases are represented in proportion to their contribution to global warming between 2010-2019 compared to 1850-1900. *Sources: warming per gas:[4], CO2 proportions[2]: [11], [12], [13], [14], non-CO2 proportions:[14], CH4 proportions:[14], [15], [16]*

This graph shows **which activities or fuels contribute to emissions of gases that recently warmed the climate the most**.

This graph also shows **how each of current GHG sources could impact temperatures in the future**.

In order to have the historical impact of each source, results should include the historical contribution of activities. Instead, this figure only represents sources based on how much they contribute to emissions of a gas now, to better visualize **how to prioritize action**. This graph is provided in a context where **all shown greenhouse gas emissions have not yet begun to decline**. Otherwise, another methodology would be more appropriate.

Most of these activities are related to energy and food systems at some point. Coal, gas and oil are required for energy production. LULUCF, livestock, rice and agriculture are required for food production.
Other activities which are relevant for tackling climate change include production of cement, use of refrigerants and waste management.

[1] 2017/2019/2020 based on available data
[2] Conversions used: coal: 334 gCO2/kWh, gas: 181 gCO2/kWh, oil: 245 gCO2/kWh[11]

1.2.6 How and why energy is used?

This part is a **practical simplification** on how energy is used.
Energy is mostly used **to move objects**.
These objects can be particles, molecules or larger objects:

- Energy can be used to move air molecules, it produces **heat**, which is **a form of energy**.
- Energy can be used to move electrons in cables, it produces **electricity**, which is **another form of energy**.
- Energy can be used to burn oil, to turn the wheels of a vehicle, it produces a **movement** which gives **kinetic energy** to the vehicle.

Example: In the motor of a vehicle, a part of the heat is converted into a movement. Approximately 1/3 of the heat creates the movement, 2/3 of the energy used result in waste heat. During winter, this "wasted" heat can be used inside the vehicle, which means that it is no longer considered waste heat.

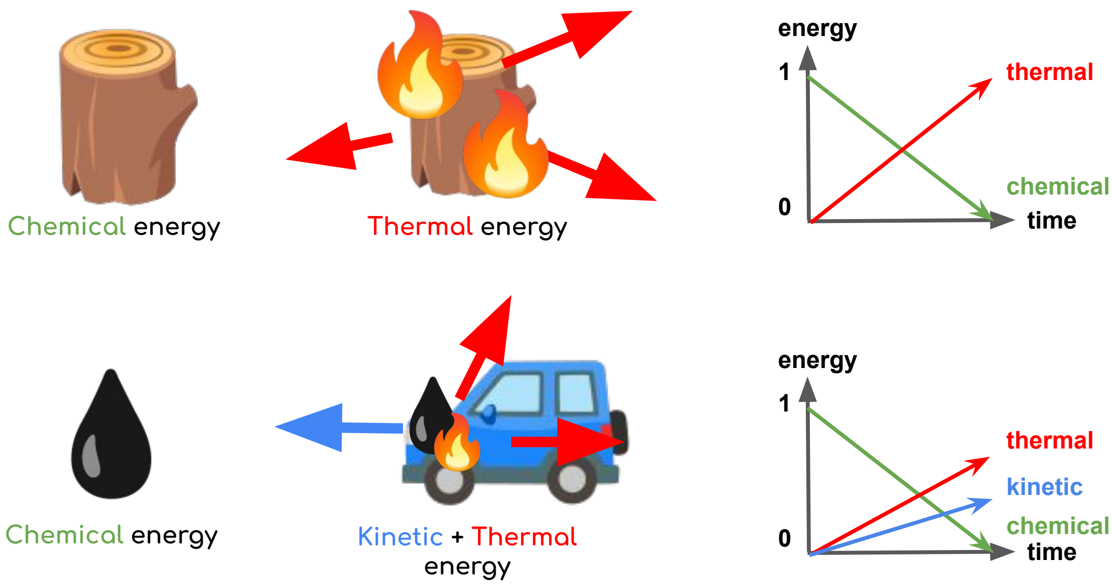


Fig. 1.4: Diagram of 1st law of thermodynamic: "energy can neither be created nor destroyed - only converted from one form of energy to another"

From a physical point of view, **energy is never lost, it is just transformed**.
From a practical point of view, energy as dissipated heat, "waste heat", is **hard to use**.
It is considered as "lost", but the energy still exists.

Replacing fossil fuels: coal, gas and oil, means that new sources of energy that are **easy-enough** to use need to be found.

Energy consumption at a given moment can be expressed in **Watt** (W), energy consumption over a certain period of time can be expressed in **Watt-hour** (Wh), kWh, MWh, GWh, TWh and PWh.

Example: moving an electric vehicle (EV) 5 meters requires 1 Watt-hour, which can be obtained by using 1W during 1h, or by using 2 Watts during half an hour.

Energy is mainly used to **improve living conditions**, including: moving food, heating up or cooling homes and food, building homes, workplaces, and transporting or transforming objects to meet society's needs.

When **an energy needs to be replaced with another form of energy**, for example by replacing oil used for cars with electricity, **new constraints can be added on living conditions**, for example a shorter range of vehicles on routes. Benefits can also be added, for example when heat that comes from burning fossil fuels or biofuels is replaced by heat from electricity, air pollution is reduced[17], as long as electricity isn't produced by burning fuels.
Transports account for a non-negligible part of fossils consumption and CO2 emissions worldwide. Alternatives to fossil fuels in transports include: using electricity directly (trains, trucks with overhead lines...), using electricity after storage (lithium or hydrogen batteries), and using biofuels.

Finally the transformation of energy from an initial source (primary energy) to a final use (useful energy) needs to be considered, as only useful energy meets a need. Figure 1.5 displays this transition.

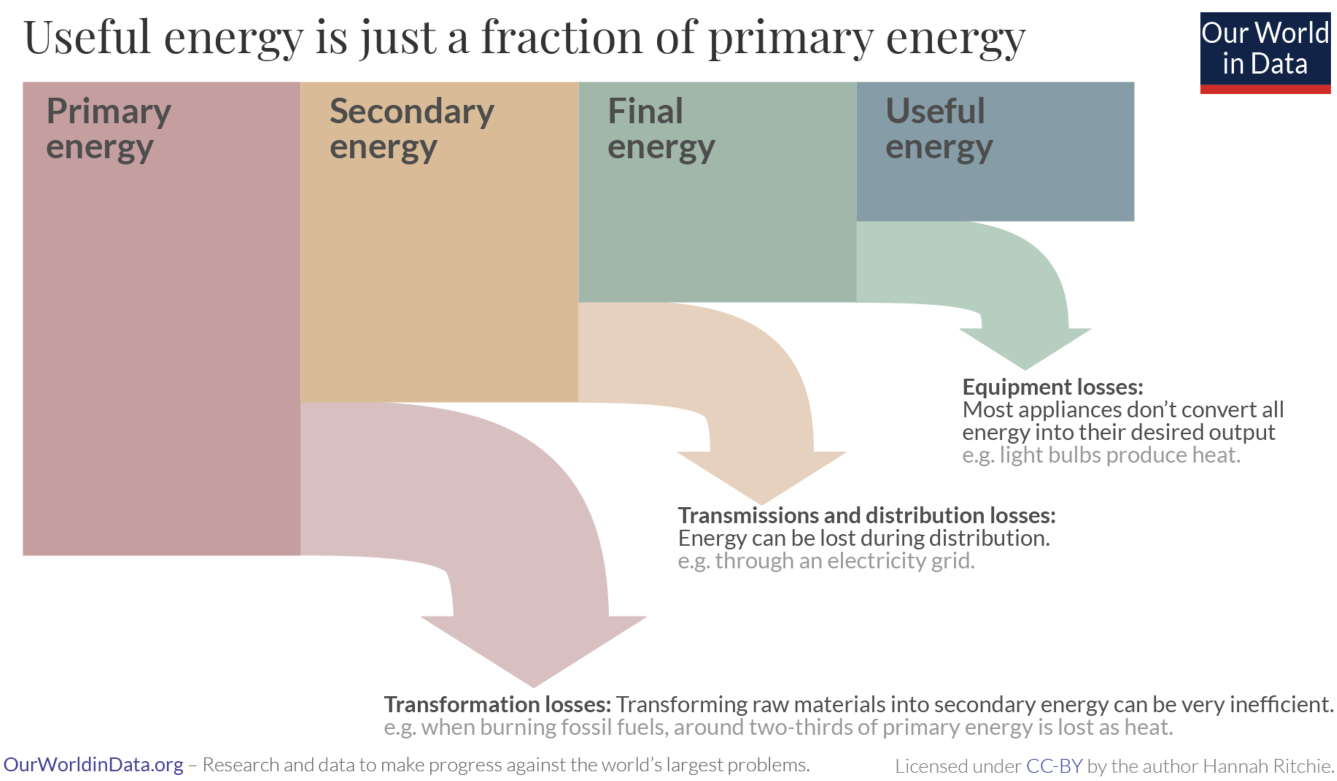


Fig. 1.5: Diagram of energy losses, source: [18], "waste" heat that comes from the use of electricity or fossil fuels can be considered as useful energy in some situations

In order to replace energy in a sector, only useful energy needs to be replaced.

In a nutshell

Climate change is **one of the biggest challenges of this century**, it will have impacts all over the world.
It's caused by GHG emissions and land usage.
It can be addressed by adjusting multiple human activities, including energy production, agriculture and specific industries.
Energy is available in different forms of different quality. It's used to improve living conditions.

1.3 Overview on energy production

As previously stated, from a physical point of view, energy is never lost nor created, it is just transformed. The activity called "energy production" is actually an energy transformation activity, **an original energy is transformed into another energy which is more practical to meet society's needs**.

A large part of the received, needed and used energy is not accounted for. Energy is not accounted for when the sun provides energy to heat buildings, or to plants required for food consumption. And when the climate system moves water in the air and makes it rain, that energy is also not accounted for.

Most of the energy measured in economy is related to human labor, under the economic convention that **human labor is paid, and natural phenomena aren't**. Thus, when electricity coming from a solar panel is paid, it pays people who installed it, people who manufactured it, people who mined the required resources, but the sun is not paid and the energy the panel received is not considered in economy.

Under this convention, measuring some sources of energy is easier than others. For example, a single person could collect wood, a biofuel, and burn it without notifying this activity to an authority. On the opposite, industries which are based on nuclear energy and oil can be monitored more precisely, as they involve more people to produce energy.

Two main measures of energy are used in this report, fossil fuel consumption [13] and electricity generation [19] [20] [21]. These two measures are correlated since fossil fuels can be used to produce electricity. Energy consumption is represented in fig. 1.6.

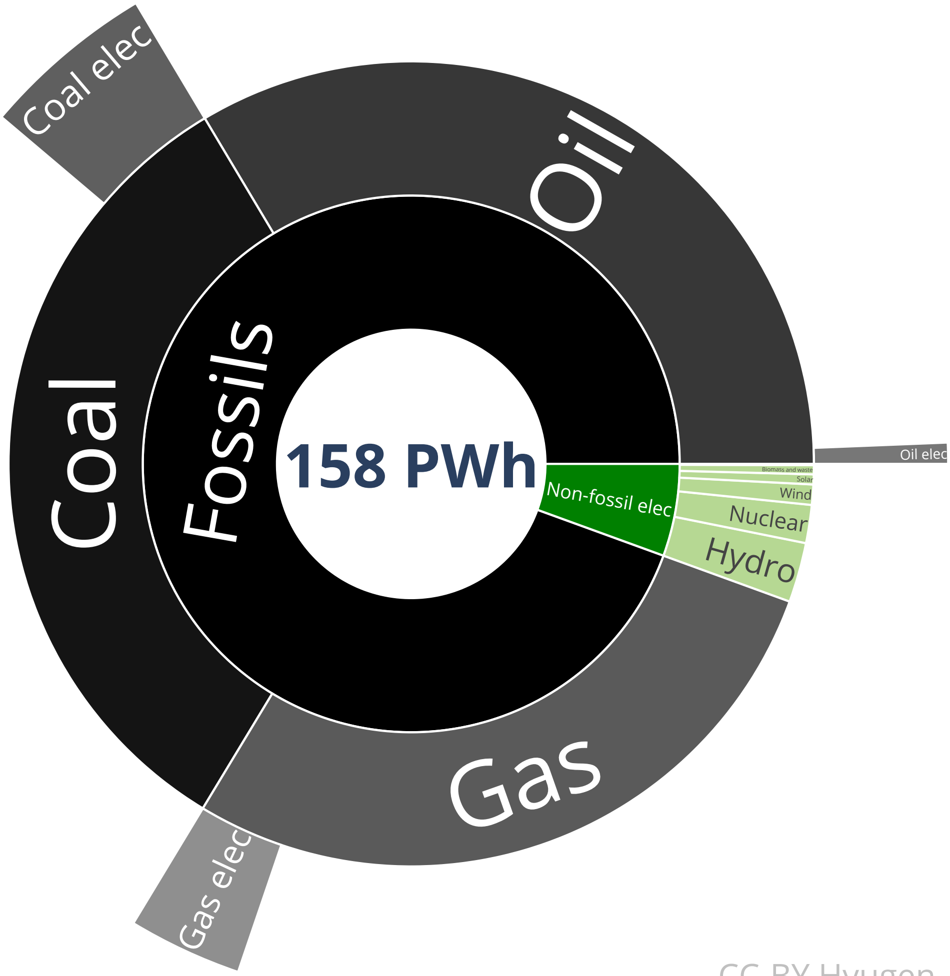


Fig. 1.6: Energy consumption diagram representing fossils and electricity, 2019, [13, 19, 20, 21], elec=electricity, non-fossil electricity includes hydroelectricity, nuclear, wind, solar, biomass and waste, geothermal, and tide and wave

Reducing GHG emissions implies to remove the "Fossils" part of the graph in fig. 1.6. This is the required "energy transition" to reduce climate change.

This graph voluntarily omits certain aspects. First, it shows nuclear electricity and not nuclear energy: nuclear energy also produces waste heat. Second, this graph includes a lot of unused heat from fossil fuels. Accounting for which part of fossils is wasted and which part is not adds complexity and requires approximations. Third, this graph omits some biofuels and heat sources due to measurement difficulties, and due to other reasons which will be detailed later.

As previously indicated, in order to replace energy in a sector, **only useful energy needs to be replaced**.

In the hypothesis where fossil fuels are completely replaced with non-fossil electricity, without any decrease or increase in energy consumption:

- **The "fossils" part of the graph doesn't need to be entirely replaced** with new energy sources because this part includes waste heat.

- **At least the "electricity" part of fossils needs to be replaced.**

- Under Carnot's theorem, because fossil fuels are used in heat engines to produce electricity, **a measurable amount of fossil energy used to produce electricity is lost as heat**. Approximately twice fossil fuel electricity is lost as heat, excluding cogeneration. This part doesn't need to be replaced.

- For fossil fuel energy that is not linked with electricity, it isn't exactly known how much of the produced heat is considered as waste or not, but it is possible to estimate these values under many hypotheses.

In order to better understand how fast these systems change, the evolution of energy production and consumption over time can be presented.

1.3.1 Evolution of energy production

Figure 1.7 presents the consumption of fossil energy over time.

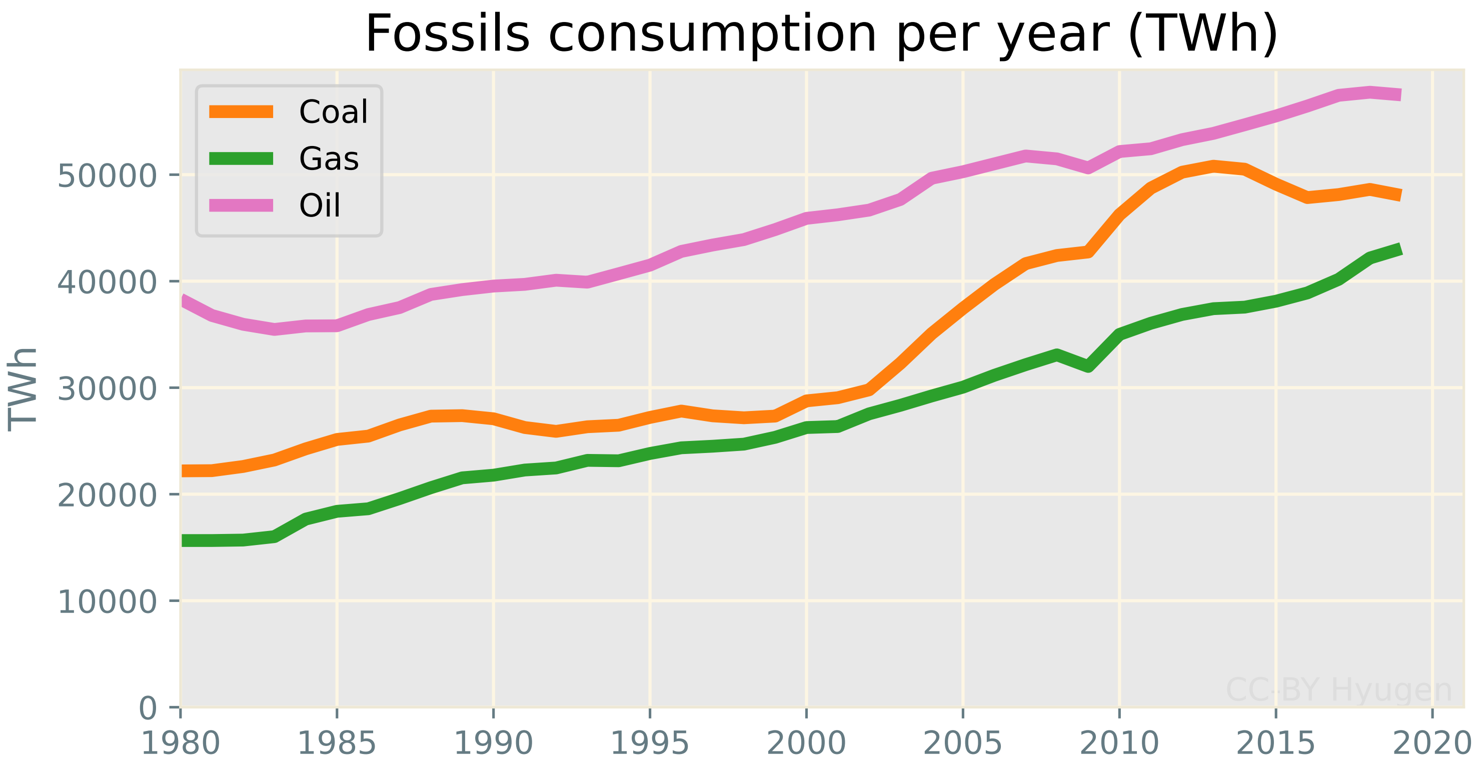


Fig. 1.7: Fossil energy consumption as a function of time, [13]

Between 1980 and 2019, world's consumption of fossil energy increased.
Figure 1.8 presents changes in electricity production over time.

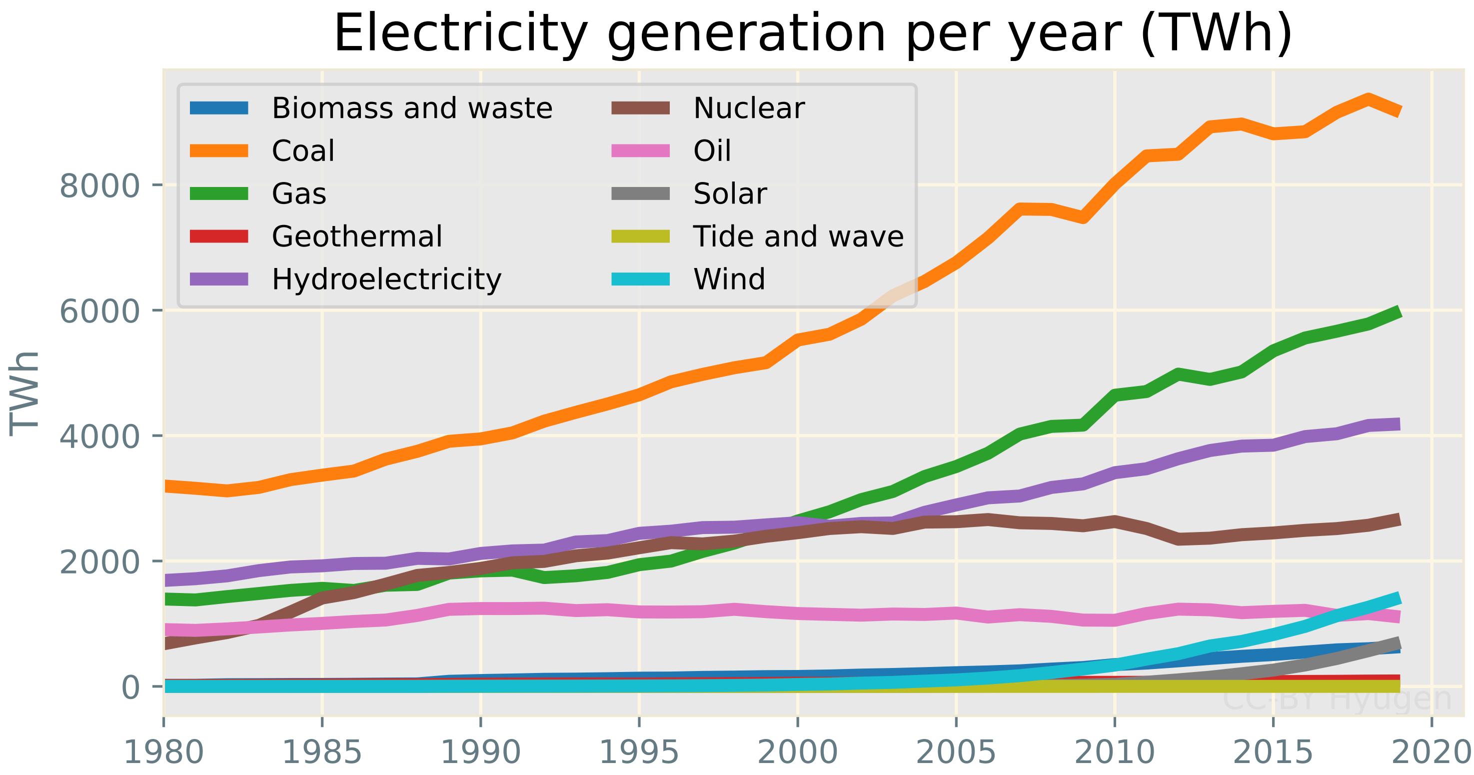


Fig. 1.8: Electricity production as a function of time, [13, 19, 20, 21]

In order, **the highest electricity generation sources in the world are coal and gas, which emit GHGs. The main sources that emit few GHGs to generate power are hydroelectricity, nuclear, wind, and solar energy.**
Biomass and waste emissions can be accounted for in different ways. Electricity from geothermal sources or tide and wave are insignificant on a global scale. They can however be useful on a local scale.

Biomass and waste can emit GHGs if they extract more carbon over a surface than what this surface can naturally regenerate. Thus, they're related to LULUCF. During previous decades, LULUCF have been a source of GHG emissions, which explains why the contribution of biomass depends on places and uses.

All sources of electricity include negative impacts on the environment: by emitting GHGs and other pollutants, by occupying and altering surfaces, by modifying natural environments, etc.

In order to produce electricity, power stations need to be installed.
Power plants have a capacity expressed in Watt. If they produce all the time all year round they have a capacity factor of 100%. Capacity factors by electricity source can be visualized in fig. 1.9, each point represents the average of all available years (1980-2019) for a source and a country.

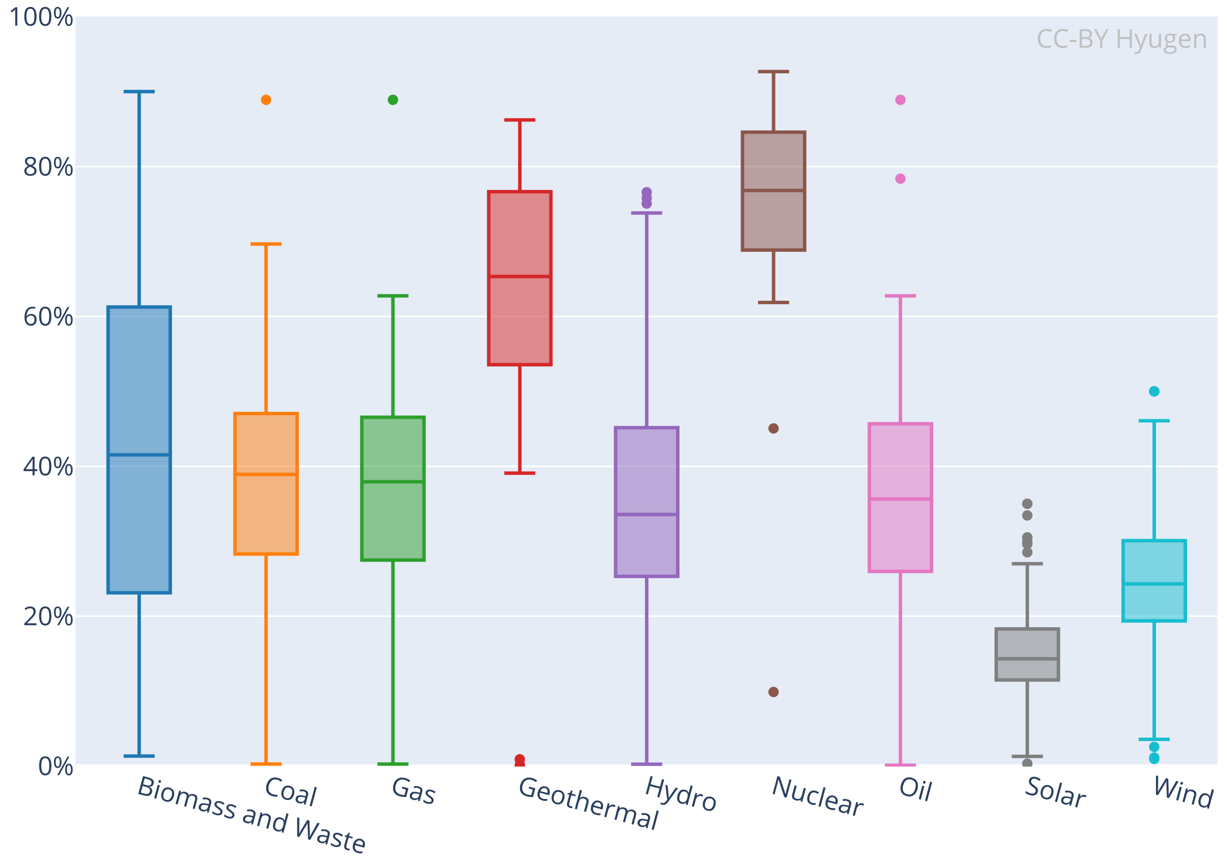


Fig. 1.9: Approximated capacity factor per electricity source, [13, 19, 20, 21, 22], each point is a country and a year

Over the world, nuclear and geothermal energy have the highest capacity factors. Solar and wind energy have the lowest capacity factors due to intermittency. Energy storage may partly compensate intermittency if and when it is available.

Energy cannot be separated from how easy it is to use and to extract from the environment. A part of this aspect is represented in the capacity factor, another part can be analyzed thanks to the EROI.

1.3.2 EROI: Energy Return On Investment

EROI, or EROEI, is the Energy Return On Investment / On Energy Invested. In order to extract energy from the environment and to later use it, it is required to use energy. Hopefully, more energy is extracted from the environment than how much was used to extract it from the environment.

Example: If 1 kWh of oil is used to extract 10 kWh of oil, the EROI is 1:10, or 10.

As suggested earlier, these considerations on energy depend on the point of view:

- If 1 kWh of oil is required to extract 10 kWh of oil, the EROI is 10.
- In another situation, 1 kWh is required from external sources, and 20 kWh of oil are required from the exploited reserve, to extract 10 kWh of oil. 10 new kWh of oil are available thanks to 1 kWh of external energy. Energy is produced,

according to how energy production is accounted for. But the EROI of such operation including the 20 kWh which came from the reserve is under 1.

Multiple conventions were defined on how to compute EROI to try to account for what researchers consider useful for their work.
Because technologies change, and, because conventions may vary between multiple researchers, EROI figures per energy source vary. Standards and research are constantly evolving on these topics for all energy sources.

Example for solar panels: . [23] identified 6 factors which contribute to discrepancies between studies: "LCA method, age of data, PV cell tech, intermittency equivalence of investment, equivalence of output energy forms, and assumptions about real-world performance". Various sources detail multiple methods: [24, 25, 26, 23]

When EROI is used in research, it can be implied that **there is a required EROI to keep good living conditions** [27, 28]. It is considered that society developed during and after the industrial era because of energy sources with a high EROI. This readily available energy allowed people to move more objects, including building homes, industries, roads, vehicles, etc. It is thus considered that, with low EROI sources, maintaining current living conditions would be more difficult. One evaluation of the "break-even EROI" to maintain economy is 1:7 [29].

This proposition is not rejected in this report. However, it is interpreted as a practical simplification, with the following reasoning:

Hypothetical scenarios

- First fictional scenario

  - A society uses 10 PWh to satisfy its needs and has 10 PWh available to produce more energy. This society is able, automatically, with indestructible machines, and without human efforts, to extract energy from an almost infinite source, without storage constraints or waste, with an EROI of 2. In this situation, more energy could systematically be produced by reducing how much energy is used to satisfy needs. Or, 10 PWh could permanently stay available to produce energy, while still having 10 PWh to maintain other uses (agriculture, transports etc.).

- Second fictional scenario

  - A society has 2 PWH available. 1 PWh is for society's needs and 1 PWh is used to produce more energy. Energy is easily extracted from a limited source with an EROI of 50.
  - This society now has 50 PWh. With this high-EROI energy source, this society wants to use more energy to grow and improve living conditions. This society now uses 30 PWh, and still has 20 PWh to produce more energy. However, it started by extracting an energy which was easy to extract. Now the EROI is 20, and 20 PWH are available to extract more energy.
  - This society now has 400 PWh. But, as this society had 30 times more energy for its needs in the first period, it now multiplies it by only 13, it's the limit to still

keep a bit of energy to re-produce energy. 390 PWh are for society's needs, and 10 PWh are to extract more energy. The energy source has now an EROI of 10.

- Now, 100 PWh are extracted. This society cannot use as much energy as it used before, in spite of having an energy source with an EROI of 10.

This society consumed 1 PWh, then 30 PWh, then 390 PWh. Now only 100 PWh are available for society and for energy systems. This growth wasn't sustainable.

These two examples show some limits of EROI:

- First, the 1st scenario shows that low-EROI sources may not represent a limit in theory. However, multiple conditions (minimal human labor, infinite source, no storage or waste constraints,...) which can be interpreted as impractical need to be fulfilled.

- Second, under the given constraints, the 2nd scenario shows that **even high-EROI sources aren't sustainable in a society seeking indefinite growth in energy consumption**.

- Third, both scenarios show that to remain constant in its energy consumption, **a society needs to keep enough energy to re-produce energy on the long run**.

Even if a society manages to keep producing the same amount of energy, if it constantly requires more human labor in proportion to all activities, other activities will be less done, which would end up creating constraints on energy production.

Example: if all individuals were required to work in the energy sector to produce enough energy, no one would be working in agriculture, and workers in the energy sector couldn't eat and work. Moreover, agriculture requires energy, so the energy sector needs to produce enough energy to maintain itself, for agriculture, and for all other high-priority sectors to work.

The energy sector can face multiple constraints. According to the previous example, increasing difficulties in the extraction of energy resources could come from an inability of the energy sector to provide enough energy to maintain a stable-enough society for the energy sector to work. The limit may not be the end of the resource, or an under 1 EROI, but rather the end of a stable-enough society to exploit this resource. This constraint is represented in fig. 1.10.

Energy source evaluation based on EROI should also include metrics on human labor and on how energy is used in the economy globally.

In the main contribution of this report, **EROI will not be used directly**, as these numbers are considered difficult to produce, to use, and to transpose to all use cases. However, a related more empirical measure will be used. This measure will be presented in chapter 2.

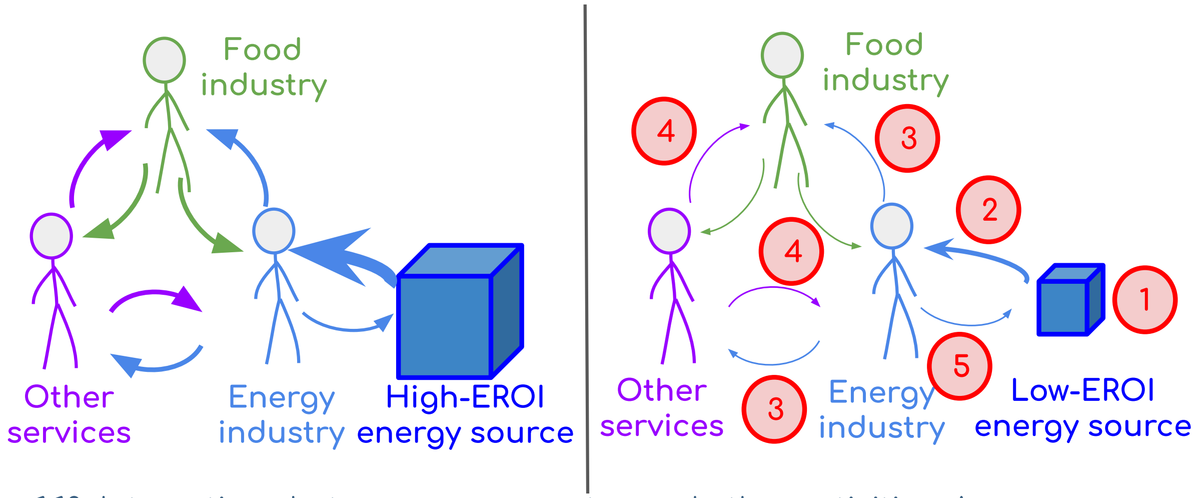


Fig. 1.10: Interactions between energy sector and other activities. Arrows represent the production of the sector (energy, food, etc.). Left: Comfortable situation. Right: (1) EROI of a source is reduced, which (2) at first reduces energy taken by the energy sector (3) which reduces energy available in other industries (4) which reduces how these industries help the energy sector (5) which impacts the ability of the energy sector to invest more energy for extraction

In a nutshell

Fossil fuels represent an overwhelming part of energy consumption. Consumption of energy coming from fossil fuels has continuously increased during the last decades.
Qualities and constraints of electricity sources vary from one source to another.
The EROI can indicate the relevance of a solution but may by itself be insufficient to complete an analysis.

1.4 Overview on demography

World demography increased continuously during the last centuries and is expected to stabilize or decrease during the 21st century. It can be visualized in fig. 1.11.

Different constraints result in different projections on population growth, **these projections can include large error intervals** which are not represented here. **These projections do not account for unpredictable yet historically relevant scenarios**, such as pandemics or world wars. Impacts of climate change or resource scarcity are also not included, and would add even more uncertainties.

Following an accounting convention, **all global uses of resources can be broken down into uses per capita**. Still following this accounting convention, without raising the efficiency of resource use above a certain threshold, any increase in demography will result in a higher cumulative use of the resource. Raising the efficiency is equivalent to raising the ratio of how much this resource profits society over how much of it society consumes.

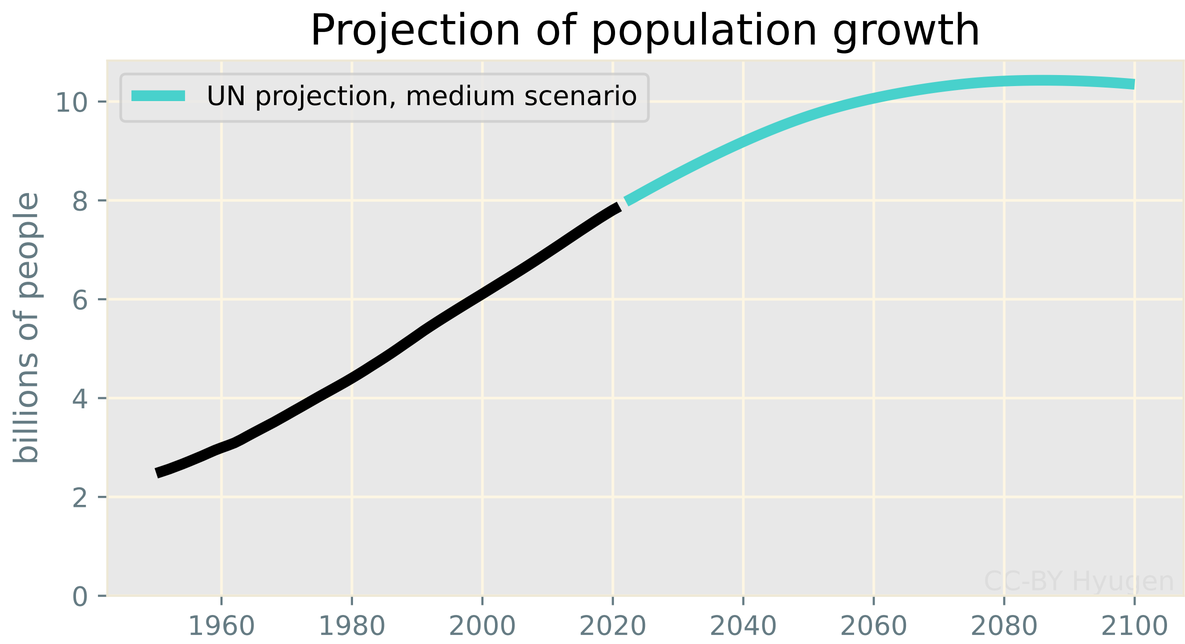


Fig. 1.11: World demography and projection, [30]

Using the assumption that **living conditions are related to the use of resources**, including energy resources, and with the idea that these resources are limited, limits related to population growth can be studied using constraints on living conditions and efficiency in how resources are used.

To evaluate the possibility to reduce global GHG emissions while population grows, the evolution of CO2 emissions per capita during the last decades is represented (fig. 1.12).

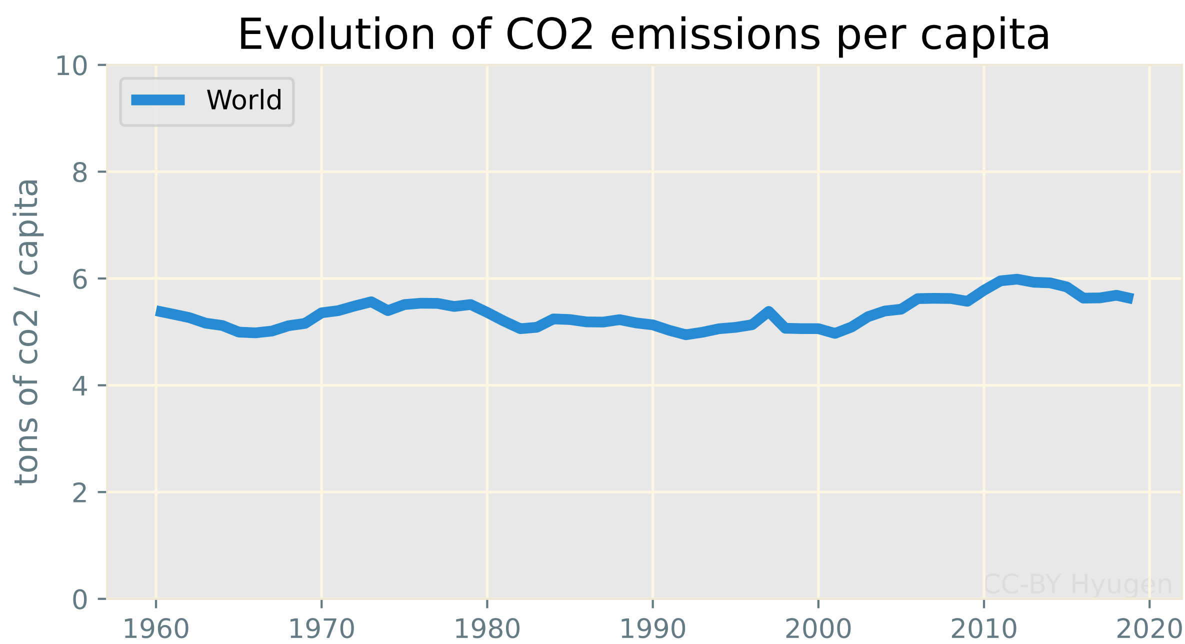


Fig. 1.12: Evolution of tons of CO2 per capita over time, including fossils, LULUCF and cement [30, 13, 14]

Tons of CO2 per capita averaged over the world **were stable at around 5t to 6t of CO2 per capita during the last 60 years.**

Considering that population is projected to grow in the next decades, **if tons of CO2 per capita also grow or are stable, cumulative emissions of CO2 over the world cannot decrease.**

Worldwide, an increased efficiency in how CO2 is emitted per capita has not been observed yet.

1.4.1 Life expectancy

Life expectancy is considered a valuable indicator in this report. This indicator is related to variations in demography, it is easy to measure under a specific convention, and it is assumed that good living conditions correlates with longer life expectancy over the whole world population.

It will be considered under the task which will be built that good living conditions are positively correlated with a high life expectancy, and that populations seek to increase their life expectancy.
As detailed earlier, it is considered in this report that energy consumption serves people's living conditions. How life expectancy correlates with useful energy consumption per country is represented in fig. 1.13.

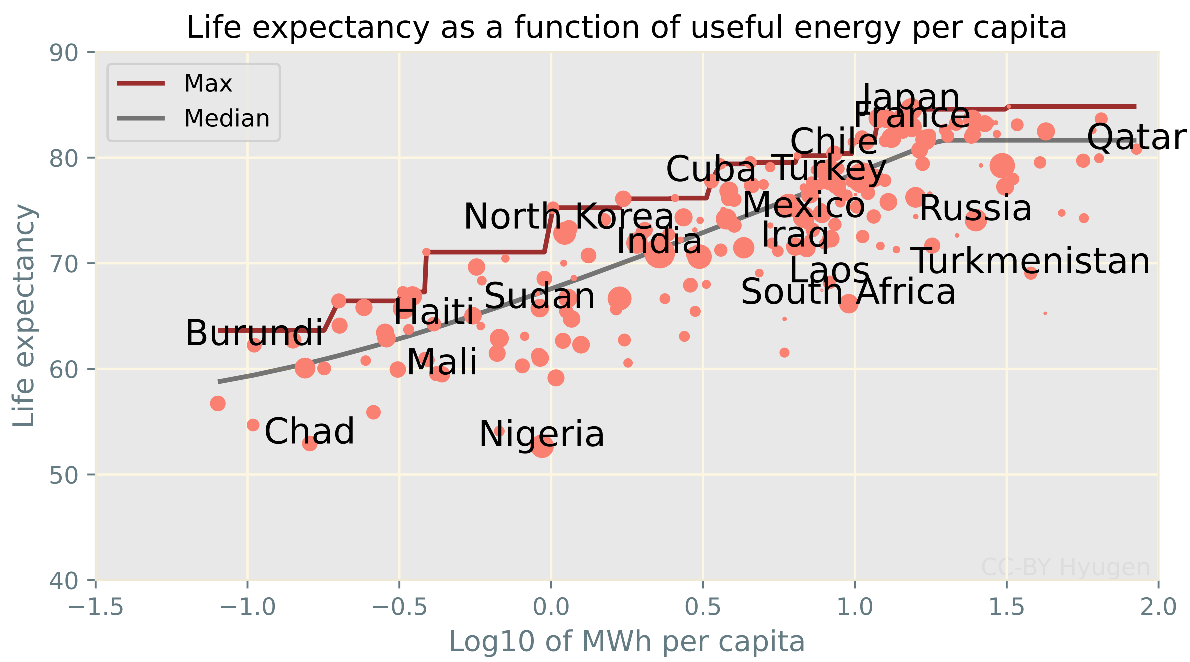


Fig. 1.13: Life expectancy in years as a function of estimated useful energy per capita in 2019, [30, 13, 19, 20, 21], circles are proportionate to demography

Measuring useful energy requires many approximations, using the per-country data from sources used in fig. 1.6, a value of approximately $2/3$ of waste heat is used for all fossil fuels and $1/10$ for electricity losses.

Figure 1.13 shows that, empirically, life expectancy has upper and lower bounds that rise with energy consumption. Life expectancy and energy consumption are correlated, based on Pearson correlation coefficient (p-value < 0.01). This correlation doesn't imply a causation.

It is assumed in this report that life expectancy and useful energy consumption per capita correlate with good living conditions. It is also assumed in this report that there is a causal relationship, with the idea that **energy improves living conditions**, by improving agriculture, transport, housing, etc., and that these better living conditions cause a higher life expectancy.
This idea is assumed as being a global trend, and not a systematic truth in all possible cases.

1.4.2 Food systems

Figure 1.3 indicates that agriculture is a non-negligible emitter of GHGs. For understandable reasons, food consumption is also related to demography, as all humans need to eat food to stay alive.

Food production can be impacted by climate change, as explained in section 1.2. And GHG emissions may vary greatly depending on the type of food. The main non-fossil source of methane is livestock (fig. 1.3), but methane emissions per meat type also vary greatly [31].

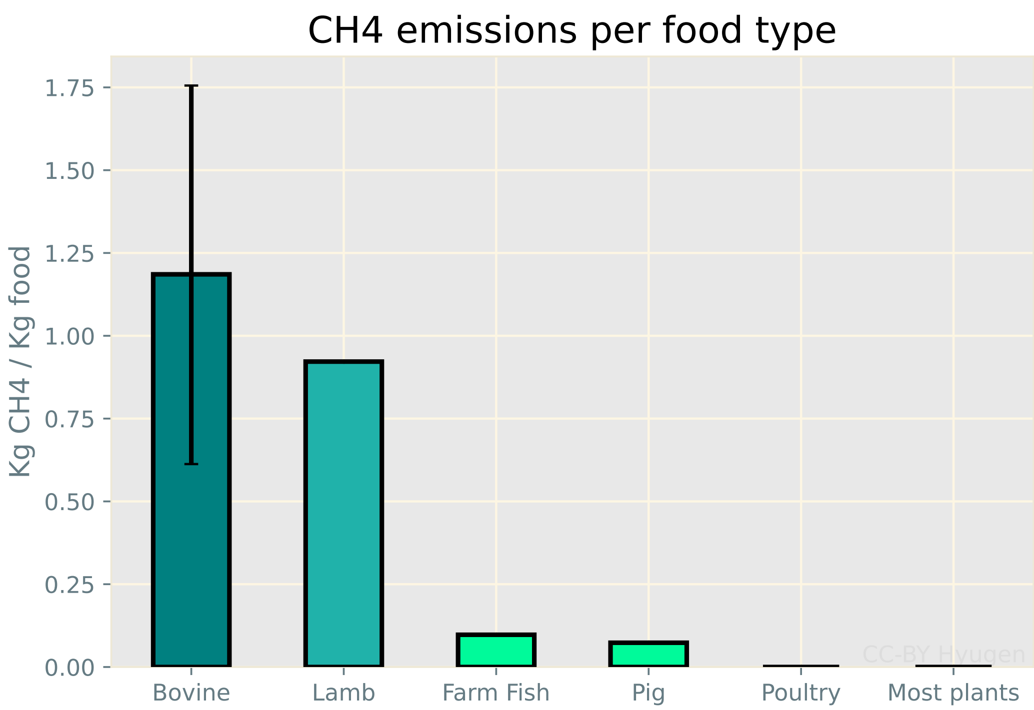


Fig. 1.14: CH4 emissions per food type [31], bovine is an average between beef/dairy herd

Based on [31], bovine and lamb emit much more methane than poultry.

Food is also related to energy. Industrialized countries use machines to harvest and plant food more efficiently. Yield data per crop type are available and data on energy are available, their correlation can be observed:

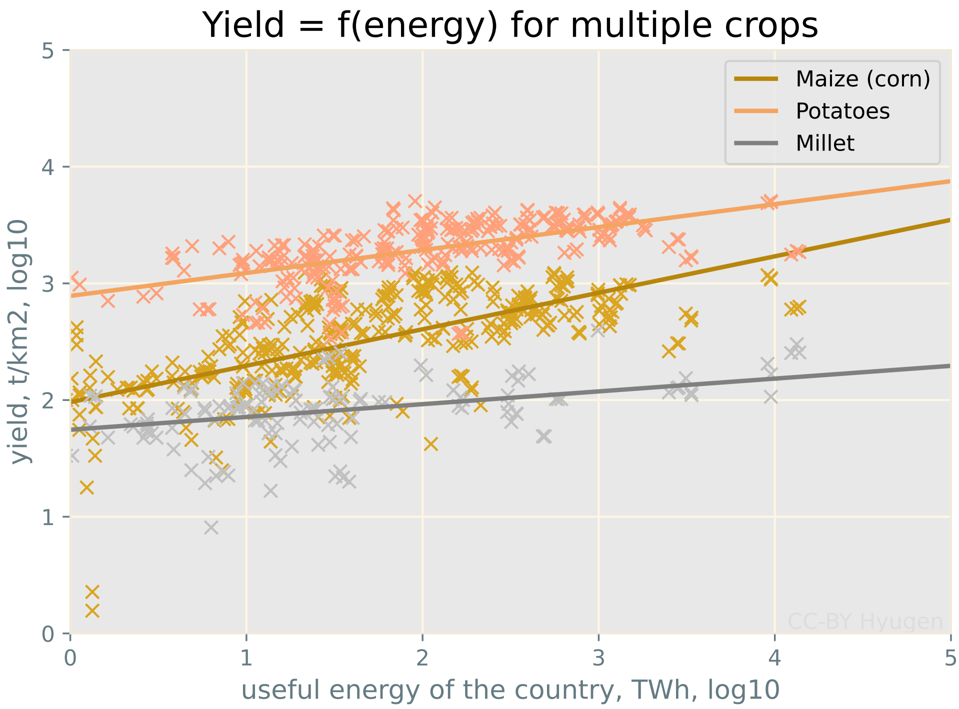


Fig. 1.15: Yield per energy for different crops, each point represents a country during one year, source: [32, 13, 19, 20, 21]

Previous studies noted the relationship between energy consumption and yield in specific and local situations [33, 34]. Energy is used for irrigation and for tractors, which improve yield.

The correlation between yield and energy at the country level can be affected in many different ways. Crop yields can be affected by climate, and energy consumption in a country can also change based on climate, which would correlate crop yield and energy without a direct causal link. It can still be assumed that agricultural machines, fertilizers and irrigation require energy and improve yield. In this report, changes in energy impact yield in some analyses based on correlations presented in fig. 1.15. Further work is however required to verify this hypothesis.

1.4.3 Pollution and deaths from energy

Pollution can be interpreted in different ways. In this report "pollution" will mostly refer to substances that can cause direct and negative health effects on humans, and most importantly the ones that are directly linked with energy.
According to this definition, the main source of pollution analyzed in this report is fine particles.

> Ambient fine particulate matter (PM2.5) is the world's leading environmental health risk factor. [17]

PM2.5 are responsible for 4 million deaths per year [17]. Fuel combustion is responsible for half of them:

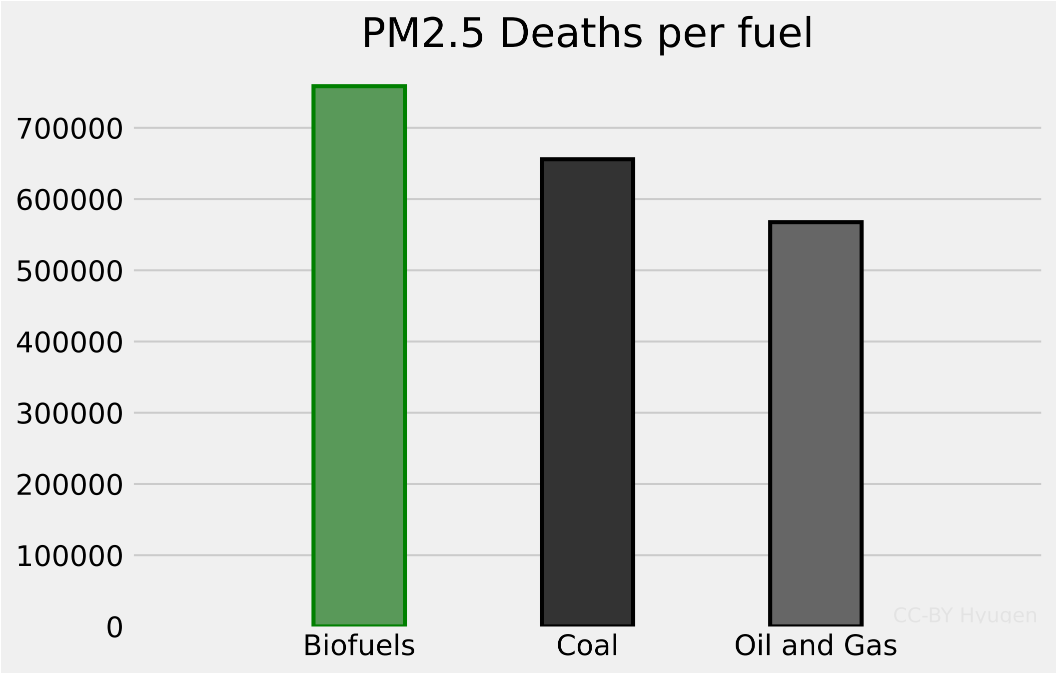


Fig. 1.16: Approximate PM2.5 deaths per year in recent years, PM2.5 data from 2021 [17], deaths data from 2019 [35]

Fossil fuels are responsible for more than 1 million deaths per year due to ambient particles.

All sources of energy can be responsible for deaths in a more or less direct way[36, 37]. Accounting for damages from fossil fuels related to climate change would be difficult, as it is not yet precisely known how climate change will directly or indirectly affect health in the future. Most deaths from various sources of energy are only obtained through statistical methods. What these statistical methods do or do not include may vary.
The death count is also an incomplete metric because sources of pollution may impair living conditions at different degrees without directly impacting deaths.
An in-depth review on deaths from nuclear energy and other sources is available in appendix D.

In a nutshell

The world's population is projected to grow during the next decades, while CO2 emissions per capita remained approximately constant during previous decades.
Life expectancy in a country is correlated with its energy consumption. However, fossil fuels and biofuels emit fine particles which are an important cause of death in the world.
Food systems emit greenhouse gases, though alternatives and solutions exist. Food systems can be vulnerable to changes in energy consumption and climate.

1.5 Definition of the task

The task to solve as it is often summarized on climate-change is as follows:

> **Holding the increase in the global average temperature to well below 2°C** above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels [38]

This is Article 2 of the **Paris Agreement**.

This task alone is defined in an incomplete way. Given this task alone, a model could come up with wars as a solution. The real task to solve includes many other explicit or implicit constraints on how the problem can be solved.
Thus, the Paris Agreement also includes in its context:

> equitable access to sustainable development and eradication of poverty [...] fundamental priority of safeguarding food security and ending hunger[...]

Apart from limiting the increase in temperature, the two main other implicit or explicit constraints identified are: **to not seriously harm the life, or quality of life of the population**.

In this report, it will be considered that:

- Not harming the life of citizens is the **"Demography" part of the task**.
- Not harming the quality of life of citizens is the **"Energy" part of the task**.
- Not exceeding 2°C is the **"Climate" part of the task**.

This is the DEC task.

Multiple interactions occur between these parts.
The trade-off between the speed of emission reductions for climate, and the demographic and energy constraints is political. This political choice implies the difficulty of the task.

It is understood from the previous sections that **a too fast reduction of emissions could damage the context detailed in the Paris Agreement regarding poverty and hunger**. It is also understood from the previous sections that **a too slow reduction could damage climate <u>and</u>, therefore, the context detailed in the Paris Agreement regarding poverty and hunger**.

In order to solve this task under the specified constraints, the DEC model is used.

Chapter 2 The DEC model

The main contribution of this report is the DEC model. The DEC model implements constraints on demography, energy and climate to provide an optimized global planning to minimize climate change. The question is: **Is it possible to find a scenario that respects the Paris Agreement?** The model is highly configurable and gives the user several degrees of freedom. It includes measures and constraints on resources, energy sources, demography, global warming per gas, emissions per source, pollution, agriculture, energy consumption, transport, etc. on a per country per year basis. The model uses historical data to estimate what is feasible or not, under the pessimistic assumption that future technologies will not drastically change the constraints, and that if they did, it could only help in a context where new unexpected and unhelpful constraints could also arise. **The model has not found a scenario compatible with the Paris Agreement.** Interpretations are proposed, and results are provided.

1 Introduction

Climate change could impact every region of the planet [4]. 195 countries agreed to limit warming to well below 2°C [38]. Climate change is due to GHGs [4] and LULUCF. Increases in GHG concentrations are caused by human activities [4]. Addressing climate change implies to address human activities.

Several plans and analyses have emerged globally and for different countries to address climate change. IEA and other agencies analyzed constraints for energy in 2050 [39, 40]. IPCC evaluated multiple solutions over the world for energy and food systems [41]. UNEP evaluates current and future strategies [42]. Multiple countries made plans related to energy or to climate change [43, 44, 45]. **Current policies and current Nationally Determined Contributions (NDCs) would both put the world above the emissions target to reach 2°C** [42]. Thus, it is necessary to change current strategies and provide new ones that would be compliant with the "well-below 2°C" target.

Previously proposed plans and analyses consider different constraints and solutions: financial investments, mining resources, required surface area, energy efficiency, industrial production, GDP growth etc.. **This report mainly proposes to produce an energy strategy, based on available useful energy as a constraint.** The proposed analysis considers that the renewal of the energy system depends on the energy system itself, and that it's not possible to simultaneously

remove fossil fuels and increase low-carbon energy production (LCEP) without considering how the removal of fossil fuels will impact the ability to increase LCEP. The DEC model implements this constraint.
The model also builds a strategy up until 2100. Some plans evaluate strategies for 2050 which can benefit to production means with short lifespans.

Finally, the DEC model does not solely focus on energy and includes measures and constraints related to food systems, other GHG emissions and climate change impacts.

2 Generic modeling considerations

Appendix G provides a generic diagram of the model to present some limits of the methodology.

The task is defined in section 1.5. Constraints on how it can be solved are based on settings and data. The task, with settings and data, is given to the model, which is also constrained in how it can solve the task. The model is programmed to produce the best possible result to solve the task. This result doesn't necessarily solve the task entirely. **If the task is impossible to solve under the specified constraints, the model gives what it computed as the scenario that comes closest to solving the task.**

This model does not consider all details regarding the strategy it produces, it is not reality, but it aims at reproducing **a simplified yet representative-enough version of reality to solve the task**. The model uses many databases from many different sources. Some databases can be wrong, some databases can be verified thanks to other databases. When data is missing, it can be found elsewhere, interpolated, or estimated with correlated values. Some databases may also be inconsistent. For example, a database could say that 1 TWh of gas was consumed, and another will say that 1 TWh of electricity came from gas, which is impossible under Carnot's theorem. Which database is correct? If a third database doesn't give a clear answer, the source that seems to be the most reliable is used. In this situation, it could be considered that electricity production is measured more accurately, and gas consumption would be updated accordingly. It's also possible to have physically yet practically unrealistic data, these situations are also processed.

3 Goals

The strategy is to reduce future anthropogenic GHG emissions, while minimizing damages on living conditions. A model is implemented to output this strategy based on constraints derived from empirical data. The model starts from the current world situation on climate and human activities (energy, agriculture, etc.)[1] and, year by year in the future, country by country, it evaluates constraints on how to change human activities.

The model has a high focus on constraints related to energy. Figure 1.3 and fig. 1.6 indicate that coal, oil and gas used in energy are the main drivers of climate change. Constraints for other sources of GHGs are less precise.
Noting the lack of climate-positive changes on global GHG emissions during the last decades, **it was also perceived as extremely necessary to model how difficult it was to act**. Doing so seems critical for the result of a model to be credible.

[1]approximated based on most recently available data

In the proposed model, changing practices in energy consumption mainly means to reduce consumption of fossil fuels, and to replace them with non-fossil electricity with some constraints. Following this objective does not mean that all fossils can, will or should be replaced. This part is detailed in the next section.
"Maintaining living conditions", a requirement of the task, is associated with maintaining useful energy per capita. Though, this constraint is configurable.
The main final task can be simplified as: **minimize GHG emissions, maximize or stabilize useful energy per capita**.

4 Constraints

Introduced constraints are considered as the main contribution of this project. Many ideas can be used to build a plan on fossil fuel removal. However, despite multiple world agreements on GHG emissions, no visible change in CO2 emissions per capita can be observed (fig. 1.12). Some less-considered constraints may be delaying this change. A plan needs to drastically change how energy is consumed, while accounting for these hidden constraints. These empirical constraints push to be conservative on the speed at which fossil fuels can be eliminated and on how fast practices can change.
A part of the challenge is to measure these constraints, and to include them in the model.

Introduced constraints can be configured in the model. Any user of this model could easily amplify, reduce or remove constraints to evaluate what he or she thinks could be reasonable in the future. The results of this model can only be analyzed with the specified constraints.
Constraints in the model are implemented based on external data, and with respect to user configuration.

4.1 General assumptions

Assumptions made in this report aim to be a balance between pessimism and optimism, and are mostly simplifications of complex hard-to-modelize considerations.

The model doesn't account for experimental technologies on which there is not enough data. The model ignores progresses that could be made on cogeneration, including nuclear cogeneration. It ignores potential new facilities on wave and tidal energy, as data are insufficient on how fast these solutions could be implemented, and existing facilities are too few to estimate these values. Concrete projects are rare [46, 47, 48, 49].

The model also forbid higher electricity generation from biomass. LULUCF are currently a source of CO2 emissions. If some countries deforest to grow crops and others use land for biofuels, the land that is dedicated to energy could be used for crops instead, and deforestation would be less required (see appendix E for more details). The EROI of biofuels and its compatibility with developed societies are still under evaluation and depend on the considered biofuels and regions of the world [50, 51, 52].

The model assumes a global cooperation on energy and climate change, this assumption is considered as optimistic. There are no trade constraints between countries. Resources available somewhere are available for all countries with the idea that no country would benefit from slowing solutions to climate change. The strategy is defined per country such that they can independently decide on what their energy mix is. Electricity transfers are not directly considered. Countries need to at least keep producing the non-fossil electricity per capita they're already producing, no matter if they use it internally or for exports. It is considered that a country should not expect other countries to replace its own fossil fuel consumption with non-fossil electricity imports. While global cooperation is possible, it can be technically or politically complex. Many of these technical and political constraints are ignored, not because they won't happen, but because how to anticipate them is unknown. Political constraints appear difficult to anticipate.

How low-carbon electricity can be used to have the same qualities as fossil fuels is not entirely considered. The model considers that 10 TWh from low-carbon electricity in the future can provide the same benefits as 10 TWh from fossil fuels. **It ignores storage or intermittency constraints on computations related to available useful energy**. This assumption is considered optimistic.

Countries are able to decide autonomously on their energy strategy. The workforce to change an energy mix and reduce climate change is considered as available. A part of plants under construction aren't considered due to lack of data.

For fossil fuels, emissions are accounted for in the country where the fossil energy is consumed. Properly attributing GHG emissions is important for accountability and awareness. However, **the model does not consider imports and exports of services and goods to transfer emissions related to energy**. Doing so would imply that importers cannot act on a part of their emissions. They can't decide alone to decarbonize an activity outside their territory, apart from their ability to stop importations. It would also imply in the model that exporters don't need to act on a part of the emissions on their territory, while these emissions are located on their territory.

Emissions can be accounted for from a consumer or producer perspective, depending on which data is available and what seems more reasonable. For example, beef consumption could be addressed by saying that beef producers will change their production, or by saying that beef consumers will change their consumption. **The consumer perspective is used for food systems; the consumer perspective is used for fossil fuels; for electricity, the producer perspective is used**.

In the model, CH4-intensive livestock can be replaced with non CH4-intensive alternatives by changing food practices (section 1.4.2).
Emissions from cement plants, waste, LULUCF, and N2O/F-Gases emissions can be reduced, either per capita (activities highly depend on demography) or globally (low dependency on demography). How they can be reduced is not considered, the user can configure how fast solutions can be deployed. The model does not provide empirical constraints for these situations. The user is encouraged to rely on reliable external reports to estimate these values.

4.2 Demography

The model needs estimates on future population per country to compute how much energy is required per country. The model can use UN medium projection [30], or custom projections. Custom projections per country are based on migration, death and birth estimates. Detailed migration data which would account for emigration and immigration per country per year are scarce, and only available for a limited amount of countries ([53, 54]). It limits the accuracy of migration projections.
Projections on demography are highly customizable in the model. The goal of this model is not to provide an accurate estimation of population size for a coun-

try, but rather to provide accurate energy and food consumption constraints for a given population size in the future. Even for the same world population size, energy consumption may vary depending on where populations will be. Higher population sizes in less energy-intensive countries with lower population sizes in more energy-intensive countries will lead to lower energy consumption for the same global population size.

Custom models are required to make scenarios in which climate change impact health and population sizes. But, because these impacts are highly difficult to anticipate even when the model knowns how much Earth warmed, these impacts are usually not included in the results of the model (including climate migrations, impact of heatwaves on health, etc.). UN projections can be used if these impacts are ignored. If they are not ignored, detailed data on these impacts are required to produce accurate and evolutive custom population projections which can take them into account.

4.3 Fossil fuel phase-out

Fossil fuel phase-out is configurable per country following multiple constraints.
For each fuel (gas, coal, oil), **a delay before starting the phase-out is configured.** Thus, by allowing gas power plants for a limited period of time, the model can be configured to use them to replace coal power plants. The model can also be configured to allow coal for a specific period before starting the phase-out, the delay can be put at 0 to instantly forbid all new coal projects everywhere. Realistic constraints must be considered. **If a country was already decreasing the use of a fuel, the default delay before phase-out is set to 0**, forbidding future increases in that fuel use. Special considerations are used for some islands which could be highly dependent on oil, with high constraints on using other energy sources (wind, nuclear, dam, etc.) and electricity transfer.
For fossils in electricity, an end date for each fuel is defined. For all power plants, a standard end date is set based on estimated lifespans without phase-out. This first estimated end date is altered such that end dates for all power plants are re-scaled before the configured global phase-out end dates.

<u>Example:</u> if the global phase-out date is 2050, all power plants are forced to have an end date before 2050, and power plants which already had an end date before 2050 will have an even sooner end date.

Gas can be configured such that it's sole use is to replace coal, thus countries which do not use coal for electricity could not increase gas use. End dates can be delayed based on constraints related to phase-out speed, based on social constraints, or, if a gas power plant is set to end while a coal power plant is used, the coal plant could be ended in place of the gas power plant.

For fossil energy which is not used to produce electricity, phase-out is defined based on other constraints. Parameters define how fast vehicles which use fossil fuels decrease, including cars, mopeds, trucks, planes and boats, which impacts total fossil energy used. Many approximations are used. For non-transport non-electricity uses of fossil fuels (heat, ...), reduction rate is defined with a global parameter (for example -2% per year).

A minimum limit is also defined, proportional to recent consumption, to keep some fossil fuels for uses which couldn't be replaced. For example, if a country used 100 TWh of oil in 2019, oil consumption won't decrease below 5 TWh if the parameter is set to 5%.

Social constraints are included and detailed in section 4.7.

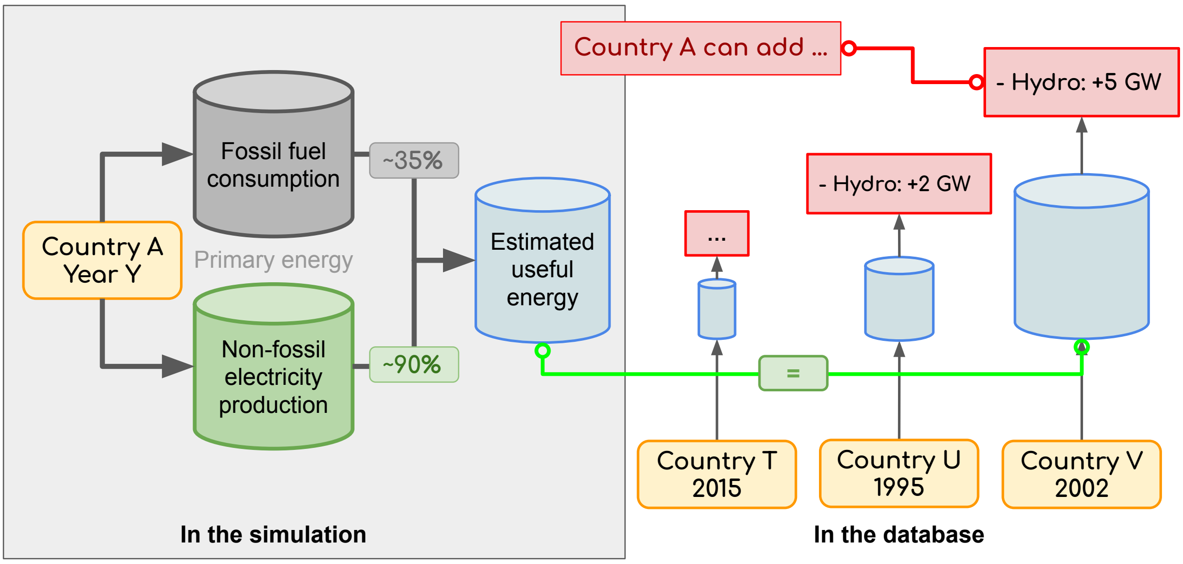


Fig. 2.1: Simplified representation of how the model evaluates the maximum potential for a country, for one year, for one source of electricity. In this representation, one example "V,2002" is used. In the model, multiple examples can be required. A multiplier can be used. Example: +5 GW (x2) = +10 GW. In this representation, the model is based on GW. The model can also use TWh, or a mix of both. True end potential involves other constraints.

4.4 Electrification: methodology and limits on speed

Power plants include any power generation system. **Main sources of electricity considered are coal, oil, gas, nuclear, geothermal, wind, solar, biomass and hydroelectricity.**

In order to replace fossil fuels, **electrification is the main solution accounted for in the model.** Other solutions can contribute, but they're not accounted for or represented in the model. **The main constraint is therefore the speed at which this electrification can go.** As the task is to raise or maintain living conditions, electrification is planned when fossil fuels are phased-out. When fossil fuels are planned to be phased out (no matter if they're used for electricity or not), how this phase out will impact useful energy per capita is evaluated. And, depending on settings and availability, **new less carbon-intensive sources of electricity are planned to replace this phase-out.**

Data from many sources were used in attempt to have an accurate representation of electricity mix, resolution is "still operating power plant" [55], per country, per year, between 1980 and 2019-2021, including capacity and production. Main sources are:[56, 12, 19, 21, 20, 22, 55].
Multiple constraints are defined **in order to implement a new power plant**:

- **A country needs to be qualified** to produce electricity from a source of energy. It can be qualified by already producing enough electricity, or by learning during a configurable amount of time.
- After it is qualified, a country can start building a power plant, the power plant starts producing at the end of the construction period.
- At the end of its configured lifespan, the power plant stops producing

A lot of constraints are also defined **to anticipate which new power plants can be added**. Each year, for each country:

- The model estimates how many new sources of electricity a country can add at most, based on historical data (see fig. 2.1). The assumption is that **the country is able to add at most what another "similar" country already added in history**. Similarity is measured with total useful energy. Parameters affect this rate: it can be a multiple of maximum historical data, and it can be a threshold so that countries cannot reproduce top 1 historical speed but rather top 5 or top 10. The model can use historical data on production, on capacity, or a mix of the two. If capacity or production is selected, the other value is estimated based on estimated capacity factors per country per source.

- **A climate rule limits this first estimate for fossil fuels** (phase-out described in section 4.3), including anticipating how gas can replace coal

- **A physical rule limits how much of that source can be added based on estimated physical constraints**, including limits in surfaces for wind and solar energy, limits on hydroelectric or geothermal potential by country, and a limit on new biomass power plants. Capacities outside populated human areas are not considered (offshore wind turbines aren't included in the model yet). This part is more detailed in section 4.5.

- A legal rule is then applied, as **nuclear energy is not allowed in multiple countries**, details in section 4.8.

- A limit in terms of controllability can be applied, such as if the controllability rate of the electric system is below a specified amount, non-controllable electric sources won't be developed, to prioritize controllable systems.

- A limit based on demography is applied, if the country is above the configured target (useful energy per capita), the model doesn't plan new power plants

- **A limit is then applied on the sum of all new productions, such that it cannot exceed historical values on this total**. If the sum exceeds historical values, settings define how values per source are modified, either by reducing all sources proportionally, or by reducing some sources rather than others.

- At this point, the model knows how much production and capacity it needs to add. **It proceeds to decompose this production/capacity as equivalent power plants**, based, if possible, on existing power plants

- **The best location for power plants is evaluated on a map based on constraints**: capacity factor for wind and solar, availability of a source from hydroelectricity and geothermal energy, safety and other constraints for nuclear energy and fossil fuels. The location of energy needs is considered.

Lifespan of power plants is considered. Climate (variation in rainfall [57]) is considered for hydroelectricity. Wear is considered for solar and wind [58, 59, 60].

4.5 Electrification: environmental limits

Power plants can only be installed where people are installed, above a threshold on density. The distribution of people on the planet is based on [61, 62]. The default density threshold used includes 95% of existing power plants from [55]. "Environmental limits" include limits which don't directly depend on the industrial pace.

Hydroelectricity is limited on where dams

can be added and how much electricity they'll produce based on [63]. The paper estimates that, at most, 50 PWh/year of hydroelectric power are available, and cite other estimates: "gross theoretical available potential of 36 to 128 PWh/year, a technical potential of approximately 8 to 26 PWh/year, and an economically feasible potential of 8 to 21 PWh/year".
With limits based on population density, a value of 15 PWh/y is obtained after processing data from [63]. A multiplier can be used on the estimated still available potential to remove optimistic projects: after the population constraint, the model indicates that Nordic and western European countries can still increase their hydroelectric production by x2-x4. This estimation can be considered as optimistic, the multiplier can be used to reduce the available production accordingly.

Capacity factor of **solar panels** is limited by [64], values are checked with [65, 55, 12]. 2000 PWh/y are estimated for solar panels just with constraints on land (no forests, no crops, above density limit). Constraints on resources, industries or storage are detailed later. Occupied and occupiable surfaces are considered based on [66, 65, 55]. The model considers that solar farms cannot replace crops, forests or urban areas. See appendix L for measures on required surface area.

Capacity factor of **wind turbines** is limited by [67], values are checked with [65, 55, 12]. 650 PWh/y are estimated on land (no forests, no crops, above density limits) and 380 PWh/y are estimated offshore (offshore depth limit -45m estimated from existing offshore wind turbines). Though, the model cannot build offshore wind turbines for now. The main reason is that offshore wind turbines would require a dedicated processing, and they are still scarce, so having realistic data on how fast they can be implemented is complex. Occupied and occupiable surfaces are considered based on [66, 65, 55]. The model considers that wind farms cannot replace forests or urban areas, though wind farms can occupy a part of the land used for crops. Competition for space between solar panels and wind turbines is included. See appendix L for measures on required surface area.

Geothermal energy is limited on where power plants can be added and how much electricity they'll produce based on [68]. Precise freely available data on the potential of geothermal energy for electricity are difficult to find. As it is unknown how optimistic estimations are, the model is configured such that 30% to 50% of existing reactors have a production below the one estimated in the dataset. New 1.2 PWh/y are estimated in populated areas.

Nuclear reactors are limited on where they can be added based on IAEA criteria[69]: "Criteria are related to the potential impact of natural hazards", constraints are simplified. The model includes: earthquakes[70], tsunamis[71], floods[72], rain[73], volcanoes[74], islands[66], mountains[66], air temperature[5], proximity with a city[66], population density[61], proximity with water[66] and existing nuclear reactors[55]. Risks are weighted. All positions of the world can be evaluated based on how suitable it is for nuclear reactors, including existing nuclear reactors, which were ranked using this criterion (see appendix M).

Fossil fuel power plants follow constraints similar to those of nuclear reactors. Weights for risks are evaluated differently.

4.6 Resources

Constraints on resources are measured but are currently **non-restrictive** in the model. The model knows if a limit is exceeded, but it won't stop the model from exceeding this limit. Limits on resources evolve constantly and the model doesn't entirely anticipate how they can change. The user can read the results and see whether the claimed consumption is realistic or not based on the limits.
Limits include reserve, resource[1] and total production per "object" (minerals, fuels, etc.).
Current limits for resources and reserves are defined for Coal[20, 75], Gas[20, 75], Oil[20, 75], Uranium[76], Aluminium[77], Copper[77], Steel[77], Concrete[77], Cobalt[77], Silver[77], Graphite[77], Lithium[77], Manganese[77], Nickel[77], Rare Earths[77], Silicon[77] and Zirconium[77]. Limits for production are also defined when available based on [78].
The model displays limits on production, but it doesn't consider this limit to estimate how fast new mines could open. The model just displays the ore demand to follow the proposed scenario and considers that this demand will be met. If the user does not consider it will, the user should re-configure and launch another scenario. The model does not account for future non-energy related uses of these minerals, though it is included in data on current production.

Material consumption for nuclear energy (reactors and fuel), solar panels, wind turbines, gas power plants and dams is estimated based on [44, 79, 80]. The introduction of fast breeder nuclear reactors and other non-U235 constrained ways to produce nuclear energy is considered.

Batteries for electric vehicles are considered by including the mix of different types of batteries per year (NMC622, NMC111, NMC811, NCA, LFP, LTO). For example, a global transition towards LFP batteries can be configured. Proportions can be configured based on [44, 81]. The average battery size of vehicles is a setting. "Vehicle mix" (proportion of cars / mopeds / trucks) is estimated per country, proportions do not change over time. Changes in the number of vehicles per capita is configurable. The model indicates the demand for minerals required for batteries with no regards to how fast they can be mined or transformed into batteries. The lifespan of electric vehicles is considered. Recycling rates per material per year are considered.

The model does not directly consider the energy required to undermine resources. The model does not directly consider the relationship between fossil energy and mining. A scenario could include zero-fossils and a lot of mining. If the user considers this solution as unrealistic, more realistic constraints on fossil fuels phase-out can be configured, as detailed in section 4.3.

4.7 Social constraints

Social constraints are implemented to simulate **how a too-fast transition is accepted or rejected by people**. One of the main constraints of the model aims at maintaining or increasing useful energy per capita. Electrification is based on a fossil fuel phase-out. If constraints on electrification make the transition too slow, individuals could experience a rapid decline in living conditions and refuse the transition. A parameter defines a limit to not reduce useful energy per capita below a threshold
Example: with a parameter set at 70%, if useful energy per capita goes below 70% compared to the initial situation, fossil fuel phase-out is stopped until electrification catches up.

[1]mining jargon, resources are more optimistic than reserves

As most social constraints are hard to anticipate, most parameters related to social constraints can be configured by the user. Including how fast emissions can be removed from planes, how fast red meat can be removed from food consumption, how fast deforestation can be stopped, how fast CO2 emissions from cement can be reduced etc.

How fossil fuels can be replaced is evaluated based on previously specified constraints. However, how fast poultry (as an example) could eventually replace beef in a scenario is unknown. It's considered a social constraint, and the user can freely define the value. The user can also decide to not replace some uses, or even to increase some uses, and see the global warming that results. The evolution of the number of vehicles per person is also configurable.

Constraints on employment are not directly considered, they are indirectly and incompletely considered based on education delays and on the other constraints introduced for electrification.

4.8 Legal constraints

Legal constraints are considered for nuclear reactors, as they are prohibited or not recommended in some countries. **Legal constraints can be configured**, all countries may be allowed, all countries except those that forbid nuclear energy may be allowed, all countries may be disallowed except those which are already using nuclear energy, all countries may be disallowed. Social constraints may impact the legality of nuclear power during a simulation according to parameters, if energy from fossil fuels is decreasing too fast, nuclear reactors may be allowed even if the global configuration disallowed them.

Legal constraints on nuclear energy include prohibition by law, phase-out by law, by declaration, and prohibition for security reasons (see appendix M.3).

Direct legal constraints on fossil fuels are ignored (including NDCs). It is considered that if a country does not succeed in its transition, it will not obey legal constraints on fossil fuel phase-out.

4.9 Feedback

Feedback relates to how results from the model one year in one country impact other or future results of the model. **Feedback is under-implemented in the model**. Some algorithms are implemented to create feedback, and the model is designed to process feedback in multiple ways. However, applying these algorithms makes the model more difficult to interpret and to verify. Nevertheless, it is still possible to estimate how feedback would act on a measure, without impacting this measure in the model. For example, the impact of energy systems on mortality can be evaluated, displayed as an information for the user, without impacting the demography that'll be considered in the model.
For each implemented situation, the following list indicates if it is "applied", meaning it impacts future results of the model, or not, meaning results are just displayed for information.

- **Future temperatures and rainfalls are estimated over the whole planet**, based on [57, 4], details in section 4.10. Future rainfalls impact the production of dams, this feedback is **applied**.

- Feedback includes **pollution from fossil fuels** per country, including PM2.5[17, 35], and lethality from all sources of electricity [36, 37]. Estimation of lethality for nuclear energy is custom, details in appendix D.1. **Not applied**.

- Impact of **extreme heatwaves on health** is implemented. **Not applied**.
- Impact of **climate change and energy changes on crop yield** is estimated. **Not applied**.
- Impact of **energy consumption on life expectancy** is estimated. **Not applied**.
- Impact of **transport electrification on electricity demand** is estimated. **Not applied**.
- The model estimates resource consumption and reserves. **Not applied**.

4.10 Estimation of GHG emissions and climate impacts

For each year, for each country, GHG emissions are estimated based on direct fossil fuel consumption and other changes in human activities (see General Assumptions: section 4.1).
Emissions and impacts of CO2, CH4, N2O, F-Gases and SO2 are estimated with a simplified climate model.
The methodology is as follows:

1. estimate how an activity which produces a gas will vary
2. estimate how the variation of this activity will impact emissions of that gas
3. estimate how emissions of that gas impact another value which is correlated to how much this gas impacts global warming; estimate global warming
4. estimate local warming and rainfalls based on global warming

More details are available in appendix J.1.
This is a simplified climate model; it doesn't represent reality. This simplification is used to reproduce results from other climate models in a predictable, controllable and simplified way. **If a new climate model gives different parameters, this model can easily be adapted to copy results from that new model.** This method also eliminates any computation time constraints.

For (1), estimations of how an activity will vary are detailed in previous sections.

For (2), estimations of how the variation of this activity will impact GHG emissions are based on data used to produce fig. 1.3.

For (3), estimations of how GHG emissions will impact global warming are based on a proxy value. For CO2, the proxy value is CO2 concentrations. For CH4, N2O, and F-Gases, the proxy value is their Global Temperature Potential (GTP) for year Y based on emissions from Y0 (oldest available data) to Y-1. For SO2, the proxy is current emissions, as it is assumed that SO2 impacts on the climate are short term.

First, the impact of emissions on the proxy value is estimated. An example with CO2 is shown in fig. 2.2.

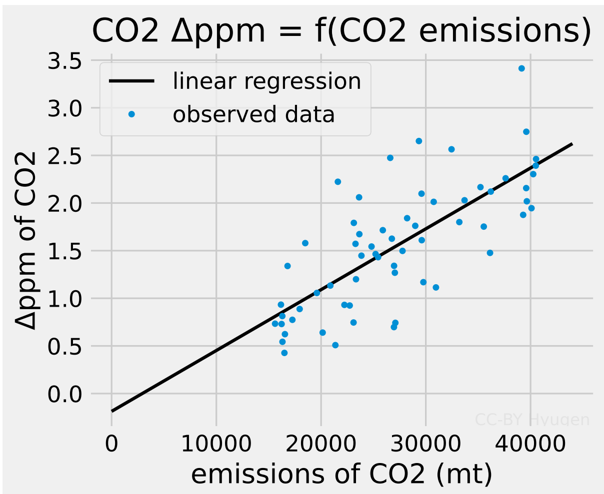


Fig. 2.2: Impact of CO2 emissions on CO2 concentrations [82, 83]

How this proxy value impacts warming is then considered.

Estimations of how the proxy value impacts global warming are estimated by linear models under constraints. Average global warming is computed as follows:

The simplified model to estimate future warming is:

$$global\_warming = \sum_{gas}^{gases} warming(gas)$$

For CO2, the equation is:

$$warming(CO2) = i_{CO2} * CO2ppm + j_{CO2}$$

where CO2ppm is the proxy value of CO2. In order to learn i and j, a dataset with CO2ppm and CO2warming per year is required. CO2 ppm per year can be found in [82]. CO2_warming is built as a function of empirical global warming: $CO2\_warming = a * global\_warming$. The same method is applied to all considered gases, giving 5 parameters a, b, c, d, and e.
a, b, c, d and e are estimated with random search. With a, b, c, d and e, historical warming per gas can be estimated, i and j can be estimated per gas, and the simplified model can be built. The error used in random search is based on:

- the distance between predicted warming per gas and warming per gas in [4]
- and distances between predicted global warming and global warming in emission scenarios of [6] (ch1, fig1.5).

Using only highly constrained linear white-box models limits the risk of overfitting and unexplainable results.

All values predicted by the model are within error bars in [4, 6]. Average distance is 0.05°C per random-search constraint, the highest distance is 0.16°C (SO2 value used by IPCC[4]: -0.49°C, predicted value by the model: -0.33°C, IPCC's likely CI: [-1,-0.1]).

Estimations of how global warming impacts local temperatures and rainfalls are based on estimated impacts of Shared Socioeconomic Pathways (SSPs) by CMIP6 (Coupled Model Intercomparison Project) [57, 4].

Local temperatures are available for multiple years and SSPs. Global warming can be estimated based on local temperatures for each year and SSP. Local temperatures and rainfalls are then linearly regressed with this average global warming. In a limited number of positions, a same average global warming can cause a wide range of local warming or rainfalls, depending on the SSP (right plot in fig. 2.3). The largest error, averaged on all years and SSPs for a position, is 0.81°C.

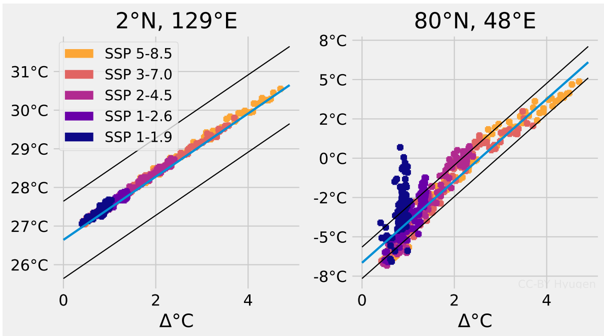


Fig. 2.3: Best (left) and worst (right) local warming regression as a function of global warming, black lines = +/- 1°C, CMIP6 SSPs:[57]

5 Settings

The model primarily provides a methodology and potential constraints.
By default, the model has few constraints. One could configure the model to only keep fossil fuels and to remove all non-fossil electricity. **Results of the model can only be interpreted based on the specified configuration**. The user of the model is responsible for this configuration.
The model currently uses more than 200 parameters.

A list of all parameters can be found in appendix H as well as an example of a configuration file in appendix I.

6 Results

The model provides a per country per year GHG emission reduction scenario based on the specified settings. The model proposes an energy mix and a resource consumption scenario, per country and globally, according to the settings. The model provides the climate impact of the proposed scenario, globally and locally.

Results for one configuration can be found in chapter 3 and chapter 4.

Findings are based on the configurations used for this work, under what the author estimated as realistic or interesting constraints. Other findings could be produced with other configurations.

Main results from simulated scenarios are:

- **No energy transition scenario to stay below +2°C with realistic parameterization was found.**
- **No energy transition scenario to electrify transports and other activities without exceeding a limit on mineral resources was found.** Resources that will be exploited in excess of reserves by 2100 when only energy transition is accounted for are Cobalt, Lithium, Silver and Uranium. Other resources close to the reserve limit in 2100 are Copper, Graphite, Nickel and Natural Gas. Resources without constraints on reserves for the transition are Aluminium, Manganese and Zirconium.
- The more low-carbon energy sources are restricted (such as nuclear energy), the harder it is for an energy transition to remove fossil fuels while maintaining living conditions.
- **In all scenarios, the total number of energy-related deaths decreases as long as the use of fossil fuels decreases.**
- Some countries can sufficiently increase their non-fossil energy consumption to replace their fossil energy consumption.
- The proportion of electricity generated from non-controllable sources is projected to increase.
- Global warming caused by methane could decrease or stabilize. Global warming caused by F-gases and N2O could increase. Global cooling caused by SO2 could decrease.

7 Discussion

Within the tested parameters:
The absence of a valid energy transition scenario which would respect the Paris Agreement goals is due to **multiple hard-to-anticipate constraints**. Energy systems are extremely complex, they involve hundreds of sub-systems (power plants, resources etc.) which are differently configured in dozens of countries with hundreds of constraints (laws, employment, education, etc.).

The configuration and evolution of some of these systems were simulated. Despite using some optimistic assumptions, like the absence of feedback from resources, from most climate change effects, the unconstrained ability to use intermittent sources of energy, **the model does not succeed in providing an under +2°C scenario**.

A deep understanding of the system dynamics would be required to fully comprehend the results. Interpretations are proposed.

Based on results, countries with a low hydroelectric potential and high consumption of fossil fuels have high constraints to electrify their energy consumption.

It is interpreted that low-carbon energy sources with an empirically too low increase rate and a short power plant lifespan can undergo an elastic effect detailed in appendix B. With high energy consumption coming from fossil fuels, the production from these low-carbon sources can greatly increase by installing more capacity. Then, energy transition applies, fossil fuels are removed, which at first decreases energy consumption, and how fast the capacity from these sources can increase. Previously installed power plants from these sources reach their end of life, which decreases production from these sources. At this moment, there is a lack of possibility of renewing these plants, as not enough energy remains. **The more energy is used now to amplify capacity from these sources, the higher the decline will be when it comes to replacing these sources, hence the elasticity.**
Accurate planning is of utter importance to avoid this elastic effect. Plans must consider the lifespan of power plants, wear, energy required to raise capacity and to replace old power plants, and impacts of fossil fuel phase-out.

While changing energy consumption and reducing other GHG emissions locally is possible, the pace of a global transition is constrained. The organization of a global strategy is yet to be done and earlier action would have helped for staying below +2°C.

Recent energy transition in some countries is highly suboptimal on the health or climate change issue (appendix D.2) and on the issue of equal access to energy (appendix F).

Future works include considering load balancing, peak load and base load. Constraints on daily electricity production and consumption should be considered more precisely to recommend a better energy mix and minimize outages. Electricity imports and exports could be considered. Current work optimizes the strategy per country, a global strategy must be considered to avoid highly suboptimal actions (appendix F, appendix C, appendix D.2). Potential for geothermal electricity and heat, and biofuels should also be further investigated.

Future works also include computing more precisely how much of fossil fuel energy ends in waste heat.

Storage needs to be calculated more accurately (lithium, pumped-storage hydroelectricity) as well as needs and industrial capacities for high-density storage (hydrogen) and electrolyzers.
Future mining potential should be estimated more accurately for additional reserves, availability of reserves, proportion of a resource used outside of energy transition, feedback should be applicable when realistic constraints on resources can be configured. Realistic reserves and resources of uranium and other elements should be further investigated.

Monte-Carlo methods could be used to find optimal scenarios, with random parameterizations in realistic intervals.

8 Conclusion

A model is proposed to address climate change and energy issues. This model includes multiple human activities and constraints on how energy systems, food systems and other GHG emitters will evolve. It also includes metrics on the impact of climate on populations and agriculture. **The DEC model did not find a scenario in which global warming could be solved without impacting living conditions in extreme ways.** New models should be made; new scenarios should be tried. Locally, transitions happened, and within a constrained environment, transitions will continue to happen. In order to minimize risks, plans are required to decide these transitions instead of undergoing them.

Chapter 3 Global results

3.1 Interpretation of results

Results from the model are not an anticipation of the future.
They should rather be perceived as what maximum decarbonization efforts could achieve, according to a specific configuration.

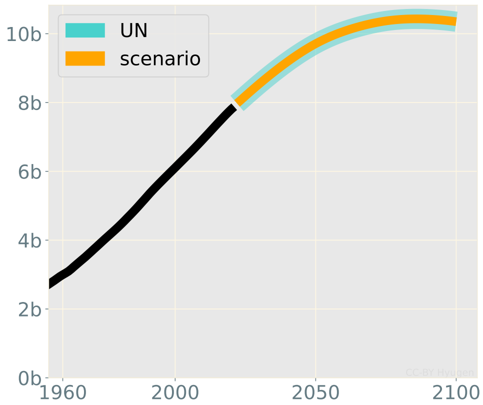
They come from a simulation under multiple constraints. The model can be configured to favor or disfavor any source of energy. The purpose of the model is to see if the given configuration allows for credible compliance with climate commitments. **Results provided in this report were made with what the author assumes realistic or interesting constraints are**, these considerations are subjective. Results are not assumed as being realistic by default.
The simulation mainly runs between 2023 and 2100 and may compute incomplete data between 2019 and 2023 if necessary. A black bar may indicate 2022 on graphs if necessary.

Results can be used to guide more precise scenarios at the country level. Approximations were used to make the model work for the whole world, these approximations reduce the accuracy of the model on a local scale.

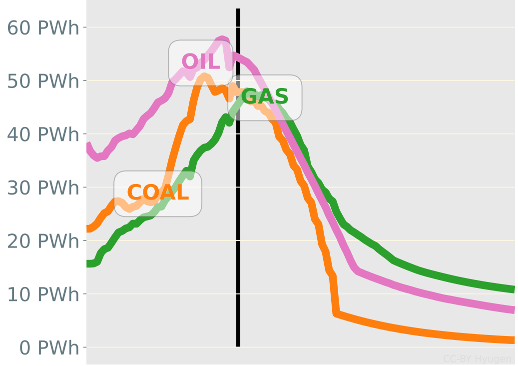
Results can be fully interpreted only with their configuration.
These results should not be interpreted as "the only DEC scenario". They represent one possible scenario with one configuration. The DEC model can produce multiple scenarios with multiple configurations. It can't be represented by only one scenario. The main contribution of this report is the DEC model, not the results of this model for only one given configuration.

Overview of one scenario

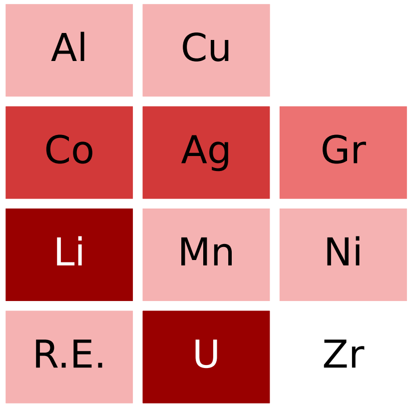
(click on results for more details)



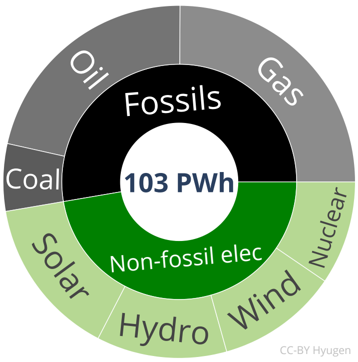
(a) World population



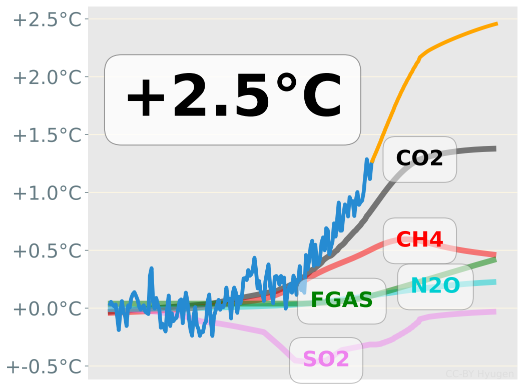
(b) Fossil consumption



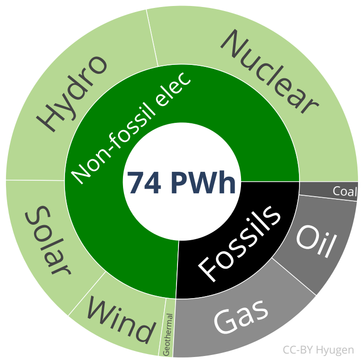
(c) Constraints on resources



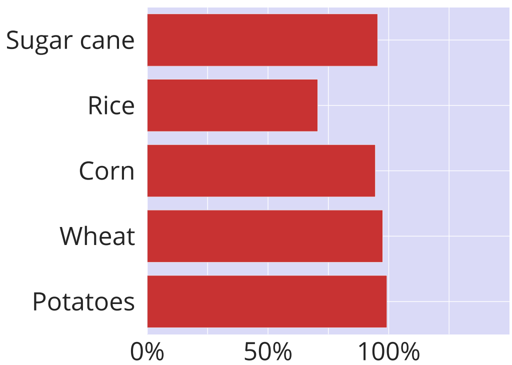
(d) Energy mix 2050



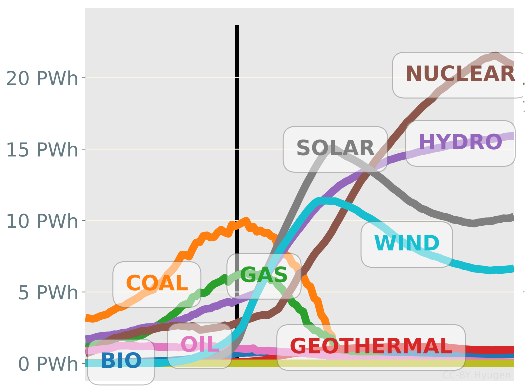
(e) Warming per gas



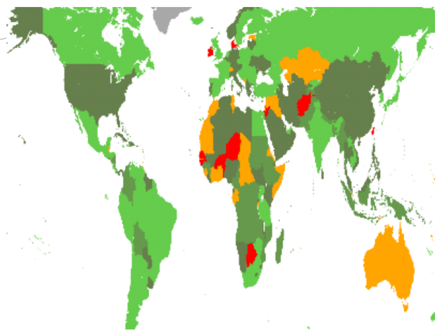
(f) Energy mix 2100



(g) Evolution of crop yields



(h) Electricity generation



(i) Energy per capita variation

Model version: **260** | Results ID: **b4fd588aa2ef73b2d32d**

3.3 Demography

The DEC task requires preserving the life of citizens. Main sub-results analyzed for demography include: global demography (fig. 3.2), life expectancy, pollution, deaths from energy sources and food supply.

World population grew from **4.4** billion in 1980 to **8.0** billion in 2022. World's needs were computed for **9.7** billion people in 2050 and **10.4** billion people in 2100.

World's population is at its highest in **2086** with **10.4** billion people.

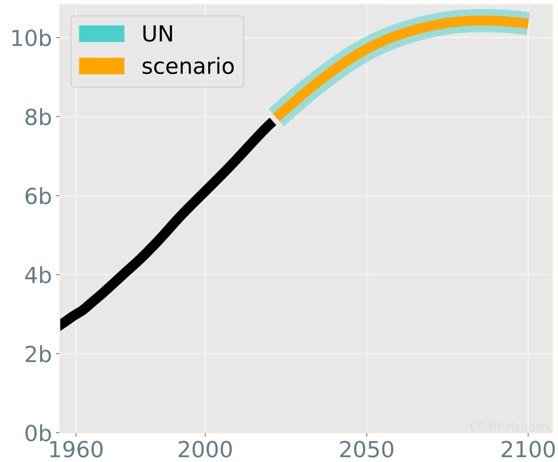


Fig. 3.2: World demography in the model, orange indicates the demography which was configured, turquoize indicates UN medium scenario [30]

3.3.1 Life expectancy

Maintaining life expectancy is a constraint of the model.

Average life expectancy at birth changed from **62.2** years in 1980 to **67.7** years in 2000 and to **73.1** years in 2019. Life expectancy is used to measure if the model preserved the quality of life of citizens.

Future life expectancy is estimated based on the variation of useful energy per capita (fig. 3.3). Based on user configuration, the model expects average life expectancy per capita to be at **71.8** years in 2050 and **70.2** years in 2100.

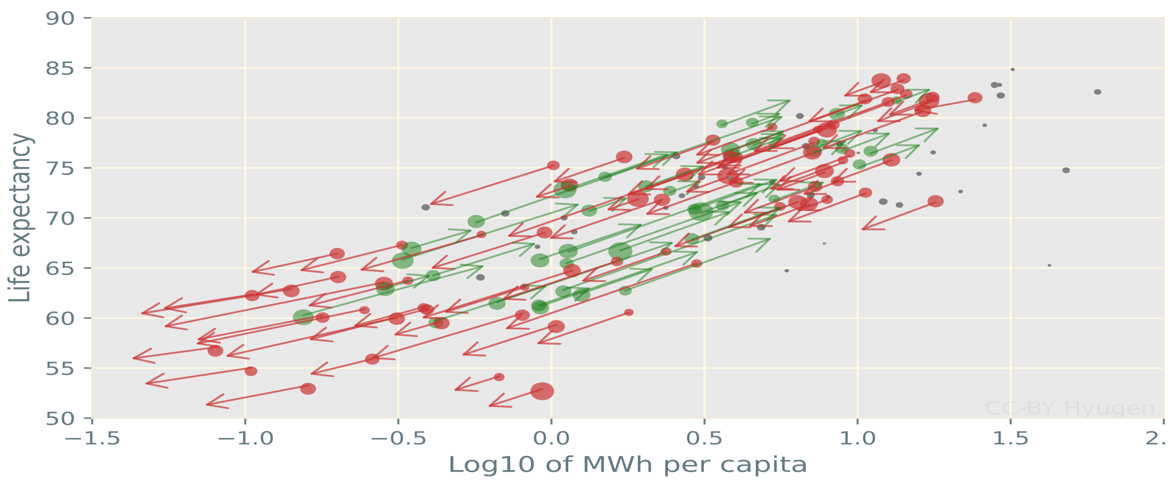


Fig. 3.3: Life expectancy as a function of useful energy per capita, arrows represent variations between 2019 and 2070, small countries and small life expectancy variations are not represented, see fig. 1.13

3.3.2 Pollution

Main measures of pollution in the model are PM2.5 deaths and deaths from all electricity sources.

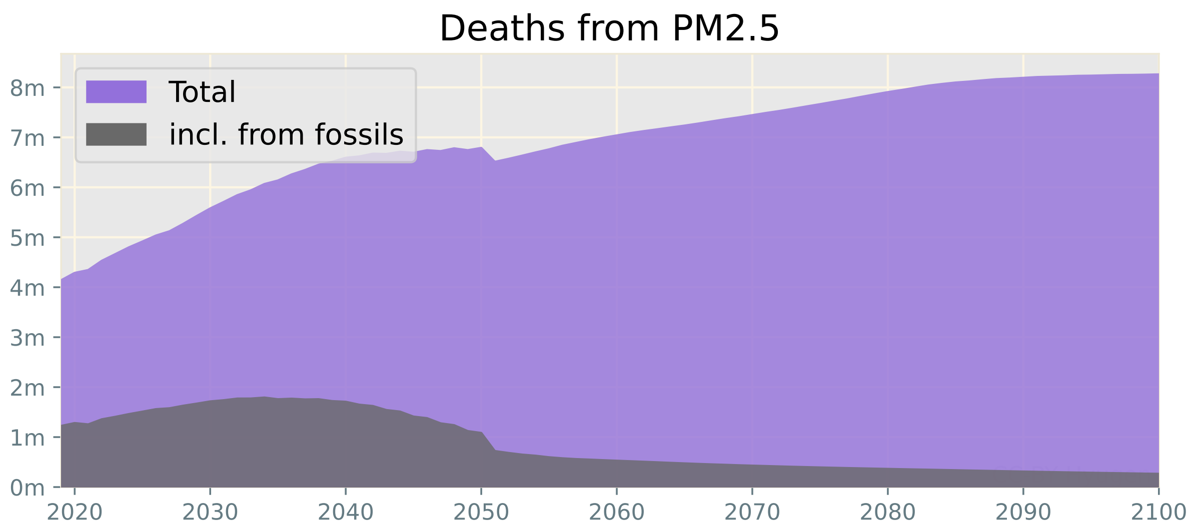


Fig. 3.4: Projected deaths from PM2.5. See section 1.4.3, [17]

Deaths from PM2.5 due to fossil fuels evolve from **1.2** million in 2019 to **0.3** million in 2100 (fig. 3.4). Total deaths from PM2.5 are estimated based on population growth and PM2.5 deaths from all causes. It's assumed that emissions of PM2.5 which don't come from fossils stay constant. As a simplification, removing X% of PM2.5 because fossil fuels were phased out removes X% of deaths from PM2.5.

The evolution of electricity-related deaths can be visualized in fig. 3.5:

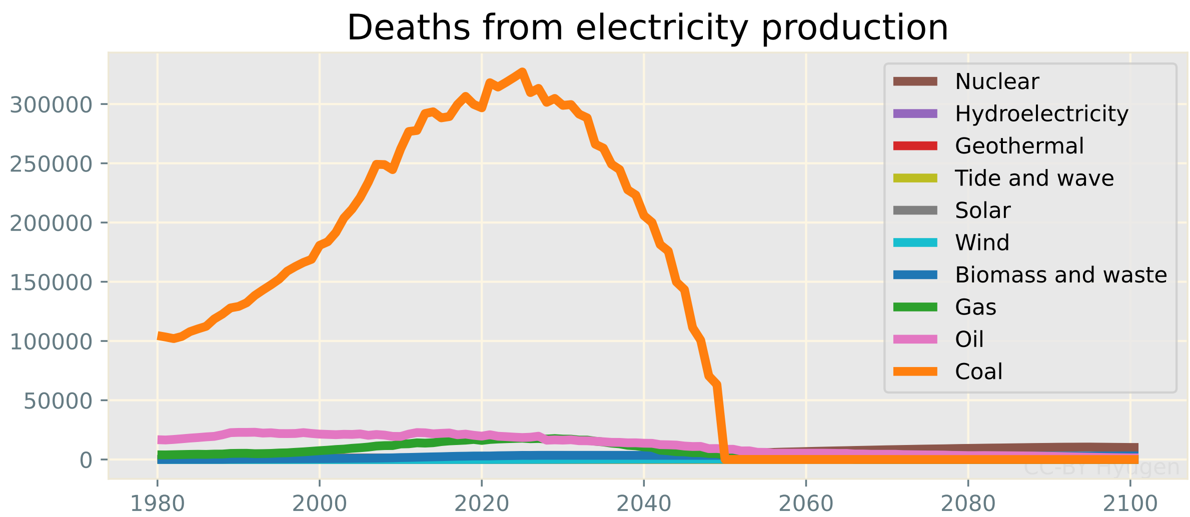


Fig. 3.5: Estimated deaths by source of electricity production per year, based on deaths / TWh by [37] and appendix D

The cumulative total of deaths related to electricity generation between 2025 and 2100 is **7.3** million in this scenario.

3.3.3 Food

Agriculture is a source of GHG emissions and can be impacted by climate change. The model evaluates how food production and consumption will vary based on user configuration.

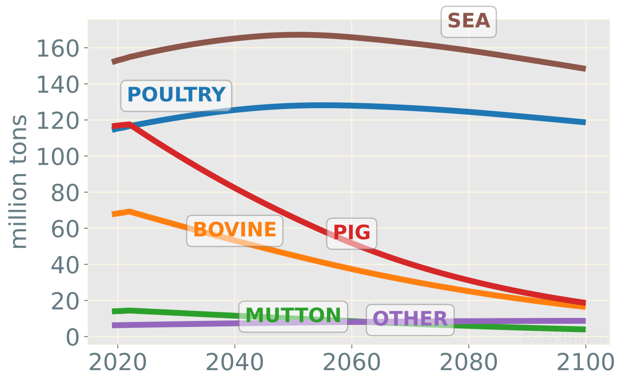


Fig. 3.6: World meat consumption based on user configuration and [84]

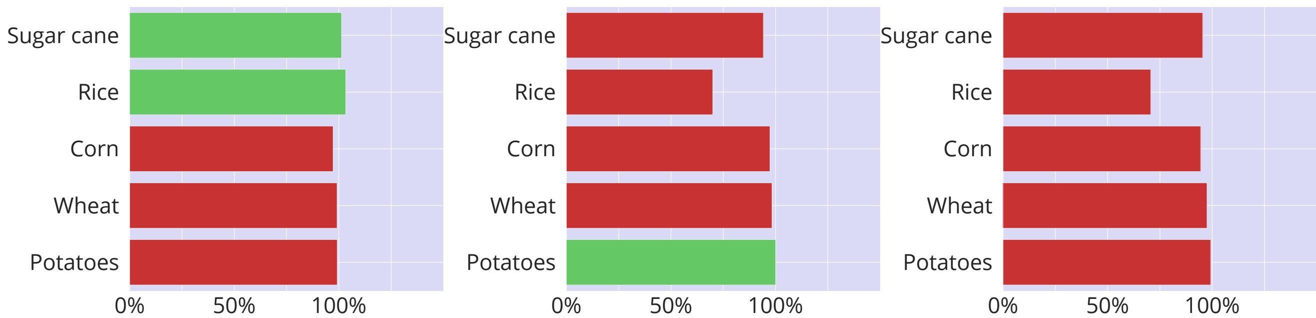
In 2019, **116.5** mt of CH4 were emitted because of livestock. Based on user configuration, livestock will emit **83.7** mt of CH4 in 2050 and **38.9** mt of CH4 in 2100. Meat consumption can be observed in fig. 3.6.

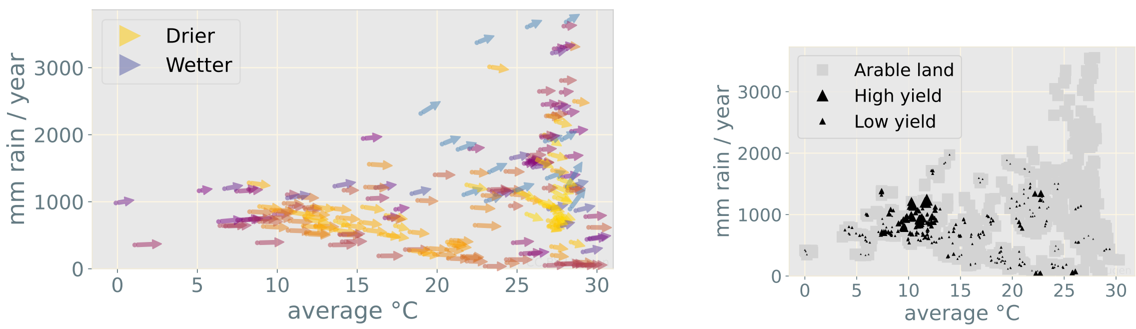
Changes in crop yield per country are correlated with changes in energy and climate in a country. Global results can be observed in fig. 3.7.

The most produced crops in the world include sugar cane, rice, corn, wheat and potatoes. In 2020, crop production for rice was **756** mt, **760** mt for wheat, **1162** mt for corn, **1869** mt for sugar cane and **359** mt for potatoes.

Fig. 3.7: Evolution of crop yields between 2019 and 2100 based on...

(a) Energy production (b) Climate change (c) Climate and energy





(a) Variations on rainfall and temperature per country, 2100-2019, weighted by population distribution

(b) Empirical wheat yield based on temperature and rainfall (corrected for energy correlation)

Fig. 3.8: Climate evolution and wheat yield

3.4 Energy

3.4.1 Overview

Results on energy focus on fossil fuels and electricity.
Based on user configuration, consumption of fossil fuels in energy can continue to raise only for **5** years for Coal, **5** years for Oil and **15** years for Gas. Consumption of fossil fuels for electricity can continue to raise only for **5** years for Coal, **5** years for Oil and **15** years for Gas.
A global transition from fossil fuels to electricity is planned, fossils may not be entirely replaced based on user configuration.

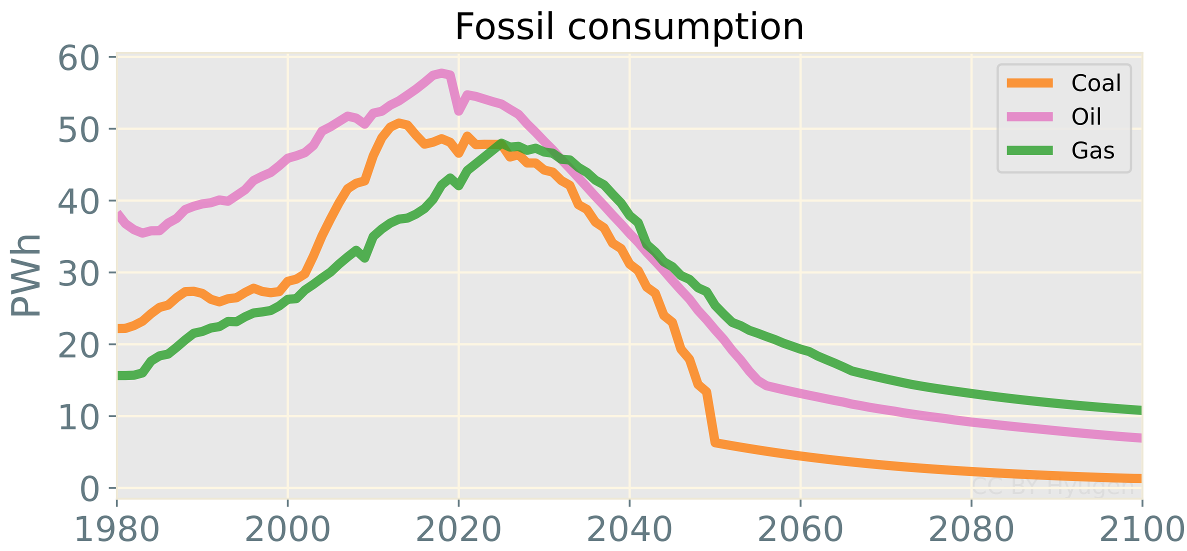


Fig. 3.9: Fossil fuel consumption per year

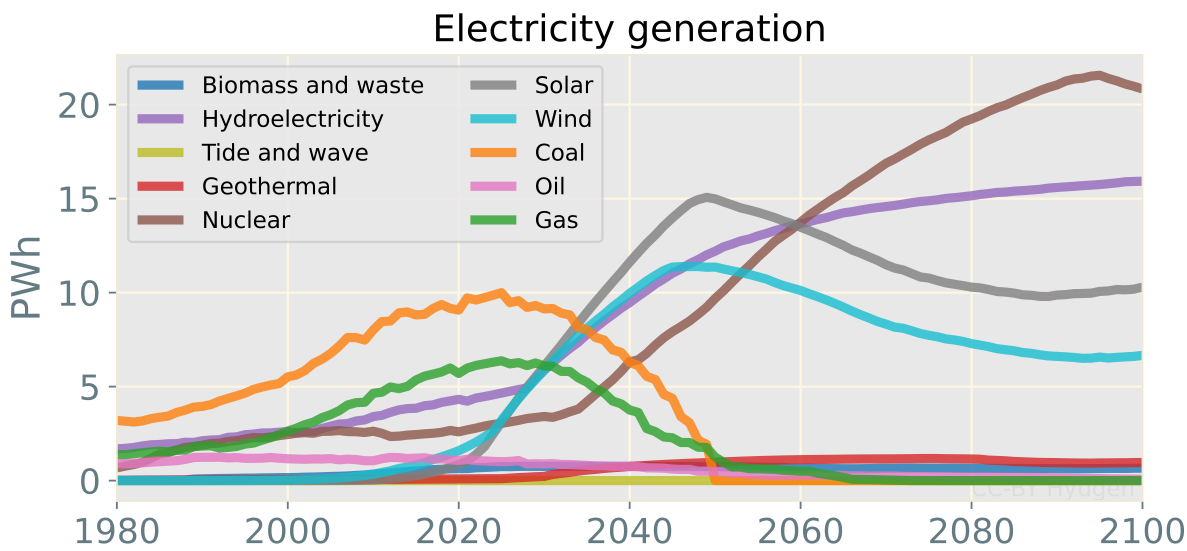


Fig. 3.10: Electricity production per year

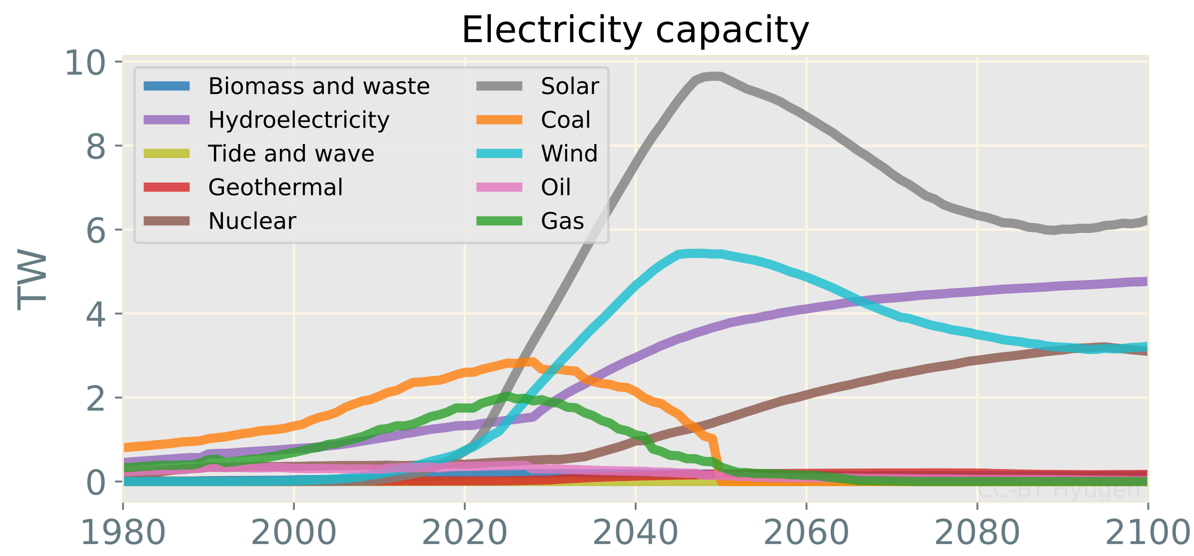


Fig. 3.11: Available capacity per year

The provided scenario mainly relies on the following sources: **Hydroelectricity, Nuclear, Solar, Wind**. Between 2019 and 2100, **electricity generation from hydroelectricity changed by a factor of x3.8.**
Electricity generation from nuclear changed by a factor of x7.8.
Electricity generation from solar changed by a factor of x14.7.
Electricity generation from wind changed by a factor of x4.7.

The proportion of useful energy generated from fossil fuels is projected to go from **85%** in 2019 to **12%** in 2100, renewable thermal sources aren't included in these computations.
The global carbon intensity of electricity (gCO2 / kWh) evolves as follows:

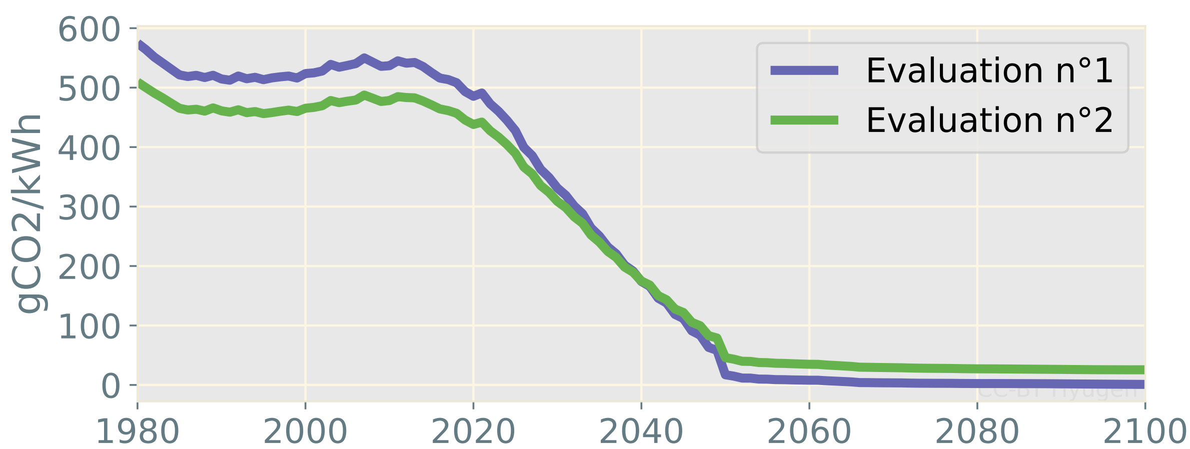


Fig. 3.12: Approximate evaluation of carbon-intensity of electricity, first evaluation only accounts for fossil fuels used in electricity and waste heat estimates, second evaluation uses lifecycle emissions from [85]

Non-fossil electricity sources don't emit CO2 directly. The carbon intensity (gCO2 / kWh) for these sources is correlated to the quantity of fossil fuels they indirectly use, which could be replaced by other sources of energy in some situations during the transition. The second evaluation is provided based on a constant carbon intensity per source, this evaluation is more precise for the current energy consumption in the world. However, it doesn't consider how the transition can itself impact CO2 emissions from low-carbon electricity sources in the future.

Power generation is computed for this scenario based on the additional and removed generation capacity per year and per source, which can be visualized in fig. 3.13.

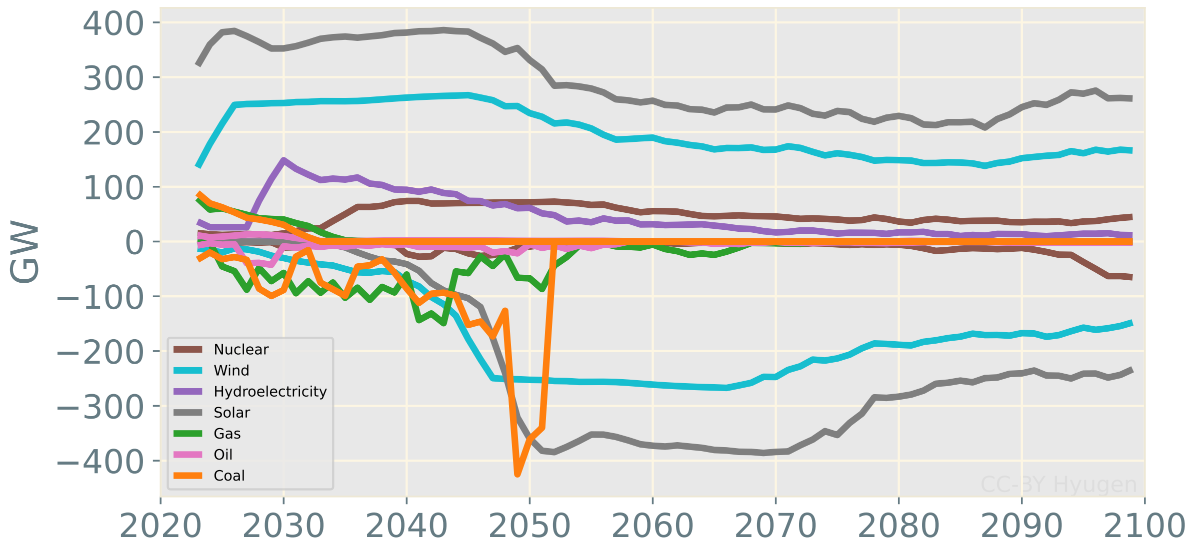


Fig. 3.13: Added and removed electricity generation capacity per year

Depending on the configuration, the capacity increase for an energy source a year may be compensated by the end of life of some power plants of that source that same year, which would void the net added capacity that year.

In order to estimate how much capacity the model can add in one year for a country and a source, the model seeks for similar examples in history.
Lifespans of power plants, construction delays and number of examples are based on user configuration per source:

Source	Lifespan	Construction delay	Education delay	Number of Examples
Nuclear	60	8	8	5
Wind	20	0.17	1	3
Solar	25	0.17	0	3
Hydroelectricity	150	6	3	5
Gas	40	3	3	5
Coal	60	3	3	5
Oil	50	3	3	5
Tide and wave	150	3	5	5
Biomass and waste	40	3	5	5
Geothermal	50	3	5	5

Table 3.1: User configuration per source, time is expressed in years

It is possible to represent how much electricity generation the model can anticipate to add per year per country based on a country's current energy consumption and based on the specified number of examples:

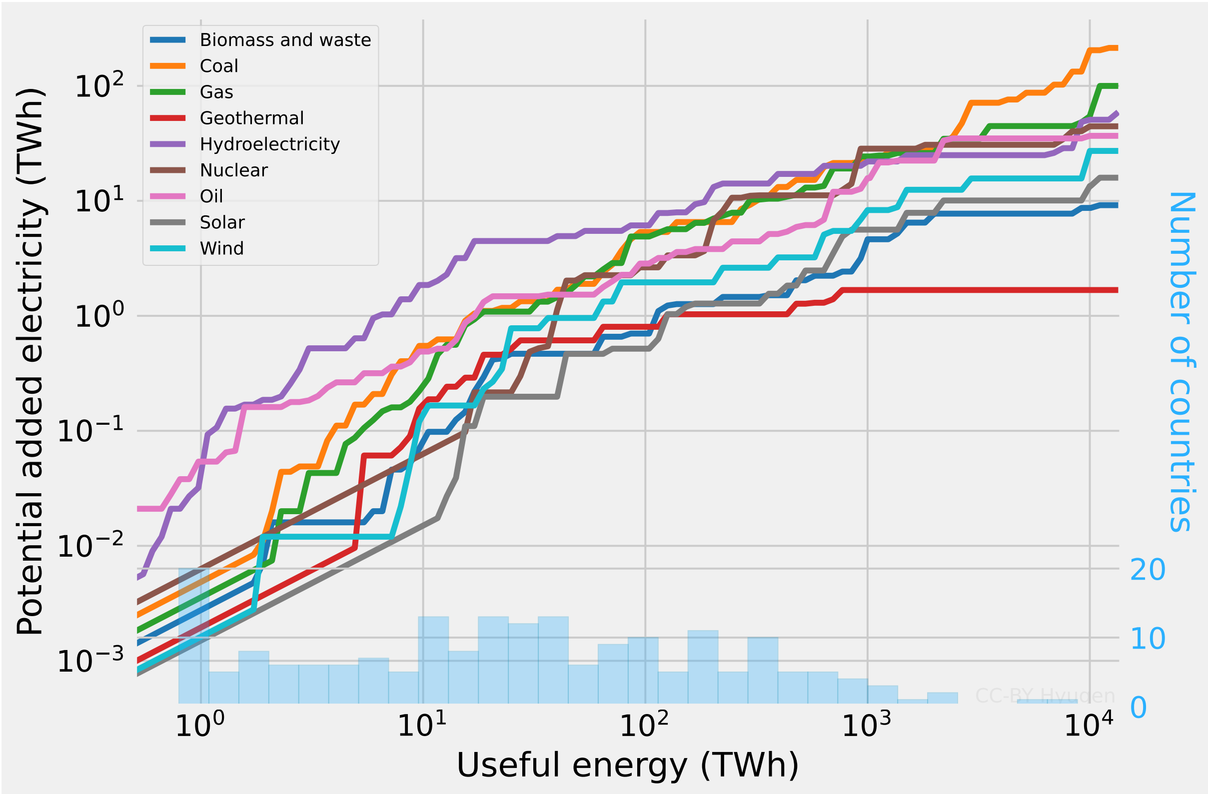


Fig. 3.14: Given an amount of energy (x-axis), how much new electricity generation at most a country can add (y-axis), based on the given number of examples which added more in the past, the histogram indicates the number of countries with the specified amount of useful energy in 2019

Results for small amounts of energy with no empirical data are linearly correlated with the closest amount. For example, if 10 GWh of Solar can be added in countries with 200 GWh of useful energy, 1 GWh of Solar can be added with 20 GWh of energy.

The main idea is that a country should be able to add less new electricity generation with more energy compared to what N other countries which added the most electricity from that source did in the past with less energy. Thanks to this design, for all results of the model, for all years, all countries and all sources, it is possible to provide N examples of countries which, in the past, added more electricity generation, with less useful energy available, except for a specific acceleration which can be configured (see "acceleration multiplier" in results per source of electricity).

The graph can be read as follows, if a country has 100 TWh of useful energy (x-axis=10^2), it can plan to add: 6.1TWh of Hydroelectricity, 5.4TWh of Coal, 4.9TWh of Gas, 2.8TWh of Oil, 2.6TWh of Nuclear, 2.0TWh of Wind, 0.8TWh of Geothermal, 0.7TWh of Biomass and waste, 0.5TWh of Solar, after the construction delay. And for each energy source, the model can provide N examples which added more in the past with less useful energy available.

In further detail, for hydroelectricity estimates come from: Mozambique in 1999 added 6.1TWh with 8TWh of useful energy, Paraguay in 1986 added 7.8TWh with 12TWh of useful energy, Paraguay in 1987 added 6.6TWh with 19TWh of useful energy, Paraguay in 2016 added 7.9TWh with 68TWh of useful energy, Portugal in 1996 added 6.4TWh with 85TWh of useful energy. Natural variations could be included but are considered negligible compared to capacity increases. This example is provided for production but same computations are done for capacity, the user decides on the metric.

For nuclear energy, estimates come from: Lithuania in 2001 added 2.8TWh with 33TWh of useful energy, Lithuania in 2002 added 2.6TWh with 36TWh of useful energy, Lithuania in 1995 added 3.3TWh with 36TWh of useful energy, Slovakia in 2000 added 3.2TWh with 80TWh of useful energy, Finland in 1981 added 7.2TWh with 87TWh of useful energy.

For wind, estimates come from: Denmark in 2019 added 2.2TWh with 72TWh of useful energy, Denmark in 2014 added 2.0TWh with 73TWh of useful energy, Denmark in 2017 added 2.0TWh with 74TWh of useful energy.

If a country has 1000 TWh of useful energy, it can add: 28.4TWh of Nuclear, 24.3TWh of Gas, 23.2TWh of Coal, 22.0TWh of Hydroelectricity, 15.8TWh of Oil, 8.3TWh of Wind, 5.6TWh of Solar, 4.6TWh of Biomass and waste, 1.7TWh of Geothermal.

For gas, estimates come from: Egypt in 2010 added 24.8TWh with 386TWh of useful energy, Spain in 2019 added 25.3TWh with 598TWh of useful energy, Spain in 2008 added 24.3TWh with 673TWh of useful energy, Mexico in 2006 added 26.0TWh with 781TWh of useful energy, United Kingdom in 2016 added 40.2TWh with 900TWh of useful energy.

If a country has 10000 TWh of useful energy, it can add: 204.2TWh of Coal, 54.3TWh of Gas, 50.7TWh of Hydroelectricity, 44.5TWh of Nuclear, 36.8TWh of Oil, 27.2TWh of Wind, 13.5TWh of Solar, 8.7TWh of Biomass and waste, 1.7TWh of Geothermal.

For coal, estimates come from: China in 2003 added 204.2TWh with 5479TWh of useful energy, China in 2004 added 208.3TWh with 6592TWh of useful energy, China in 2005 added 213.8TWh with 7362TWh of useful energy, China in 2006 added 289.2TWh with 8135TWh of useful energy, China in 2007 added 318.9TWh with 8771TWh of useful energy.

Data may include approximations, which is why multiple examples are required.

A multiplier can be applied per source to artificially amplify or reduce how much of a source of electricity countries can add. This multiplier is used to provide a bonus for energy sources that would be considered as emerging by the user (i.e. historical potential is not representative of future potential). This metric is more practical to use in this model than the EROI, but it doesn't supersede the original EROI. If the EROI provided by a Life Cycle Analysis is insufficient for a specific project, it needs to be considered.

The model evaluates: "how much new electricity generation could be added in the future?", based on how much was added in the past with similar constraints.

The same method is applied for capacity and, depending on the source, either capacity (GW) is used, generation (TWh) is used, or an average of both, and an estimate of capacity factor, in order to evaluate how much new capacity a country can anticipate to add in the future.

The model re-schedules closure dates for fossil fuel power stations:

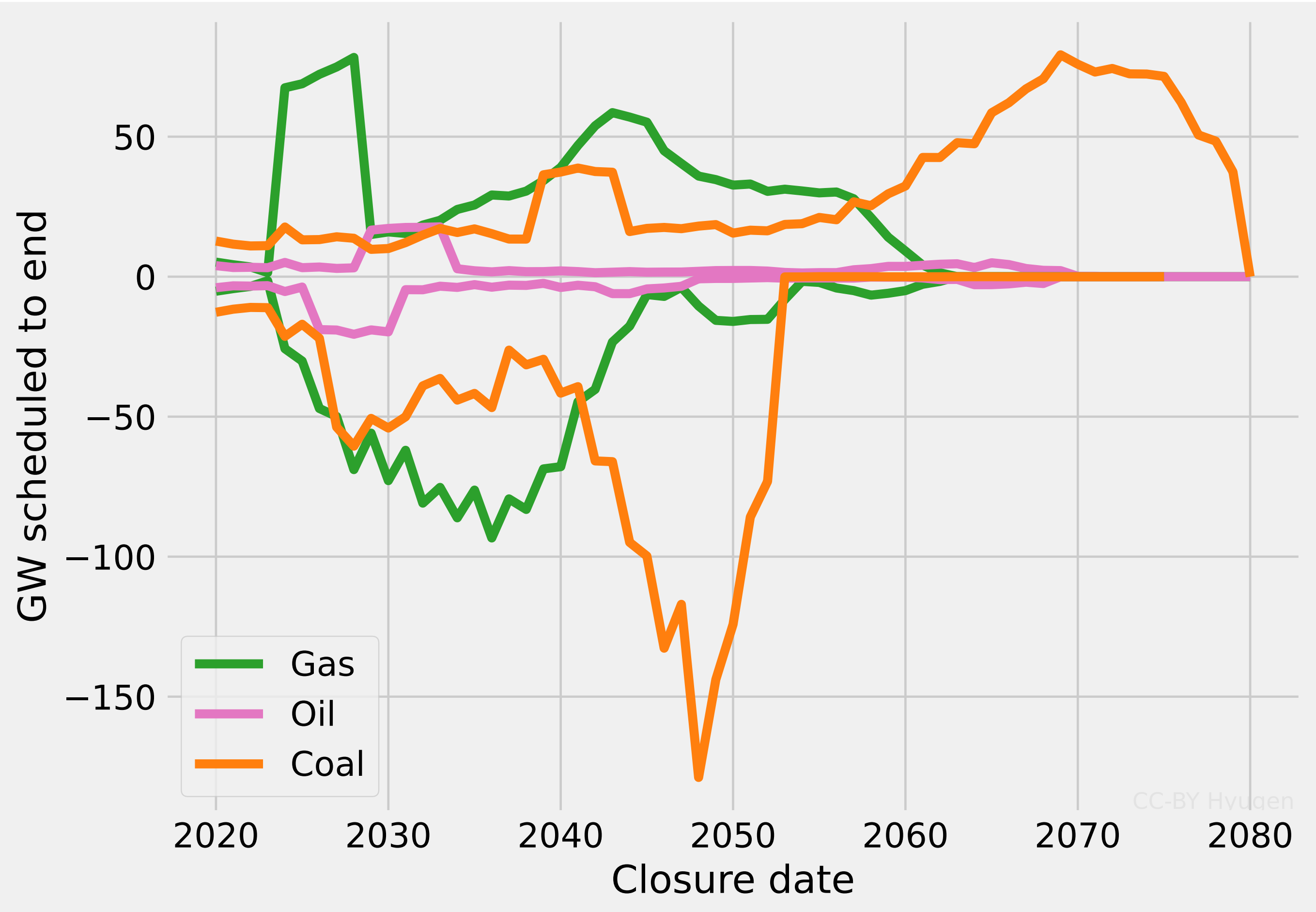


Fig. 3.15: Closure dates of fossil fuel power stations, positive values indicate estimates of original closure dates, negative values indicate re-scheduled closure dates, delays may be applied per country

If it is configured as such by the user, a fossil fuel phase-out can be observed. It ends fossil fuel power plants in a much more abrupt way that what is configured by default.

The model estimates changes in useful energy per capita between 2019 and 2100:

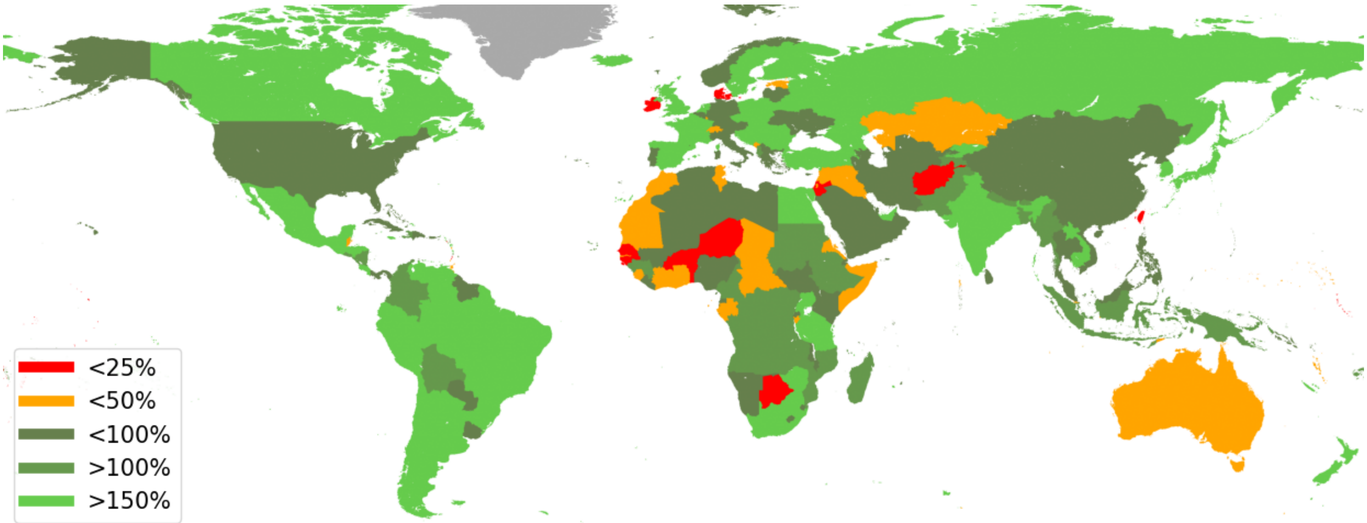


Fig. 3.16: Variations on available useful energy per capita per country between 2019 and 2100, in this scenario, based on user configuration

Some sources of electricity are able to produce based on demand, others depend on the environment and are more difficult to use alone.

Low controllability may imply high storage needs or strong needs for adaptation, which may not be realistic.

The model doesn't evaluate if it is realistic or not. The user may consider whether the specified amount of controllable and intermittent energy is credible or not. **Non-controllable electricity generation includes 100% of wind, solar and tide electricity, and 10% of hydroelectricity.** Proportions of controllable electricity can be observed in fig. 3.17.

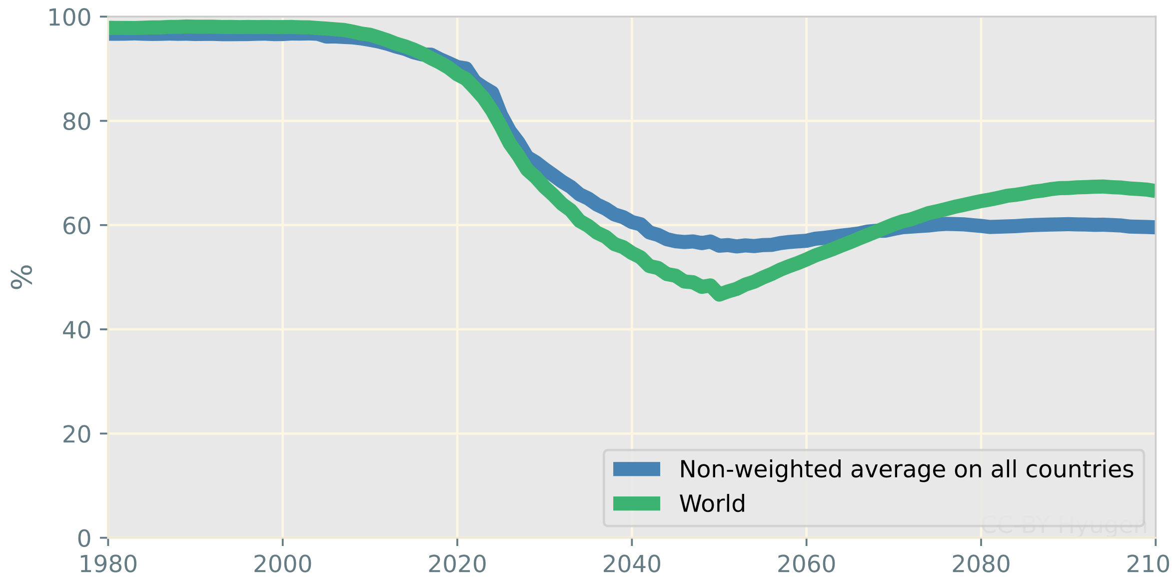


Fig. 3.17: Proportion of controllable TWh of electricity per year in this scenario

3.4.2 Transports

The user is able to configure how the main fossil fuel transportation systems will evolve, including: road transports, planes and boats. Results for road vehicles can be observed in fig. 3.18.

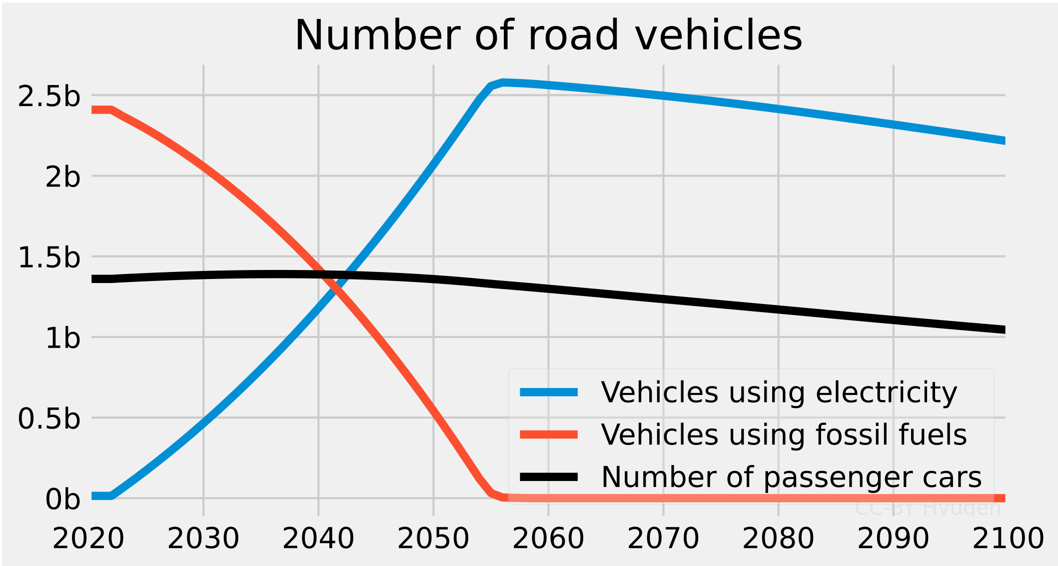


Fig. 3.18: Evolution of the number of road vehicles per year in the world, including cars, trucks (heavy vehicles) and mopeds (very light vehicles), based on user configuration, appendix K and [86]

The model does not consider industrialization pace, it computes how transports evolve based on user configuration, and it estimates the associated needs on electricity generation and resources. The user can re-schedule the fossil fuel phase-out in transports.

The model aims at replacing each road vehicle using fossil fuels with an electric vehicle, with some constraints. According to user configuration:
Per-capita evolution of road vehicles using fossil fuels is **-2.0%** per year.
Per-capita evolution of road vehicles using electricity is **-0.3%** per year.
The user configured a battery size of **50** kWh for cars. Electric heavy vehicles require **7** times this amount, and electric mopeds require **0.1** times this amount. Evolution of different types of batteries is configured by the user in fig. 3.19.

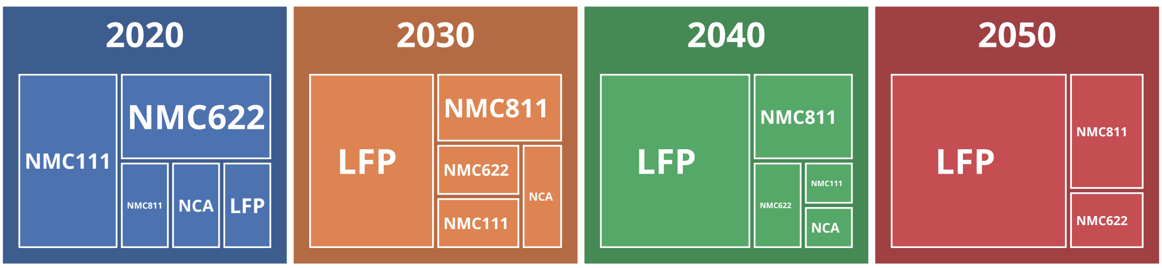


Fig. 3.19: Evolution of battery types based on user configuration, 2020: [81, 44]

The average distance traveled per vehicle is estimated based on available data and per capita oil consumption. Power consumption of cars is estimated based on the average travel distance per car and the number of cars.

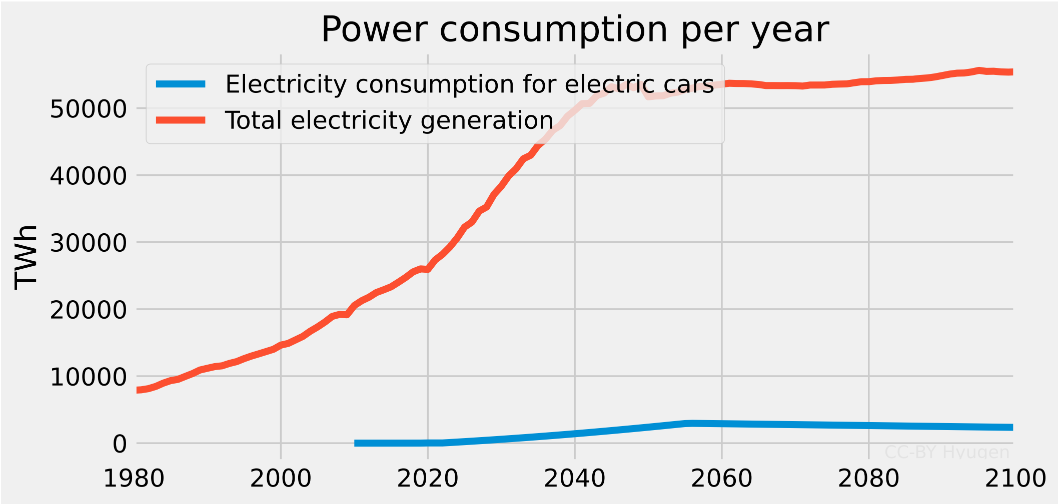


Fig. 3.20: Electricity consumption per year for passenger cars compared to total electricity generation in the world

Detailed per-country per-year evolution of heavy / standard / very-light proportions in total vehicles is not yet included in the model, proportions are considered constant per country.

3.4.3 Resources

Resource needs are estimated by the model, but evaluated constraints are not applied and don't impact the transition. The model estimates resource needs for EVs' lithium batteries and power stations. Resource needs for non-EV related storage systems are ignored. **Copper consumption for large scale grid interconnections is not included**.
The model includes estimates for **Aluminium, Copper, Steel, Concrete, Cobalt, Silver, Graphite, Lithium, Manganese, Nickel, Rare Earths, Silicon, Uranium, Zirconium**. This list doesn't include all resources required for the transition.

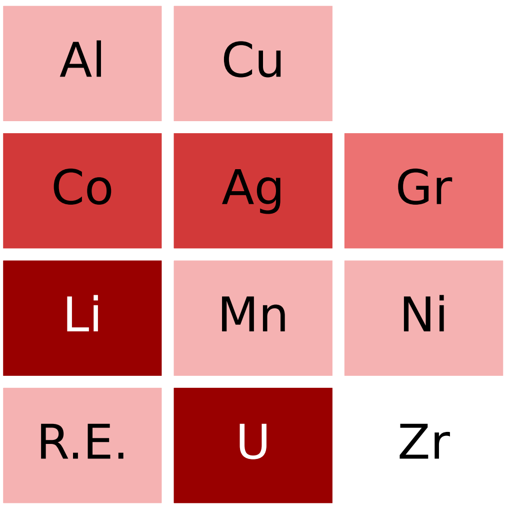
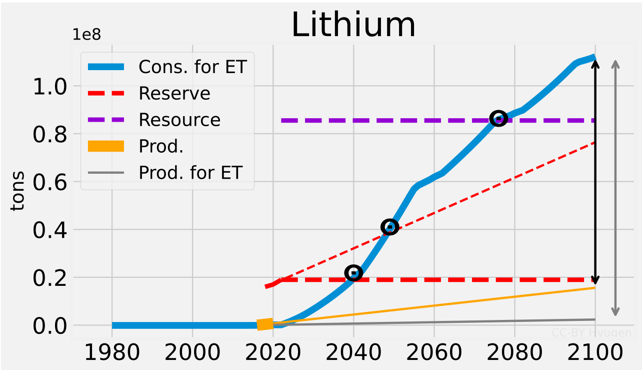


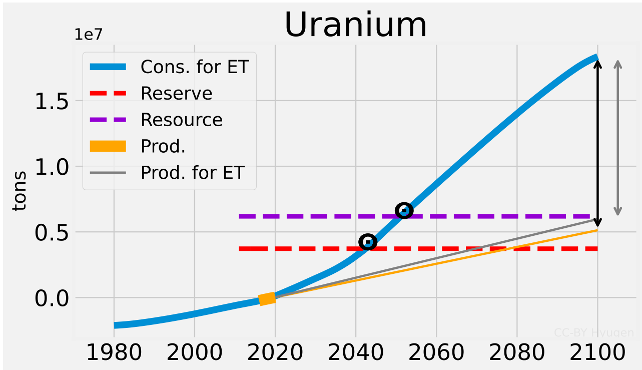
Fig. 3.21: Constraints on resources. White: no constraints expected. Dark red: many constraints expected. Gr=Graphite, RE=Rare Earths

Five types of constraints are considered on resources. (1) Whether consumption will exceed estimated current reserves, (2) whether consumption will exceed anticipated reserves, (3) whether consumption will exceed estimated resources, (4) whether consumption could exceed estimated future total production, (5) whether consumption will exceed estimated future production dedicated to energy transition.

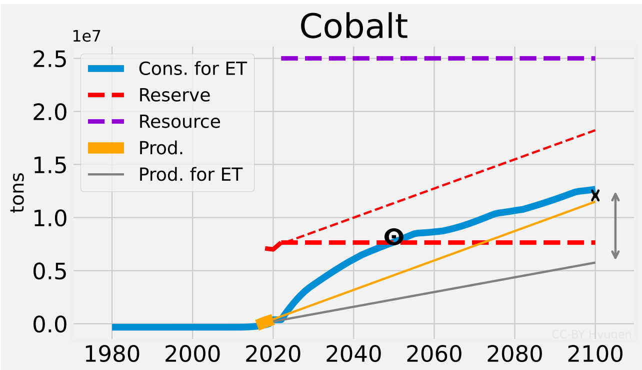
Arrows and targets represent constraints* (targets may be slightly off their correct position), ET = Energy Transition :



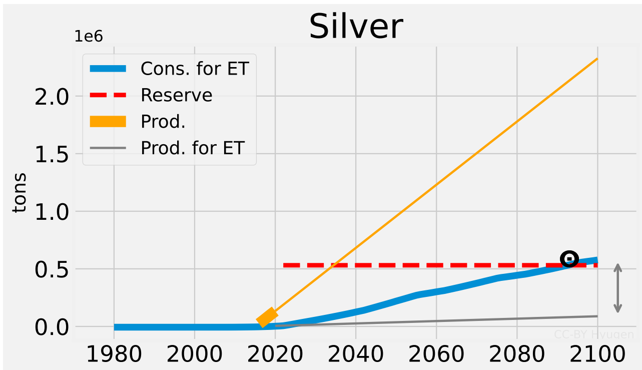
(a) Lithium: 5 constraints*



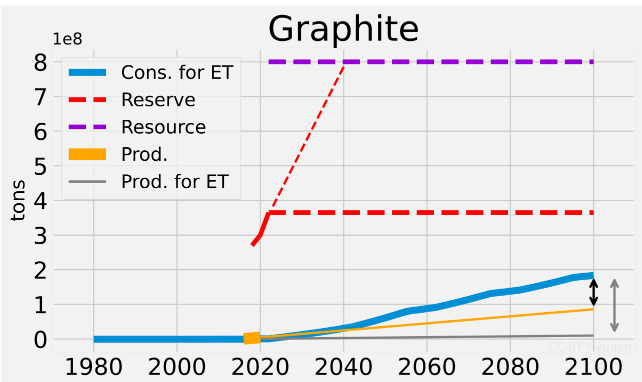
(b) Uranium: 5 constraints*



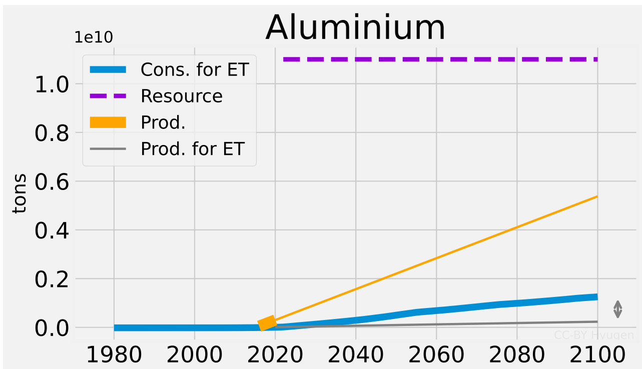
(c) Cobalt: 3 constraints*



(d) Silver: 3 constraints*



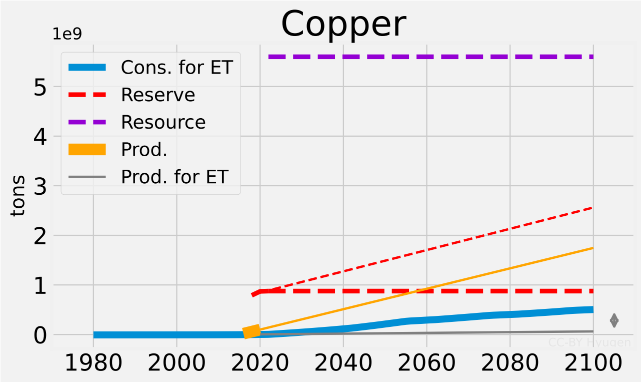
(e) Graphite: 2 constraints*



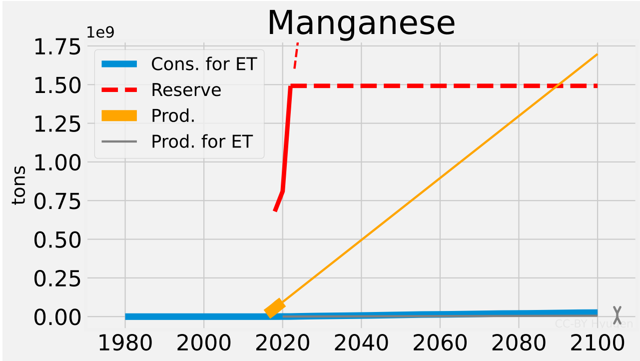
(f) Aluminium: 1 constraint*

Fig. 3.22: Resource consumption - Part 1

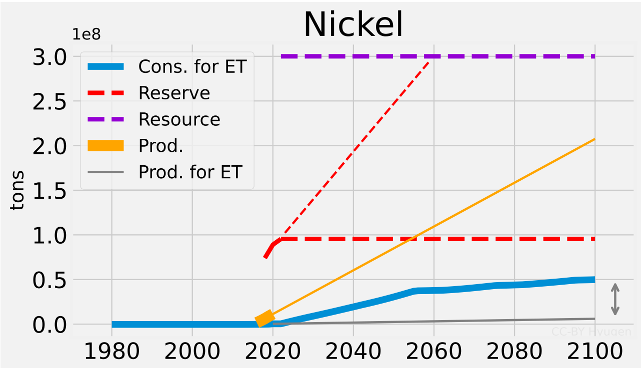
*As evaluated by the model. The model doesn't evaluate all possible constraints on each resource.



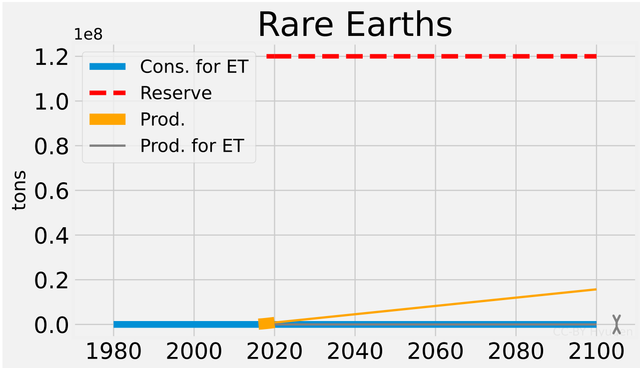
(a) Copper: 1 constraint*



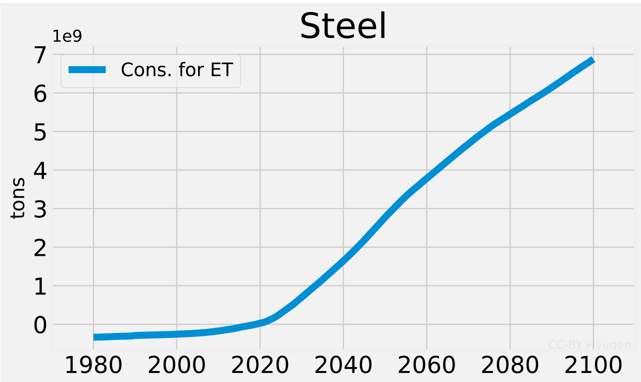
(b) Manganese: 1 constraint*



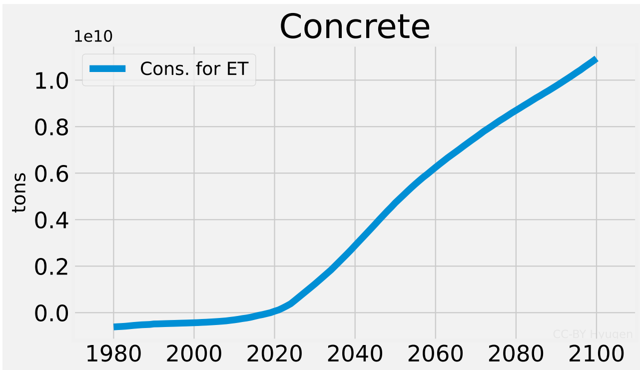
(c) Nickel: 1 constraint*



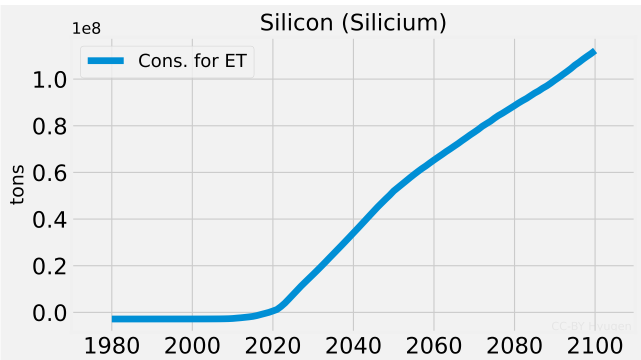
(d) Rare Earths: 1 constraint*



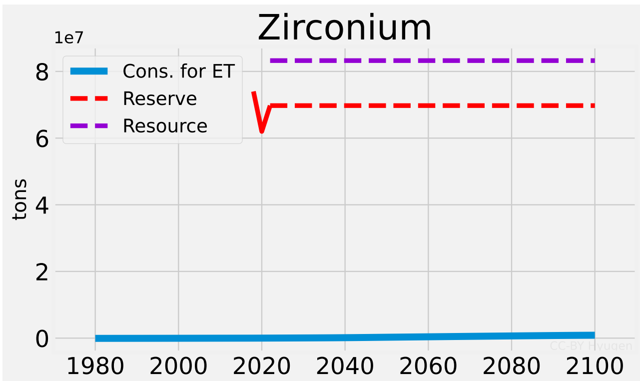
(e) Steel: 0 constraint*



(f) Concrete: 0 constraint*



(g) Silicon: 0 constraint*



(h) Zirconium: 0 constraint*

Fig. 3.23: Resource consumption - Part 2

Data for consumption and production is cumulated over the years and includes recycling. Resource, reserve and production data are not available for all resources.

Multiple metrics are estimated: what future reserves will be like, based on a linear regression on recent evolution of newly discovered reserves. What future production could be, based on a linear regression on recent evolution of production, and what future production available for energy transition will be, based on estimated previous production attributed to the energy transition.

Constraints are calculated as follows:

- If consumption exceeds current reserves, one target is added
- If consumption exceeds future reserves, one target is added
- If consumption exceeds resources, one target is added
- If consumption exceeds future production, a black arrow is drawn
- If consumption exceeds future production dedicated to the transition, a grey arrow is drawn

Recycling is considered:

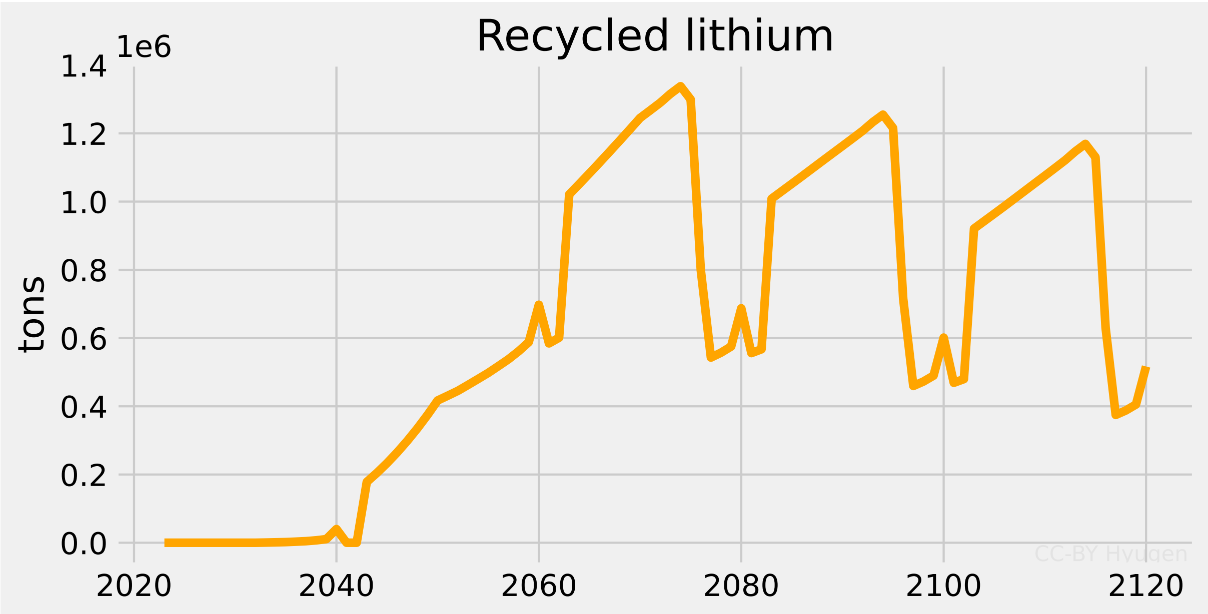


Fig. 3.24: Recycled lithium per year

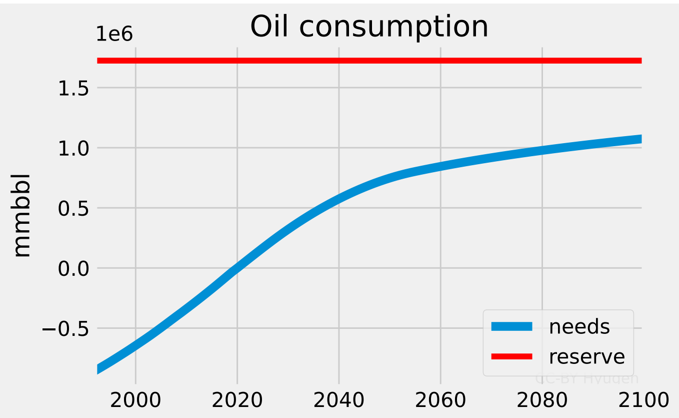
Observed patterns in fig. 3.24 are related to the replacement of vehicles using fossil fuels and to the **20** years lifespan configured for electric vehicles. After all vehicles using fossil fuels are replaced, demand in new electric vehicles is suddenly reduced which creates a discontinuity.

User configured world averaged end-of-life recycling rates as follows:

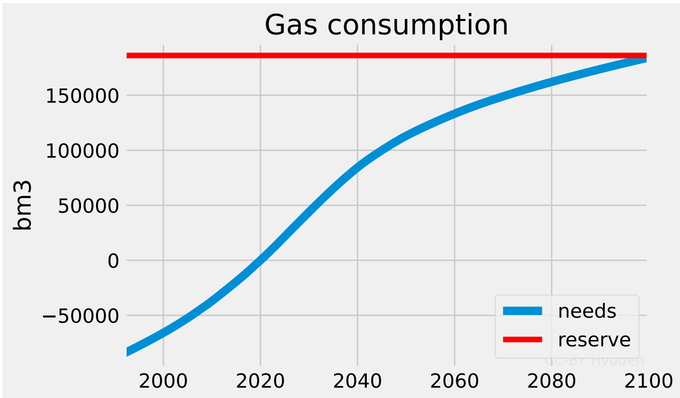
Resource	2020	2030	2040	2050
Aluminium	50	50	50	50
Copper	50	50	50	50
Steel	50	50	50	50
Concrete	10	10	10	10
Cobalt	11	20	30	30
Silver	15	15	15	15
Graphite	5	5	5	5
Lithium	0	10	25	40
Manganese	10	10	10	10
Nickel	70	70	70	70
Rare Earths	0	0	0	10
Silicon	0	0	0	0
Uranium	2	10	20	20
Zirconium	0	0	0	0

Table 3.2: Configured recycling rate (%, EOL-RR), world average, [87, 88, 89, 90]...

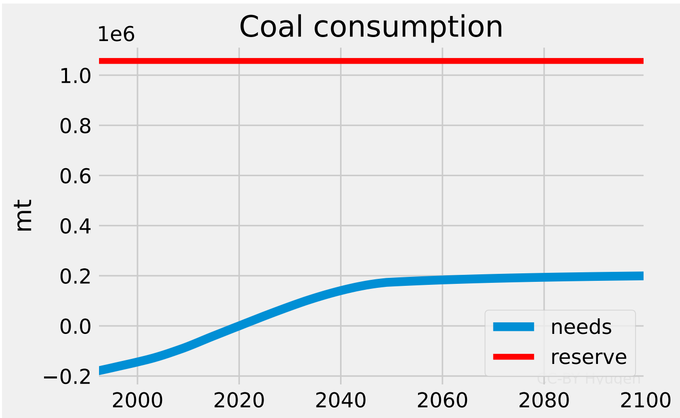
Consumption of fossil fuels evolves as follows:



(a) Oil consumption



(b) Gas consumption



(c) Coal consumption

3.4.4 Biomass and waste

Electricity generated from biomass or waste is not configured to increase in the model, as detailed in section 4.1.
The model aims at maintaining constant electricity generation from biomass and waste, while still considering other constraints (end of life of power plants, useful energy per capita, etc.).

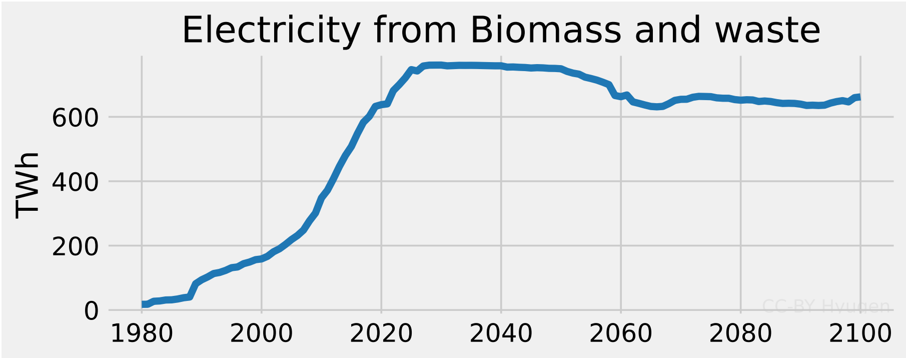


Fig. 3.26: Electricity generation from biomass and waste

Top producers of electricity from biomass and waste are:

Country	TWh
China	121
USA	70
Germany	56
Brazil	54
United Kingdom	41

(a) Production, 2019

Country	TWh
China	165
USA	70
Germany	57
United Kingdom	50
Japan	36

(b) Production, 2100

Country	MWh/capita
Finland	2.5
Sweden	1.44
Denmark	1.17
Estonia	1.08
Uruguay	0.73

(c) Production per capita, 2019

Country	MWh/capita
Finland	1.54
Sweden	1.06
Germany	0.83
South Korea	0.8
United Kingdom	0.72

(d) Production per capita, 2100

Table 3.3: Biomass and waste, Top 5 electricity producers

3.4.5 Coal

Electricity generation from coal is planned to be entirely replaced by low-carbon alternatives. The power plant removal pace cannot go faster than x3 historical examples of coal phase-out, per user configuration.

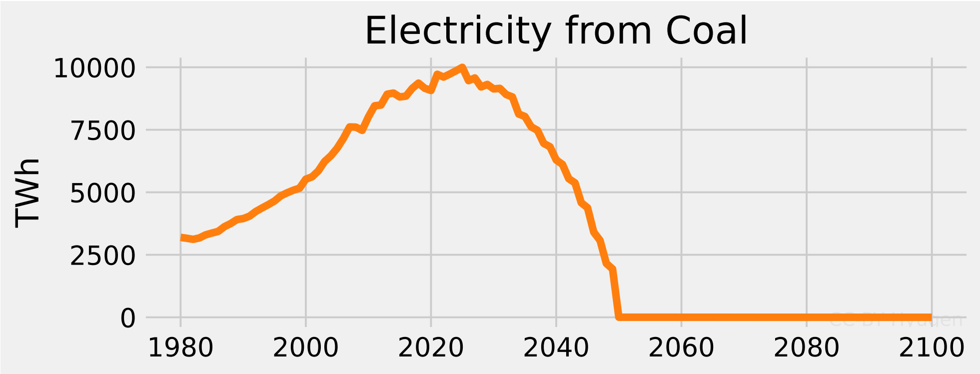


Fig. 3.27: Electricity generation from Coal

Country	TWh
China	4431
India	1217
USA	961
Japan	311
South Korea	227

(a) Production, 2019

Country	TWh
Afghanistan	0.0
Albania	0.0
Algeria	0.0
USA	0
Angola	0.0

(b) Production, 2100

Country	MWh/capita
Australia	5.55
Taiwan	5.21
South Korea	4.4
Kazakhstan	3.82
Kosovo	3.55

(c) Production per capita, 2019

Country	MWh/capita
Afghanistan	0.0
Albania	0.0
Algeria	0.0
USA	0.0
Angola	0.0

(d) Production per capita, 2100

Table 3.4: Coal, Top 5 electricity producers

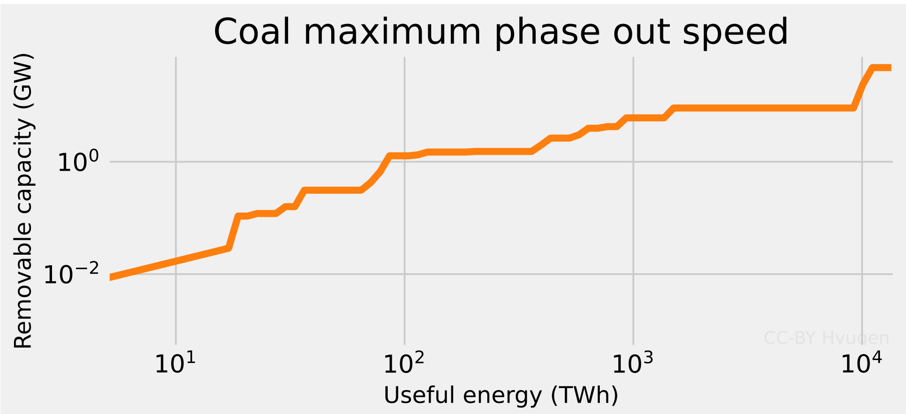


Fig. 3.28: Historical pace of coal phase-out

3.4.6 Gas

Electricity generation from gas is planned to be replaced by low-carbon alternatives, or to replace coal. The power plant removal pace cannot go faster than x3 historical examples of gas phase-out, per user configuration.

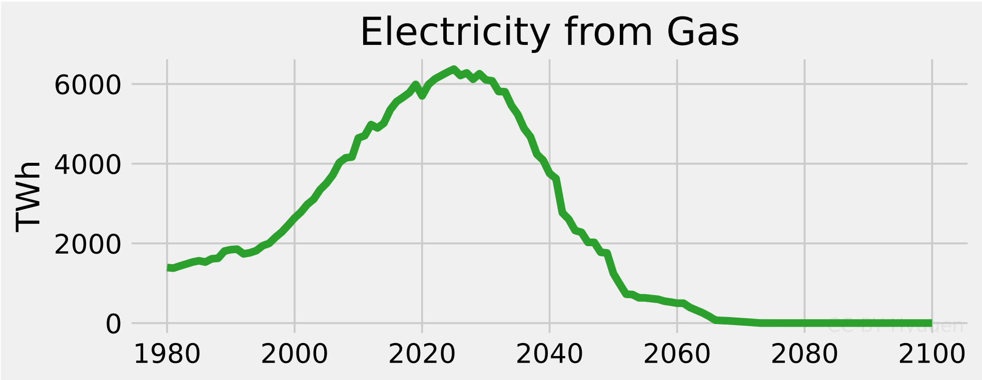


Fig. 3.29: Electricity generation from Gas

Country	TWh
USA	1592
Russia	487
Japan	346
China	226
Saudi Arabia	213

(a) Production, 2019

Country	TWh
Mauritius	0.4
Afghanistan	0
Albania	0.0
Algeria	0
USA	0

(b) Production, 2100

Country	MWh/capita
Bahrain	21.02
Qatar	16.83
Kuwait	15.96
United Arab Emirates	13.72
Brunei	10.63

(c) Production per capita, 2019

Country	MWh/capita
Mauritius	0.45
Afghanistan	0.0
Albania	0.0
Algeria	0.0
USA	0.0

(d) Production per capita, 2100

Table 3.5: Gas, Top 5 electricity producers

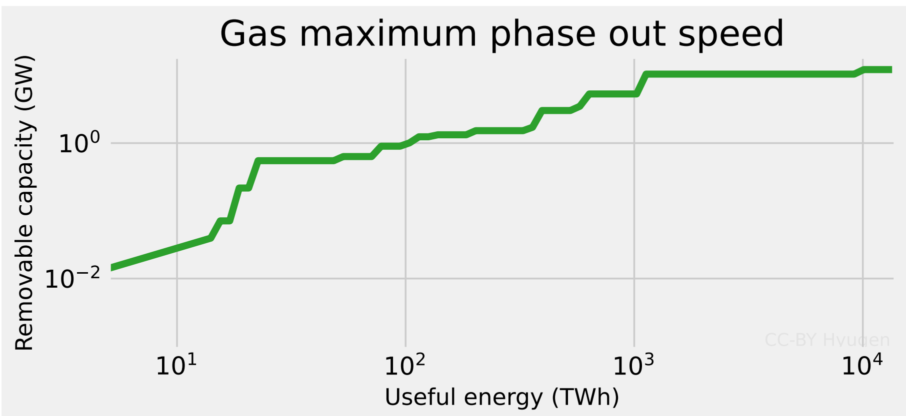


Fig. 3.30: Historical pace of gas phase-out

3.4.7 Geothermal electricity

Electricity generation from geothermal energy is planned to increase where available. World new potential is estimated to be **1209** TWh by the model.
The configured acceleration multiplier is x**3** (compared to pre-2020 data).

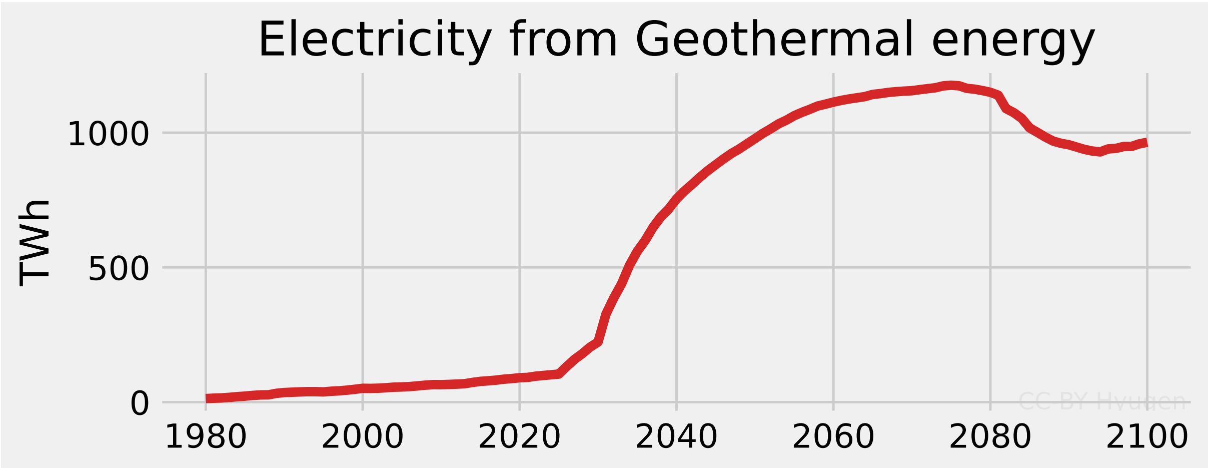


Fig. 3.31: Electricity generation from Geothermal energy

Country	TWh
USA	15
Indonesia	14
Philippines	10
Turkey	9.0
New Zealand	7.8

(a) Production, 2019

Country	TWh
USA	235
Mexico	135
Japan	91
Philippines	61
Indonesia	46

(b) Production, 2100

Country	MWh/capita
Iceland	16.19
New Zealand	1.59
Costa Rica	0.3
El Salvador	0.23
Nicaragua	0.12

(c) Production per capita, 2019

Country	MWh/capita
New Zealand	5.32
Serbia	4.57
Croatia	3.15
Greece	3.09
El Salvador	1.88

(d) Production per capita, 2100

Table 3.6: Geothermal, Top 5 electricity producers

A map with the estimated location of geothermal sources is proposed in fig. 3.32. The ability of countries to add new geothermal production is represented in fig. 3.33.

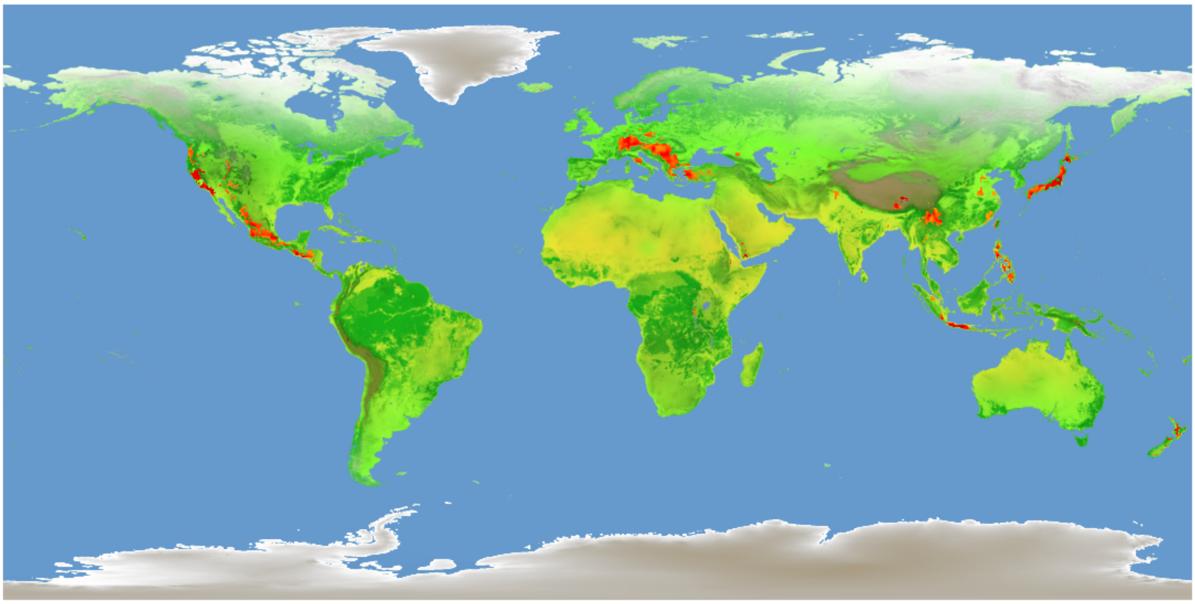


Fig. 3.32: Estimated location of **new** power potential for geothermal electricity, details in section 4.5

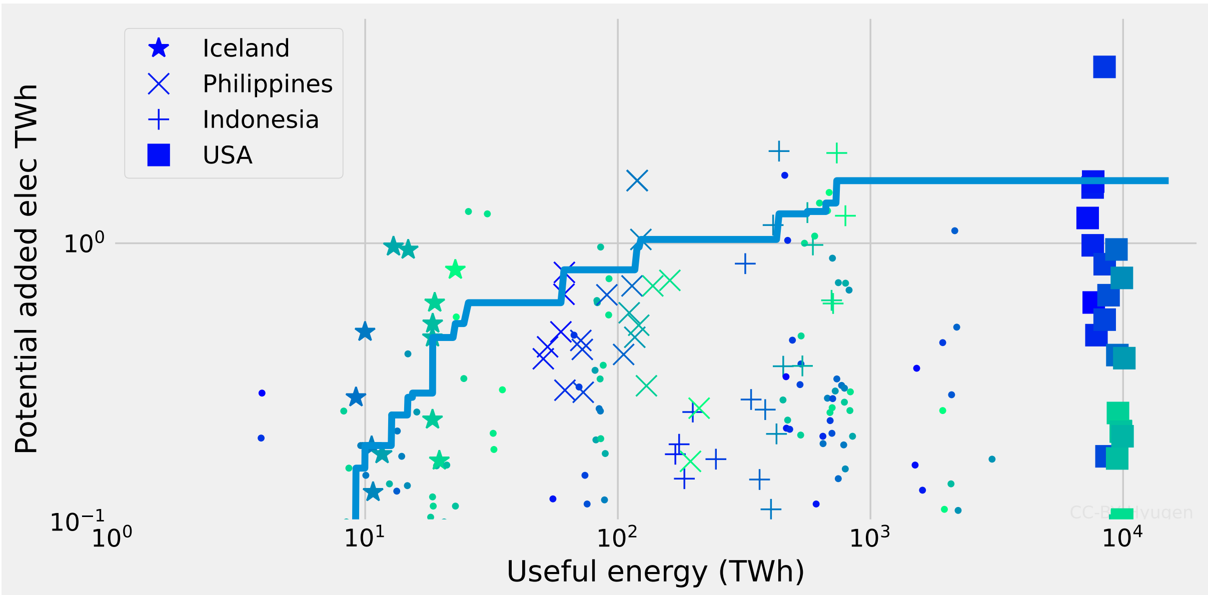


Fig. 3.33: Potential new electric geothermal production per year (curve). Each point represents a country and a year before 2019, darker colors indicate older years, the line indicates how much TWh a country with this amount of useful energy can anticipate to add, based on **5** (geothermal) examples with less useful energy (← left of the graph) which added more TWh in the past (↑ top of the graph), bonus/malus multiplier configured by the user are not displayed

3.4.8 Hydroelectricity

Electricity generation from hydroelectricity is planned to increase where available. World new maximum potential is estimated to be **13375** TWh by the model. The configured acceleration multiplier is x**1** (compared to pre-2020 data).

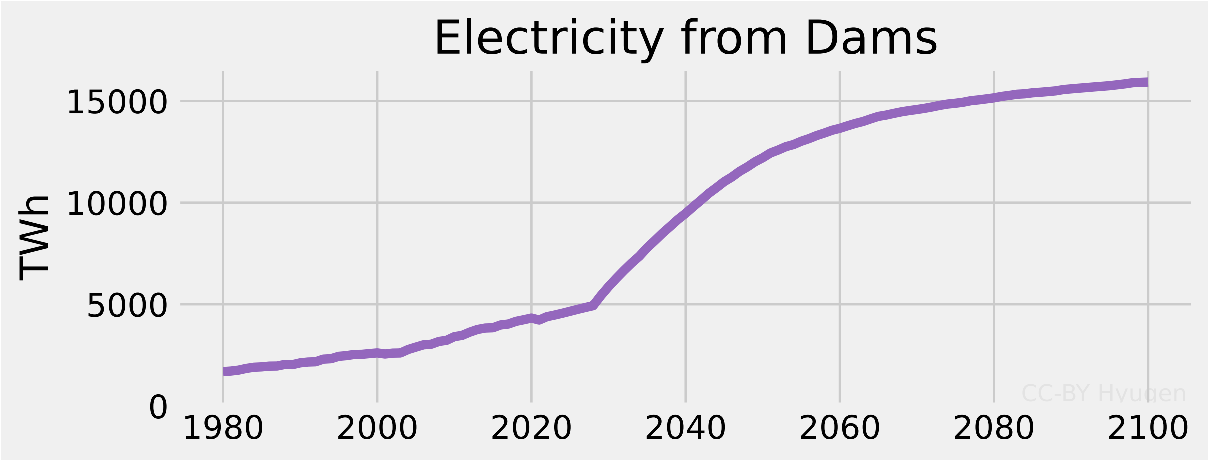


Fig. 3.34: Electricity generation from Dams

Country	TWh
China	1314
Brazil	397
Canada	375
USA	287
Russia	194

(a) Production, 2019

Country	TWh
China	3285
India	1262
Russia	1109
Canada	1047
Brazil	819

(b) Production, 2100

Country	MWh/capita
Iceland	37.31
Norway	23.21
Bhutan	11.7
Canada	10.08
Paraguay	7.54

(c) Production per capita, 2019

Country	MWh/capita
Iceland	87.38
Norway	20.73
Bhutan	20.48
Canada	19.43
New Zealand	15.01

(d) Production per capita, 2100

Table 3.7: Hydroelectricity, Top 5 electricity producers

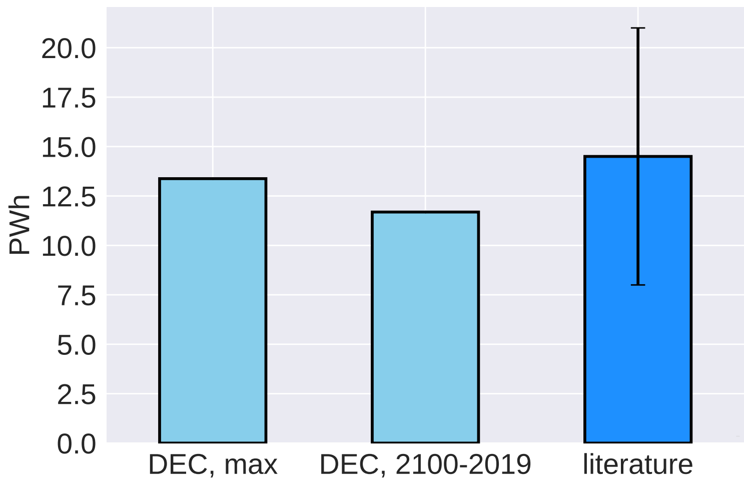


Fig. 3.35: Newly installed/installable production of hydroelectricity, comparison with literature (8-21 PWh interval indicated in [63])

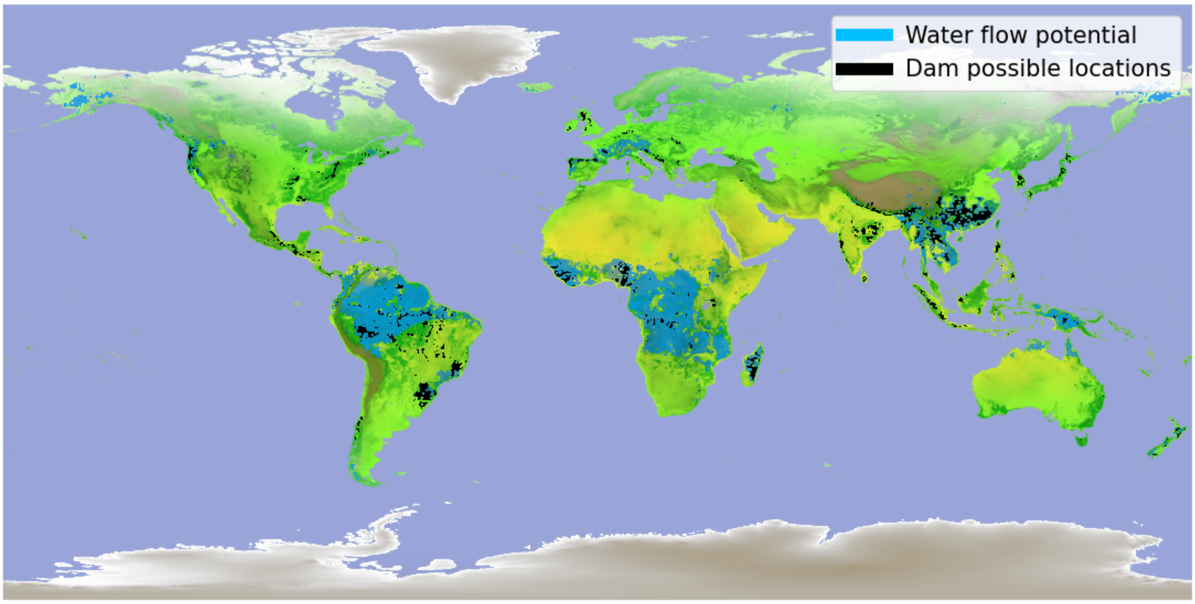


Fig. 3.36: Estimated location of **new** power potential for hydroelectricity, possible locations for dams are based on population and energy density, details section 4.5

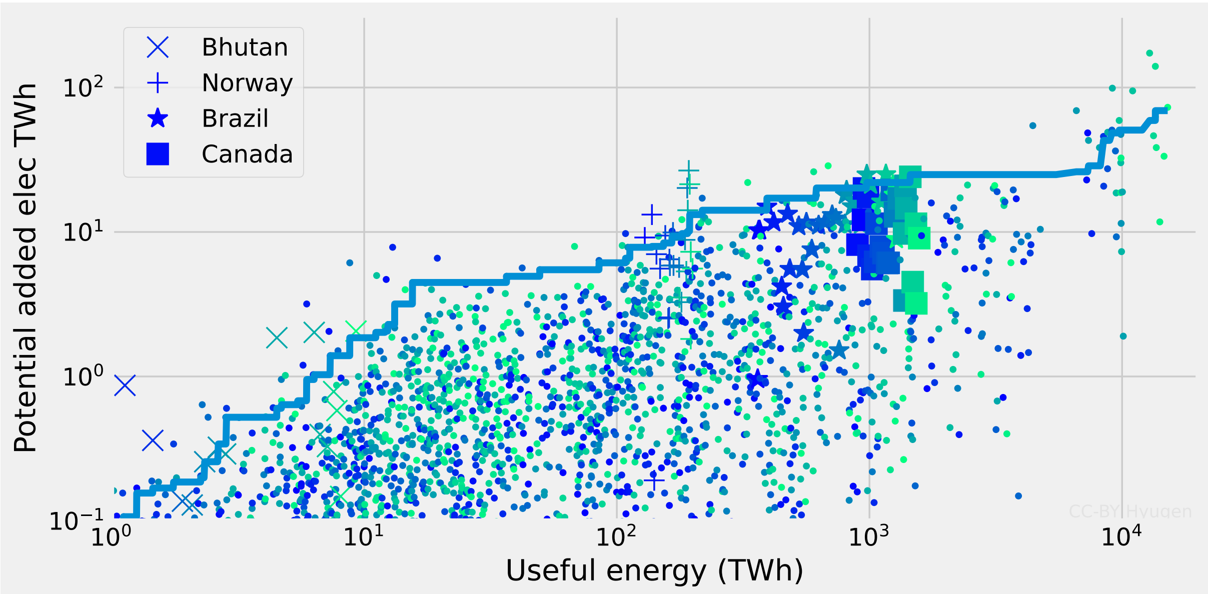


Fig. 3.37: Potential new hydroelectric production per year, details fig. 3.33

3.4.9 Nuclear

Configuration used for nuclear energy for this scenario is: **restrictive**. In this configuration, **nuclear is only allowed in countries which allow and already produce nuclear energy (or which are building NPPs)**. The configured acceleration multiplier is x1 (compared to pre-2020 data).

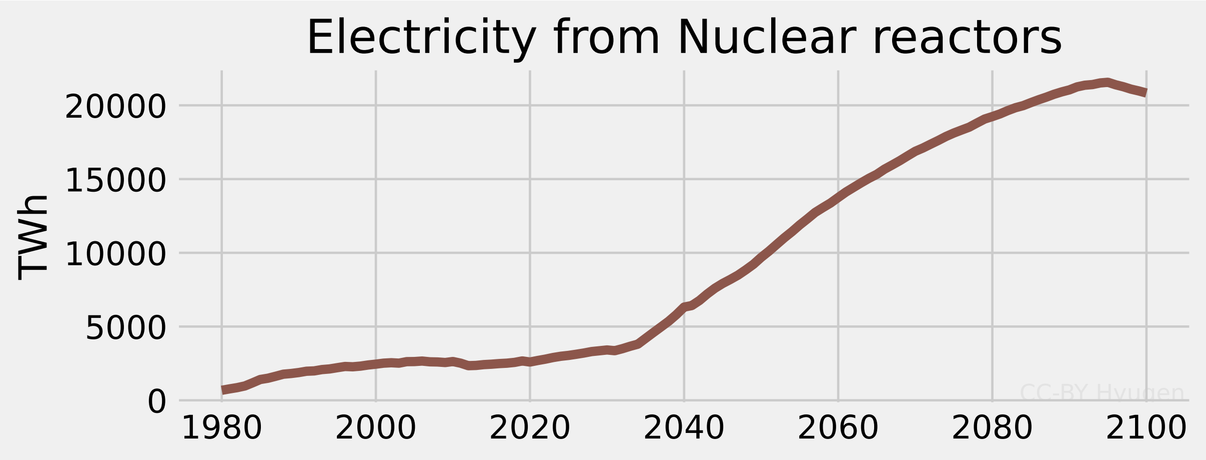


Fig. 3.38: Electricity generated from Nuclear reactors

Country	TWh
USA	809
France	379
China	348
Russia	195
South Korea	138

(a) Production, 2019

Country	TWh
China	2789
USA	2241
India	1791
Pakistan	1422
Russia	1369

(b) Production, 2100

Country	MWh/capita
Sweden	6.3
France	5.64
Finland	4.15
Belgium	3.6
Switzerland	2.96

(c) Production per capita, 2019

Country	MWh/capita
United Arab Emirates	38.73
South Korea	24.76
Canada	21.13
Netherlands	21.11
Sweden	16.42

(d) Production per capita, 2100

Table 3.8: Nuclear, Top 5 electricity producers

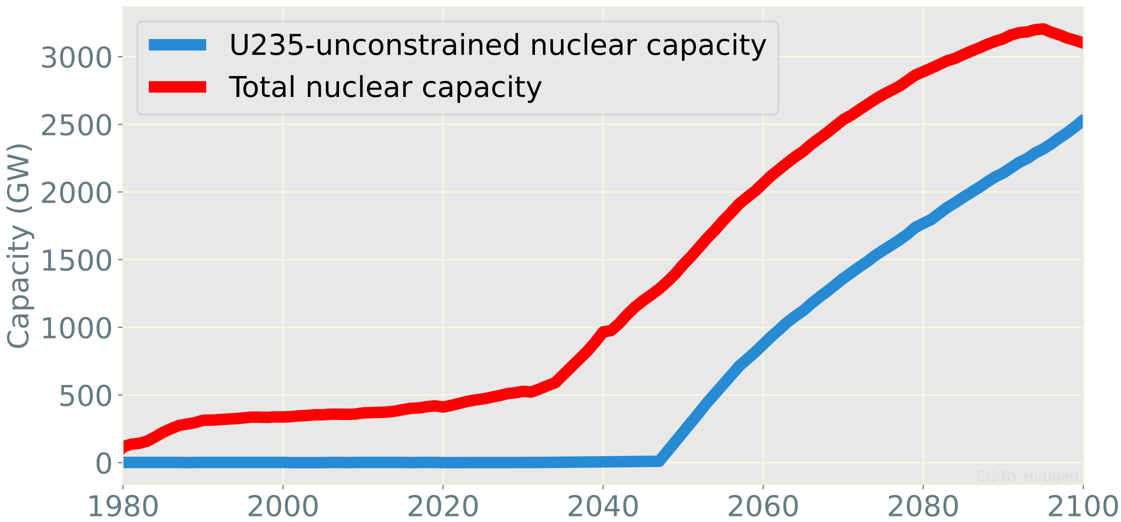


Fig. 3.39: Installed capacity of nuclear reactors per year

Constraints on the location of new nuclear power plants are detailed in appendix M. The selected score under which new reactors can't be built on that location is **48.21**. The year from which U235 won't be a constraint anymore for new reactors is configured to be **2040** by the user. From this date, new reactors don't count as consuming Uranium in the resource analysis. U235-unconstrained solutions include fast-breeders, thorium reactors, etc.

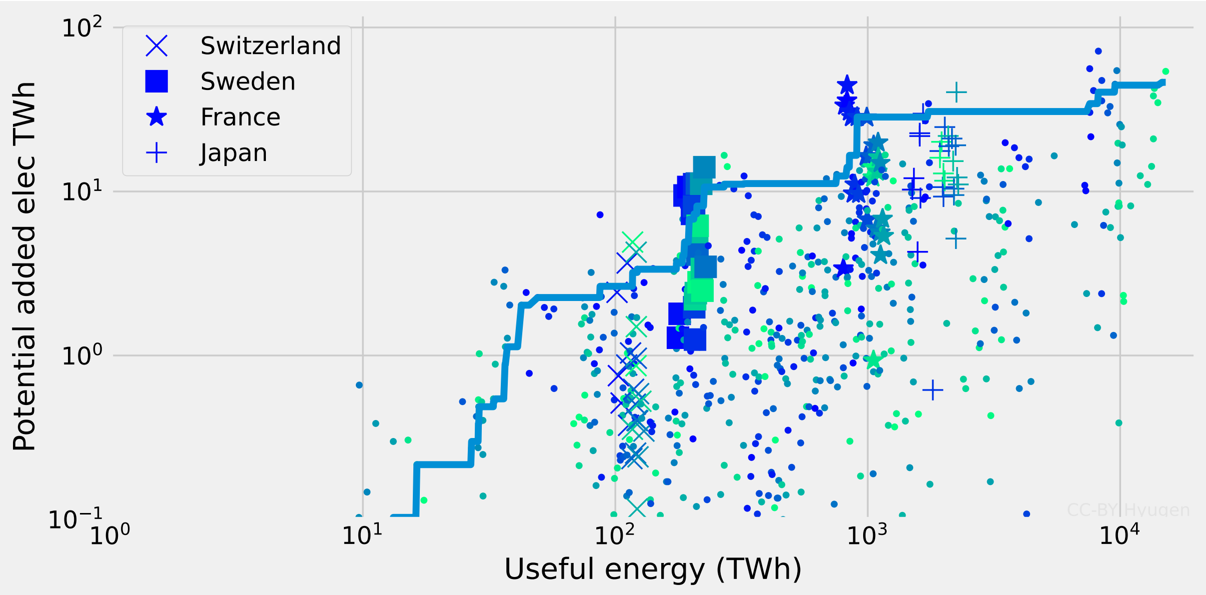


Fig. 3.40: Potential new nuclear production per year, details fig. 3.33

3.4.10 Oil

Electricity generation from oil is planned to be replaced by low-carbon alternatives. The power plant removal pace cannot go faster than x3 historical examples of oil phase-out (user configuration). Small islands that depend on oil may partially avoid the phase-out.

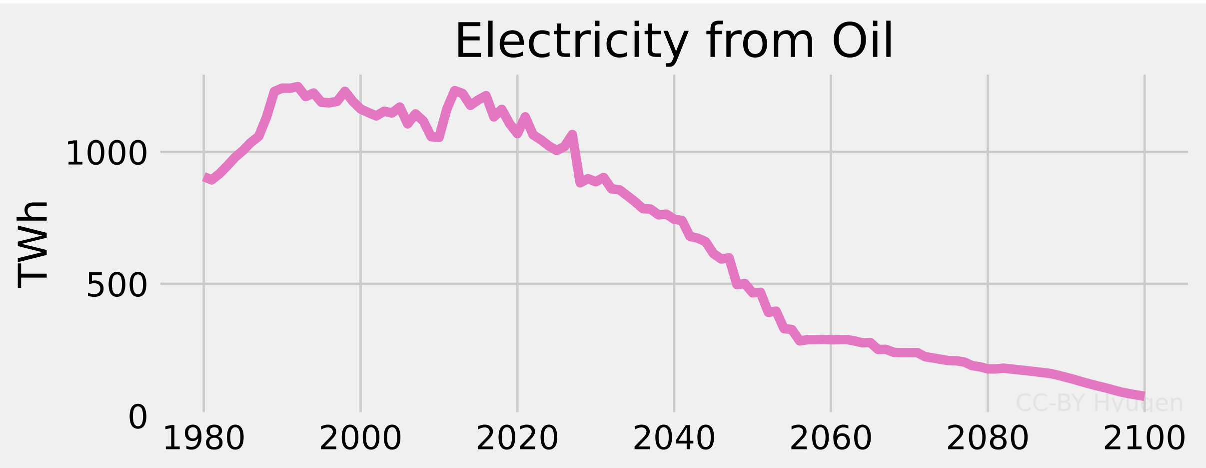


Fig. 3.41: Electricity generation from Oil

Country	TWh
China	179
Saudi Arabia	148
Iran	87
Japan	83
USA	50

(a) Production, 2019

Country	TWh
Bahrain	39
Haiti	12
Cyprus	4.2
Malta	3.7
Equatorial Guinea	2.9

(b) Production, 2100

Country	MWh/capita
Palau	9.51
Aruba	7.28
The Bahamas	5.21
Seychelles	4.71
Saint Kitts and Nevis	4.35

(c) Production per capita, 2019

Country	MWh/capita
Bahrain	19.52
Malta	9.51
Seychelles	8.03
Palau	5.75
Antigua and Barbuda	3.57

(d) Production per capita, 2100

Table 3.9: Oil, Top 5 electricity producers

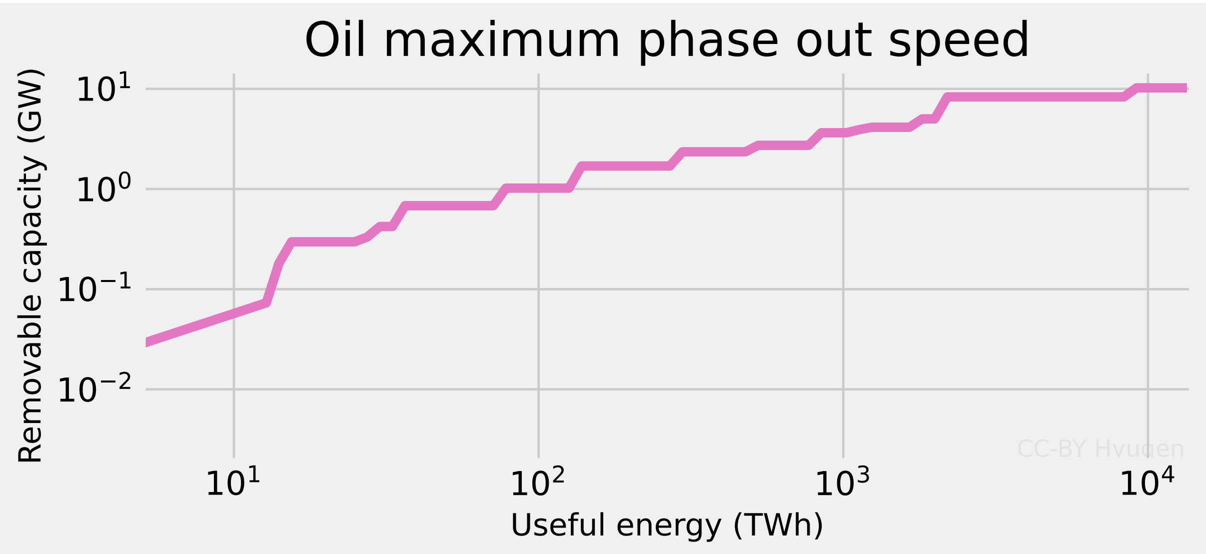


Fig. 3.42: Historical pace of oil phase-out

3.4.11 Solar

Electricity generation from solar panels is planned to increase, capacity factor per location is estimated and considered as well as land use. The configured acceleration multiplier is x**2.3** historical pace (compared to pre-2020 data).

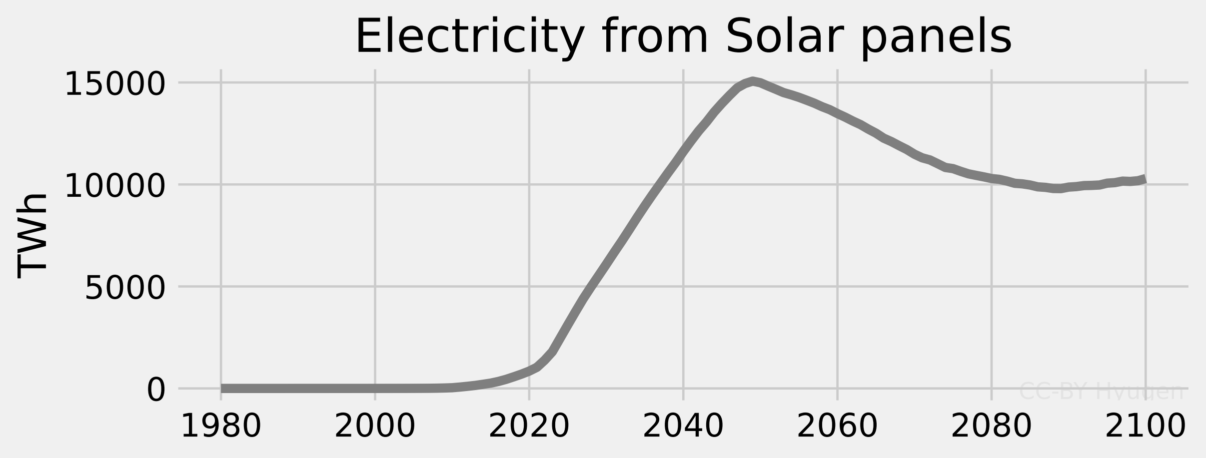


Fig. 3.43: Electricity generation from solar panels

Country	TWh
China	225
USA	107
Japan	69
India	46
Germany	44

(a) Production, 2019

Country	TWh
USA	1026
Pakistan	963
India	930
China	920
Iran	714

(b) Production, 2100

Country	MWh/capita
Cook Islands	0.87
Liechtenstein	0.71
Australia	0.59
Japan	0.55
Germany	0.53

(c) Production per capita, 2019

Country	MWh/capita
United Arab Emirates	18.08
Qatar	16.7
Oman	10.21
Saudi Arabia	9.12
Iran	8.94

(d) Production per capita, 2100

Table 3.10: Solar, Top 5 electricity producers

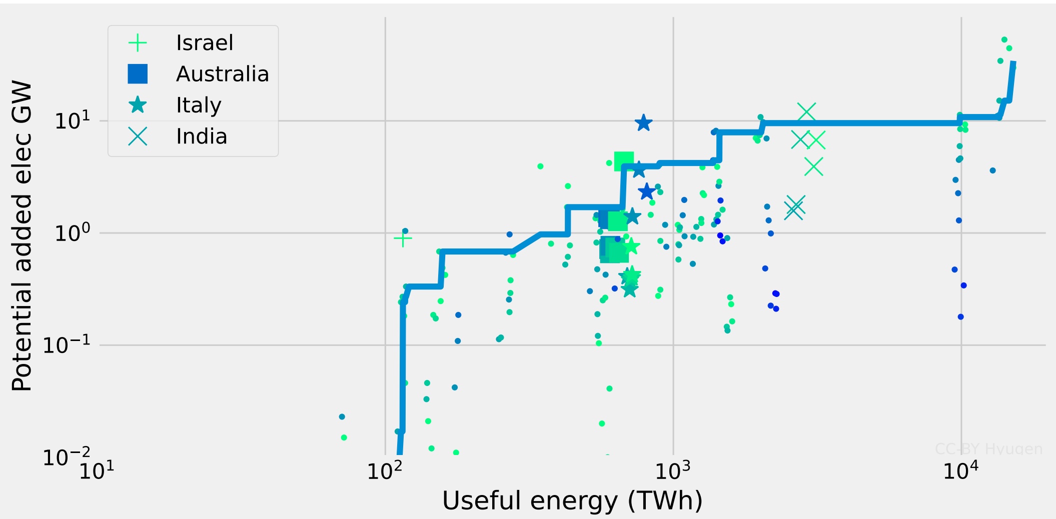


Fig. 3.44: Potential new solar capacity per year, details fig. 3.33

The model locates future solar farms based on user configured constraints. The strategy is optimized per country and not globally, appendix F indicates why it could be sub-optimal. Locations of people and needs are considered. The trade-off between choosing productive locations and locations with the most demand is partially integrated. Cabling constraints are not considered.

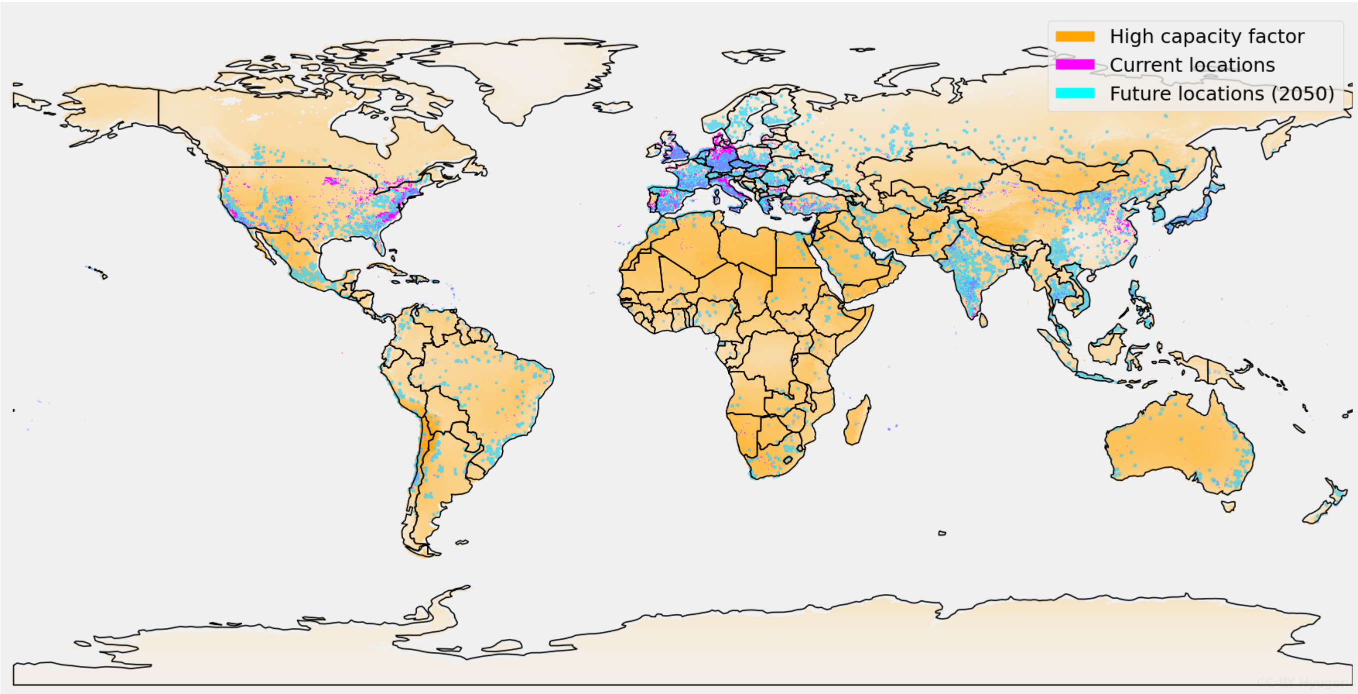


Fig. 3.45: Solar panel locations, the model optimizes the location per country and not globally, details appendix F and section 4.5

3.4.12 Tide and wave

Tide and wave is not yet configured to change in the model.

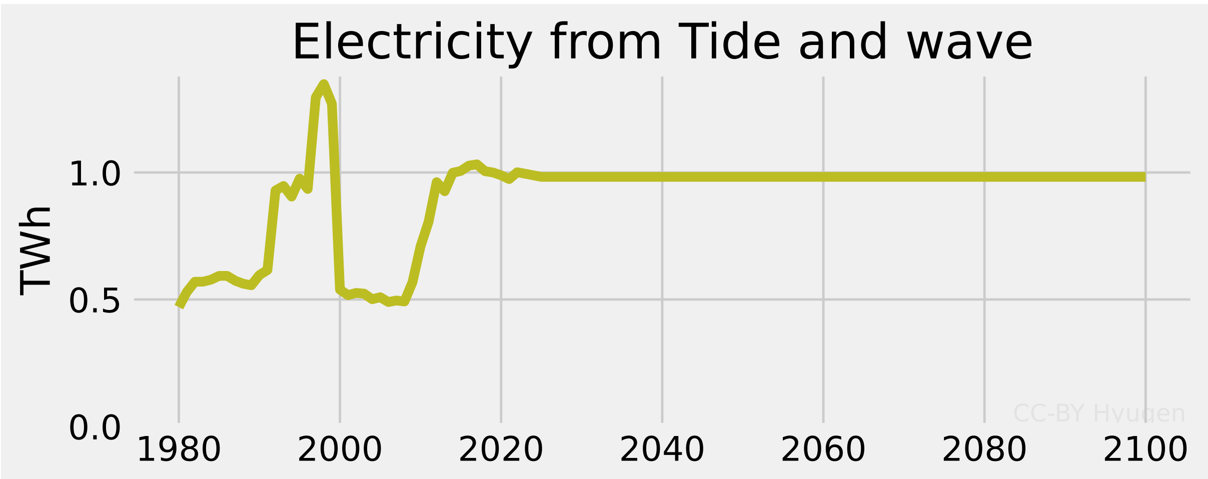


Fig. 3.46: Electricity generation from tide and waves

Country	TWh
France	0.5
South Korea	0.5
Spain	0.0
United Kingdom	0.0
China	0.0

(a) Production, 2019

Country	TWh
France	0.5
South Korea	0.4
Spain	0.0
China	0.0
Netherlands	0.0

(b) Production, 2100

Country	MWh/capita
South Korea	0.01
France	0.01
Spain	0.0
United Kingdom	0.0
Canada	0.0

(c) Production per capita, 2019

Country	MWh/capita
South Korea	0.02
France	0.01
Spain	0.0
Netherlands	0.0
Portugal	0.0

(d) Production per capita, 2100

Table 3.11: Tide and wave, Top 5 electricity producers

3.4.13 Wind

Electricity generation from wind turbines is planned to increase, capacity factor per location is estimated and considered as well as land use. The configured acceleration multiplier is x**1.65** (compared to pre-2020 data).

The model locates wind farms based on user configured constraints. The model optimizes the strategy per country. Locations of people and needs are considered. The trade-off between choosing productive locations and locations with the most demand is partially integrated. Cabling constraints are not considered.

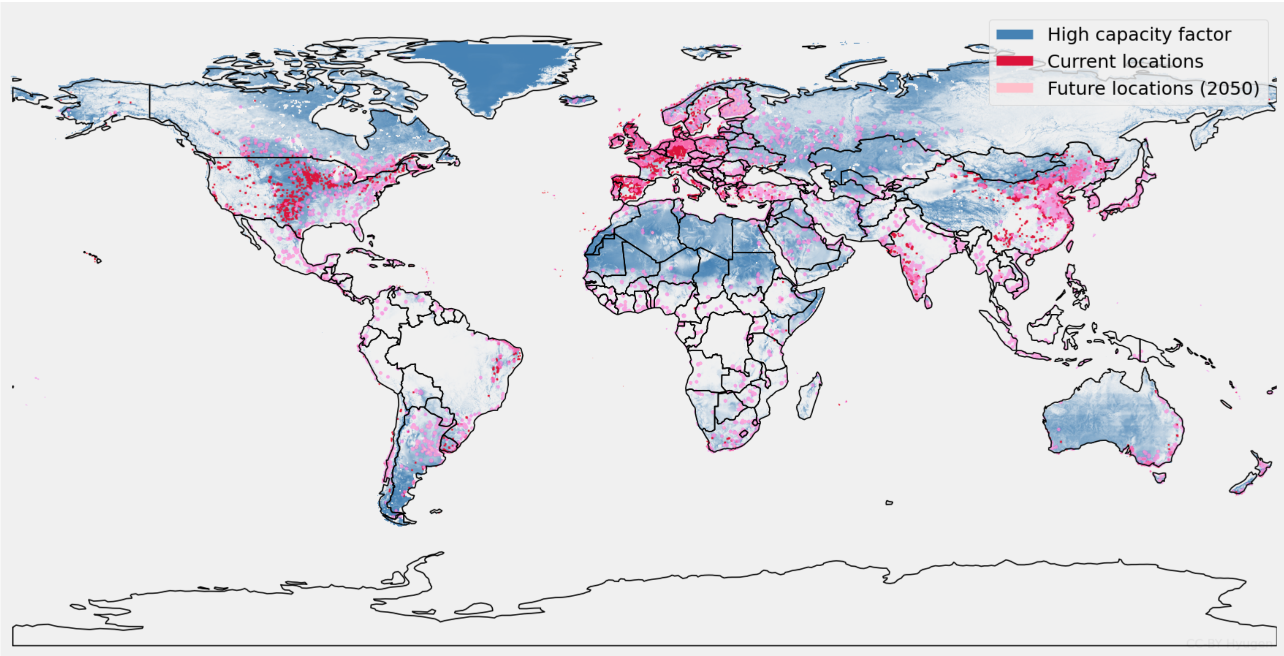


Fig. 3.47: Onshore wind farm locations, details section 4.5. A slight offset between country borders and presented locations can be visible.

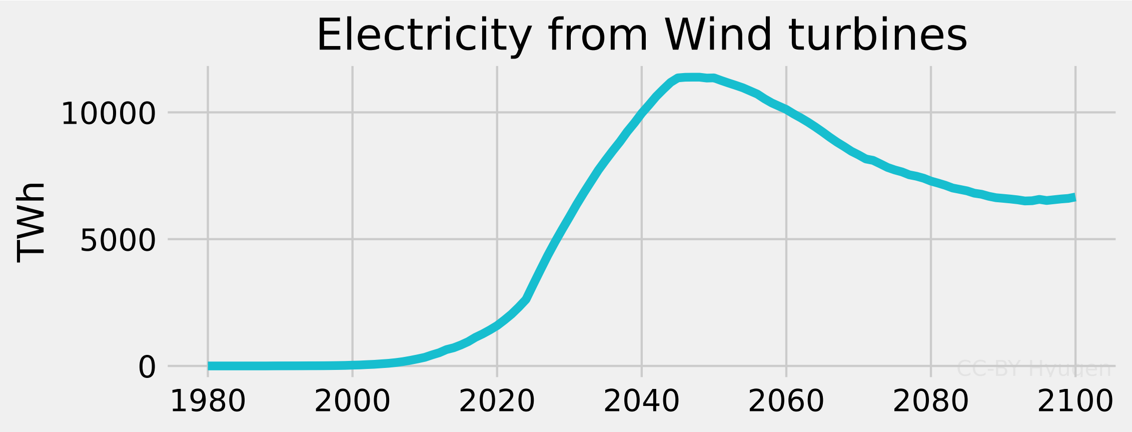


Fig. 3.48: Electricity generation from wind turbines

Country	TWh
China	406
USA	296
Germany	123
India	67
United Kingdom	63

(a) Production, 2019

Country	TWh
China	937
USA	427
India	360
Pakistan	332
Russia	301

(b) Production, 2100

Country	MWh/capita
Denmark	2.79
Republic of Ireland	2.06
Sweden	1.94
Germany	1.49
Uruguay	1.39

(c) Production per capita, 2019

Country	MWh/capita
Qatar	15.85
Kuwait	9.13
Norway	8.81
Turkmenistan	8.65
Faroe Islands	8.25

(d) Production per capita, 2100

Table 3.12: Wind, Top 5 electricity producers

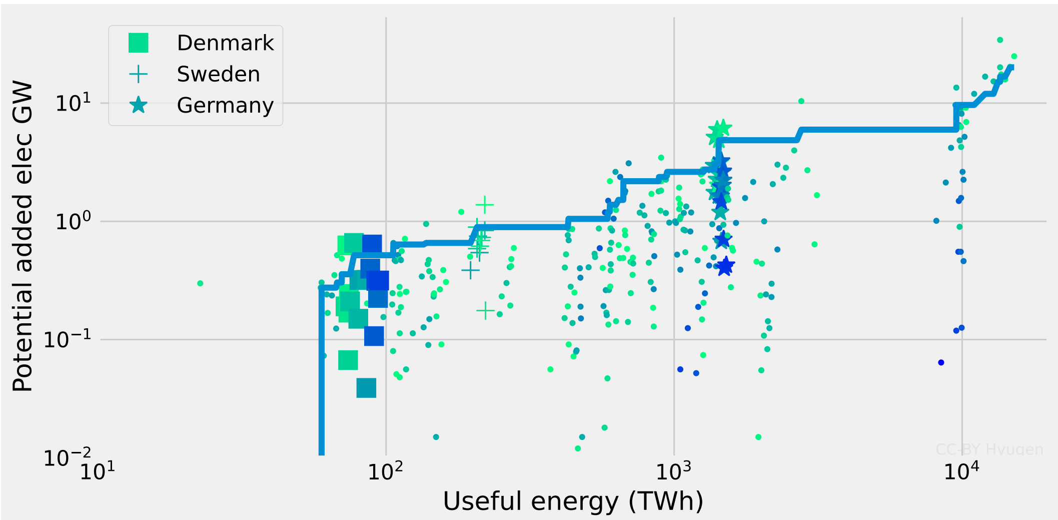


Fig. 3.49: Potential new wind capacity per year, details fig. 3.33

3.4.14 Detailed historical pace of fossil fuel phase-out

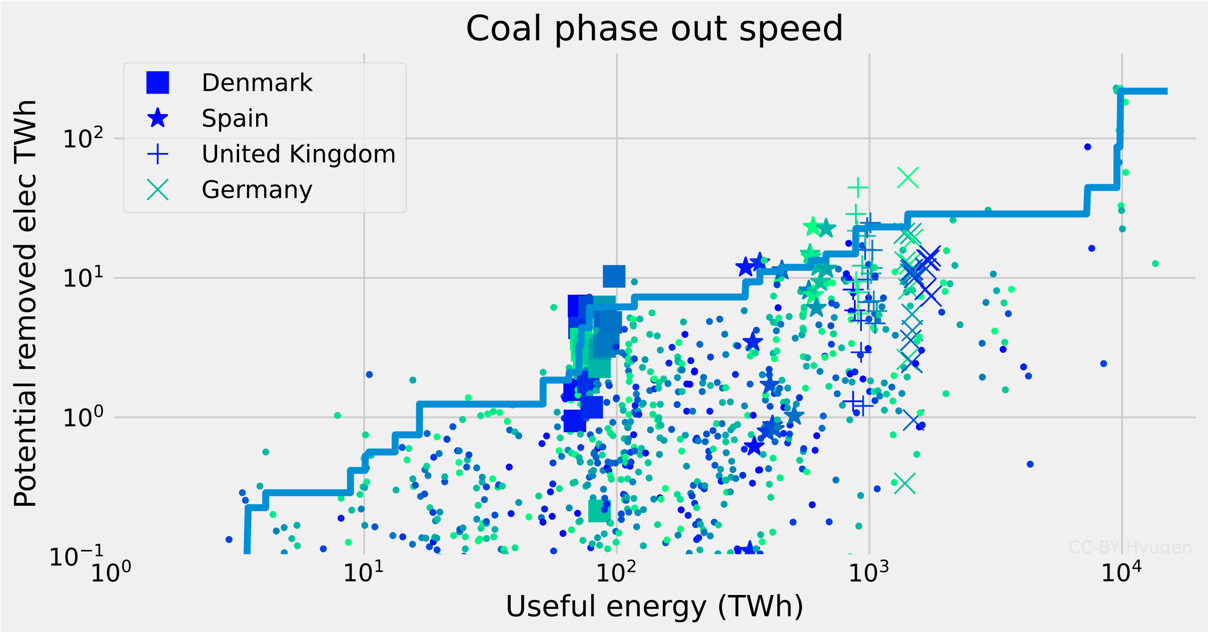


Fig. 3.50: Historical coal decline rate, same methodology as in fig. 3.33 with the focus on removed electricity production

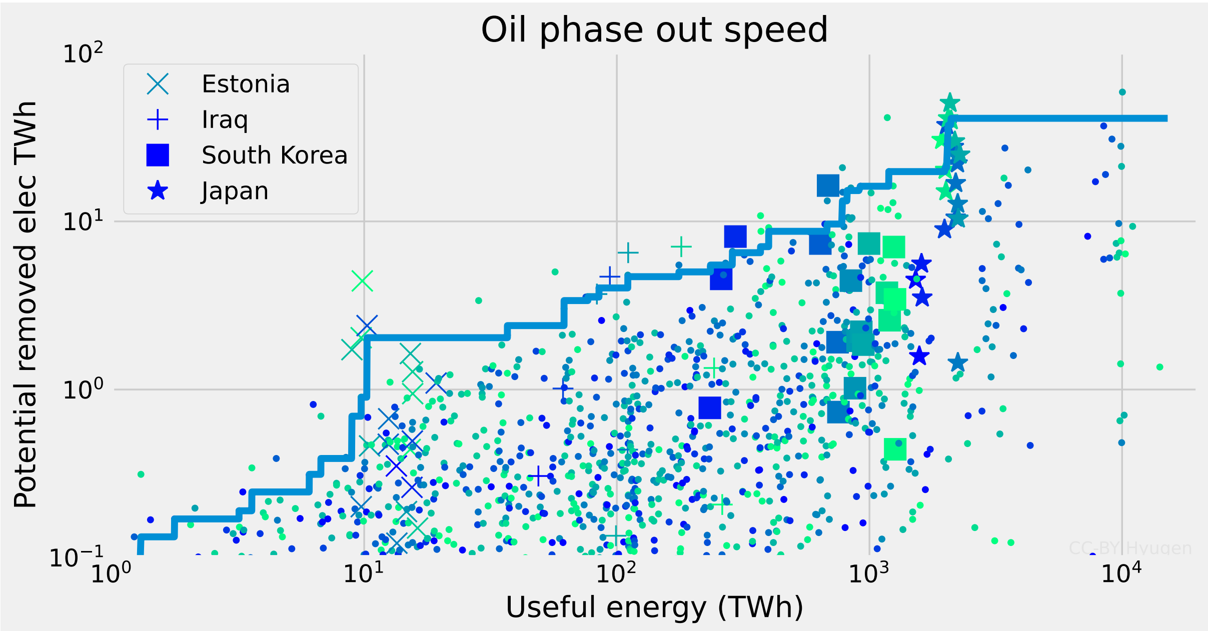


Fig. 3.51: Historical oil decline rate, same methodology as in fig. 3.33 with the focus on removed electricity production

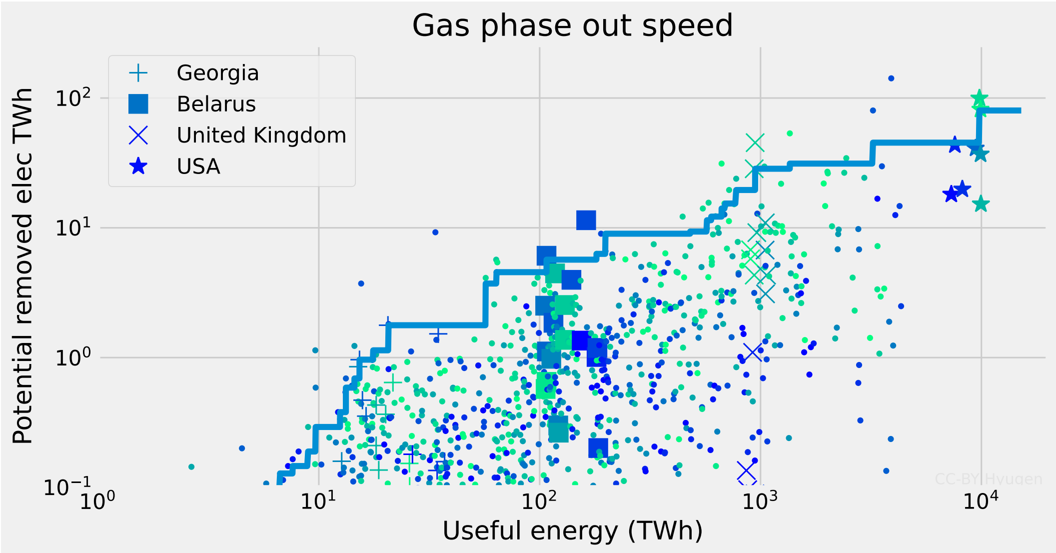


Fig. 3.52: Historical gas decline rate, same methodology as in fig. 3.33 with the focus on removed electricity production

3.4.15 Electricity storage needs

Required power (Watts) for the storage system is approximated using different assumptions.
Consumed electricity generation for the year (TWh/year) can be broken down into an average required capacity (GW) for each moment of the year. The real average is different between the "day" (when people are awake) and the night, in the model: required day capacity = 1.5x required night capacity. And this amount can also be modified based on seasons and specific events, in the model: maximum required capacity = 2x average required day capacity.

In order to guarantee power availability without disrupting activities during those days, the maximum required capacity must be installed.

The model computes the required capacity in table 3.13, based on existing controllable and available capacity, which includes: **90% of Nuclear capacity, 80% of Geothermal capacity, 90% of Biomass and waste capacity, 90% of Gas capacity, 90% of Oil capacity, 90% of Coal capacity, 50% of Hydroelectricity capacity**. This capacity is considered to be "controllable", "available" on demand, for situations which can be planned.

Country	Installed controllable and available capacity (GW)	Estimated required capacity to guarantee power availability (GW)
France	97	76
Germany	125	79
USA	906	573
Italy	76	38

Table 3.13: Installed and required capacity for some countries in 2019. Displayed countries broadcast official figures for comparison with estimated figures. France:[91], USA:[92], Italy:[93], Germany:[94]

The difference between the required capacity, and the estimated controllable and available capacity, is the required power of the storage system to guarantee power availability (fig. 3.53).

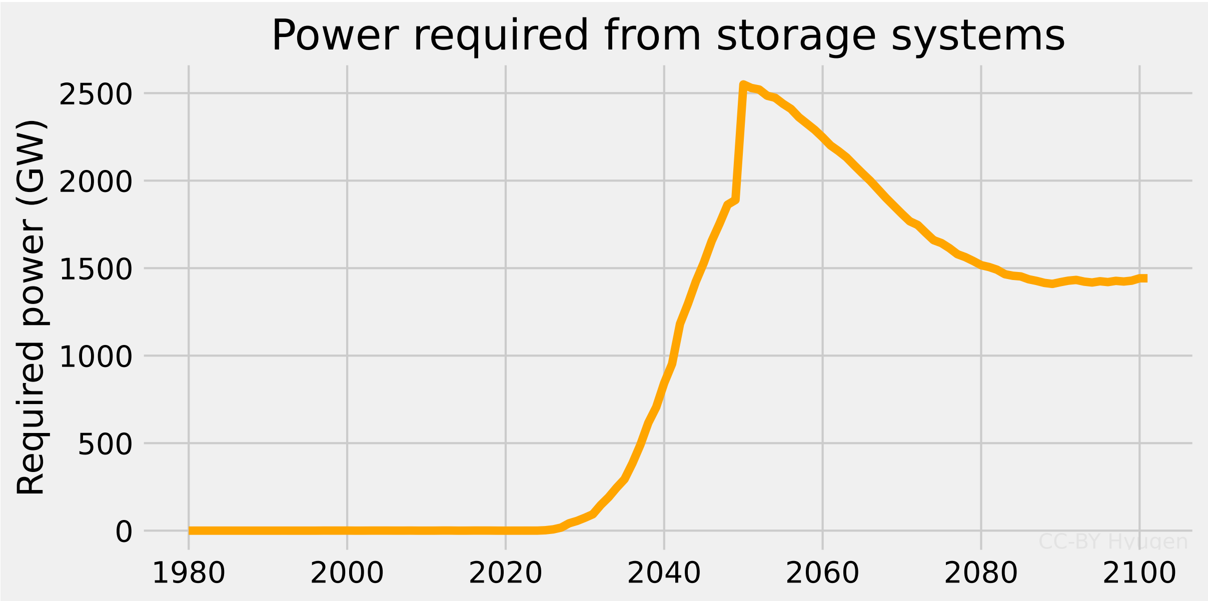


Fig. 3.53: Required power of storage systems, per year, for all countries, to guarantee electricity availability

3.4.16 Capacity factor per source over the world

To assess how realistic this scenario is, capacity factors per source can be compared before and after the simulation.

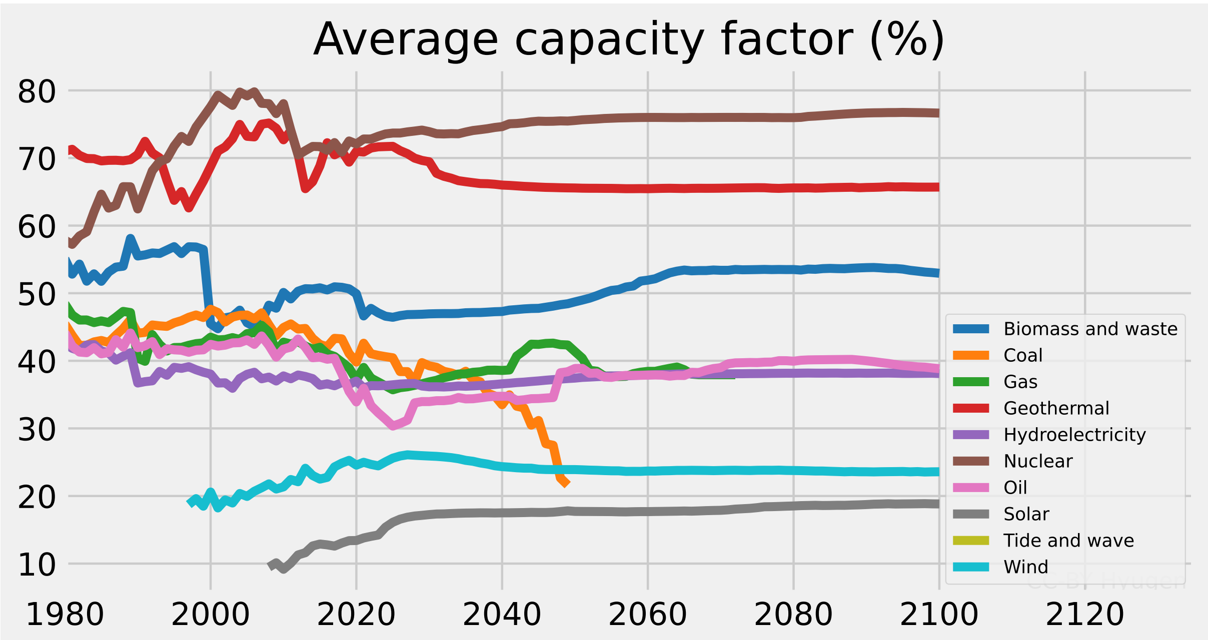


Fig. 3.54: Estimates on average capacity factor over the world per electricity source

3.4.17 Land used for solar and wind

The average energy productivity of land used for wind and solar energy can be visualized in fig. 3.55, in order to verify this scenario.

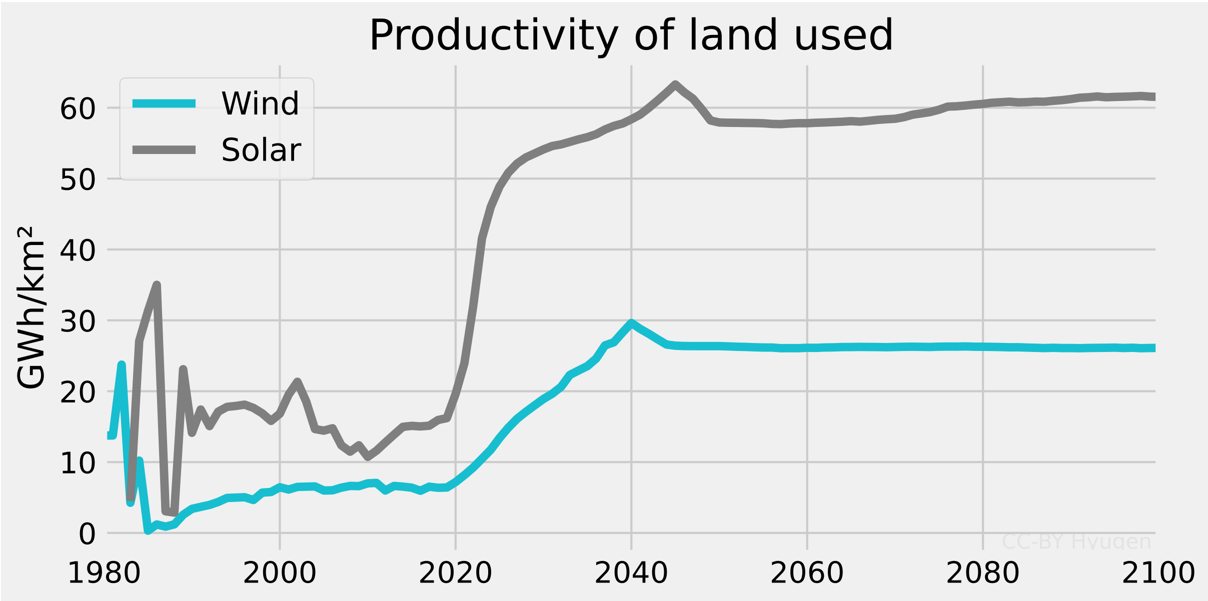


Fig. 3.55: Estimated world average production of wind turbines and solar farms per square kilometer, based on appendix L, pre-2019 results are incomplete

3.5 Climate

Based on this configuration, the model evaluates global warming to be **+2.5°C** compared to pre-industrial era.

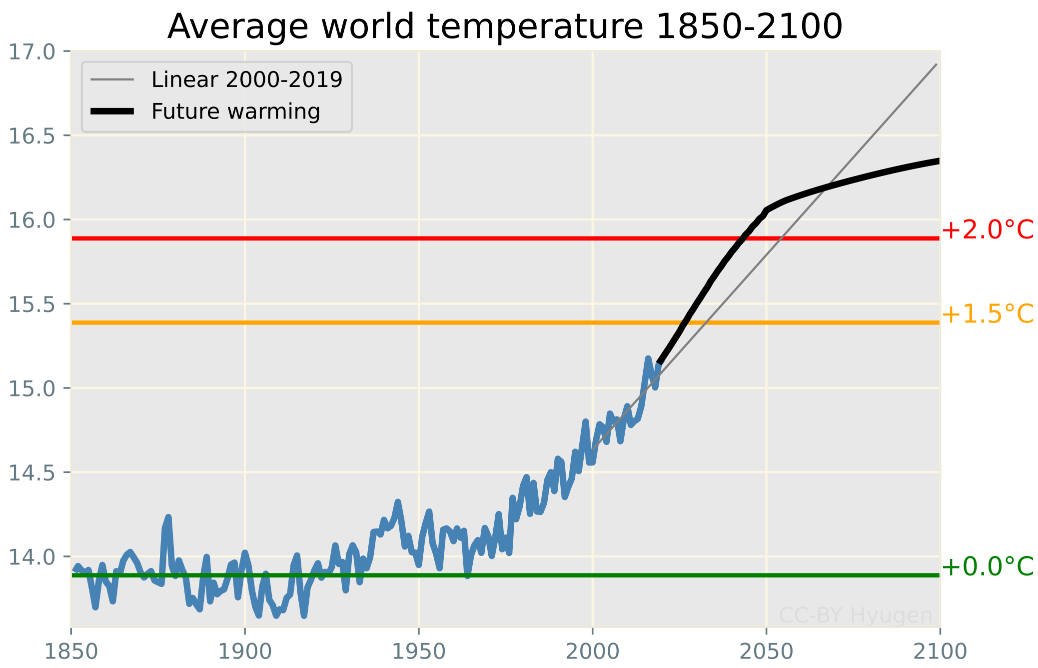


Fig. 3.56: Global warming, average temperature over the world, details section 4.10

3.5.1 Emissions per gas

The previously detailed evolution of activities impacts emissions for different gases. For CO_2, user configured a change of **-2.0%** per year for LULUCF emissions and a change of **-2.0%** per year for cement emissions. CO_2 emissions evolve as follows:

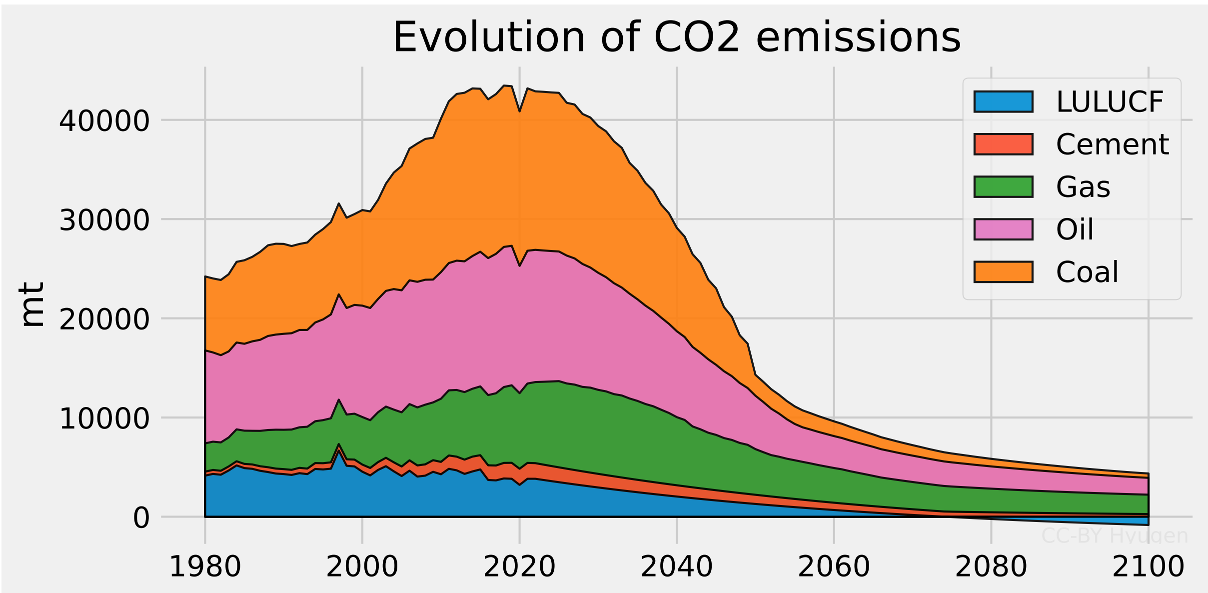


Fig. 3.57: Evolution of CO_2 emissions by sources

The model evaluates the evolution of CO2 emissions per capita:

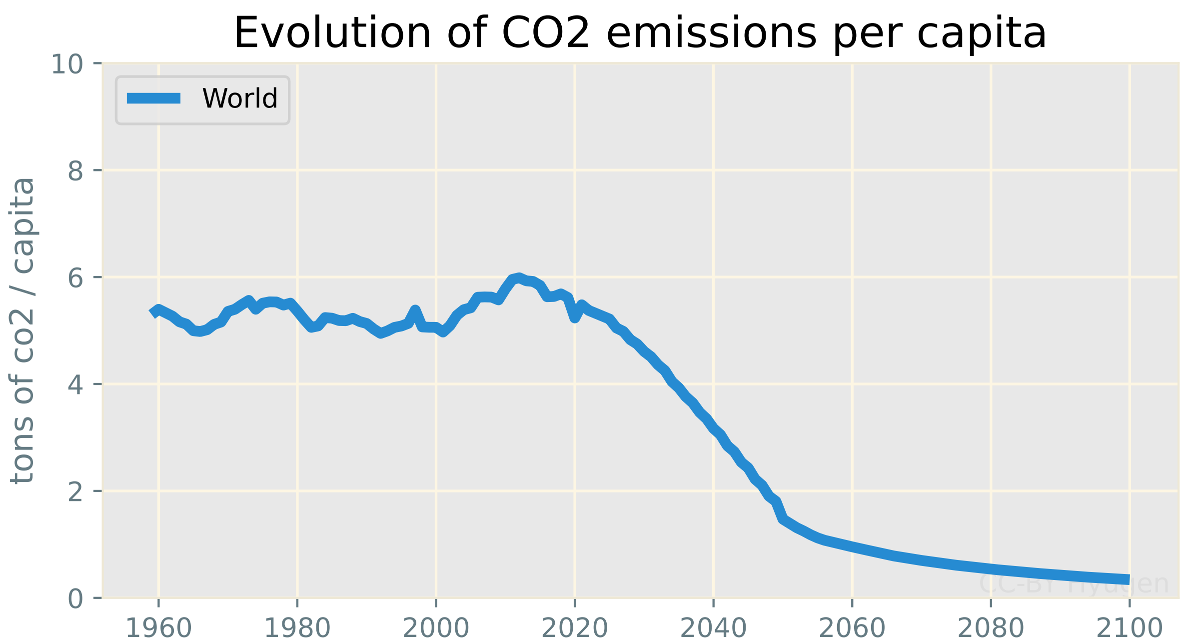


Fig. 3.58: Evolution of CO2 emissions per capita between 1960 and 2100, incl. cement and LULUCF

For CH4, user configured a change of **0%** per year per capita for Waste emissions. Changes for LULUCF emissions are the same as for CO2, emissions from other agricultural processes are related to demography. CH4 emissions evolve as follows:

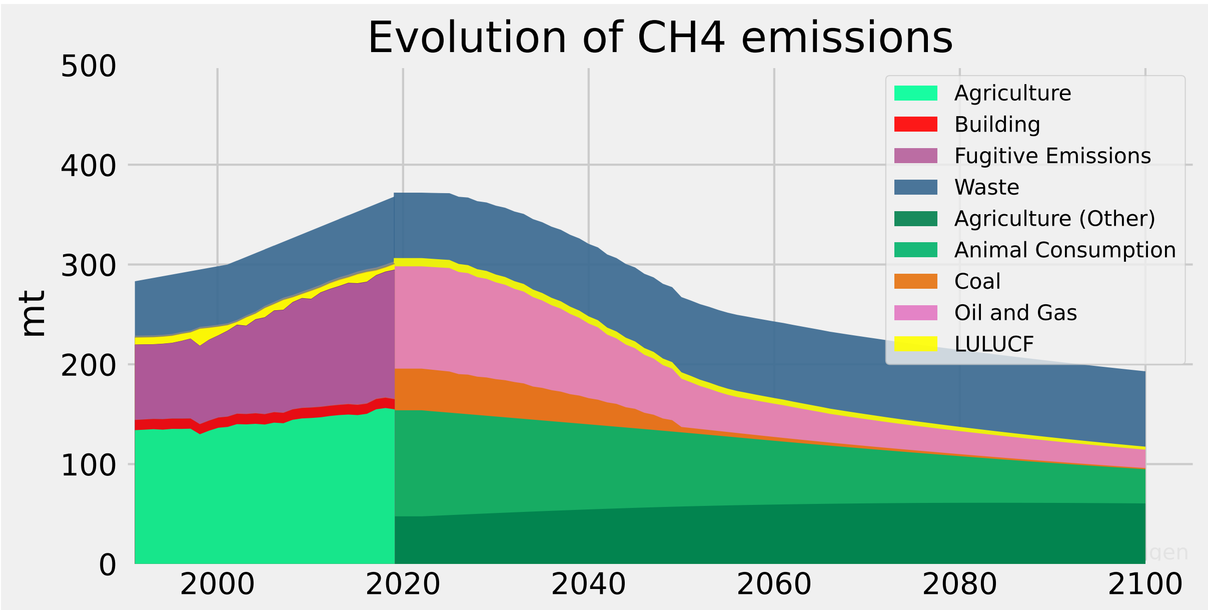


Fig. 3.59: Evolution of CH4 emissions by sources, discontinuity in labels indicate re-assignment of sources for the model

For N2O, user configured a change of **-1.0%** per year per capita for all sources.

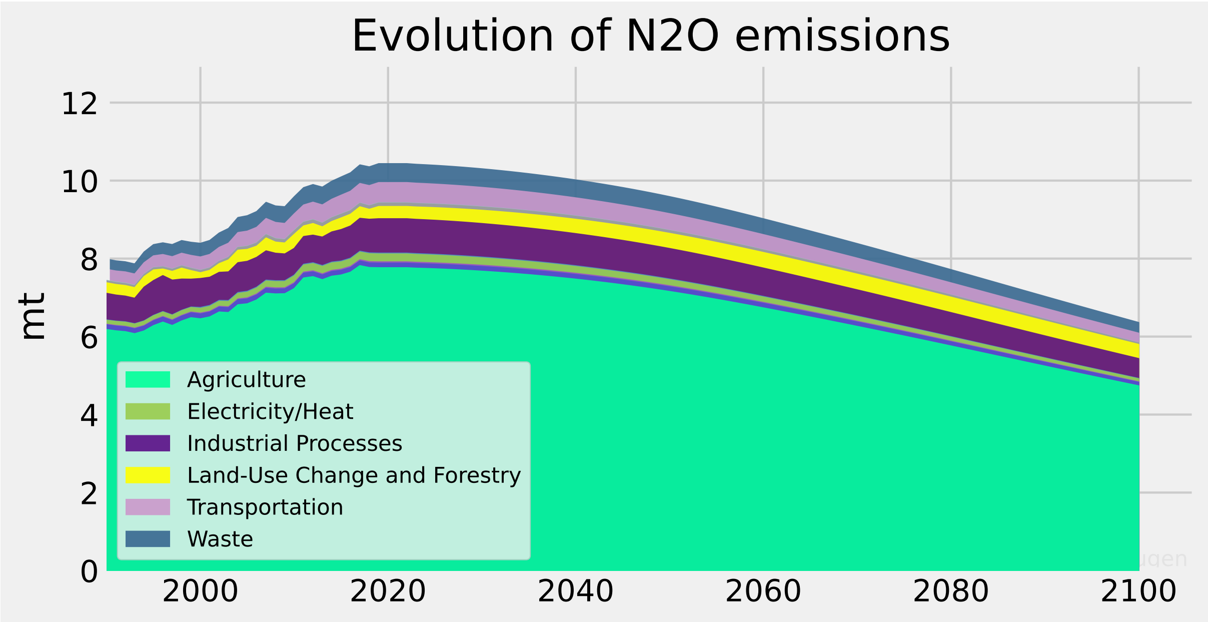


Fig. 3.60: Evolution of N2O emissions

For F-Gases, user configured a change of **0%** per year per capita for all sources. Evolution is impacted by population changes.

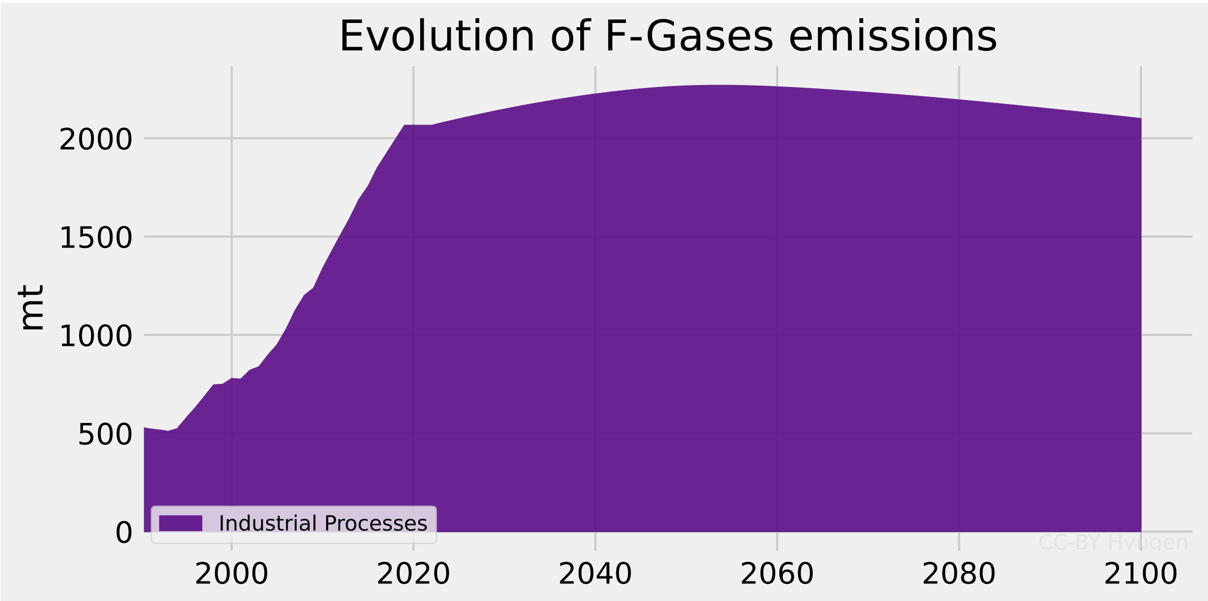


Fig. 3.61: Evolution of F-Gases emissions

For SO2, user configured a change of **-2.0%** per year per capita for emissions from industries.
SO2 emissions are displayed in fig. 3.62.

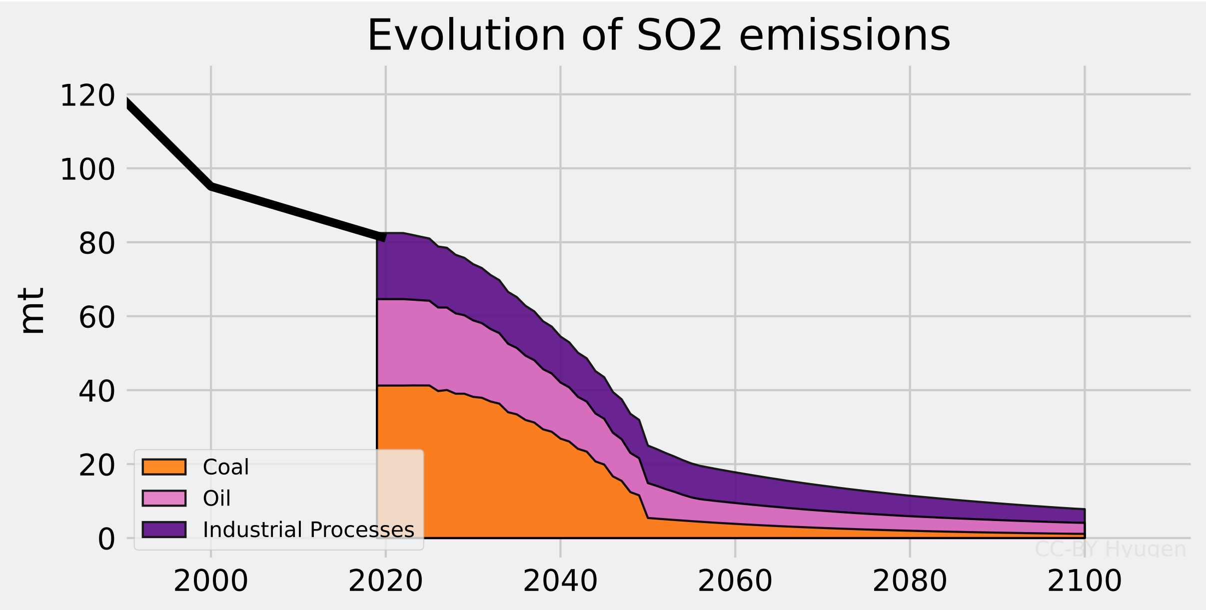


Fig. 3.62: Evolution of SO2 emissions

3.5.2 Warming per gas

Emissions from CO2, CH4, N2O and F-Gases don't impact climate directly in the model, they first impact a proxy value which is used by the model to estimate the warming caused by the gas.
For CO2, the proxy value is CO2 concentration:

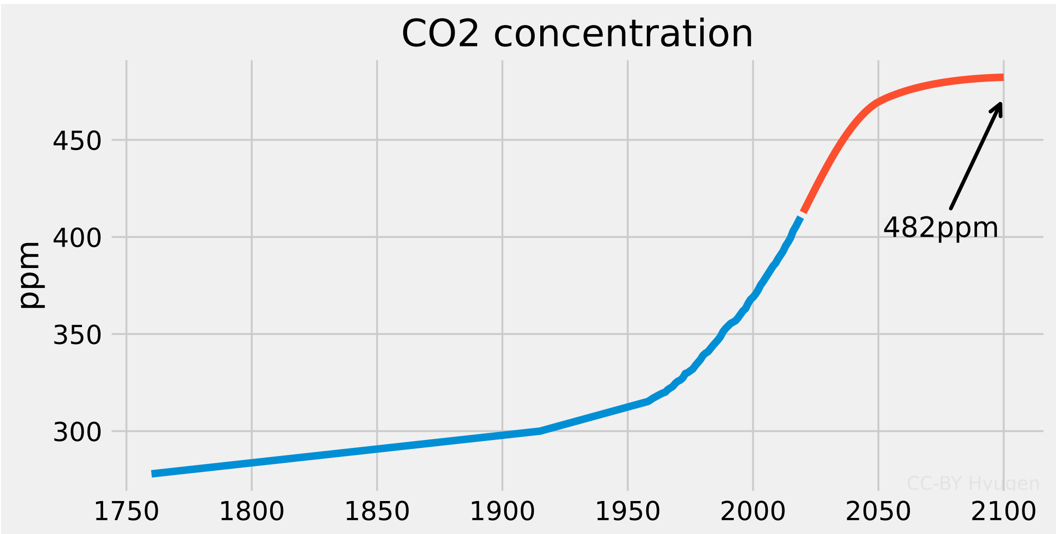


Fig. 3.63: Evolution of CO2 concentration

For CH4, N2O and F-Gases the proxy value is their cumulative GTP:

$$CumulativeGTP_{gas}(Y) = \sum_{y\approx 1760}^{Y} GTP_{gas}(Y-y) * emissions_{gas}(y).$$

The model computes the cumulative GTP of CH4 emissions in fig. 3.64, of N2O emissions in fig. 3.65 and of F-gases emissions in fig. 3.66.

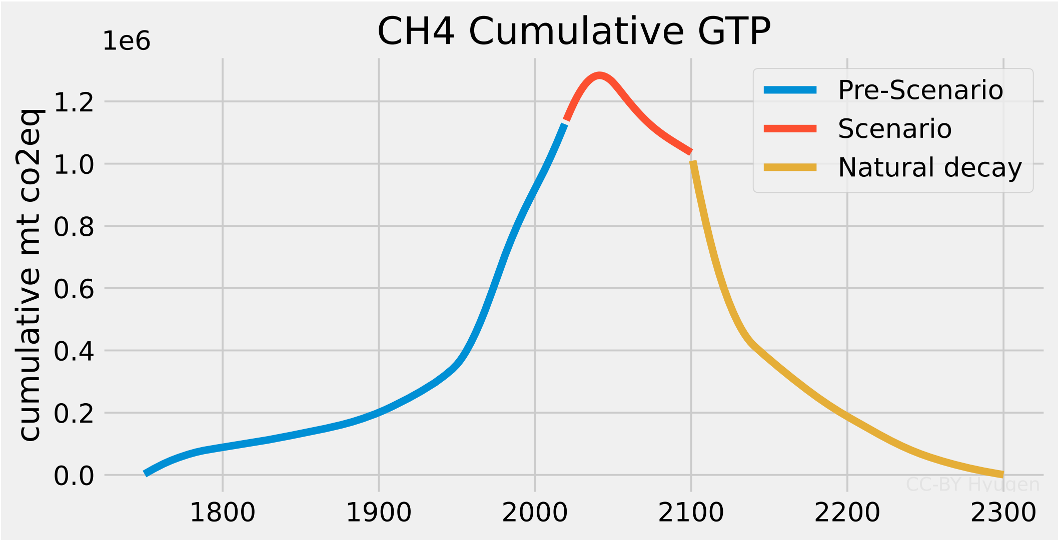


Fig. 3.64: Evolution of cumulative CH4 CO2eq (GTP)

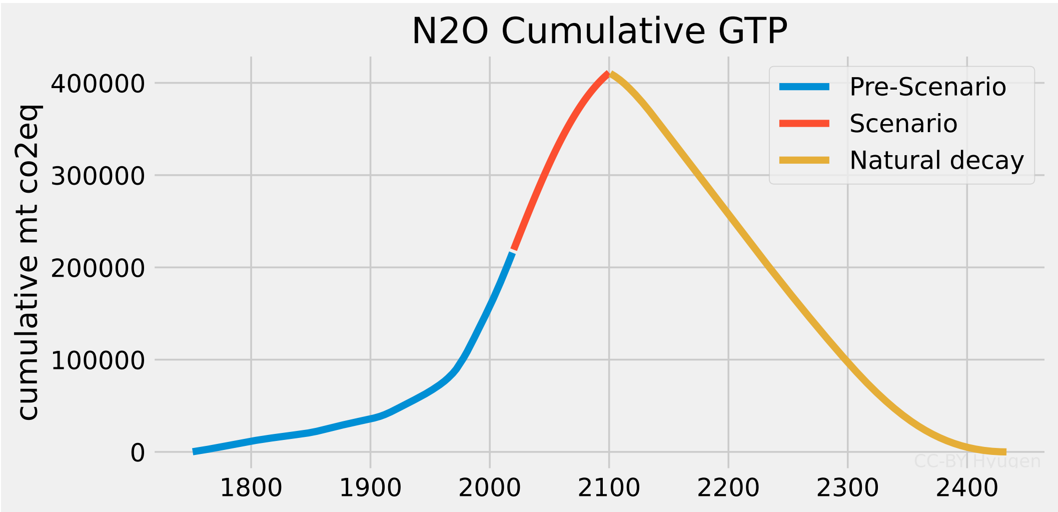


Fig. 3.65: Evolution of cumulative N2O CO2eq (GTP)

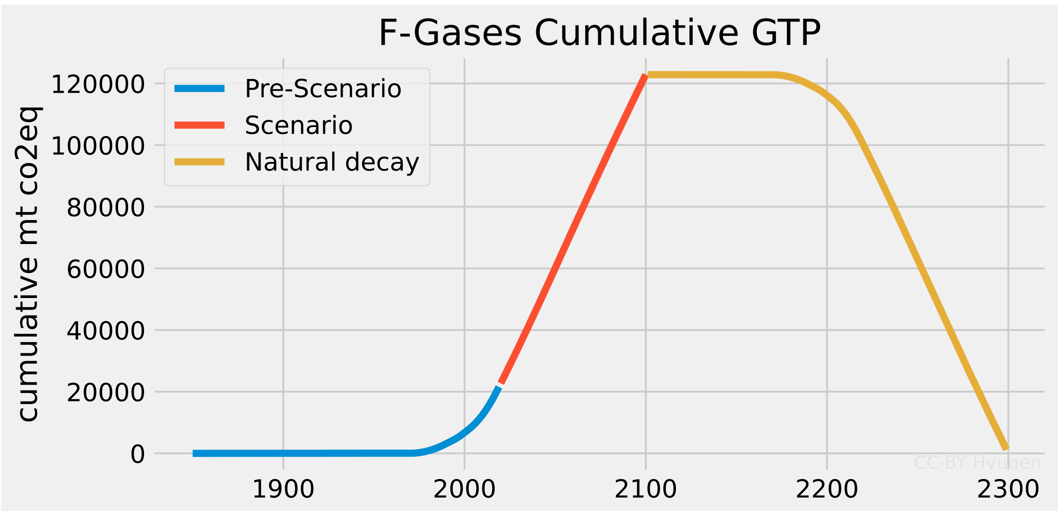


Fig. 3.66: Evolution of cumulative F-Gases CO2eq (GTP)

The final warming per gas is estimated with linear models on their proxy value: CO2 concentration for CO2, GTP for CH4, N2O, F-Gases and direct emissions for SO2. Results are displayed in fig. 3.67.

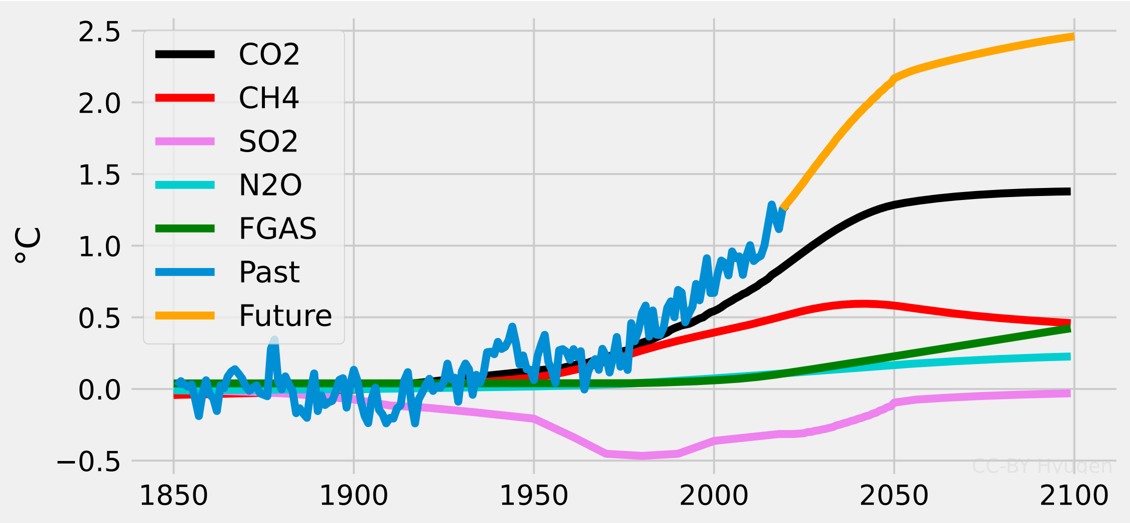


Fig. 3.67: Warming per gas, based on previously detailed climate models in section 4.10

3.5.3 Localized warming and rainfalls

Localized warming and rainfalls over the world are estimated based on the mean of CMIP6 models.

	Warming	Rainfalls (2020)	Rainfalls (2100)
Global	+2.5°C	1060	1080
Land	+3.8°C	806	820
Sea	+2.0°C	1160	1182
Populations	+3.3°C	1124	1155
Arable lands	+3.6°C	913	932
Forests	+3.9°C	1261	1272
Ice	+3.2°C	278	301

Table 3.14: Localized climate variation, warming between 2100 and pre-industrial era, rainfalls in mm/year, urbanization is not considered

The global warming is projected to be **+2.5°C** in 2100. The global warming where people are located (weighted by population distribution) is projected to be **+3.3°C** in 2100.

The model computes the local warming based on global warming and modeled SSPs, as detailed in section 4.10. Figure 3.68 shows a map of global warming and fig. 3.69 shows a world map of changes in precipitations.

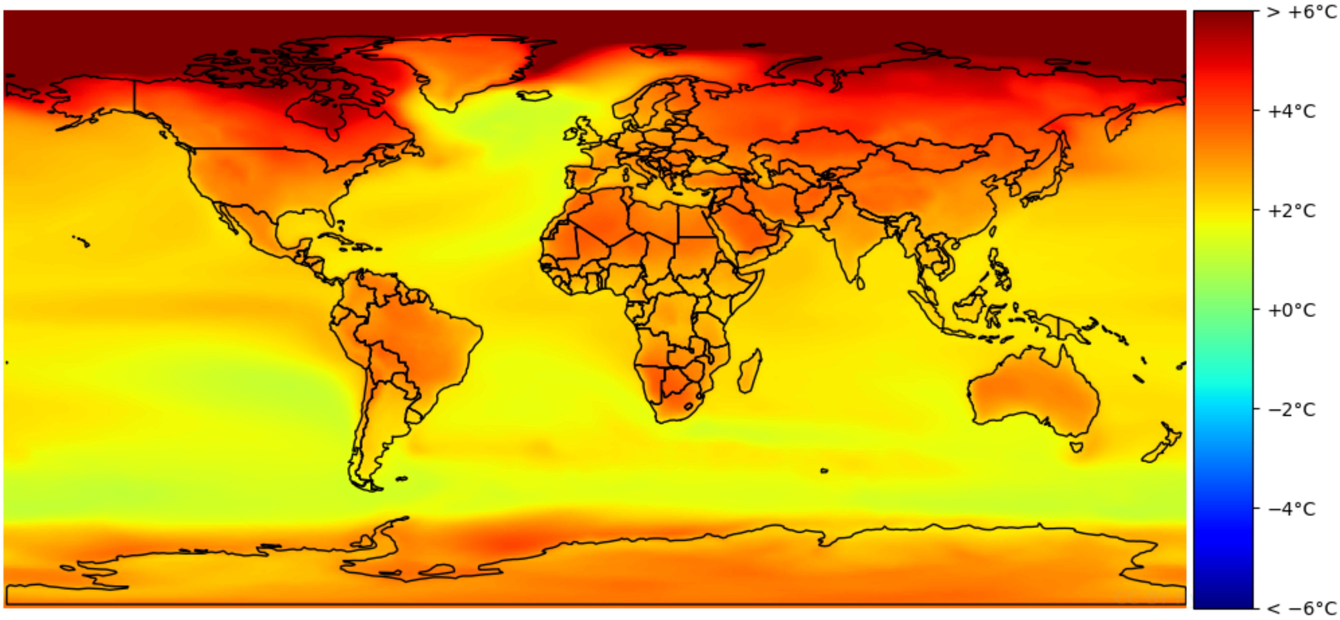


Fig. 3.68: Warming on Earth between pre-industrial era and 2100. Methodology in section 4.10 and appendix J.1

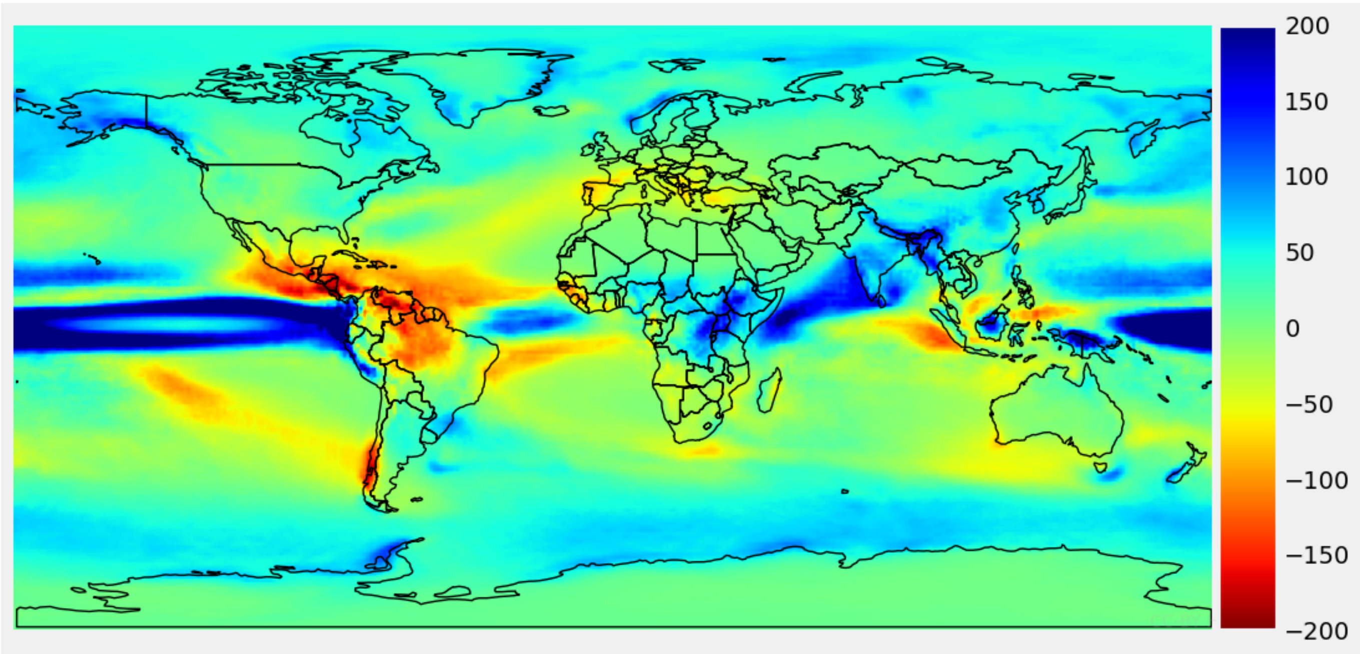


Fig. 3.69: Rainfall **variations** between 2020 and 2100, mm/year, (average estimates for 2020 and 2100), values are clipped in [-200,200]. Methodology in section 4.10 and appendix J.1

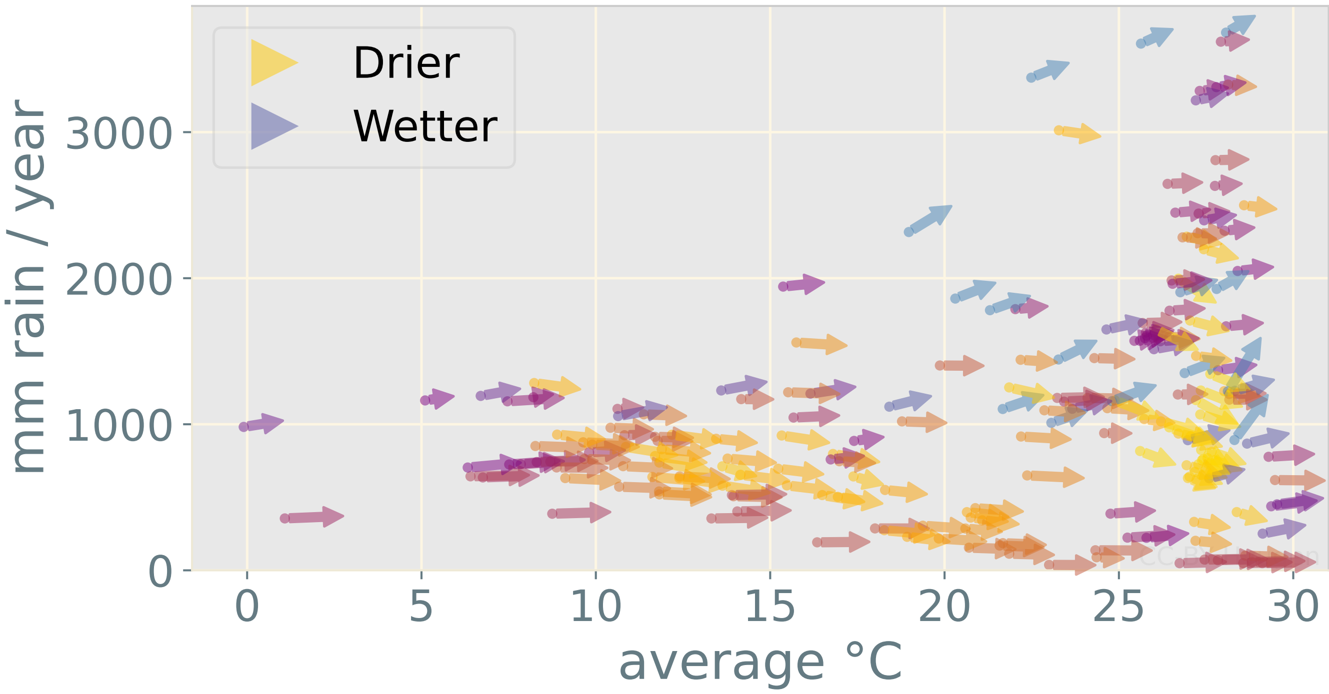


Fig. 3.70: Variations on rainfall and temperature, each arrow is a country, changes between 2019 and 2100, weighted by population distribution (larger version). Based on previously detailed climate models in section 4.10, and appendix J.1

Countries that will experience the most significant changes are:

	Warming	**ΔRainfalls** (mm, 2100-2020)
Highest warming		
Russia	+3.7°C	9.4
Mongolia	+3.7°C	17.7
Kazakhstan	+3.7°C	12.7
Canada	+3.6°C	25.4
Iraq	+3.6°C	-2.2
More rains		
Nauru	+2.1°C	394.2
Kiribati	+2.1°C	335.6
Bhutan	+2.7°C	195.2
Uganda	+2.5°C	142.4
Sri Lanka	+2.1°C	138.2
More dry		
Guyana	+2.7°C	-122.5
Honduras	+2.9°C	-129.2
Guatemala	+2.7°C	-153.4
Nicaragua	+2.7°C	-177.5
Costa Rica	+2.4°C	-181.4

Table 3.15: Countries with the highest estimated variations on rainfalls and warming, weighted by population distribution, warming is 2100 temperatures minus preindustrial-era temperatures, see section 4.10, appendix J.1

Chapter 4 Results per country

Detailed results are presented for multiple countries.

The same precautions applies as the ones detailed in section 3.1. Presented results are the output of a model with a specific configuration and with specific assumptions.

Results should not be perceived as a recommendation or an anticipation of the future, but rather as an estimation of what maximum decarbonization efforts could achieve, according to previously specified data, constraints, and configuration.

Results can be provided for all countries of the world. In order to minimize the size of the report, results for a reduced number of countries are provided.


China

Demography overview

Population in China changes as follows:

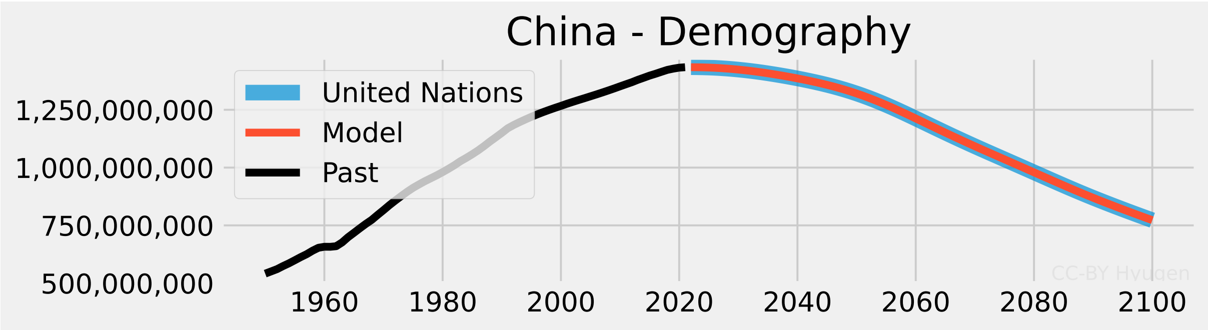


Fig. 4.1: Demography in China, UN:[30]

Life expectancy in China could evolve as follows:

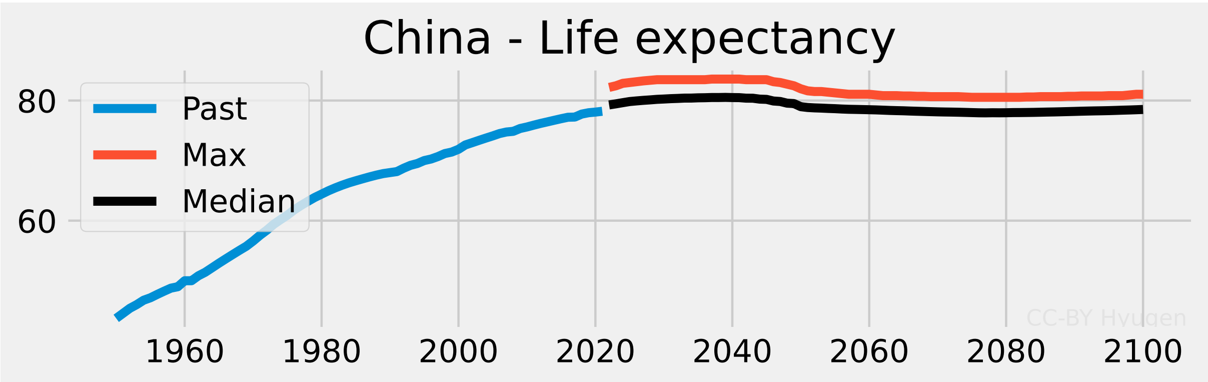


Fig. 4.2: Life expectancy in China, UN:[30], max and median from fig. 1.13

Meat consumption of China is configured by the user:

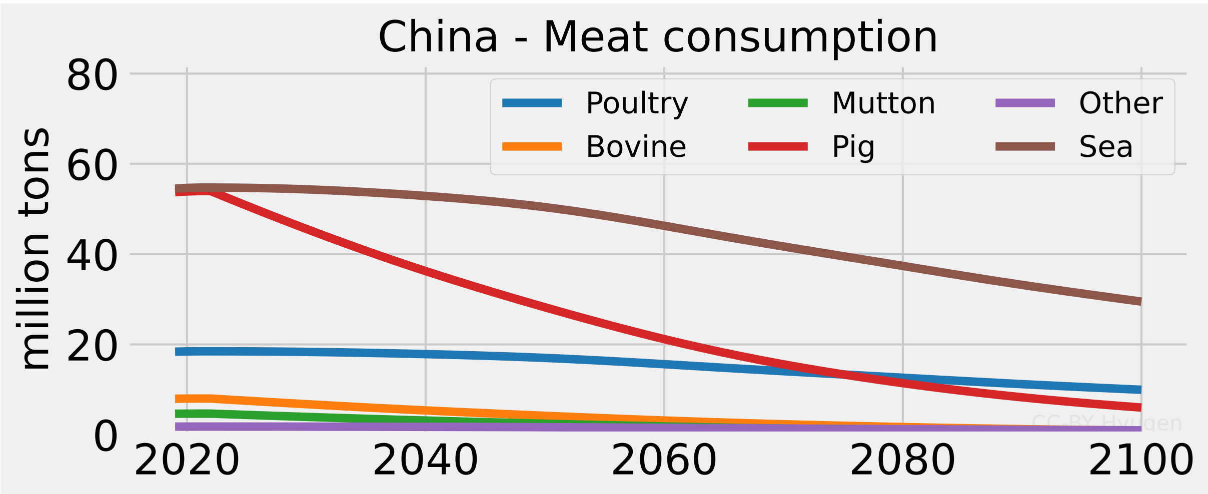


Fig. 4.3: Meat consumption in China, initialized with [84]

Climate change impacts on crops can be visualized as follows:

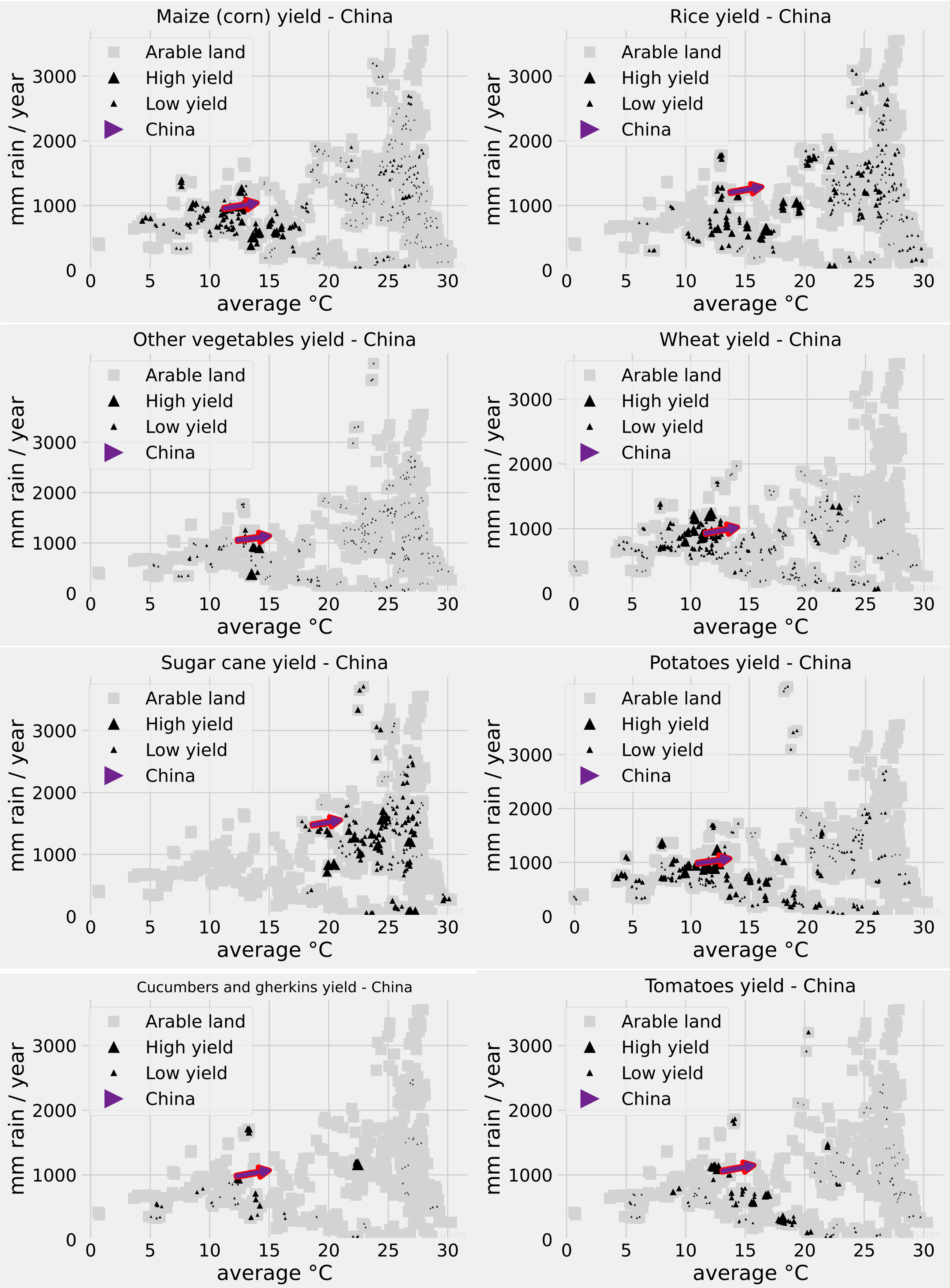


Fig. 4.4: Yields for different crops, arrow represents warming between 2100 and pre-industrial era, yield source:[32]

Energy overview

Changes related to power generation in China since 1980 can be presented:

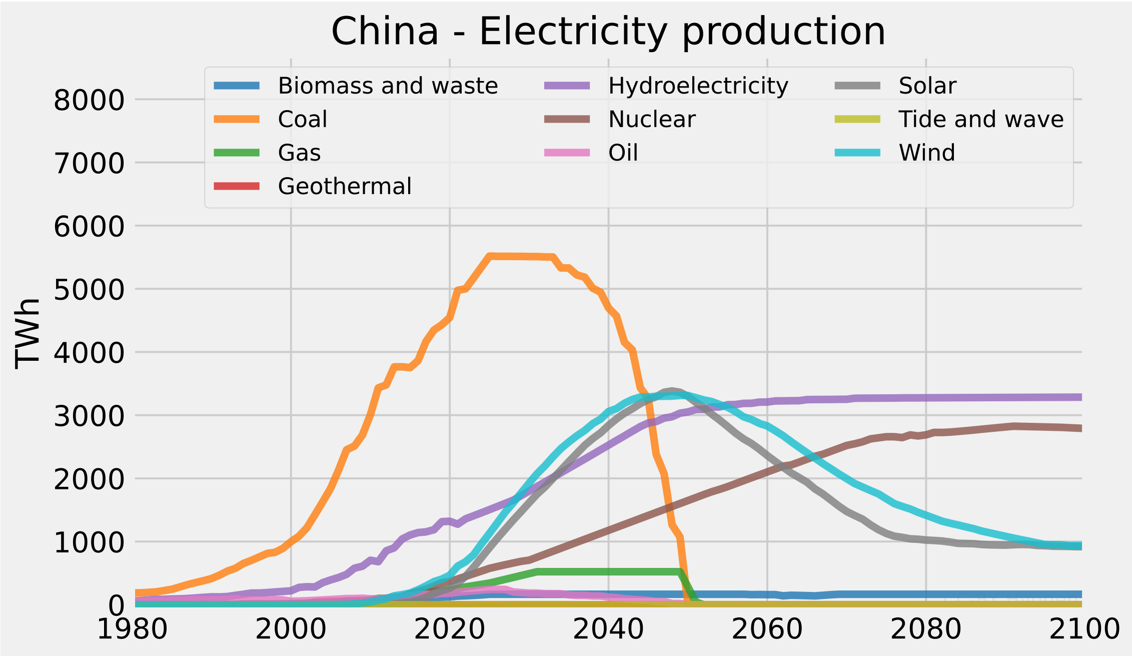


Fig. 4.5: Electricity production in China

Changes related to electrical capacity in China since 1980 can be presented:

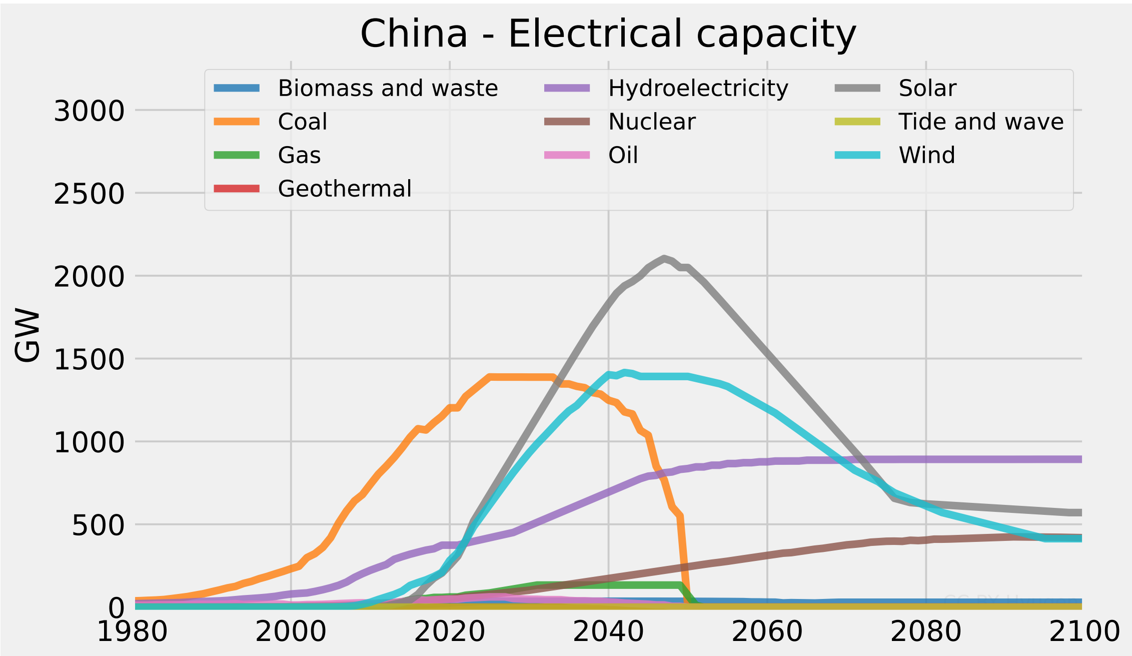


Fig. 4.6: Electrical capacity in China since 1980

Estimated capacity factors can be computed for multiple sources of electricity in China since 1980:

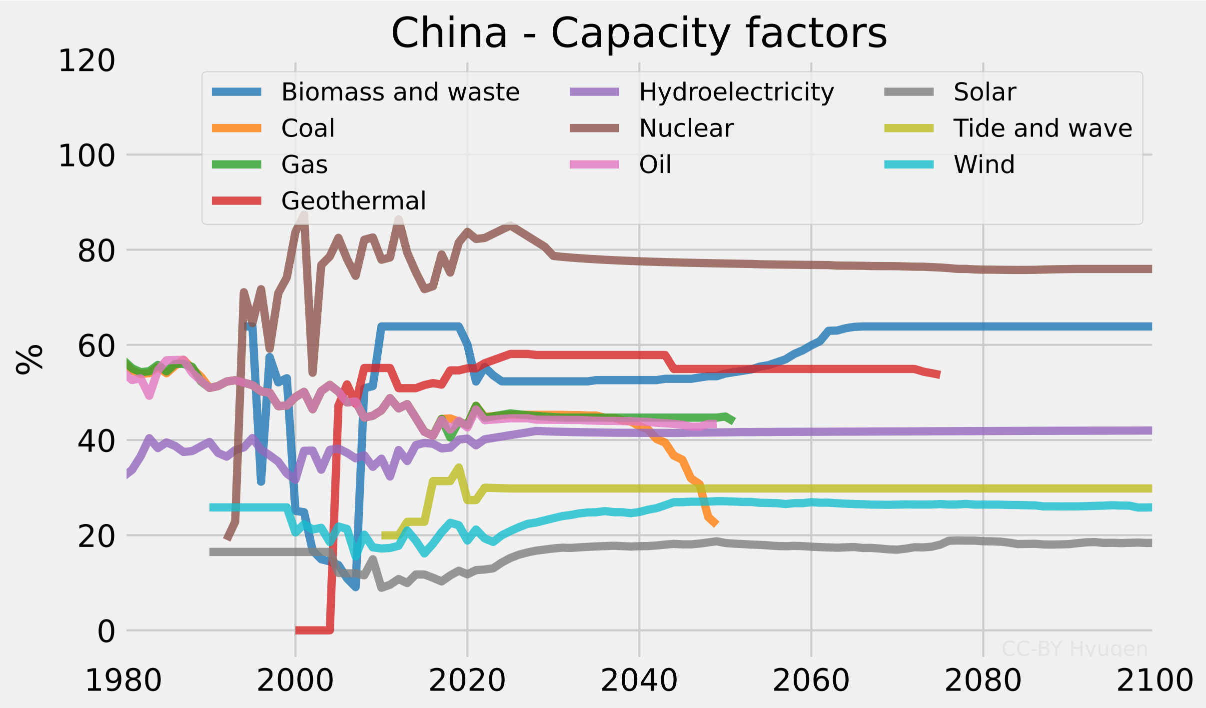


Fig. 4.7: Estimated capacity factors for electricity sources in China

Consumption of fossil fuels in China evolves as follows:

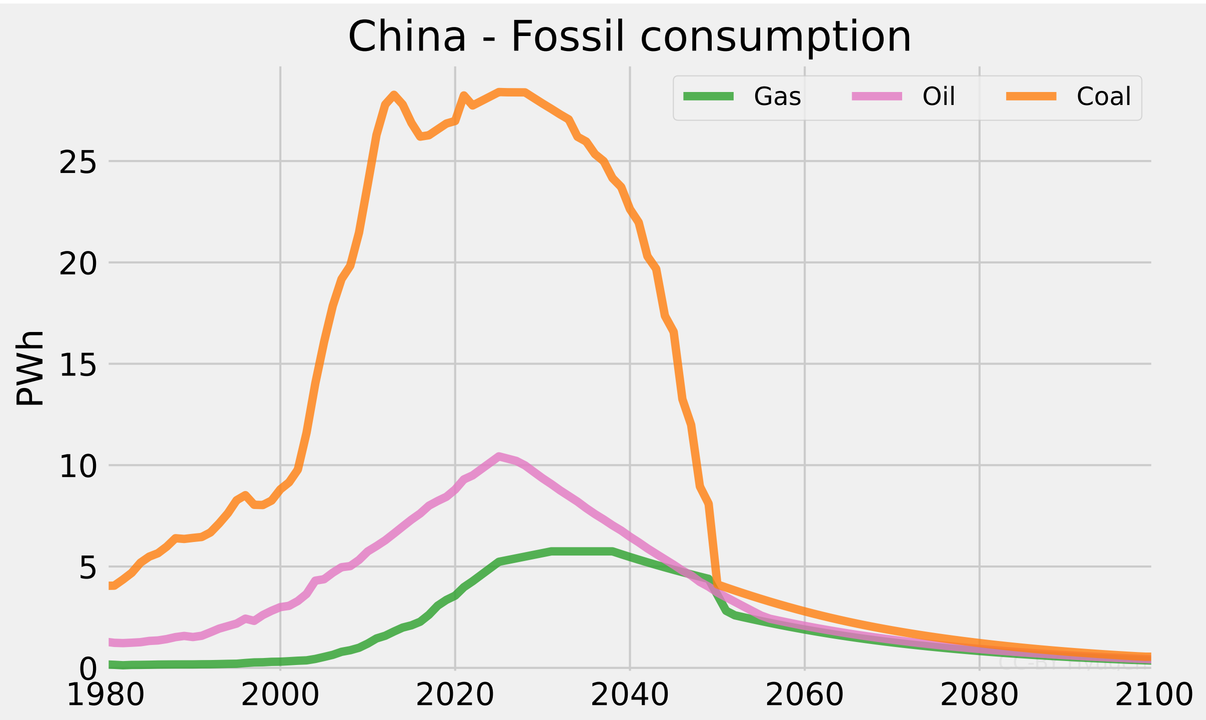


Fig. 4.8: Consumption of fossil fuels in China

Useful energy consumption per capita in China since 1980 can be compared with the useful energy consumption of other countries:

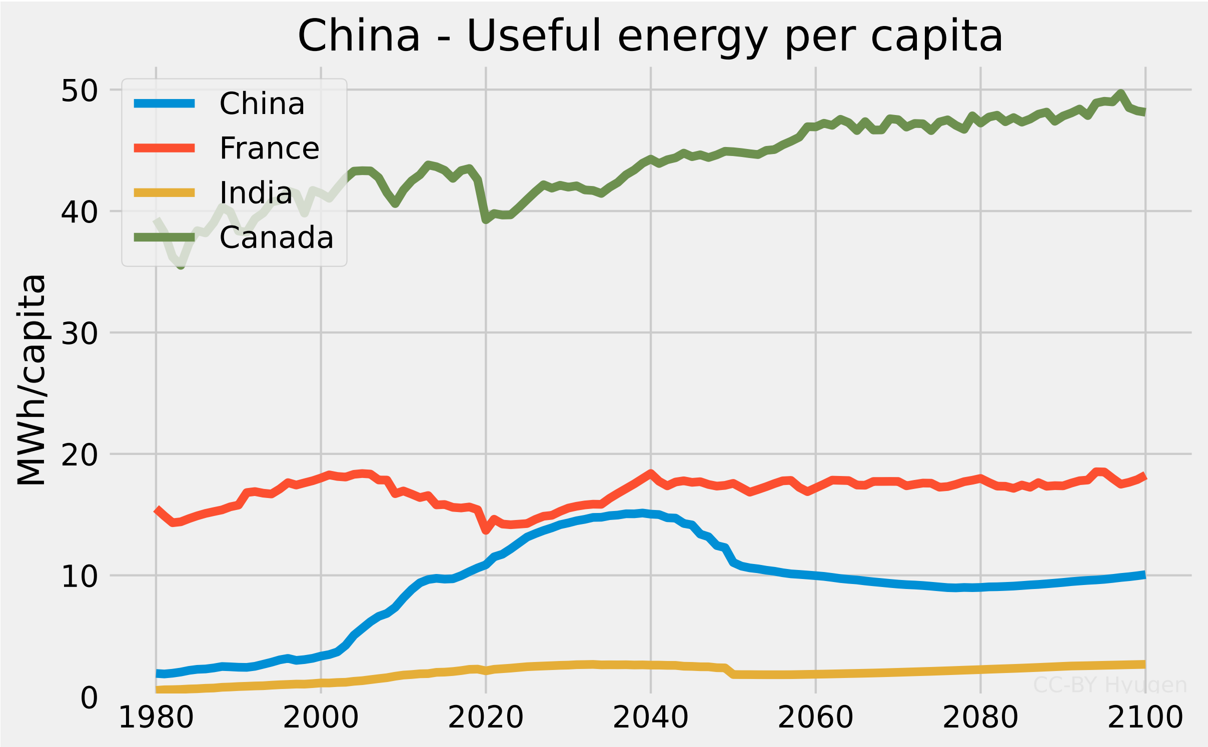


Fig. 4.9: Useful energy in China, cumulates electricity production and fossil consumption, ignores electricity imports/exports

Added and removed capacity per source of electricity are represented:

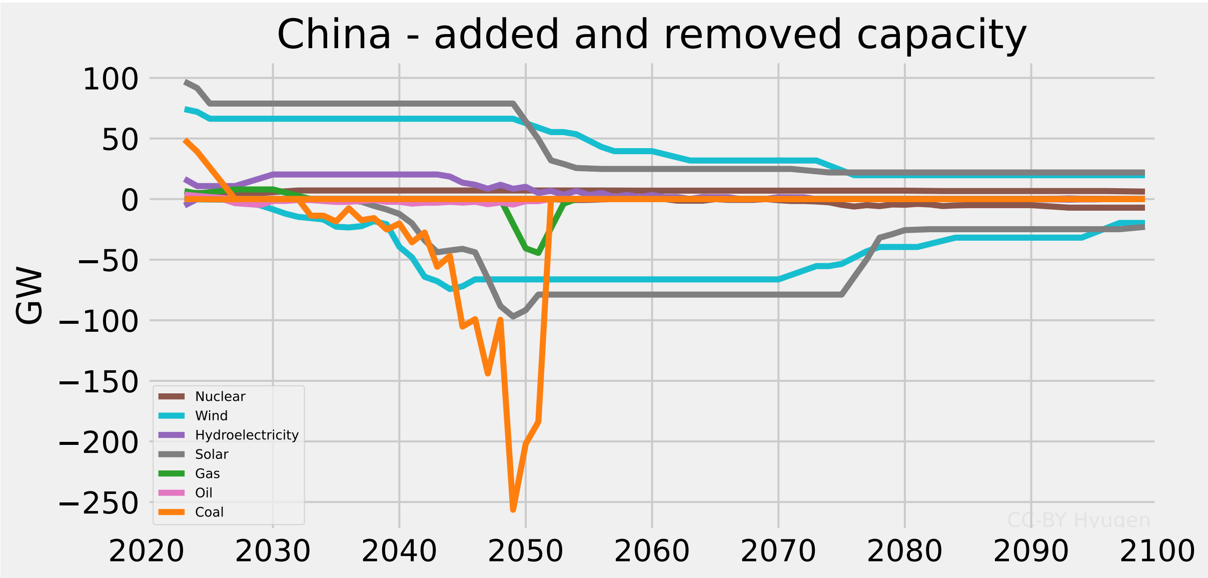
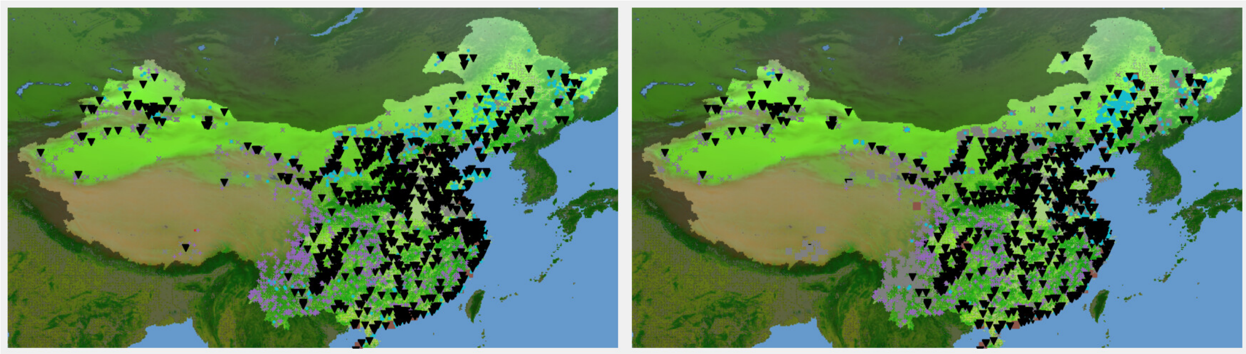
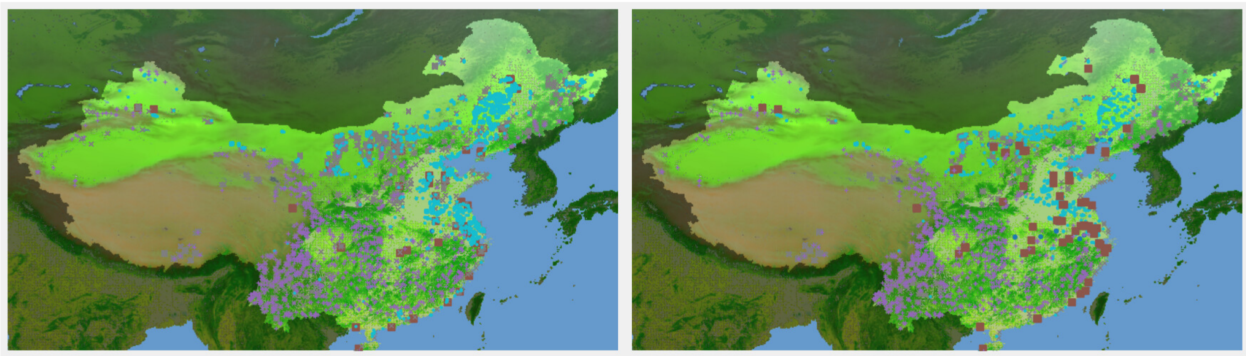


Fig. 4.10: Added / removed capacity per year by electricity source

Power plants are mapped over the country:



(a) 2019 (b) 2040



(c) 2060 (d) 2080

Fig. 4.11: Map of power plants in China, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.) , 2019:[55]

Changes related to carbon intensity of electricity in the country are represented in fig. 4.12.

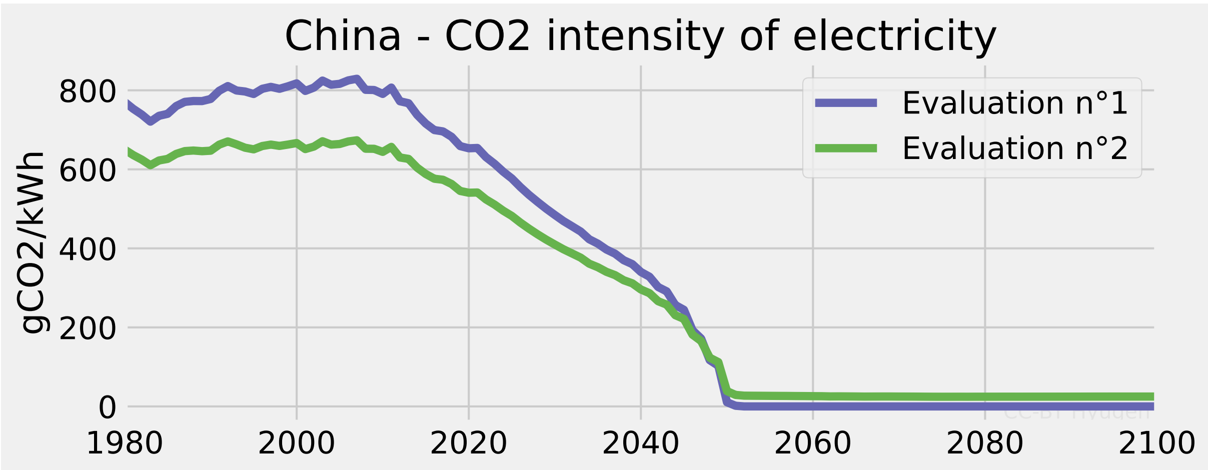


Fig. 4.12: Carbon intensity of electricity in China. Details in fig. 3.12

Reserves for multiple elements are included in the model:

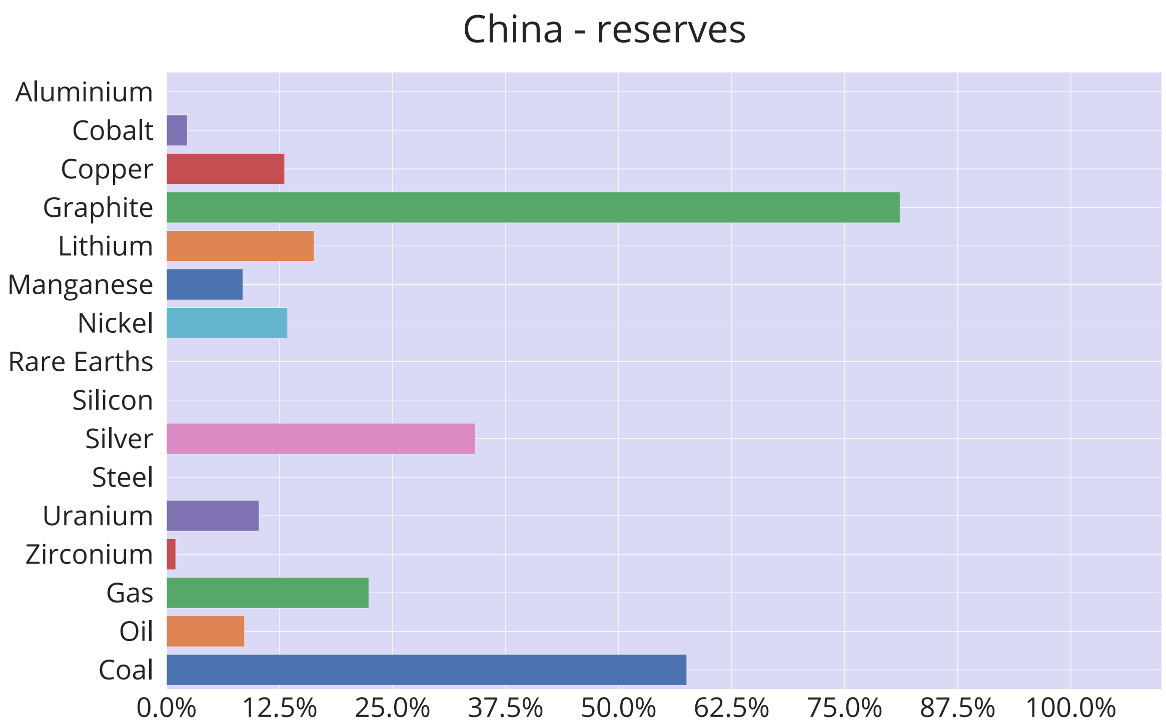


Fig. 4.13: Reserves of China as a proportion of the country with the most reserves (proportionally small reserves compared to the largest in the world may not be represented), source:[77]

The number of road vehicles in China evolves as follows:

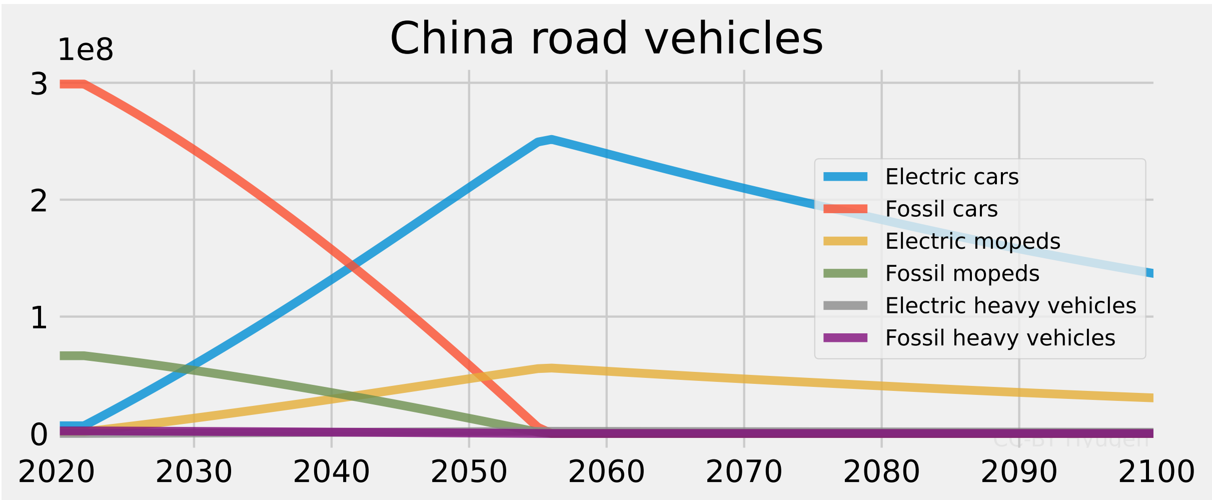


Fig. 4.14: Evolution of road vehicles in China. Details in fig. 3.18

Proportion of controllable electricity in China is included in the model:

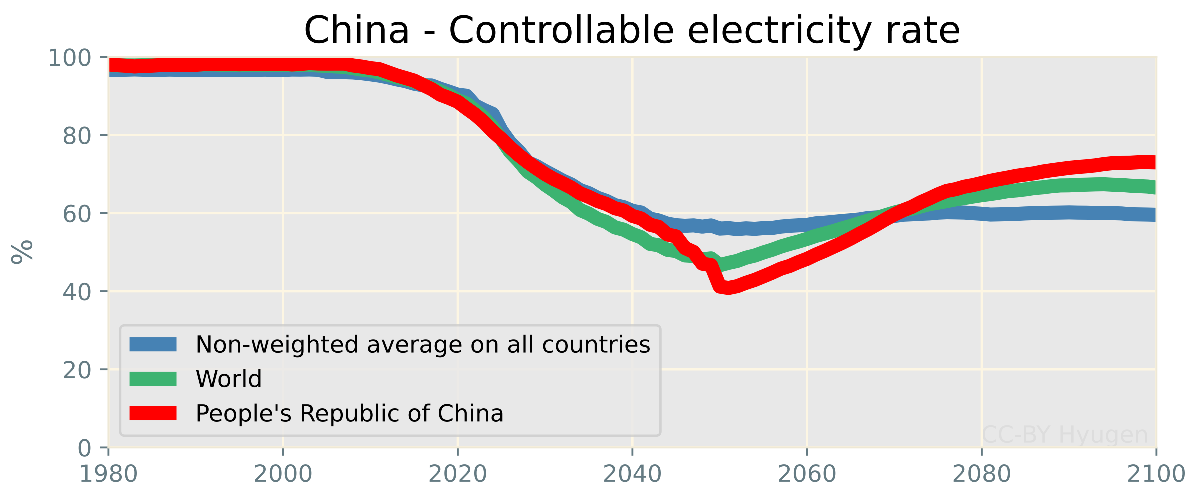


Fig. 4.15: Controllable electricity rate in China. Details in fig. 3.17

Power required from storage systems in China is modeled:

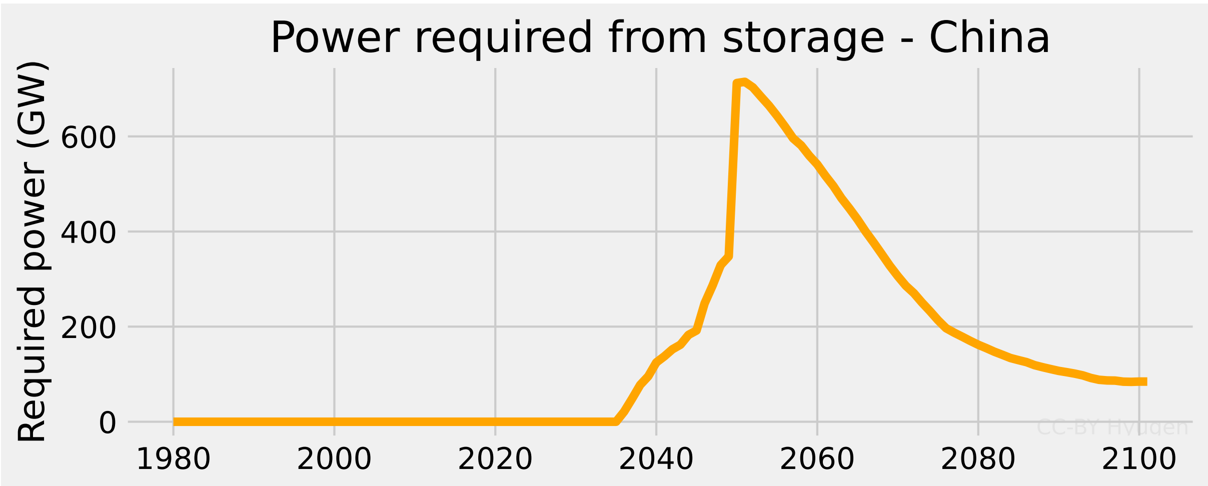


Fig. 4.16: Power required from storage systems in China. Details in fig. 3.53

Climate overview

Changes related to CO2 emissions in China can be visualized:

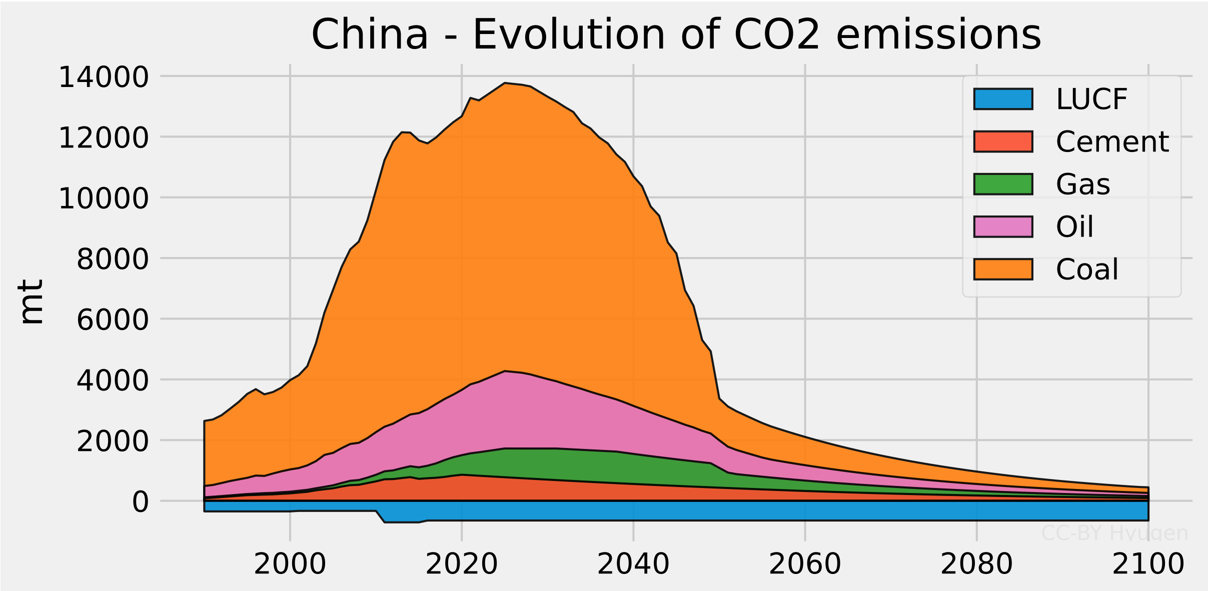
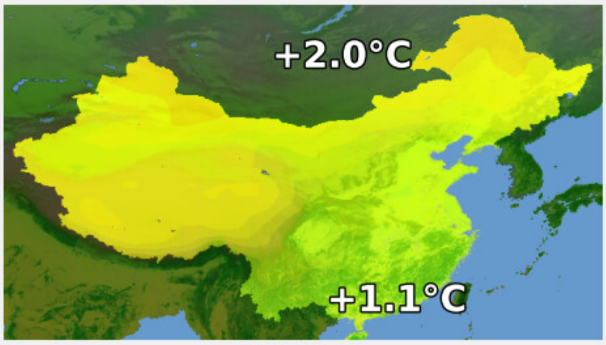


Fig. 4.17: CO2 emissions from China, pre-2020 source:[95, 83]

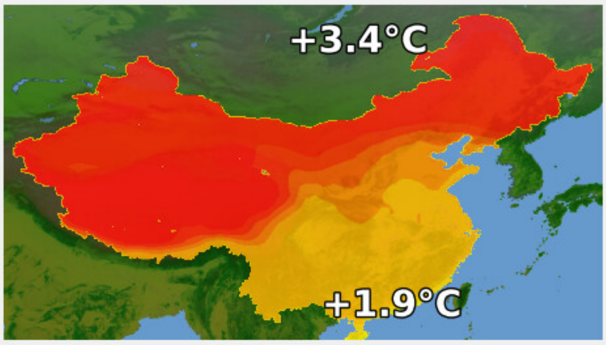
Climage changes in China are considered. Warming in the country will range from **+1.9°C** to **+4.0°C** in 2100 compared to pre-industrial era. Average temperature in 2100 weighted by population distribution is **17.6°C** in the model, with an average warming of **+2.9°C** on populations.
Countries which, before global warming, had similar temperatures compared to temperatures in China in 2100 are:

Country	Temperatures	Rainfalls (mm)
Jordan	19.2°C	167
Rwanda	19.0°C	1734
Eswatini	18.4°C	1404
Tunisia	18.3°C	240
Syria	17.8°C	330
- China	14.7°C => 17.6°C	1156 => 1261
Bhutan	17.6°C	2111
Morocco	17.5°C	267
South Africa	17.3°C	1031
Peru	17.0°C	1035
Vatican City	16.9°C	583

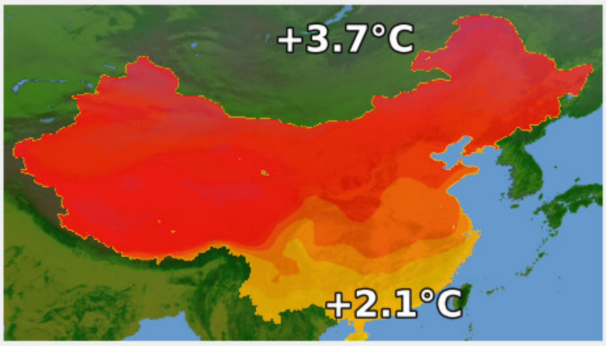
Table 4.1: Comparison of temperatures of China in 2100 with temperatures of other countries before global warming, weighted based on current population distribution. Methodology in section 4.10, based on [57, 62]



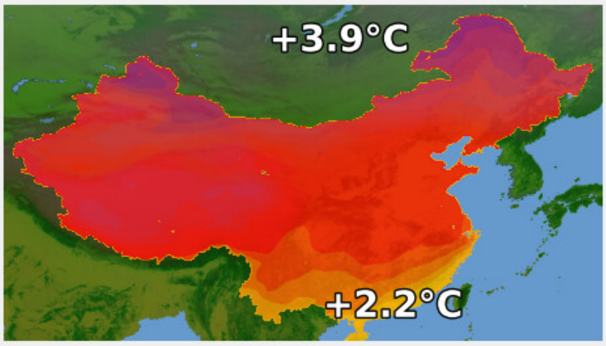
(a) 2020



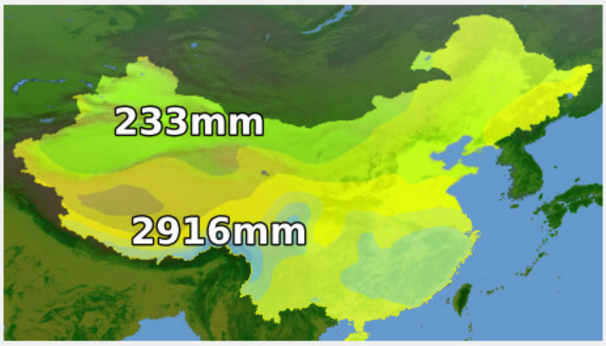
(b) 2050



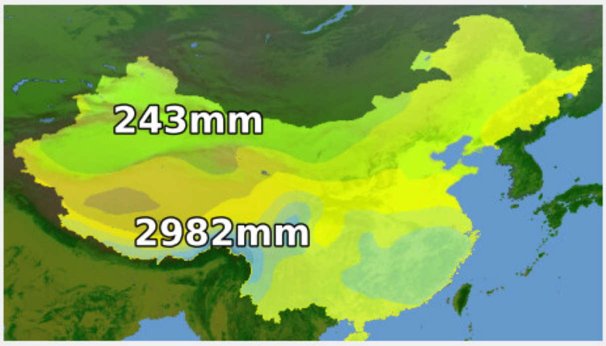
(c) 2070



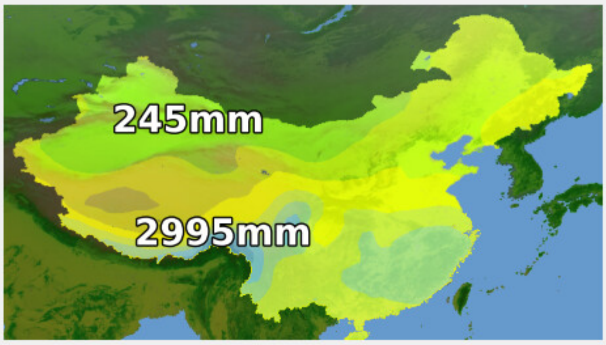
(d) 2100



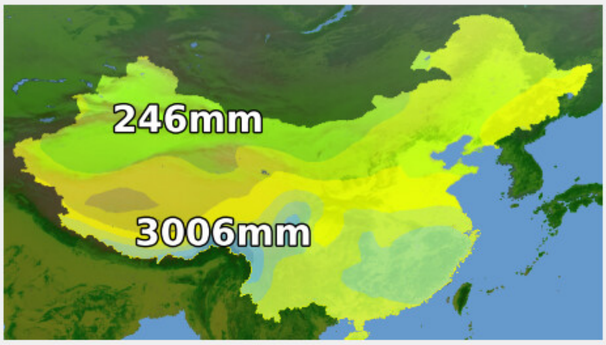
(e) 2020



(f) 2050



(g) 2070



(h) 2100

Fig. 4.18: Maps of global warming and rainfalls between 2020 and 2100

USA

Demography overview

Population in USA changes as follows:

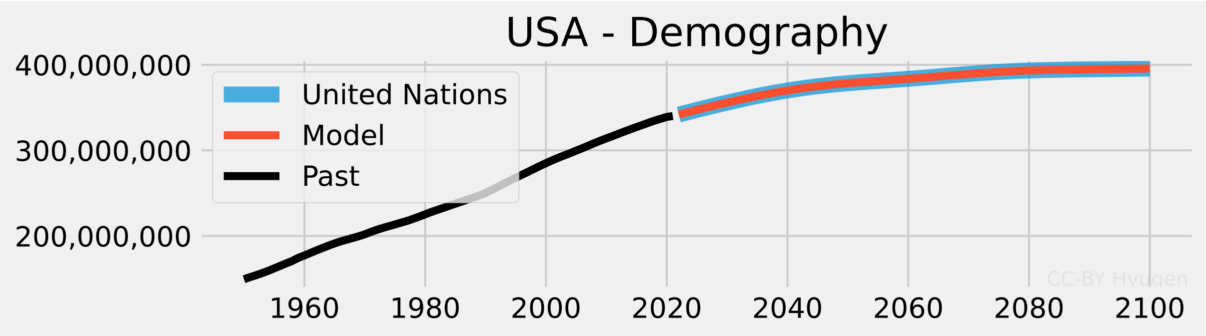


Fig. 4.19: Demography in USA, UN:[30]

Life expectancy in USA could evolve as follows:

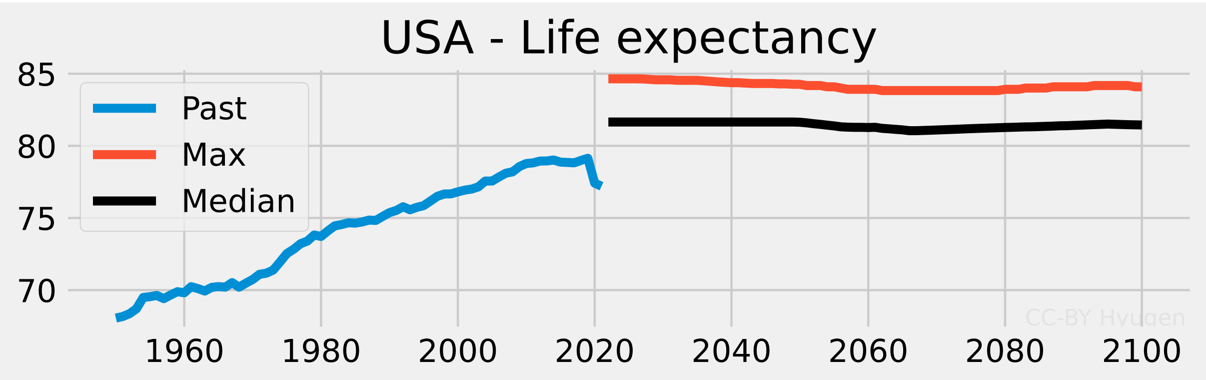


Fig. 4.20: Life expectancy in USA, UN:[30], max and median from fig. 1.13

Meat consumption of USA is configured by the user:

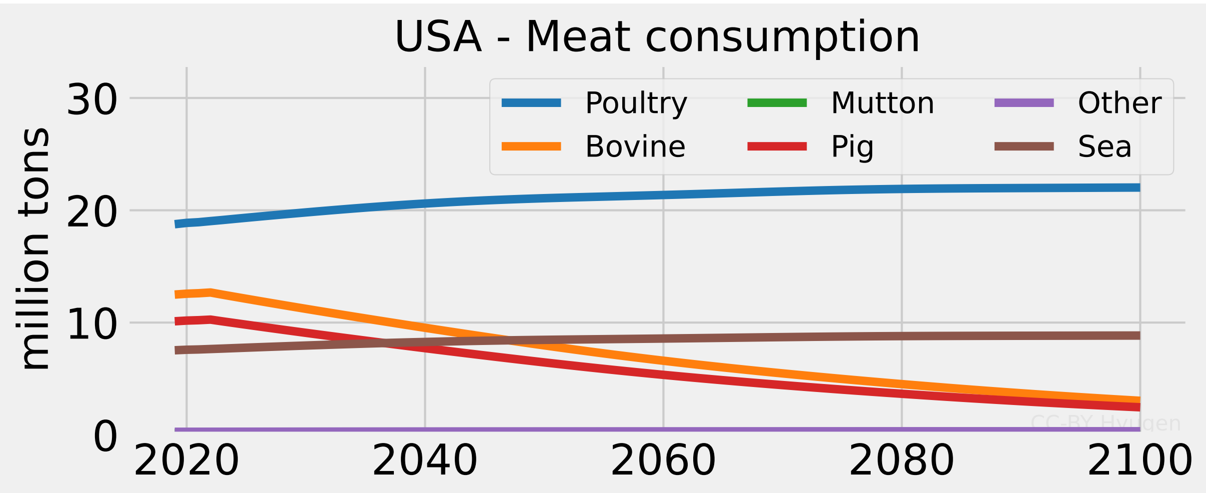


Fig. 4.21: Meat consumption in USA, initialized with [84]

Climate change impacts on crops can be visualized as follows:

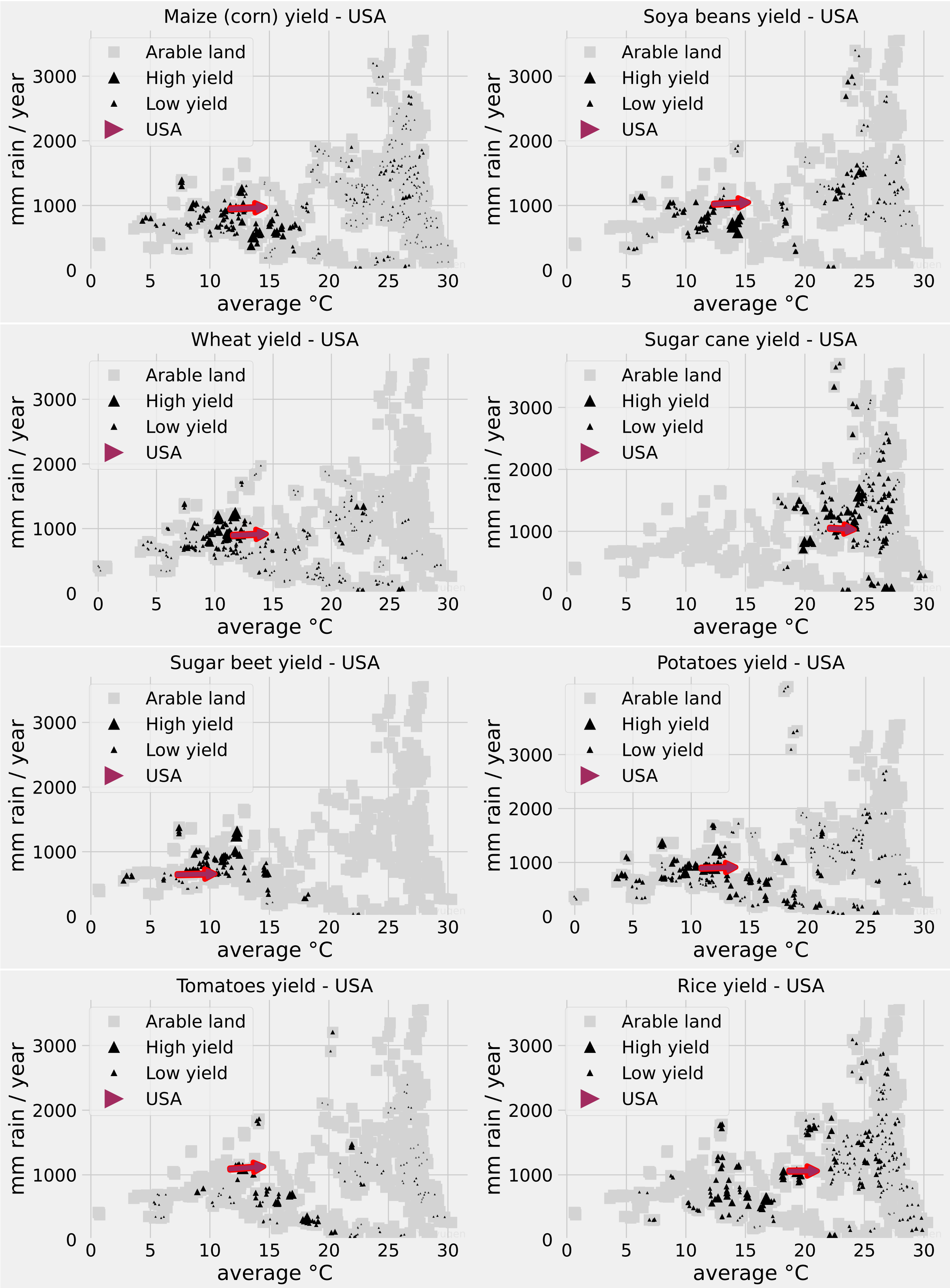


Fig. 4.22: Yields for different crops, arrow represents warming between 2100 and pre-industrial era, yield source:[32]

Energy overview

Changes related to power generation in USA since 1980 can be presented:

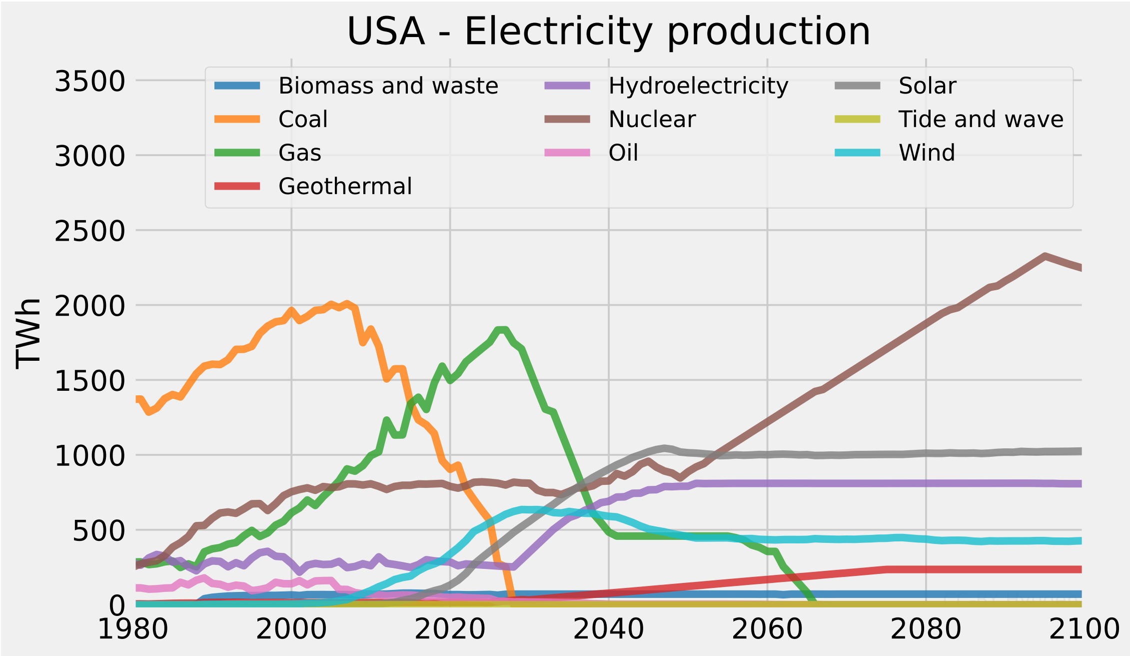


Fig. 4.23: Electricity production in USA

Changes related to electrical capacity in USA since 1980 can be presented:

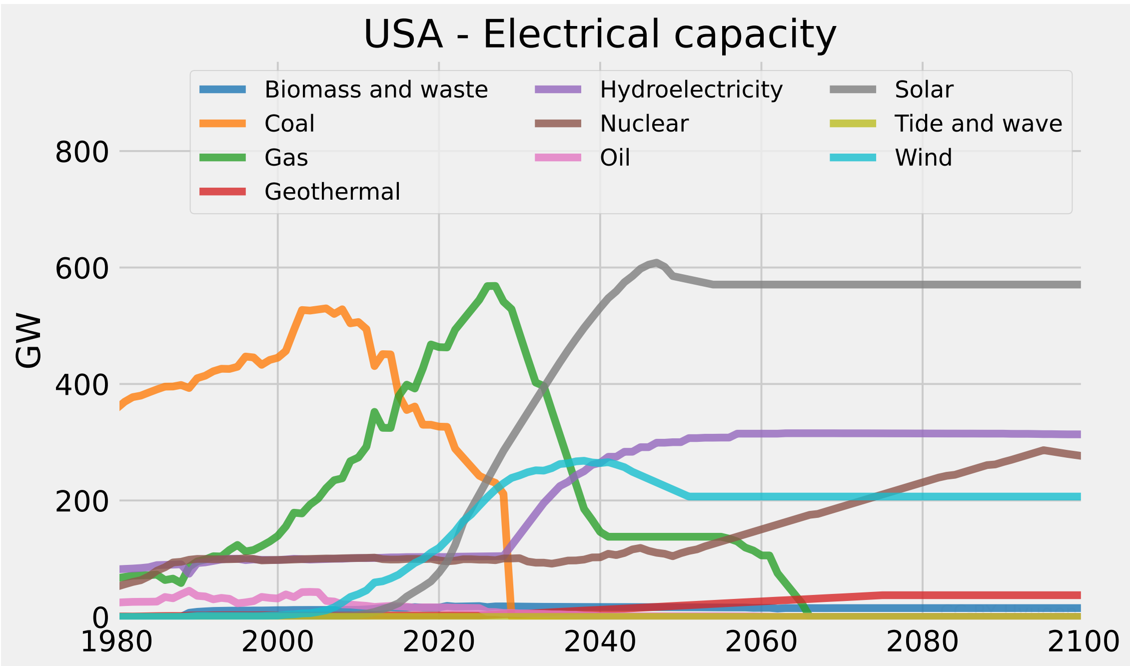


Fig. 4.24: Electrical capacity in USA since 1980

Estimated capacity factors can be computed for multiple sources of electricity in USA since 1980:

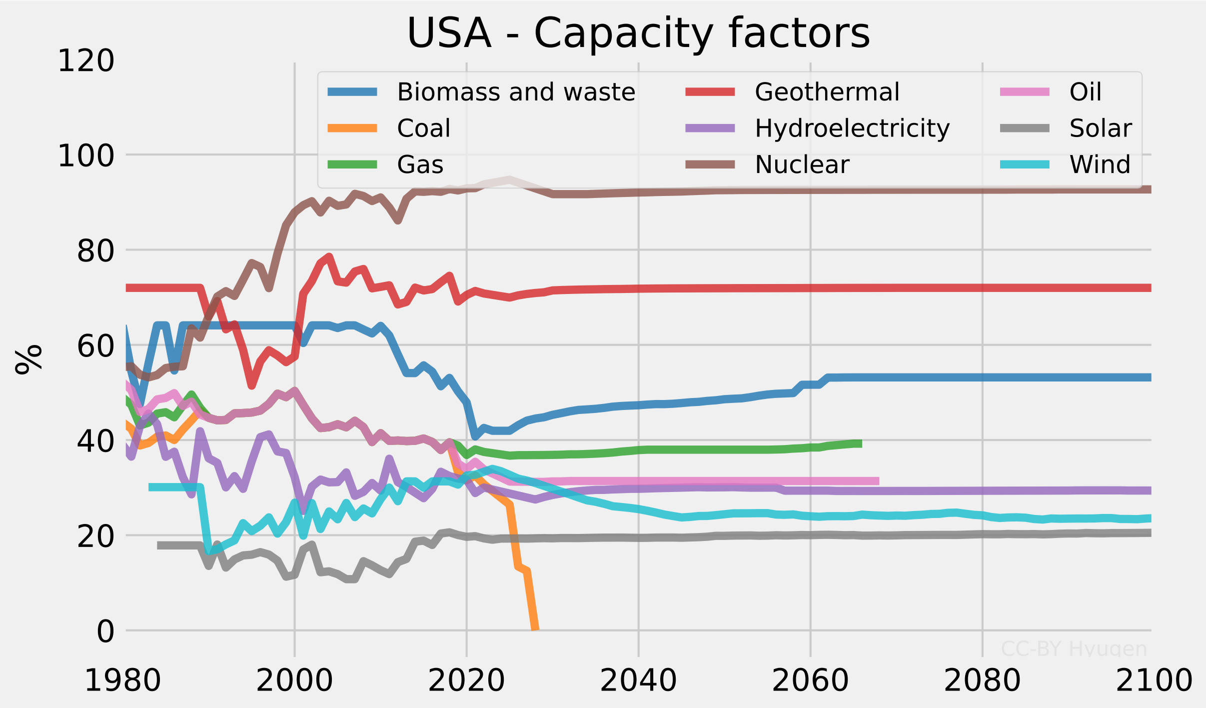


Fig. 4.25: Estimated capacity factors for electricity sources in USA

Consumption of fossil fuels in USA evolves as follows:

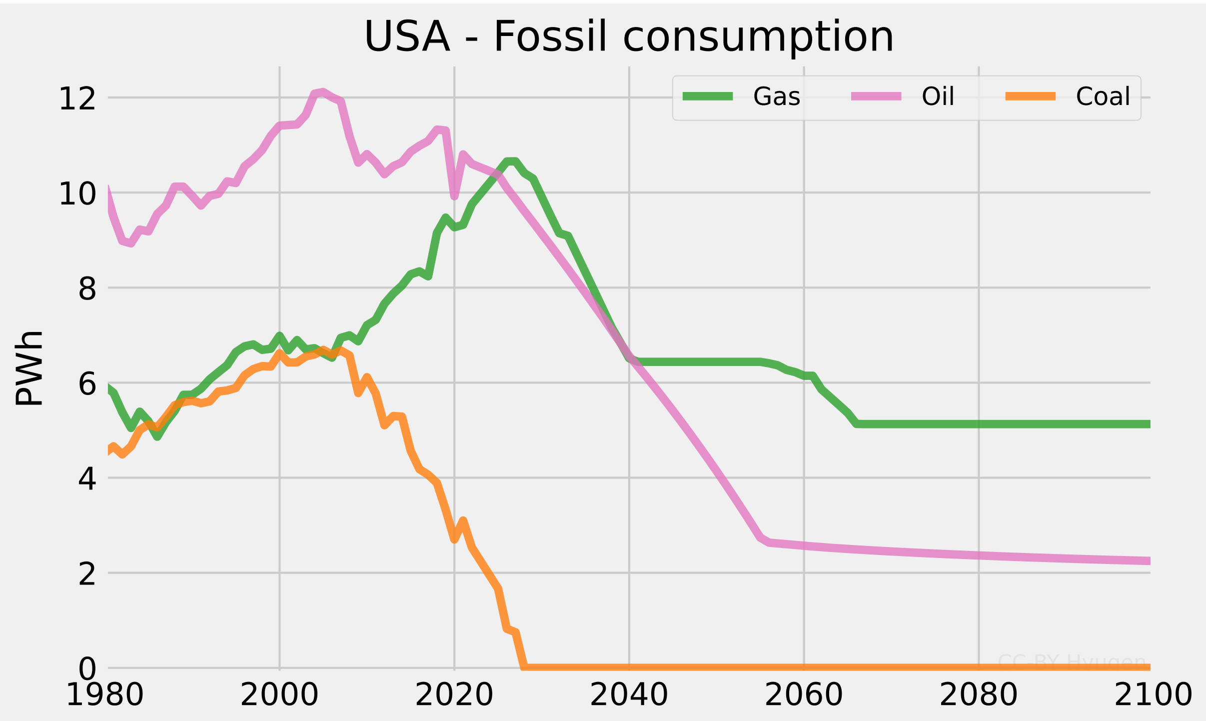


Fig. 4.26: Consumption of fossil fuels in USA

Useful energy consumption per capita in USA since 1980 can be compared with the useful energy consumption of other countries:

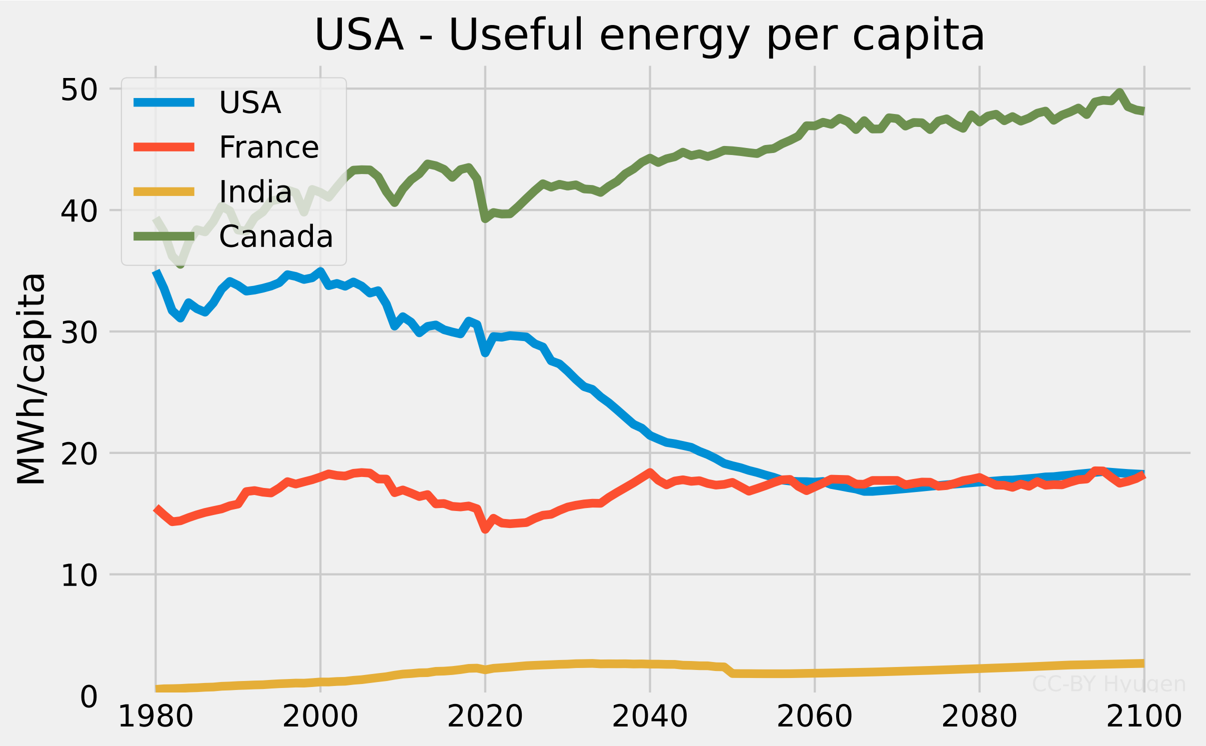


Fig. 4.27: Useful energy in USA, cumulates electricity production and fossil consumption, ignores electricity imports/exports

Added and removed capacity per source of electricity are represented:

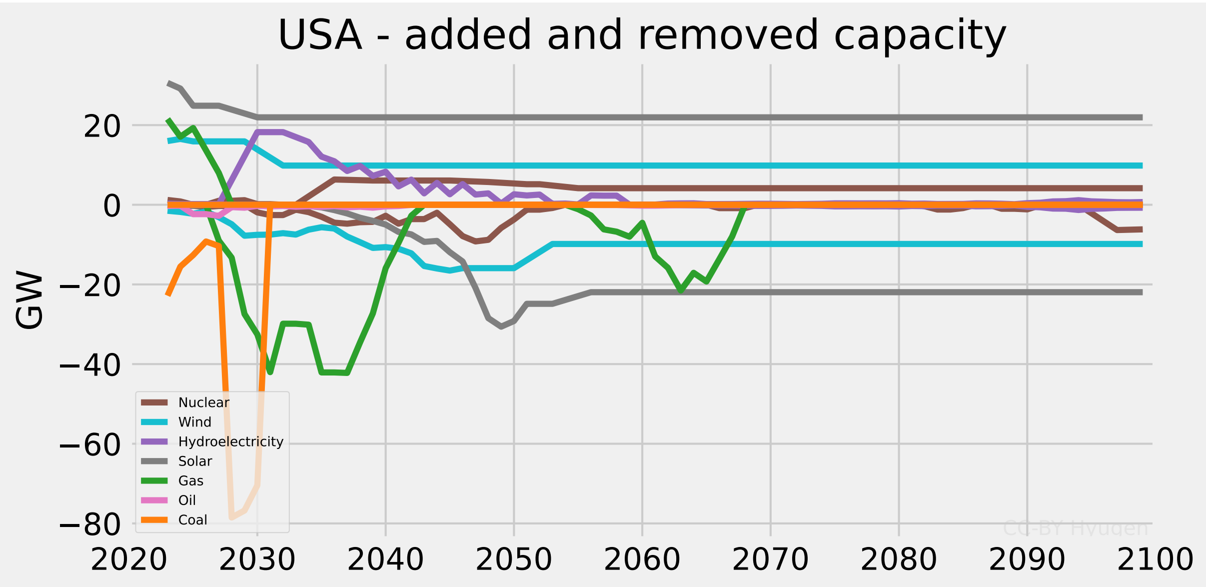
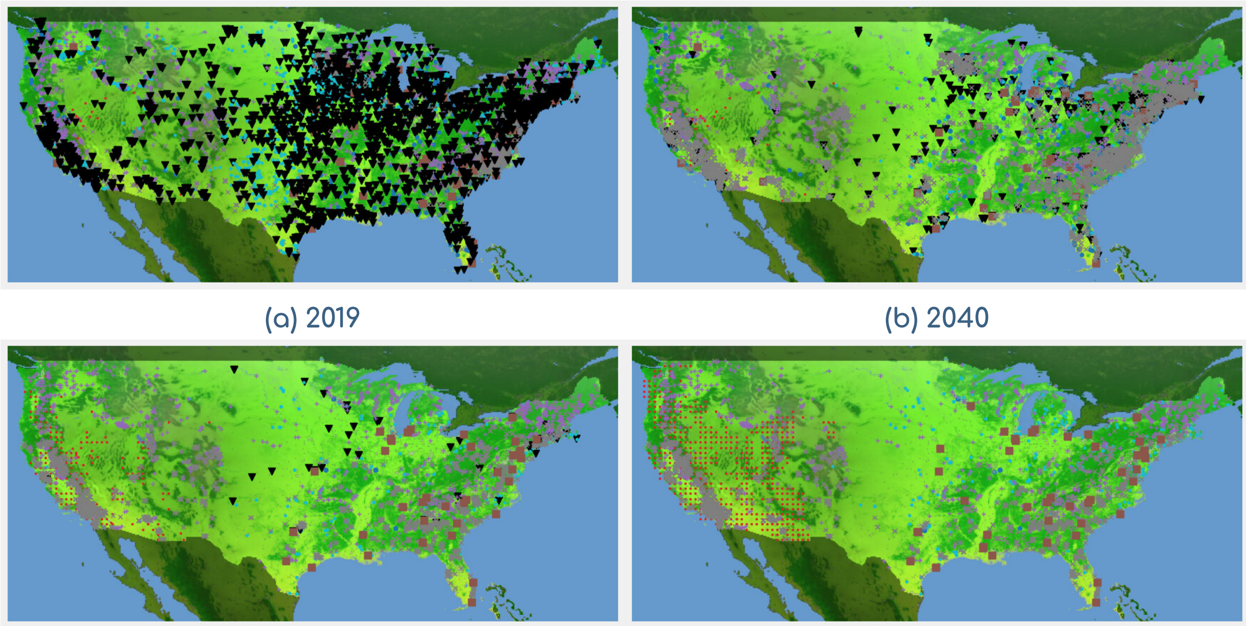


Fig. 4.28: Added / removed capacity per year by electricity source

Power plants are mapped over the country:



(a) 2019 (b) 2040

(c) 2060 (d) 2080

Fig. 4.29: Map of power plants in USA, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.) , 2019:[55]

Changes related to carbon intensity of electricity in the country are represented in fig. 4.30.

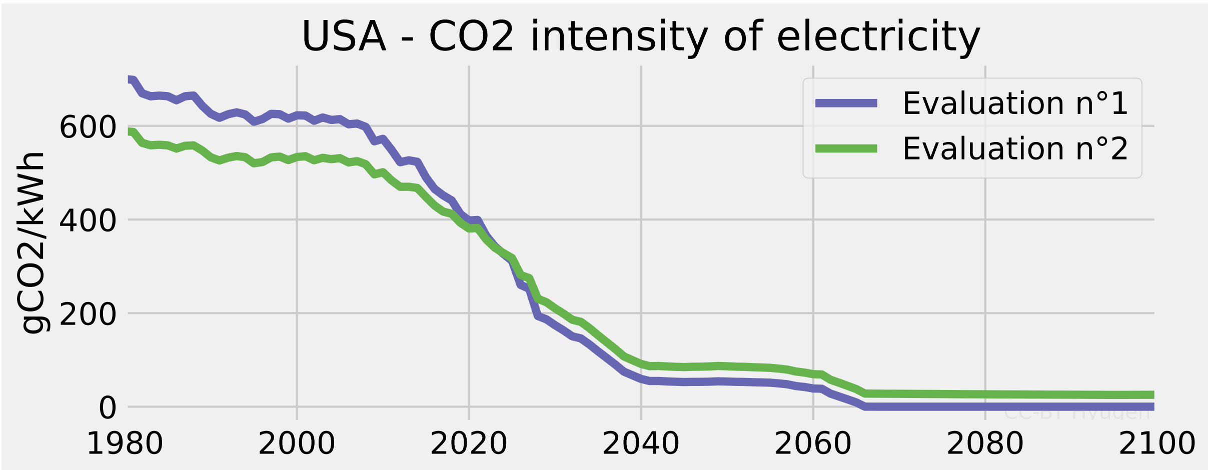


Fig. 4.30: Carbon intensity of electricity in USA. Details in fig. 3.12

Reserves for multiple elements are included in the model:

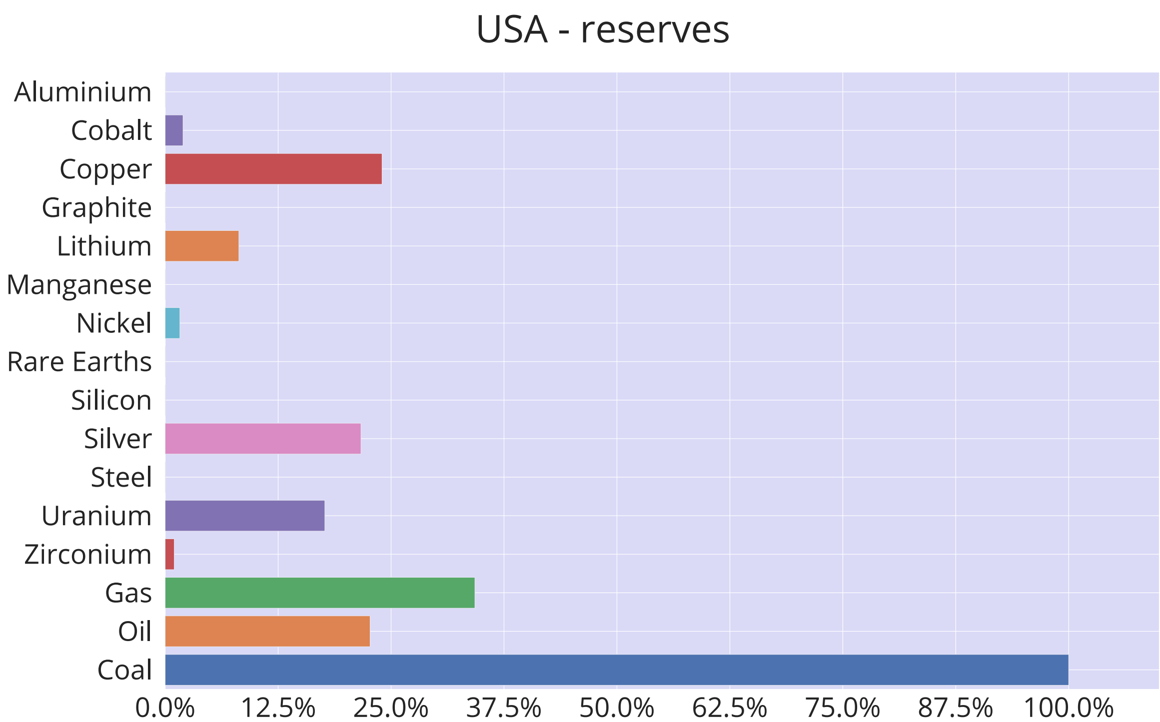


Fig. 4.31: Reserves of USA as a proportion of the country with the most reserves (proportionally small reserves compared to the largest in the world may not be represented), source:[77]

The number of road vehicles in USA evolves as follows:

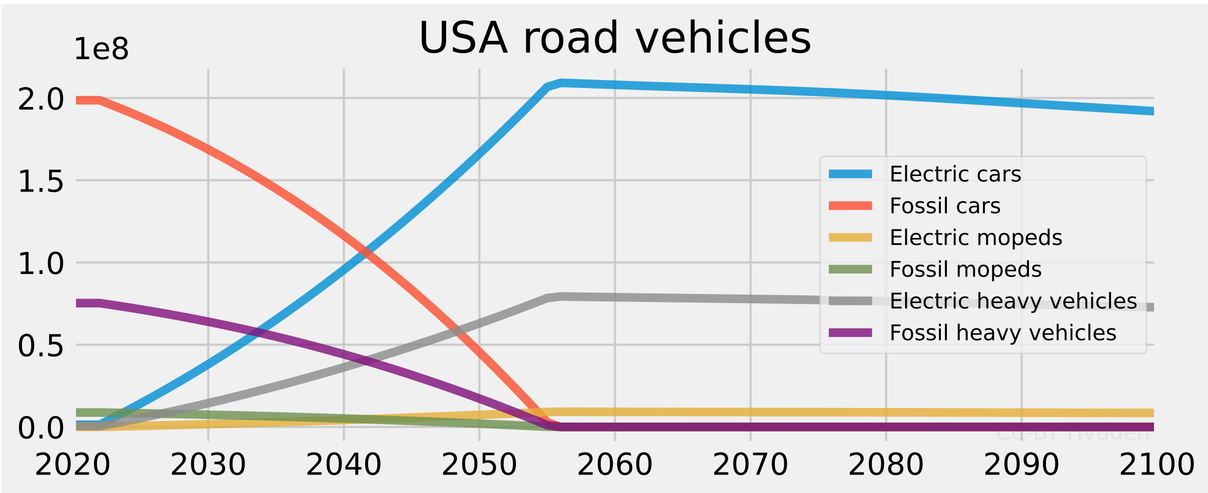


Fig. 4.32: Evolution of road vehicles in USA. Details in fig. 3.18

Proportion of controllable electricity in USA is included in the model:

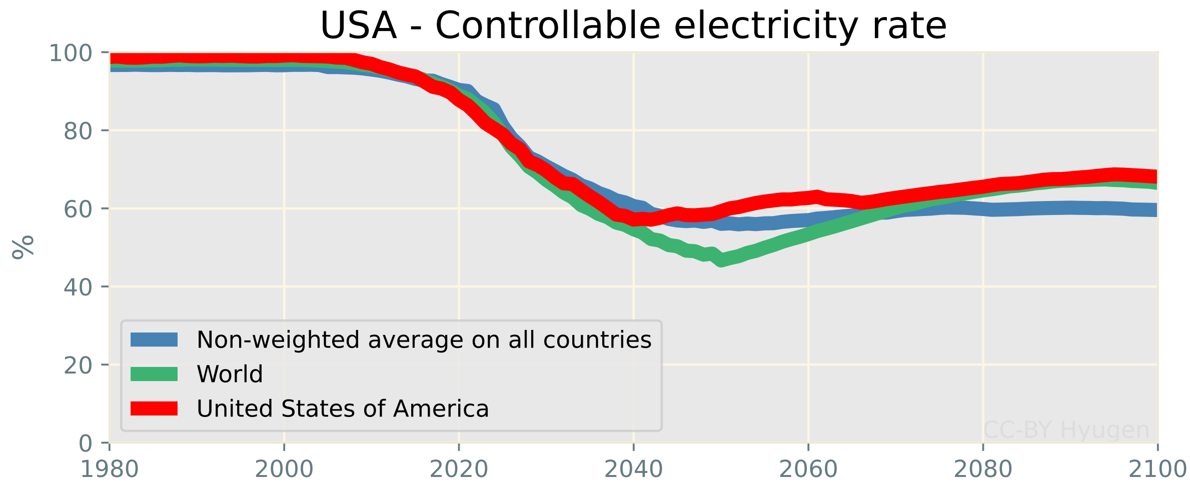


Fig. 4.33: Controllable electricity rate in USA. Details in fig. 3.17

Power required from storage systems in USA is modeled:

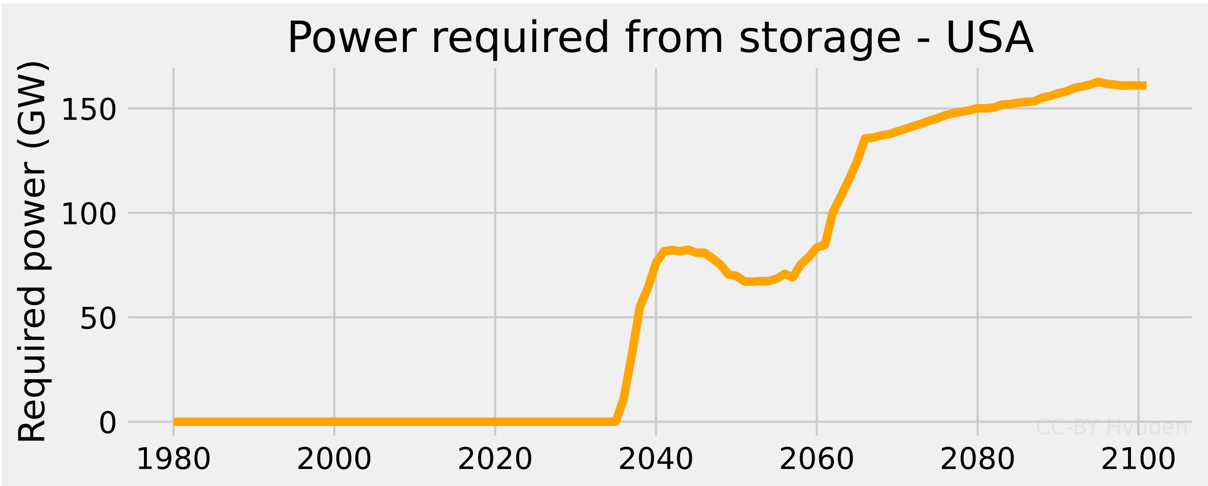


Fig. 4.34: Power required from storage systems in USA. Details in fig. 3.53

Climate overview

Changes related to CO2 emissions in USA can be visualized:

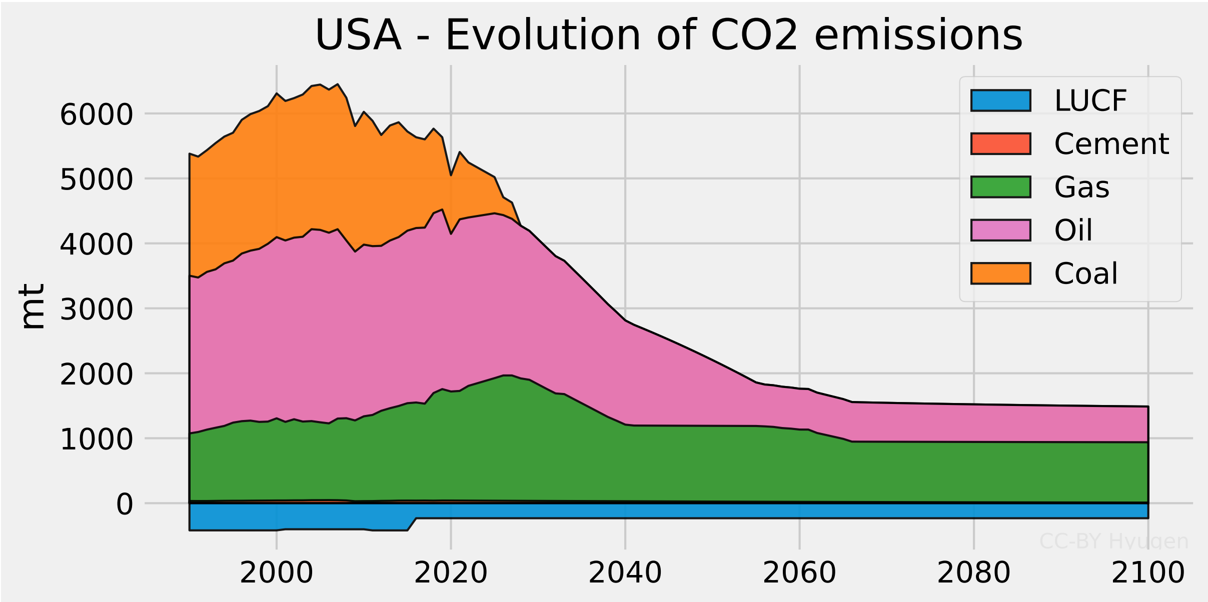
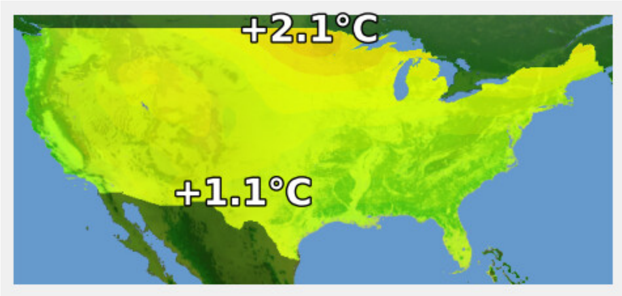


Fig. 4.35: CO2 emissions from USA, pre-2020 source:[95, 83]

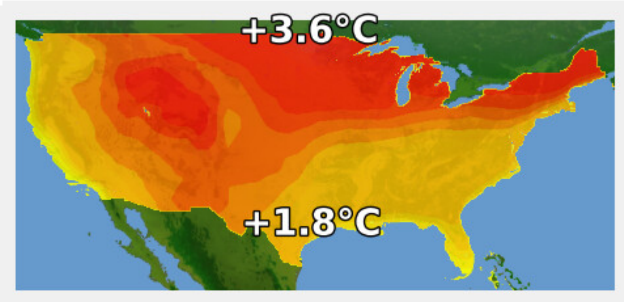
Climage changes in USA are considered. Warming in the country will range from **+1.7°C** to **+6.6°C** in 2100 compared to pre-industrial era. Average temperature in 2100 weighted by population distribution is **17.1°C** in the model, with an average warming of **+3.0°C** on populations.
Countries which, before global warming, had similar temperatures compared to temperatures in USA in 2100 are:

Country	Temperatures	Rainfalls (mm)
Tunisia	18.3°C	240
Syria	17.8°C	330
Bhutan	17.6°C	2111
Morocco	17.5°C	267
South Africa	17.3°C	1031
- USA	14.1°C => 17.1°C	1029 => 1061
Peru	17.0°C	1035
Vatican City	16.9°C	583
Algeria	16.6°C	310
Uruguay	16.4°C	853
Portugal	16.3°C	709

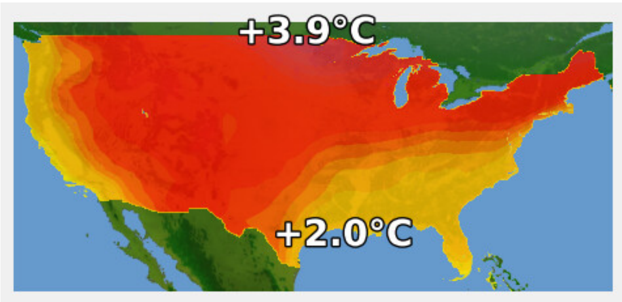
Table 4.2: Comparison of temperatures of USA in 2100 with temperatures of other countries before global warming, weighted based on current population distribution. Methodology in section 4.10, based on [57, 62]



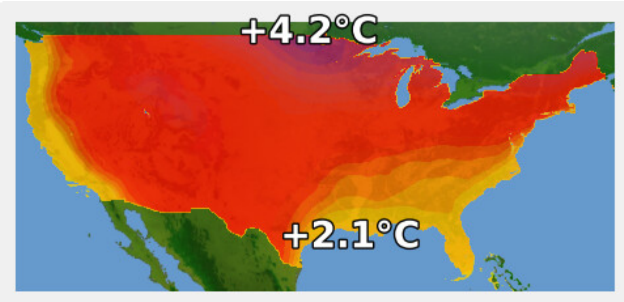
(a) 2020



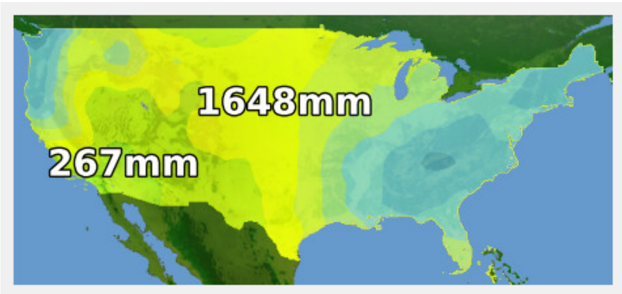
(b) 2050



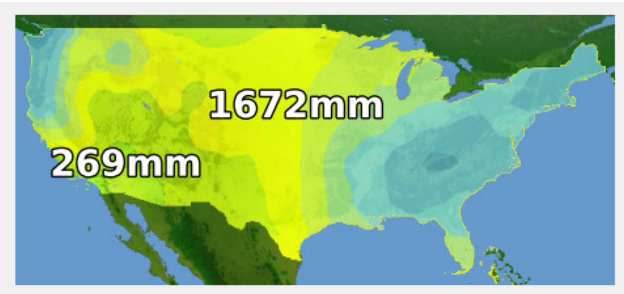
(c) 2070



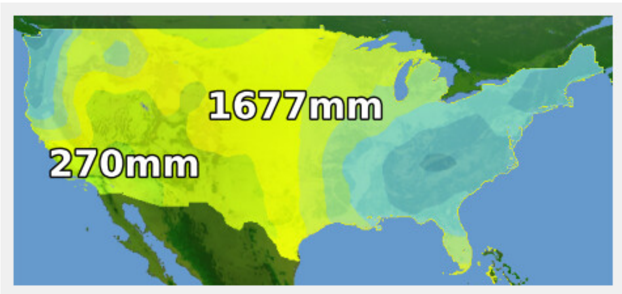
(d) 2100



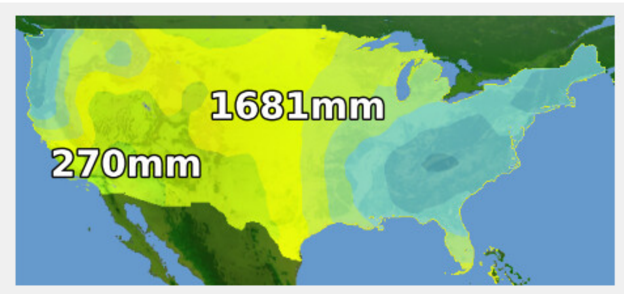
(e) 2020



(f) 2050



(g) 2070



(h) 2100

Fig. 4.36: Maps of global warming and rainfalls between 2020 and 2100

France

Demography overview

Population in France changes as follows:

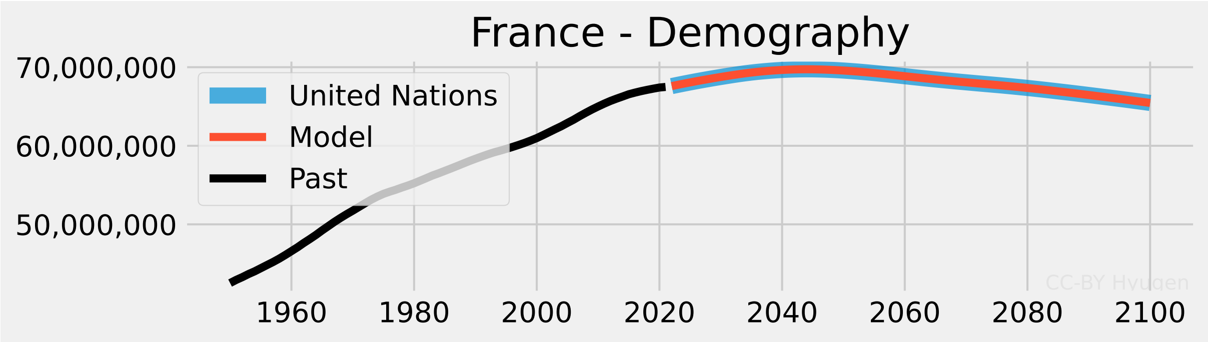


Fig. 4.37: Demography in France, UN:[30]

Life expectancy in France could evolve as follows:

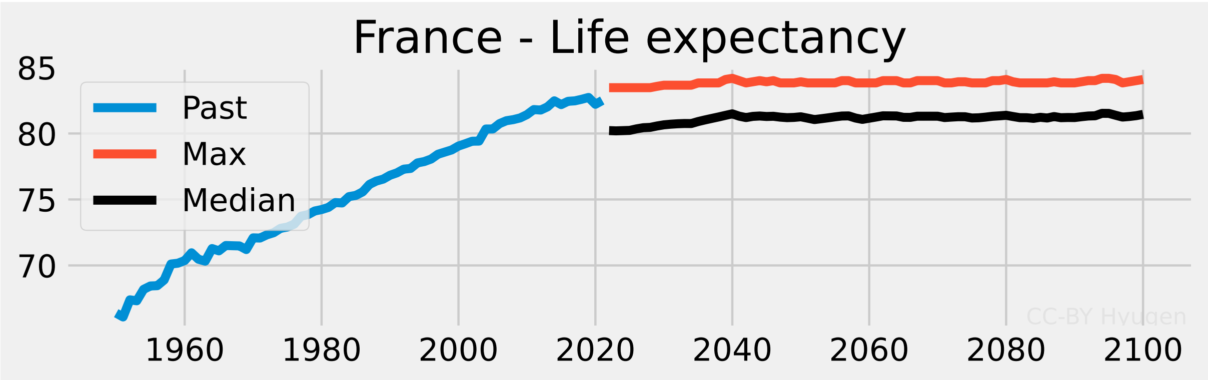


Fig. 4.38: Life expectancy in France, UN:[30], max and median from fig. 1.13

Meat consumption of France is configured by the user:

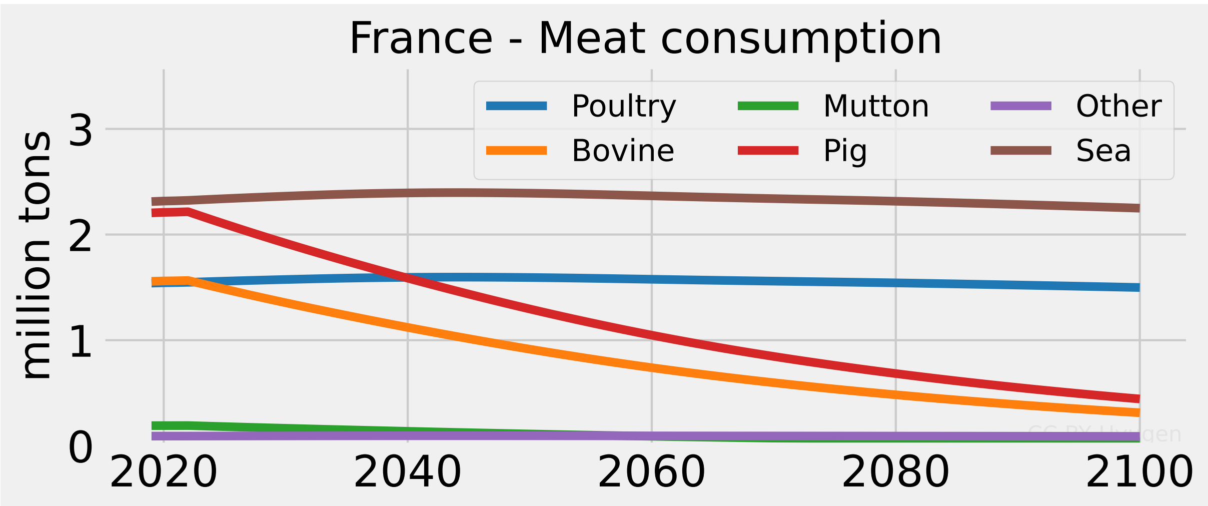


Fig. 4.39: Meat consumption in France, initialized with [84]

Climate change impacts on crops can be visualized as follows:

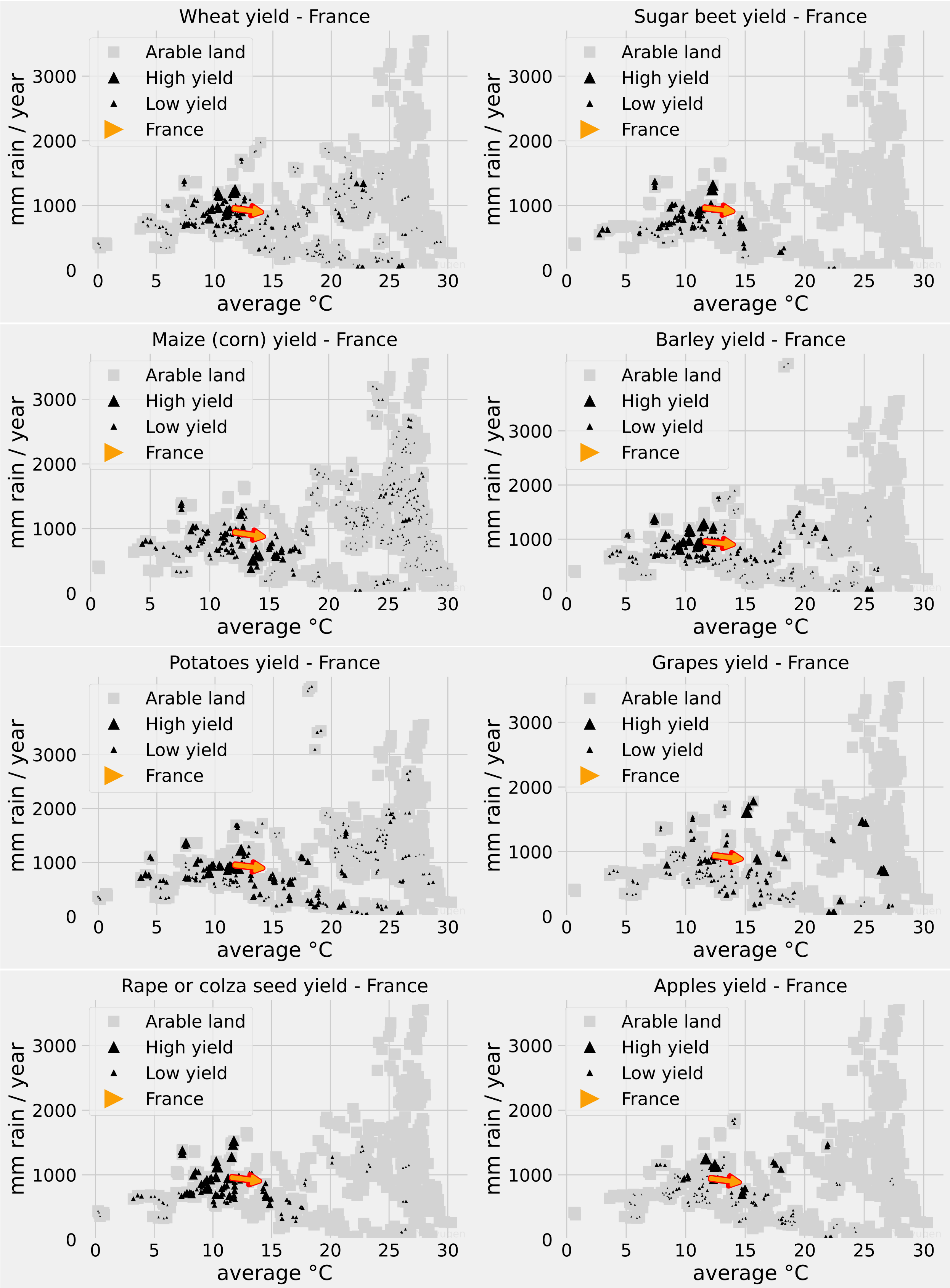


Fig. 4.40: Yields for different crops, arrow represents warming between 2100 and pre-industrial era, yield source:[32]

Energy overview

Changes related to power generation in France since 1980 can be presented:

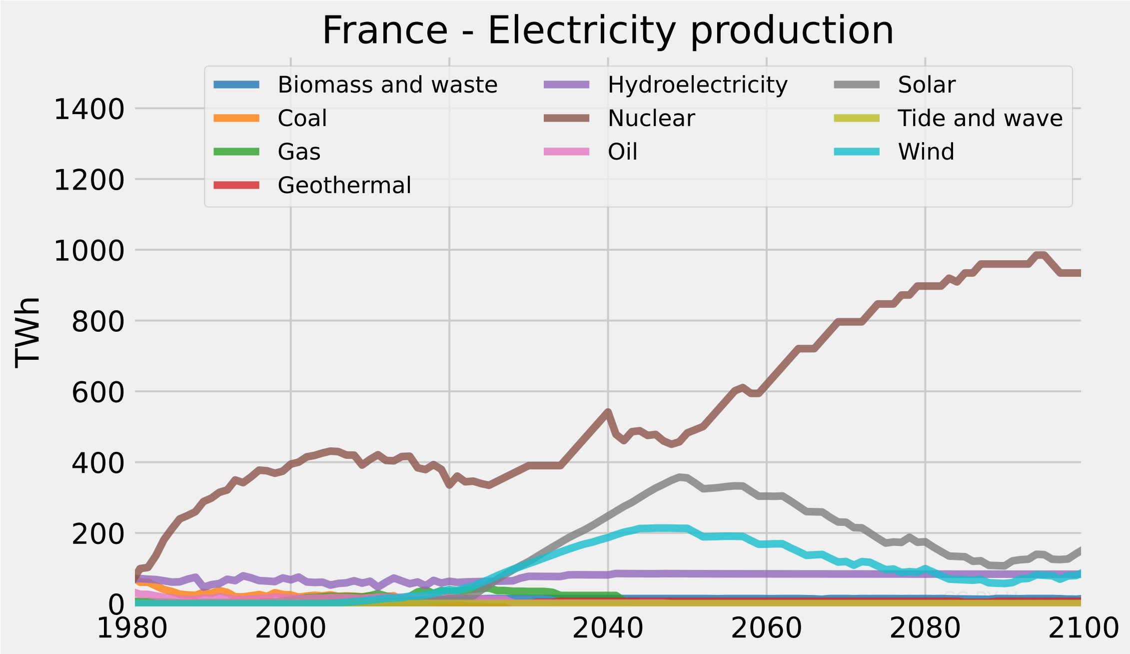


Fig. 4.41: Electricity production in France

Changes related to electrical capacity in France since 1980 can be presented:

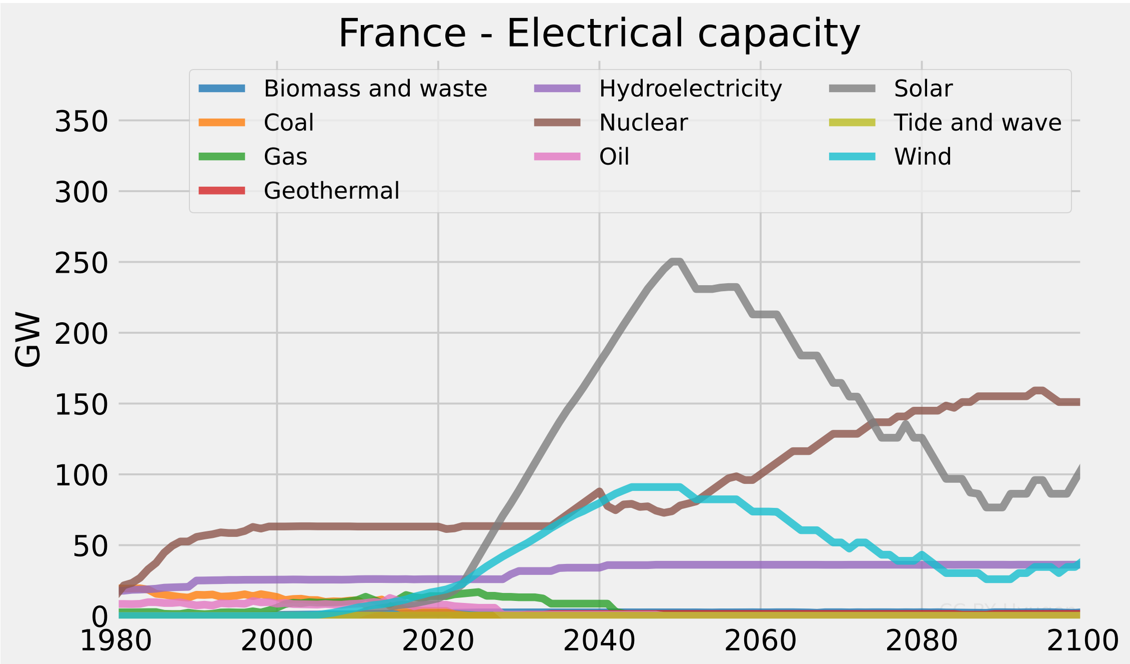


Fig. 4.42: Electrical capacity in France since 1980

Estimated capacity factors can be computed for multiple sources of electricity in France since 1980:

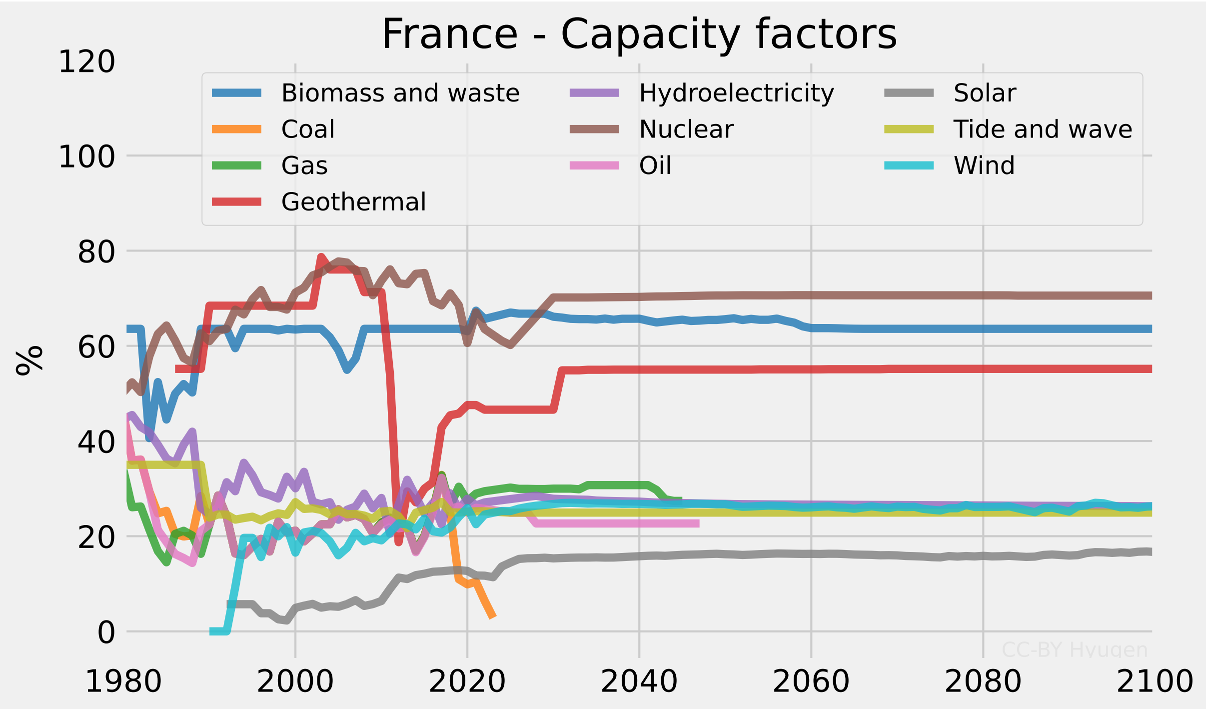


Fig. 4.43: Estimated capacity factors for electricity sources in France

Consumption of fossil fuels in France evolves as follows:

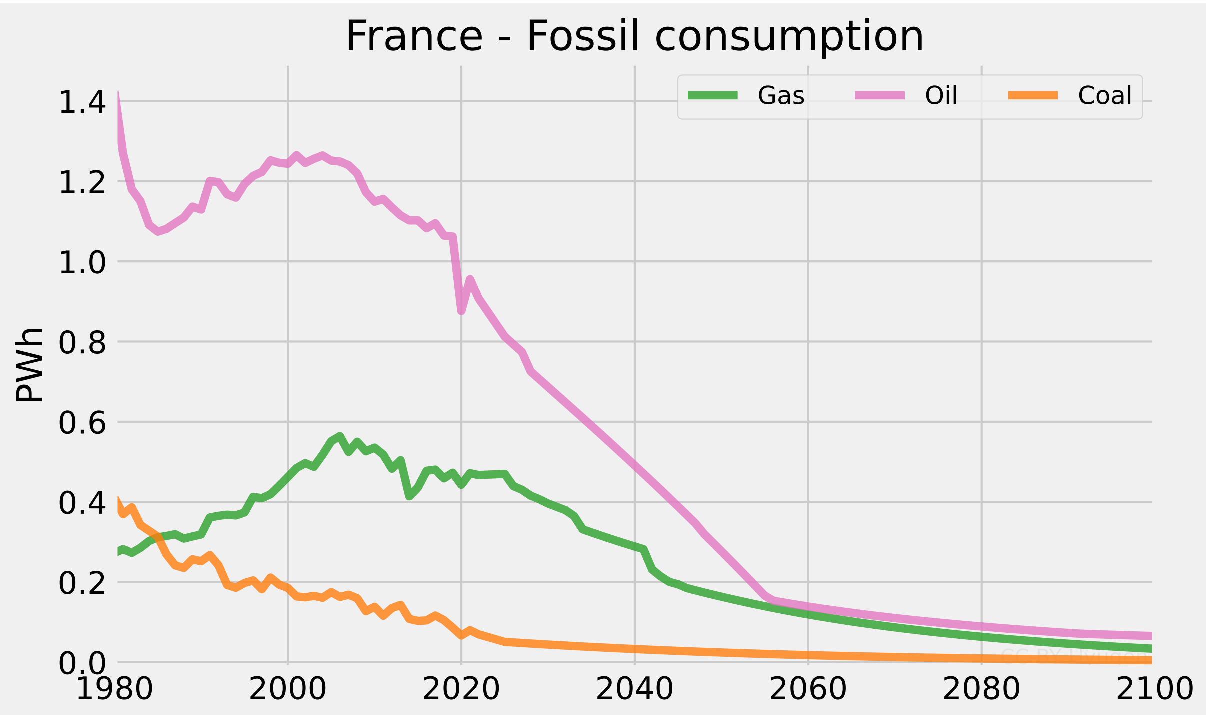


Fig. 4.44: Consumption of fossil fuels in France

Useful energy consumption per capita in France since 1980 can be compared with the useful energy consumption of other countries:

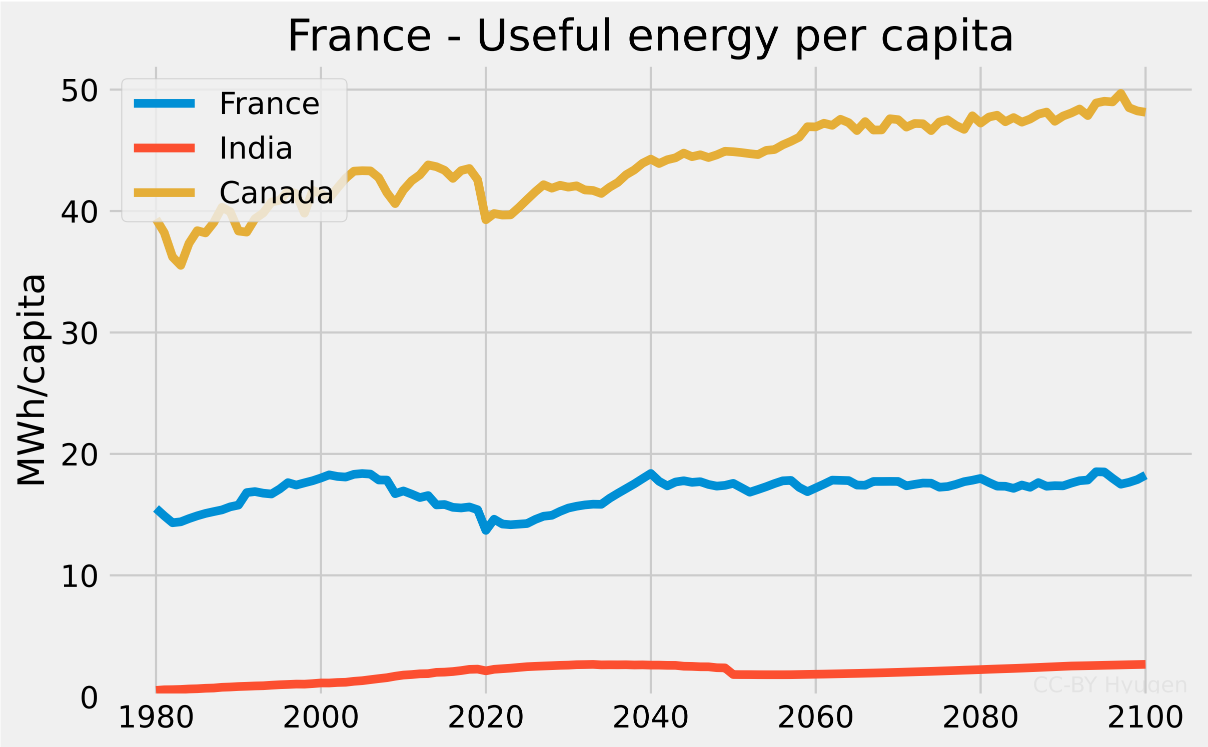


Fig. 4.45: Useful energy in France, cumulates electricity production and fossil consumption, ignores electricity imports/exports

Added and removed capacity per source of electricity are represented:

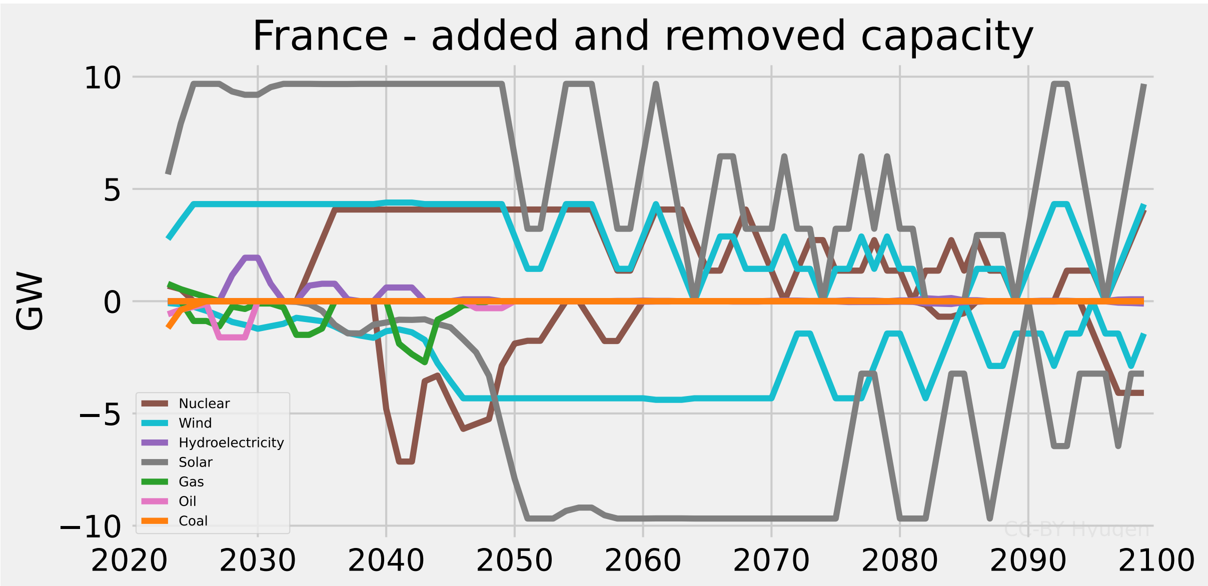
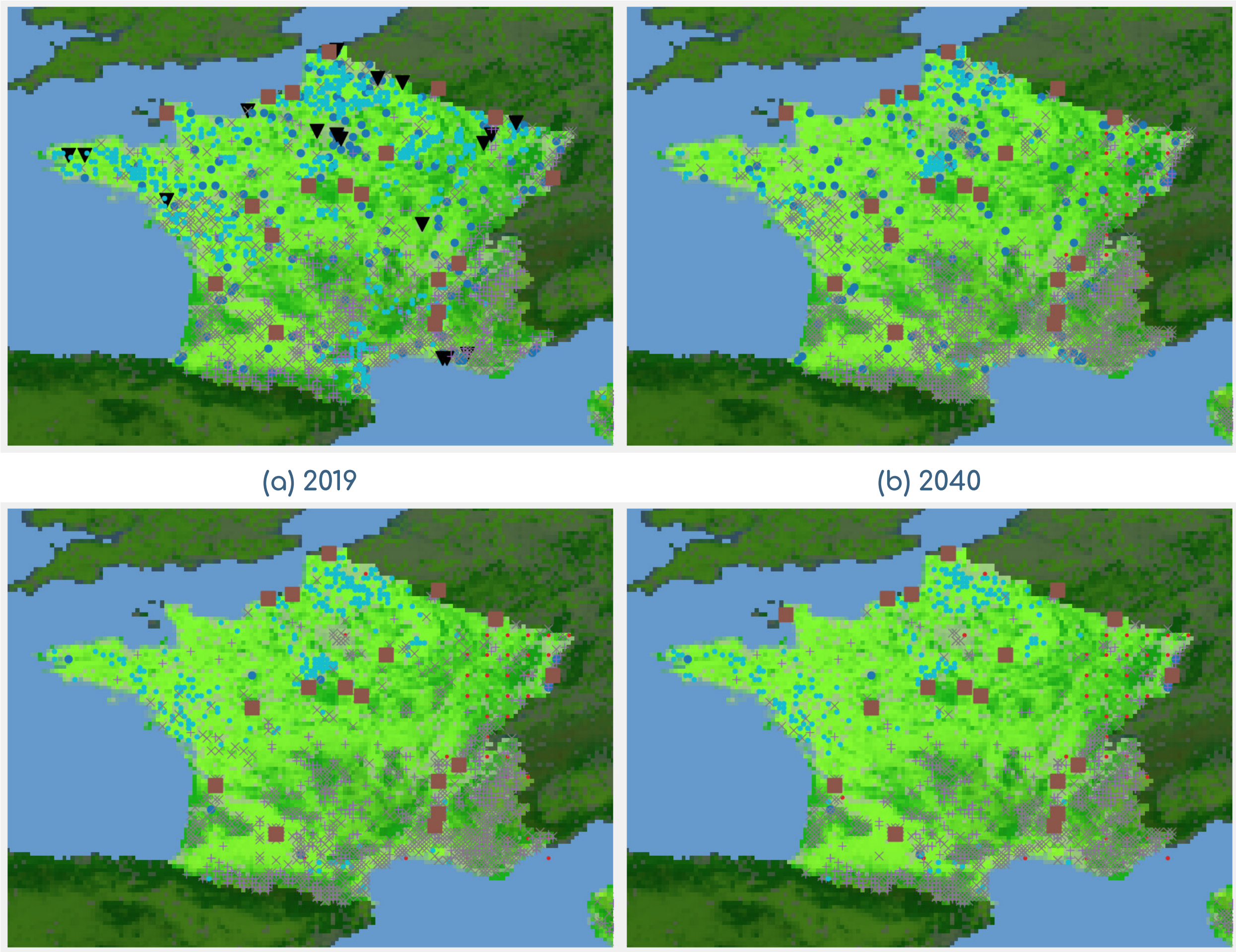


Fig. 4.46: Added / removed capacity per year by electricity source

Power plants are mapped over the country:



(a) 2019 (b) 2040

(c) 2060 (d) 2080

Fig. 4.47: Map of power plants in France, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.) , 2019:[55]

Changes related to carbon intensity of electricity in the country are represented in fig. 4.48.

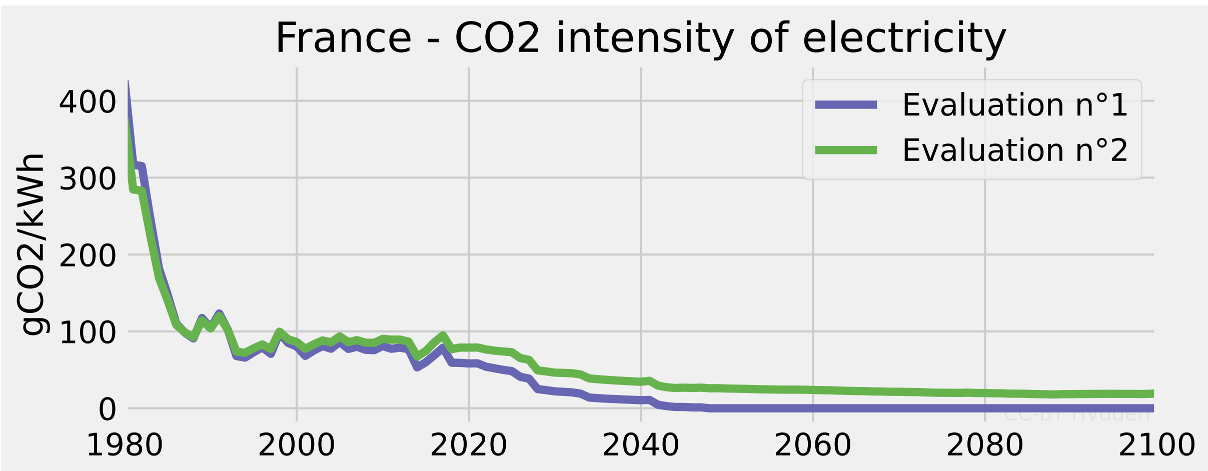


Fig. 4.48: Carbon intensity of electricity in France. Details in fig. 3.12

Reserves for multiple elements are included in the model:

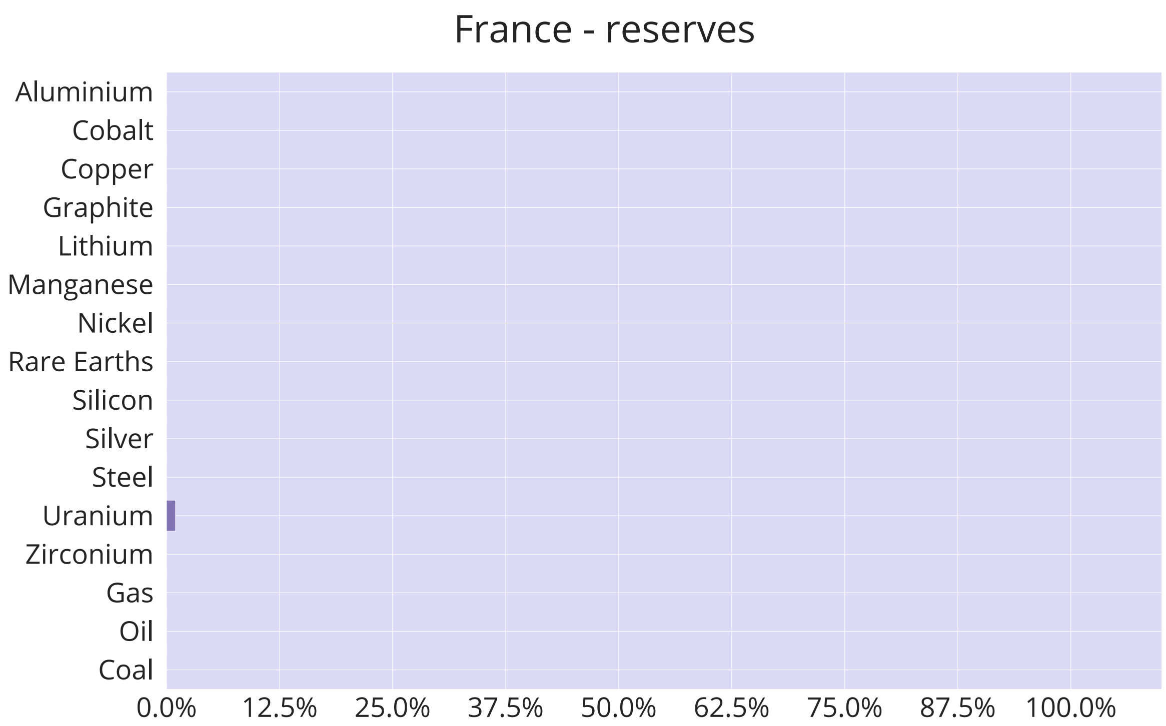


Fig. 4.49: Reserves of France as a proportion of the country with the most reserves (proportionally small reserves compared to the largest in the world may not be represented), source:[77]

The number of road vehicles in France evolves as follows:

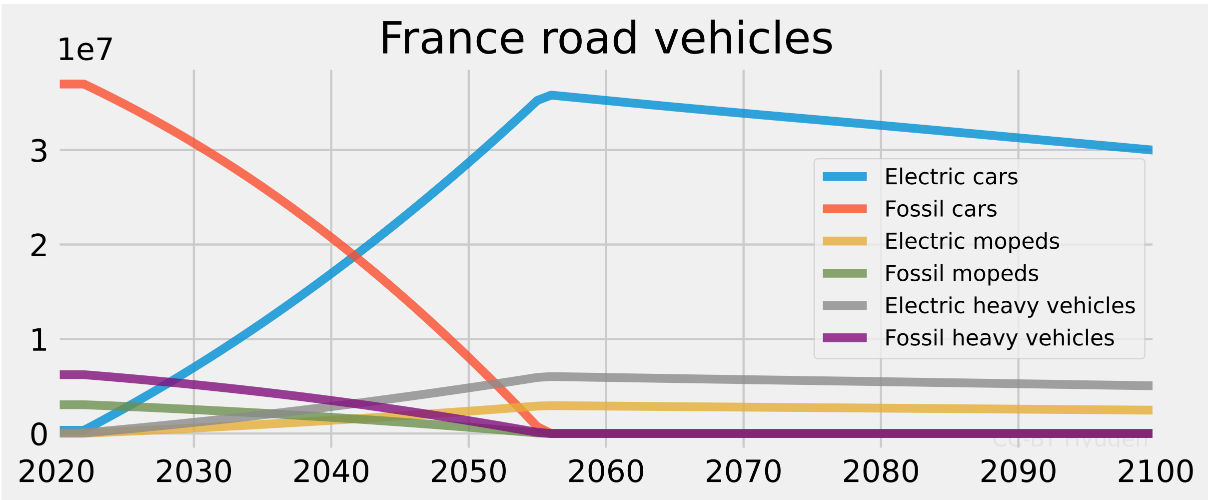


Fig. 4.50: Evolution of road vehicles in France. Details in fig. 3.18

Proportion of controllable electricity in France is included in the model:

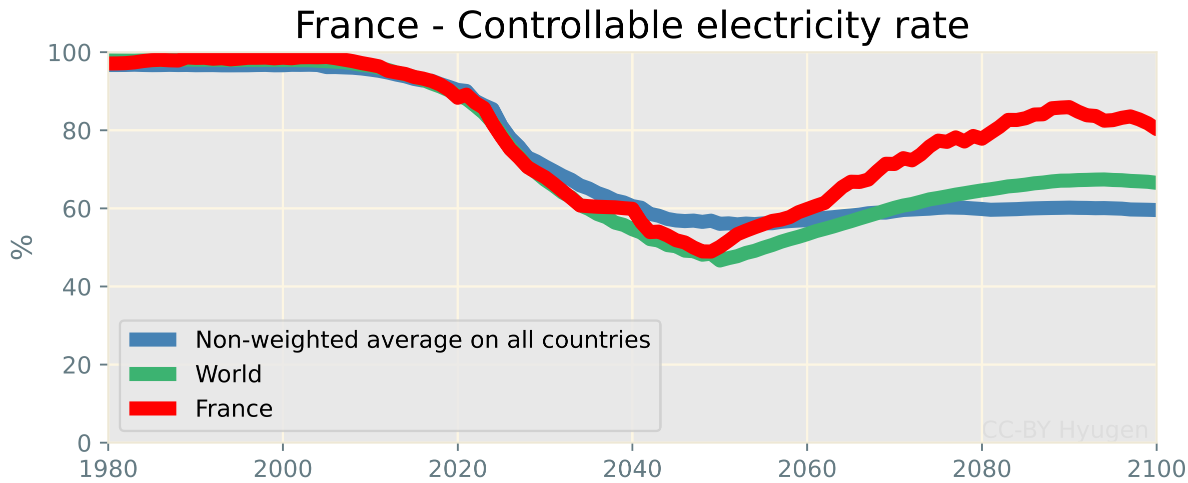


Fig. 4.51: Controllable electricity rate in France. Details in fig. 3.17

Power required from storage systems in France is modeled:

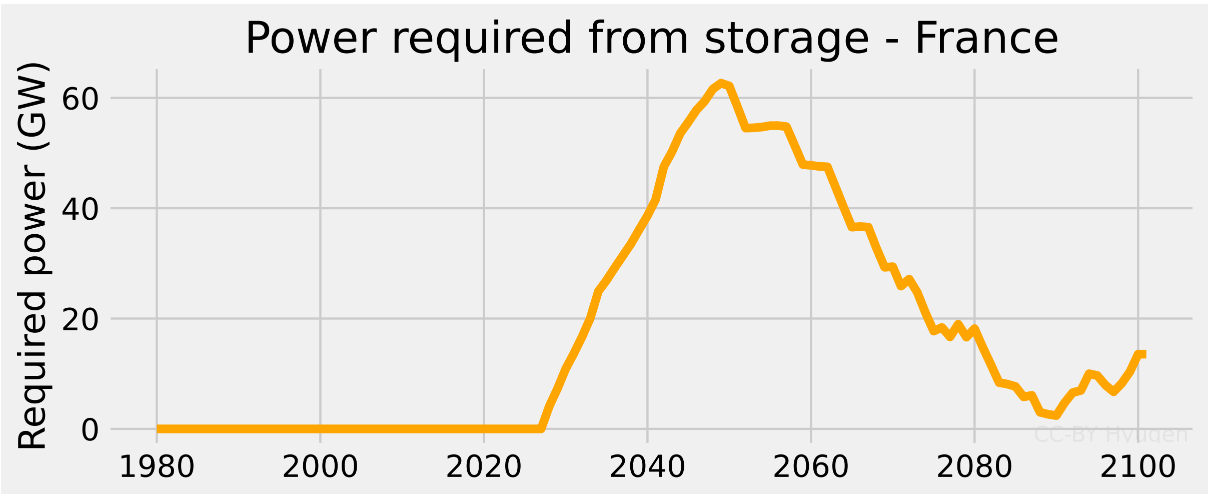


Fig. 4.52: Power required from storage systems in France. Details in fig. 3.53

Climate overview

Changes related to CO_2 emissions in France can be visualized:

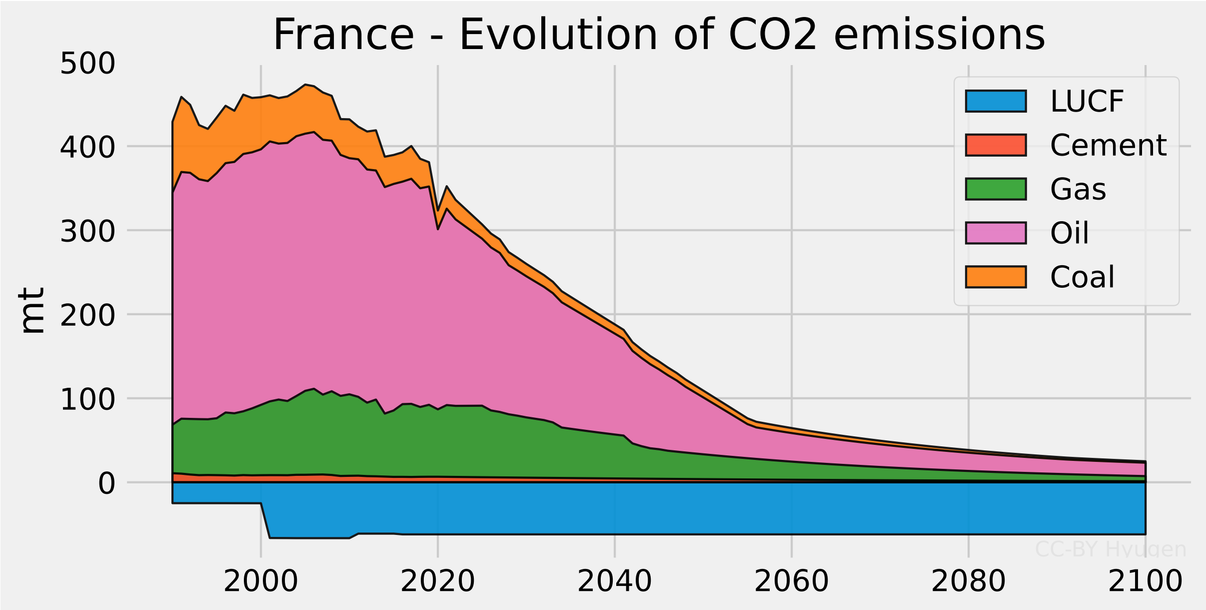
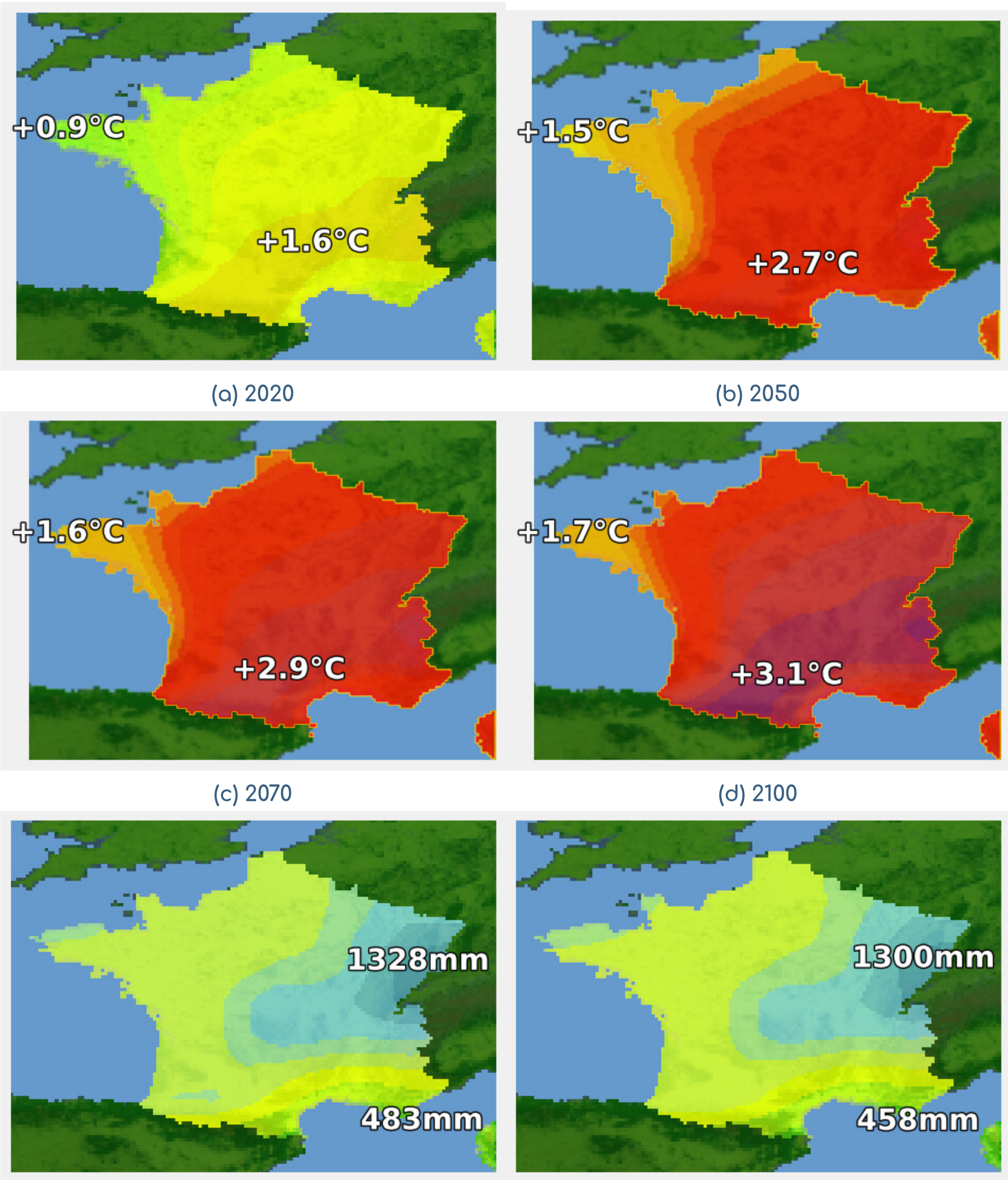


Fig. 4.53: CO2 emissions from France, pre-2020 source:[95, 83]

Climage changes in France are considered. Warming in the country will range from **+1.3°C** to **+3.2°C** in 2100 compared to pre-industrial era. Average temperature in 2100 weighted by population distribution is **14.8°C** in the model, with an average warming of **+2.7°C** on populations.
Countries which, before global warming, had similar temperatures compared to temperatures in France in 2100 are:

Country	Temperatures	Rainfalls (mm)
Australia	15.8°C	761
Argentina	15.6°C	730
Greece	15.5°C	556
Albania	15.3°C	859
Spain	15.1°C	568
- France	12.1°C => 14.8°C	933 => 869
People's Republic of China	14.7°C	1156
Turkmenistan	14.6°C	187
United States of America	14.1°C	1029
Bolivia	14.1°C	1584
Japan	14.0°C	1908

Table 4.3: Comparison of temperatures of France in 2100 with temperatures of other countries before global warming, weighted based on current population distribution. Methodology in section 4.10, based on [57, 62]

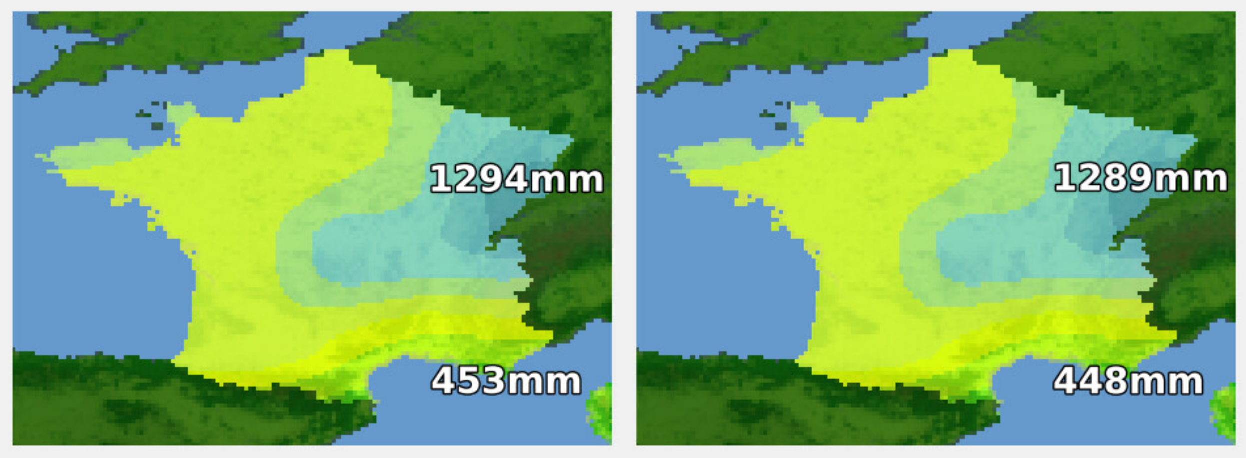


(a) 2020 (b) 2050

(c) 2070 (d) 2100

(e) 2020 (f) 2050

Fig. 4.54: Maps of global warming and rainfalls between 2020 and 2100



(a) 2070 (b) 2100

Fig. 4.55: Maps of global warming and rainfalls between 2020 and 2100


Germany

Demography overview

Population in Germany changes as follows:

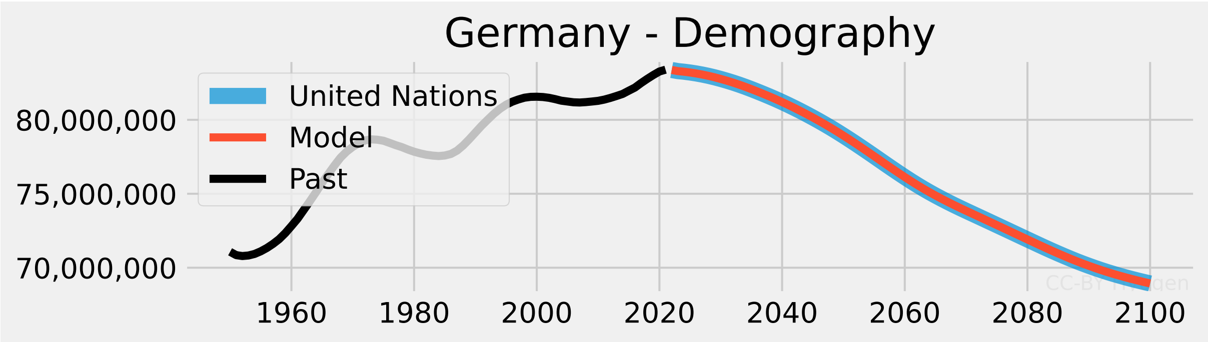


Fig. 4.56: Demography in Germany, UN:[30]

Life expectancy in Germany could evolve as follows:

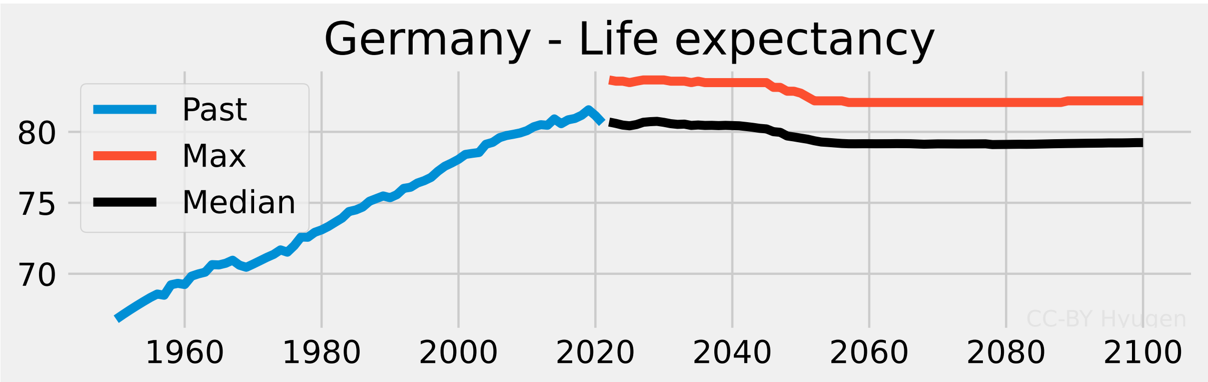


Fig. 4.57: Life expectancy in Germany, UN:[30], max and median from fig. 1.13

Meat consumption of Germany is configured by the user:

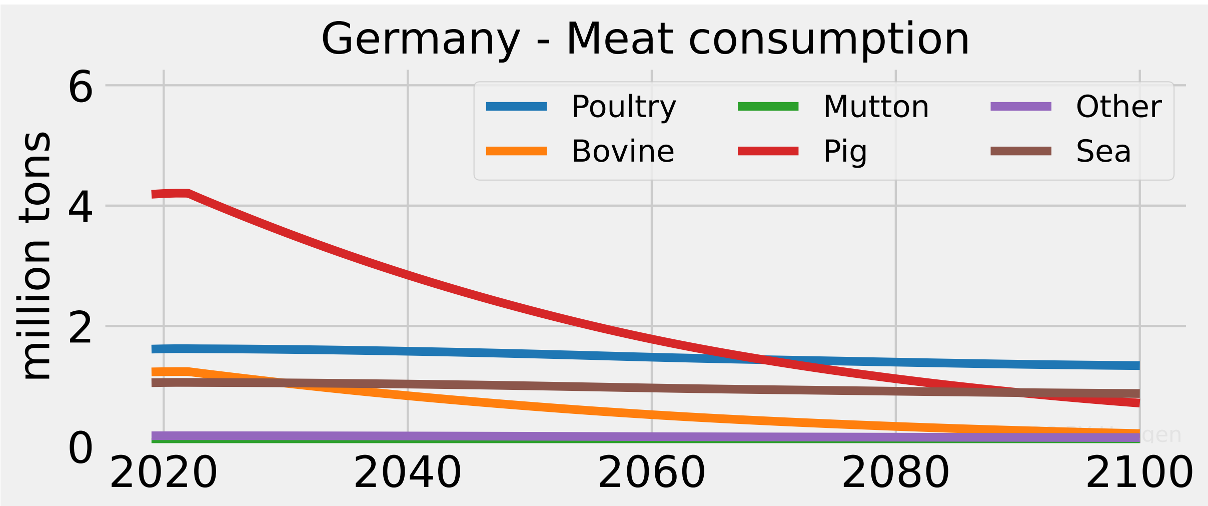


Fig. 4.58: Meat consumption in Germany, initialized with [84]

Climate change impacts on crops can be visualized as follows:

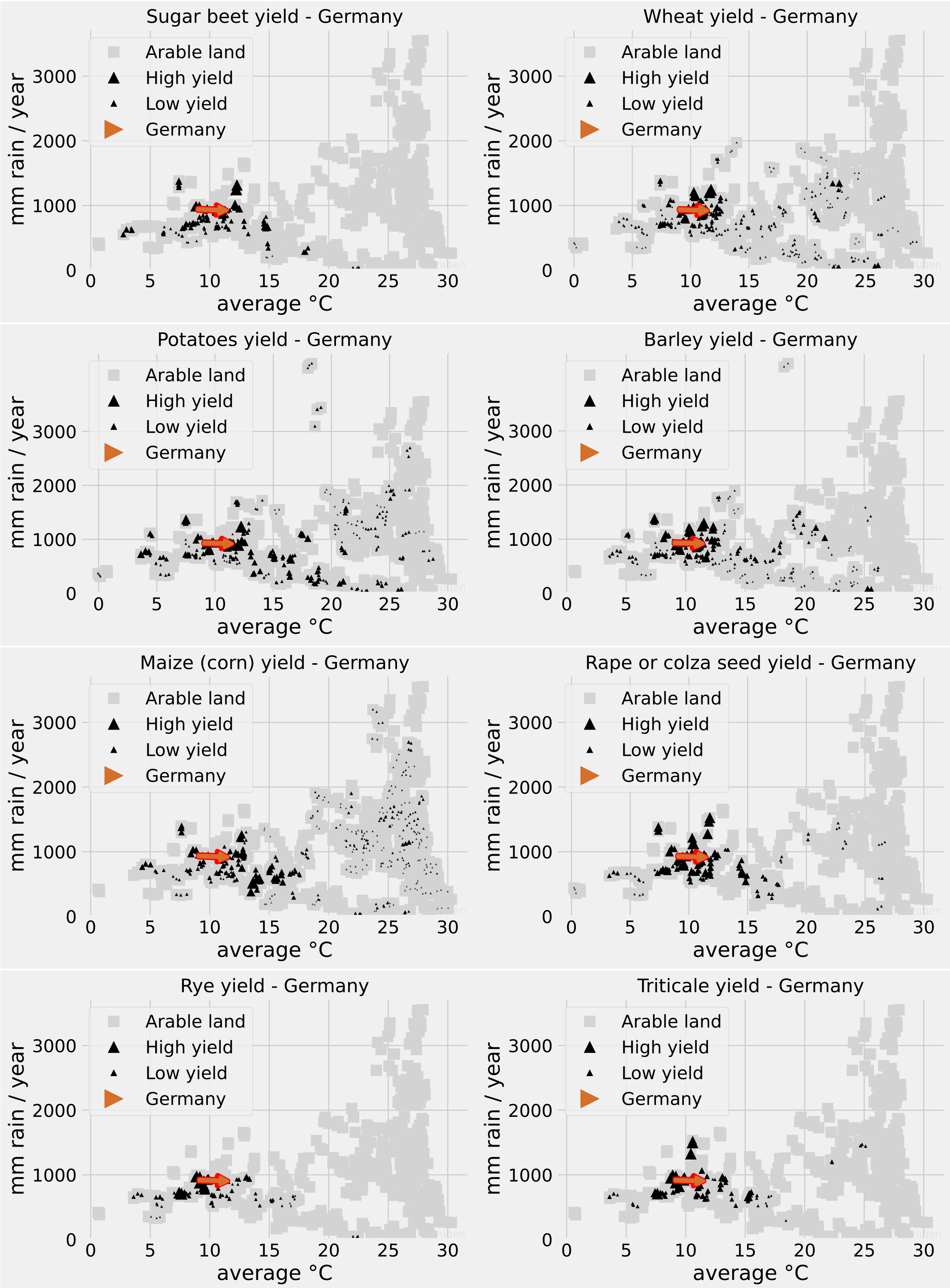


Fig. 4.59: Yields for different crops, arrow represents warming between 2100 and pre-industrial era, yield source:[32]

Energy overview

Changes related to power generation in Germany since 1980 can be presented:

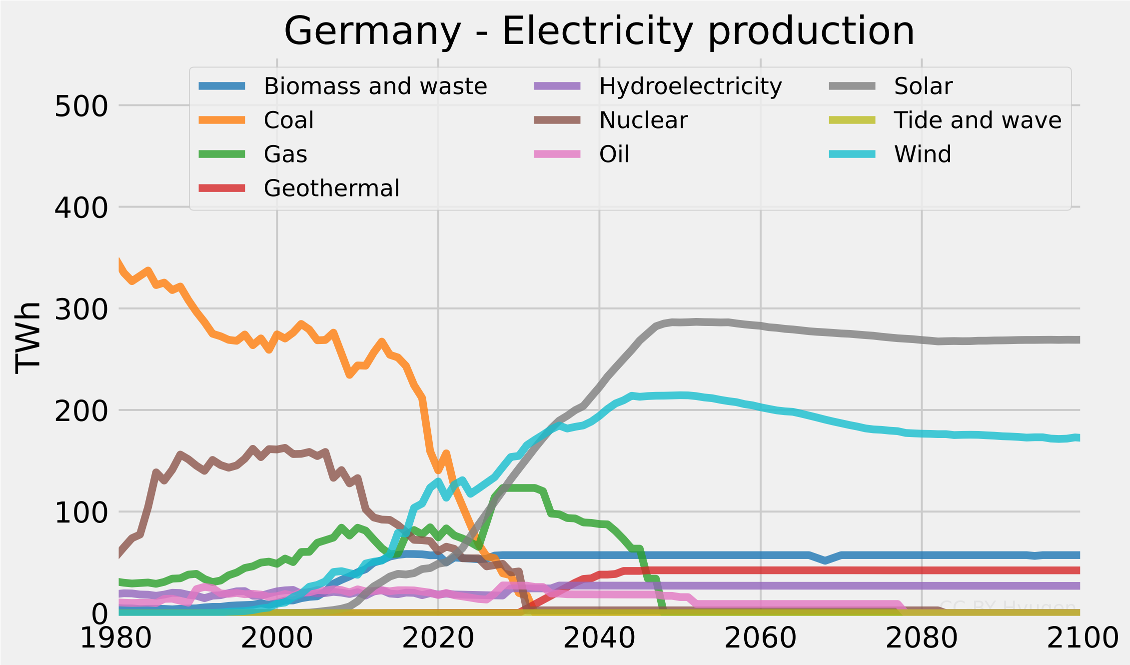


Fig. 4.60: Electricity production in Germany

Changes related to electrical capacity in Germany since 1980 can be presented:

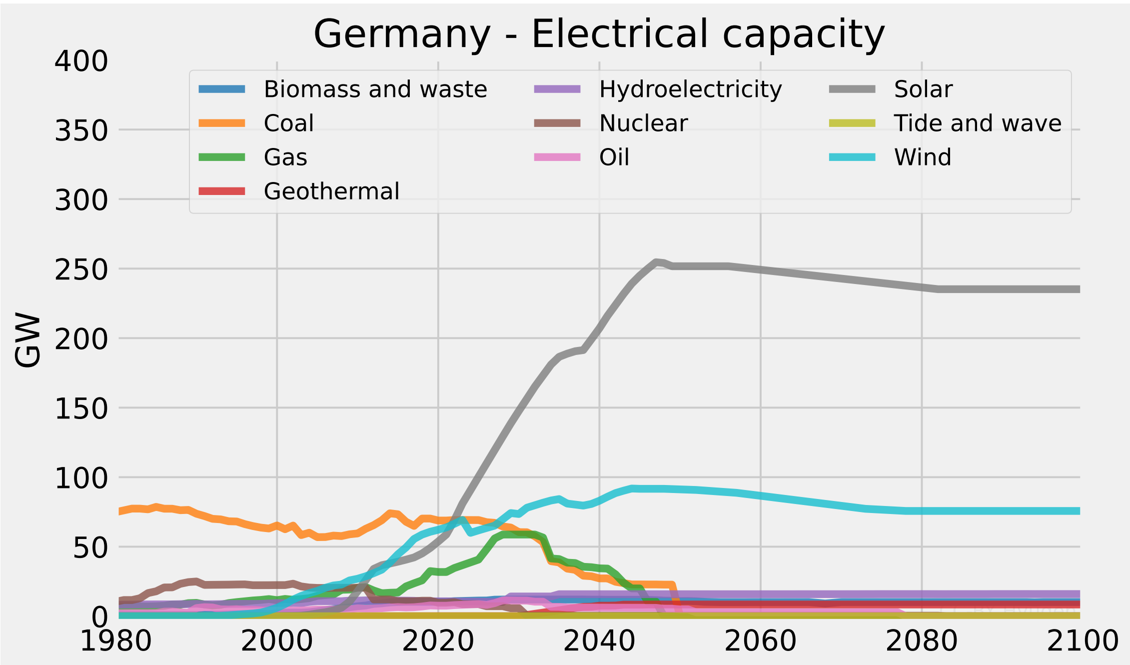


Fig. 4.61: Electrical capacity in Germany since 1980

Estimated capacity factors can be computed for multiple sources of electricity in Germany since 1980:

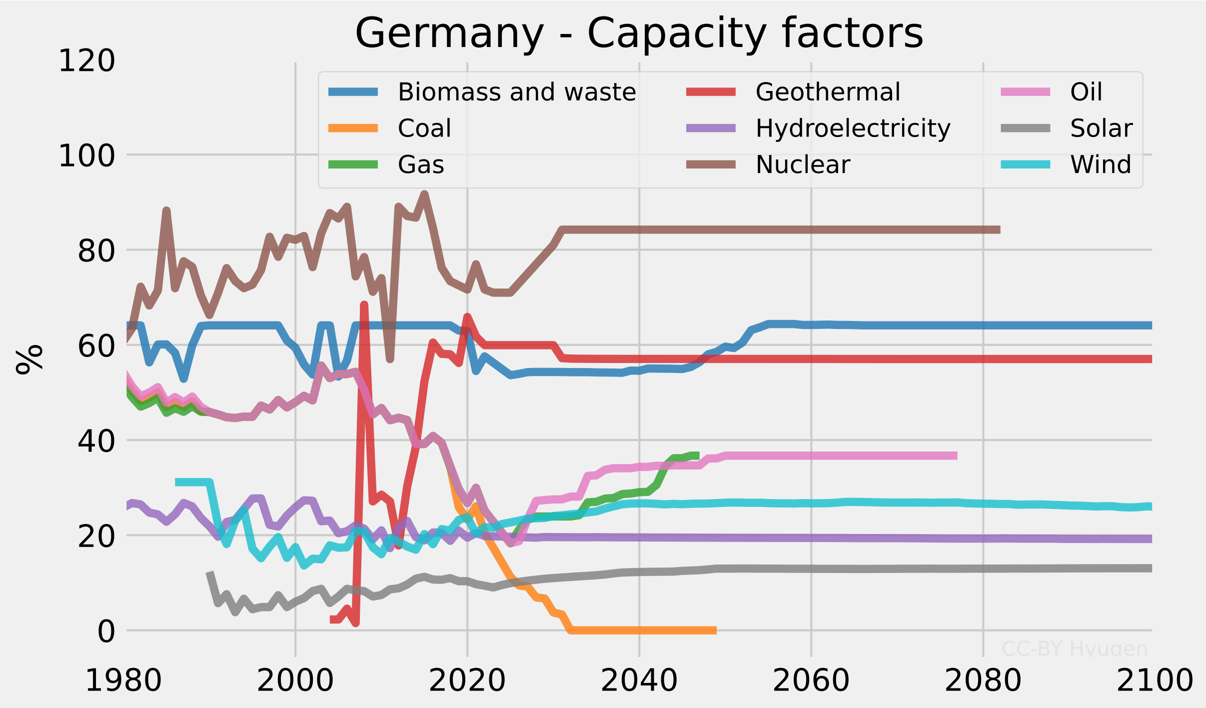


Fig. 4.62: Estimated capacity factors for electricity sources in Germany

Consumption of fossil fuels in Germany evolves as follows:

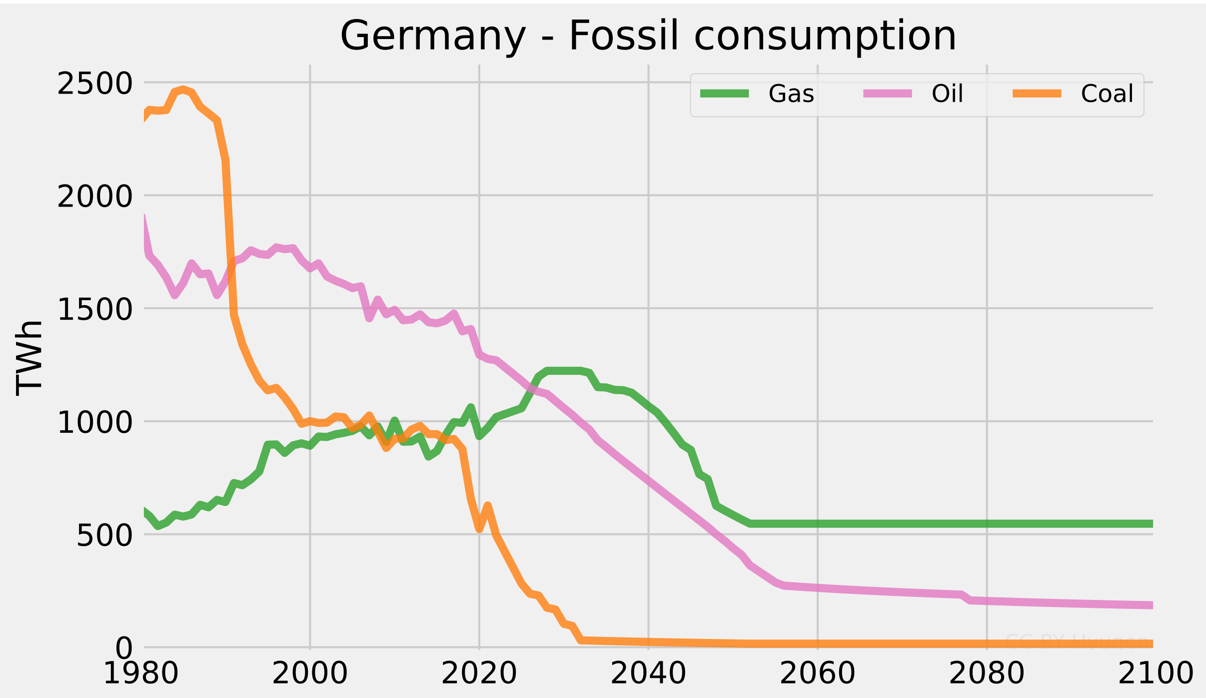


Fig. 4.63: Consumption of fossil fuels in Germany

Useful energy consumption per capita in Germany since 1980 can be compared with the useful energy consumption of other countries:

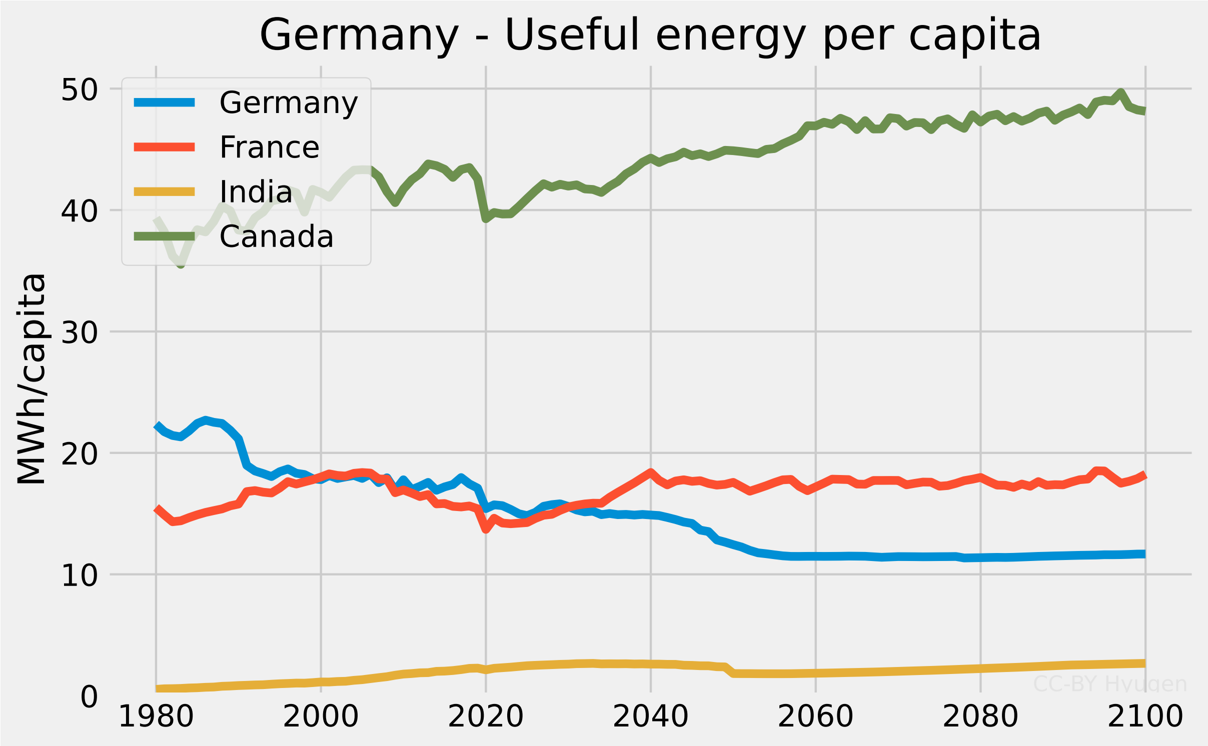


Fig. 4.64: Useful energy in Germany, cumulates electricity production and fossil consumption, ignores electricity imports/exports

Added and removed capacity per source of electricity are represented:

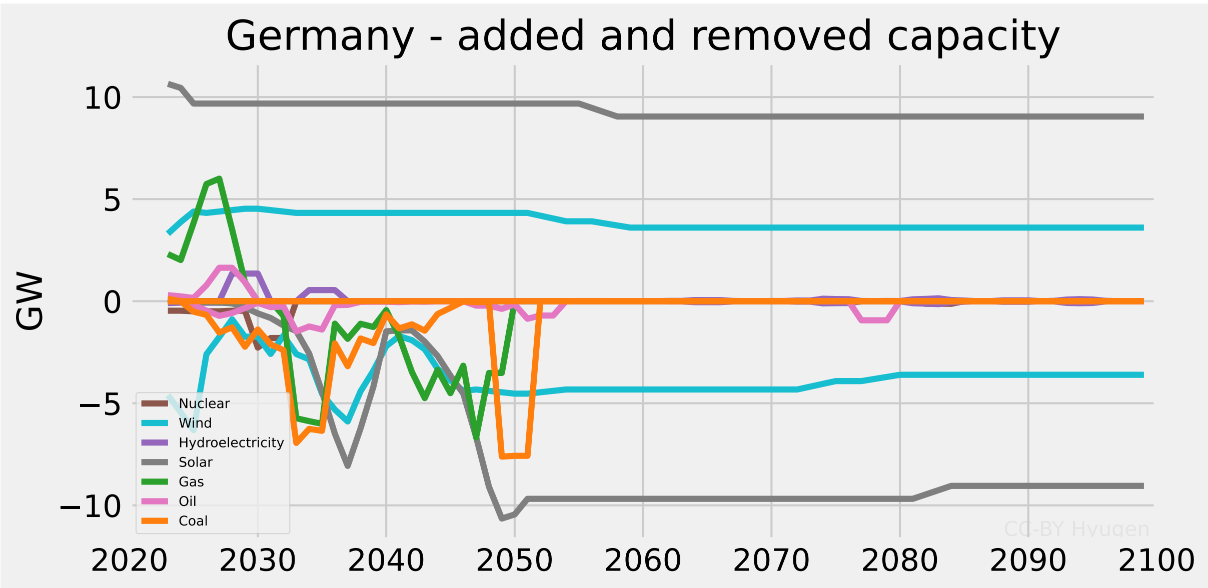
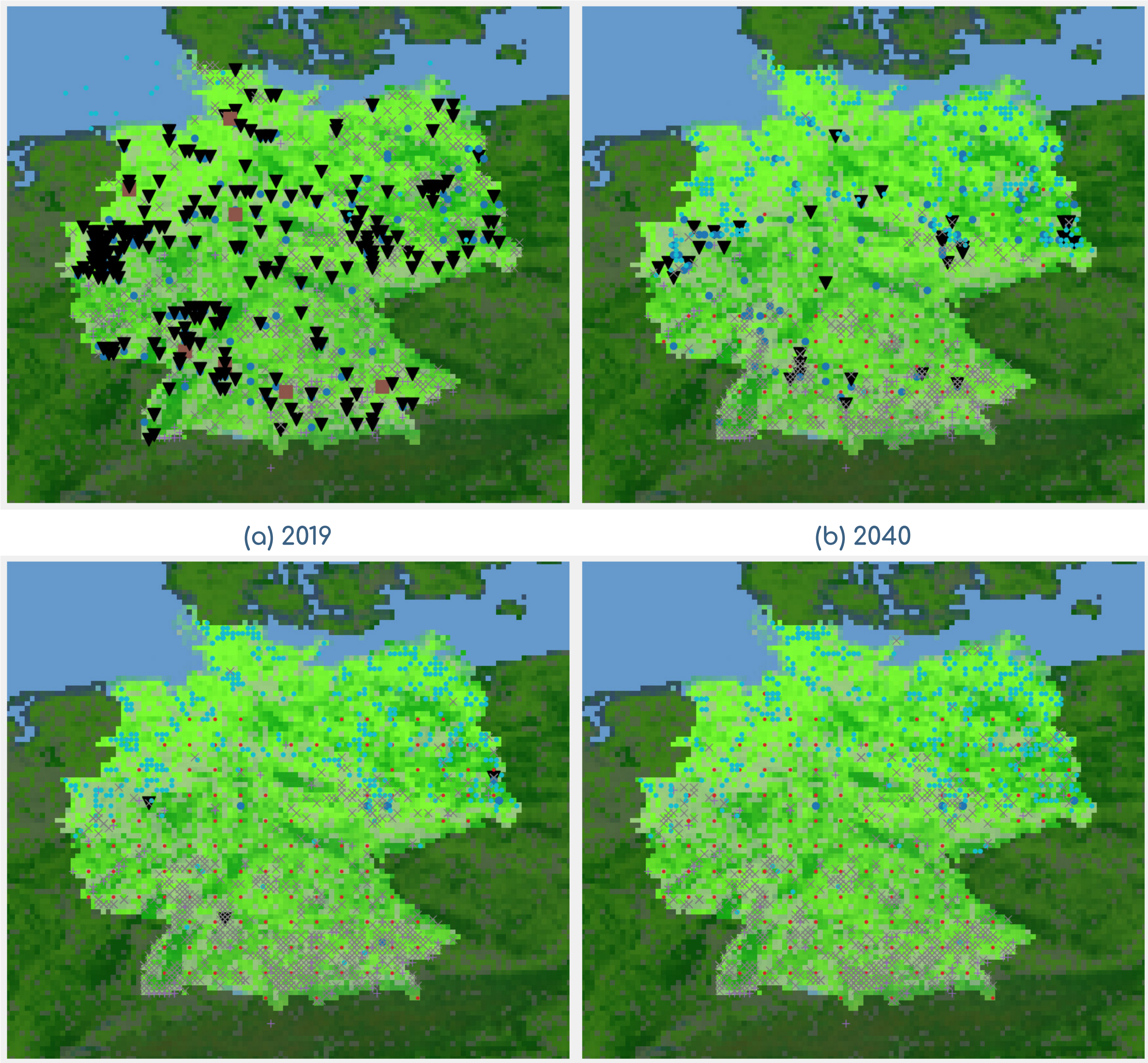


Fig. 4.65: Added / removed capacity per year by electricity source

Power plants are mapped over the country:



(a) 2019 (b) 2040

(c) 2060 (d) 2080

Fig. 4.66: Map of power plants in Germany, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.) , 2019:[55]

Changes related to carbon intensity of electricity in the country are represented in fig. 4.67.

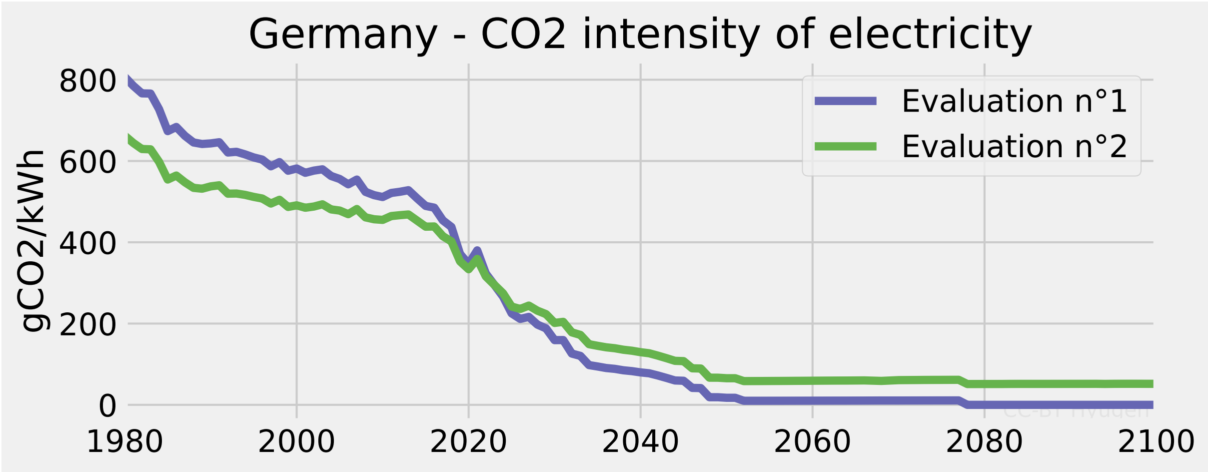


Fig. 4.67: Carbon intensity of electricity in Germany. Details in fig. 3.12

Reserves for multiple elements are included in the model:

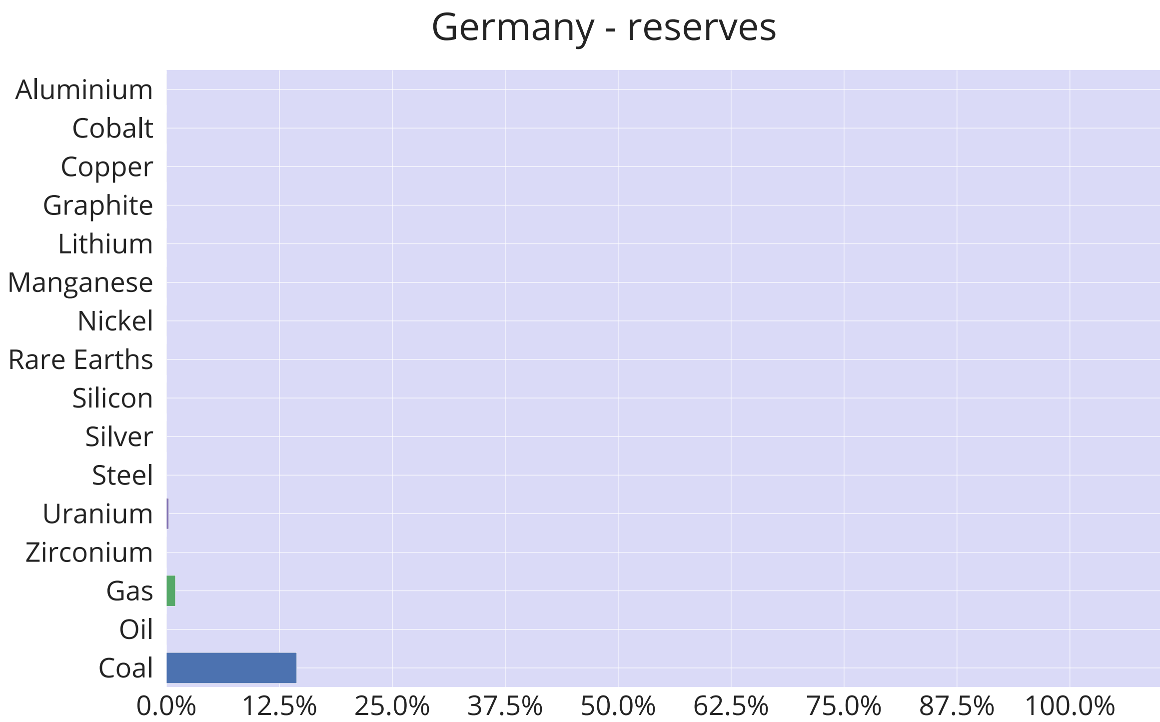


Fig. 4.68: Reserves of Germany as a proportion of the country with the most reserves (proportionally small reserves compared to the largest in the world may not be represented), source:[77]

The number of road vehicles in Germany evolves as follows:

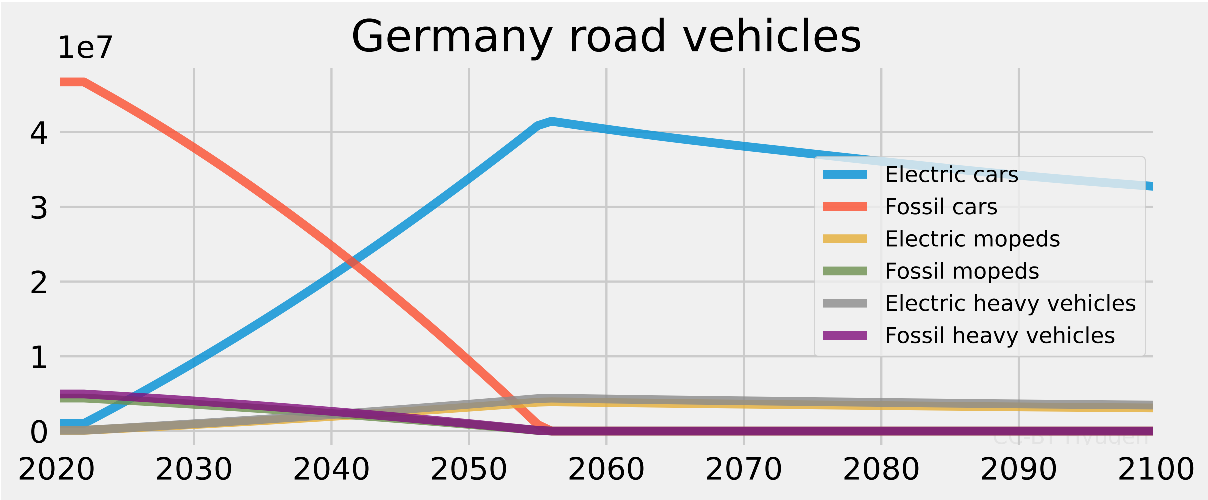


Fig. 4.69: Evolution of road vehicles in Germany. Details in fig. 3.18

Proportion of controllable electricity in Germany is included in the model:

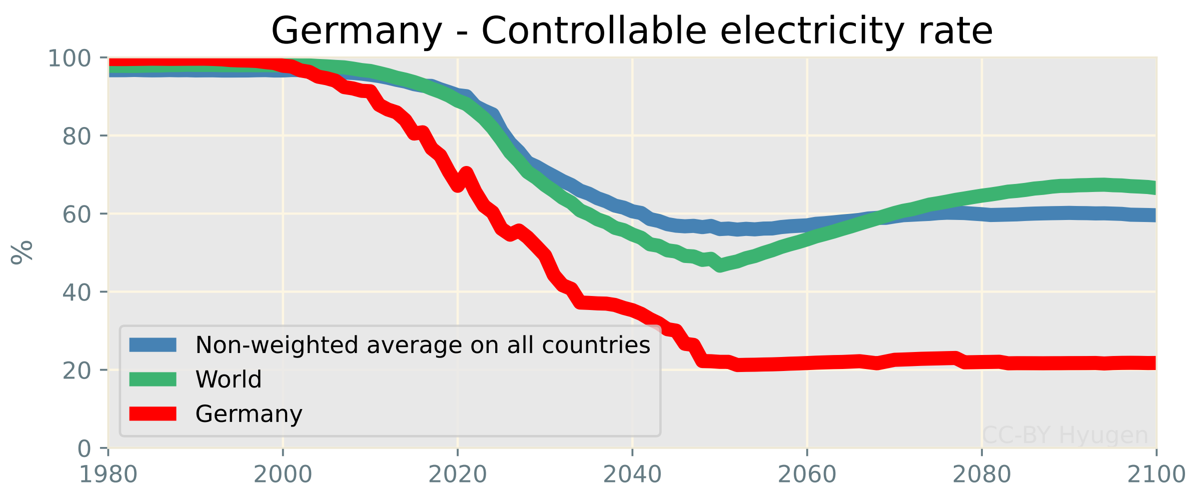


Fig. 4.70: Controllable electricity rate in Germany. Details in fig. 3.17

Power required from storage systems in Germany is modeled:

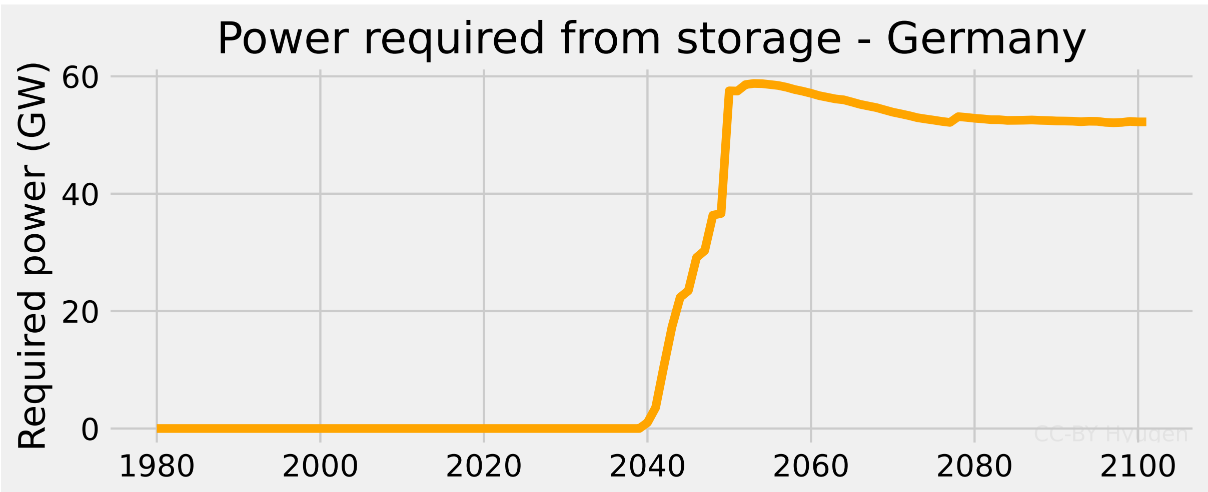


Fig. 4.71: Power required from storage systems in Germany. Details in fig. 3.53

Climate overview

Changes related to CO2 emissions in Germany can be visualized:

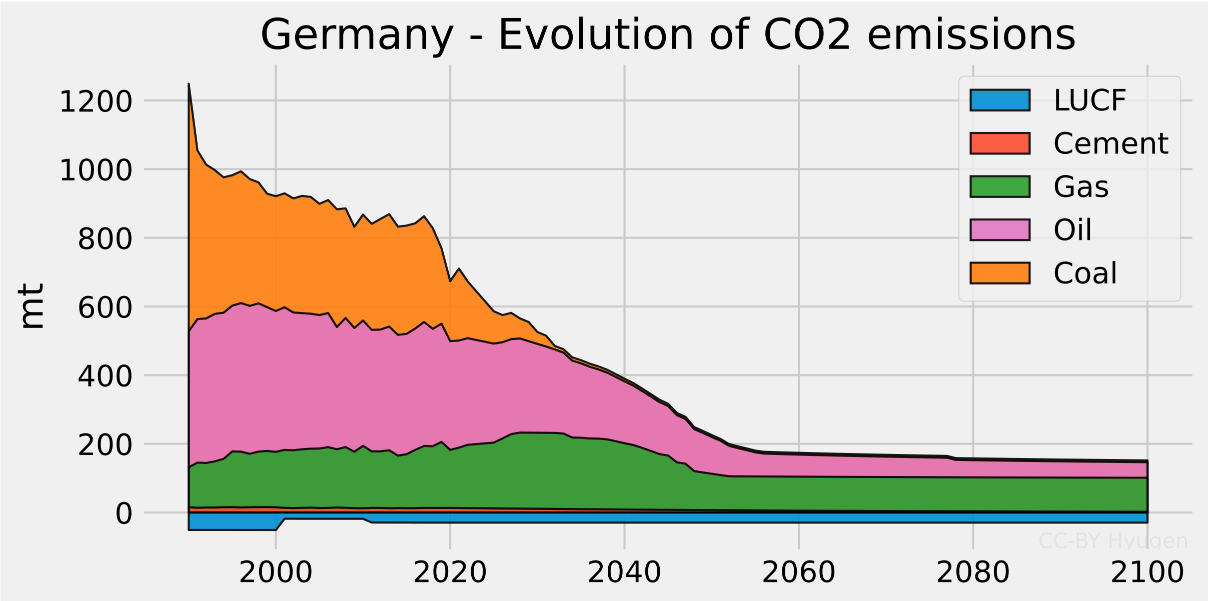
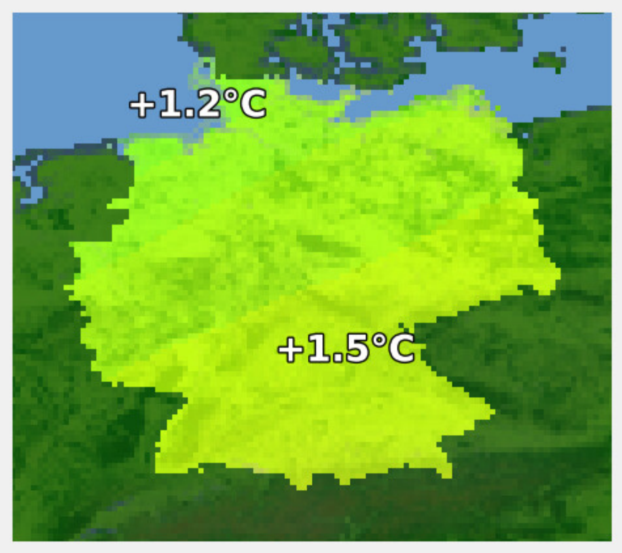


Fig. 4.72: CO2 emissions from Germany, pre-2020 source:[95, 83]

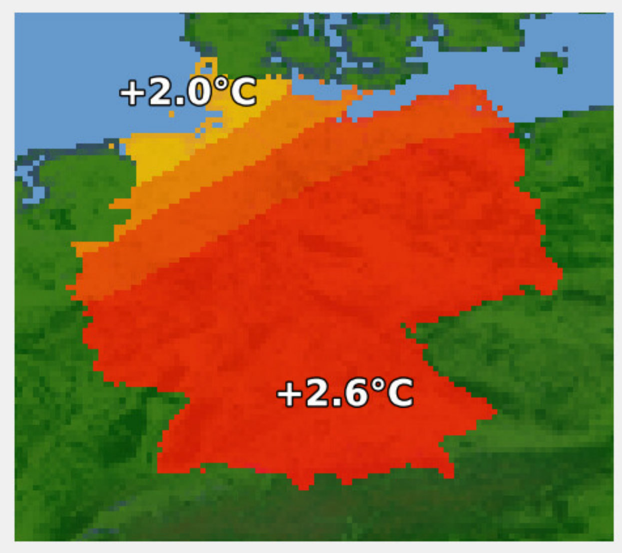
Climage changes in Germany are considered. Warming in the country will range from **+2.1°C** to **+3.0°C** in 2100 compared to pre-industrial era. Average temperature in 2100 weighted by population distribution is **11.8°C** in the model, with an average warming of **+2.8°C** on populations.
Countries which, before global warming, had similar temperatures compared to temperatures in Germany in 2100 are:

Country	Temperatures	Rainfalls (mm)
Croatia	12.2°C	797
Tajikistan	12.1°C	507
South Korea	12.1°C	1163
France	12.1°C	933
Andorra	12.1°C	636
- Germany	9.0°C => 11.8°C	988 => 964
Afghanistan	11.5°C	348
Hungary	10.7°C	662
Bulgaria	10.7°C	682
Netherlands	10.6°C	889
Bosnia and Herzegovina	10.5°C	979

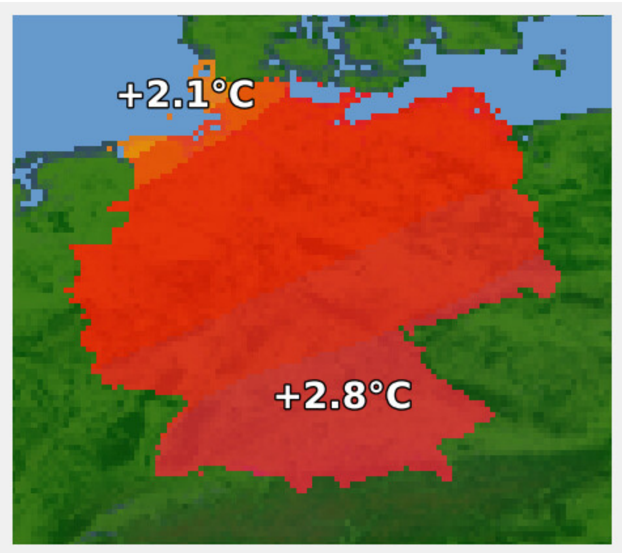
Table 4.4: Comparison of temperatures of Germany in 2100 with temperatures of other countries before global warming, weighted based on current population distribution. Methodology in section 4.10, based on [57, 62]



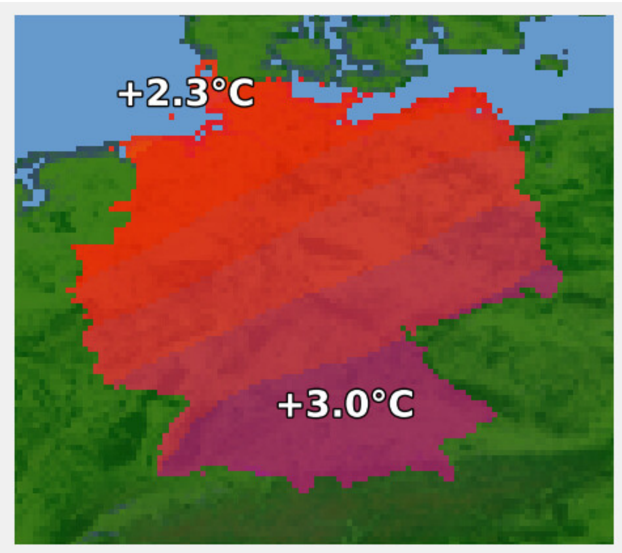
(a) 2020



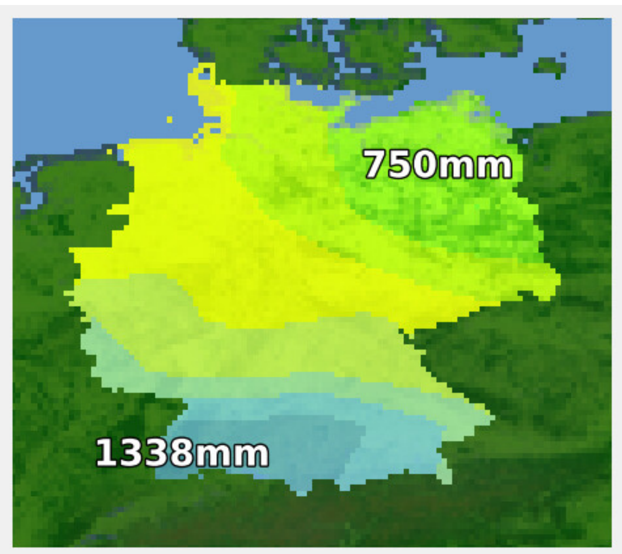
(b) 2050



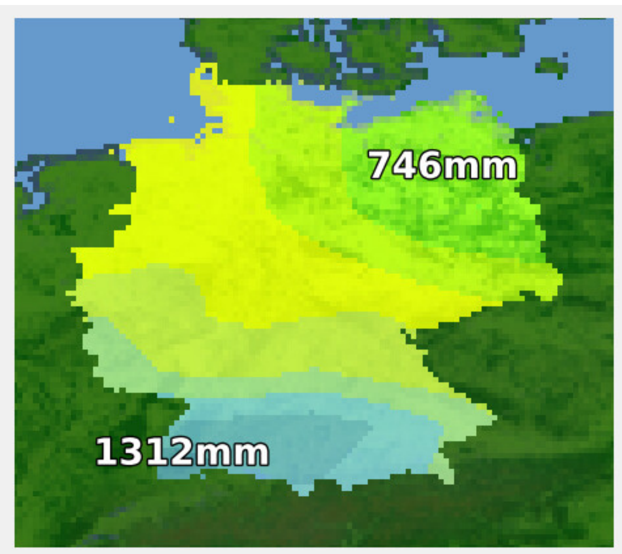
(c) 2070



(d) 2100

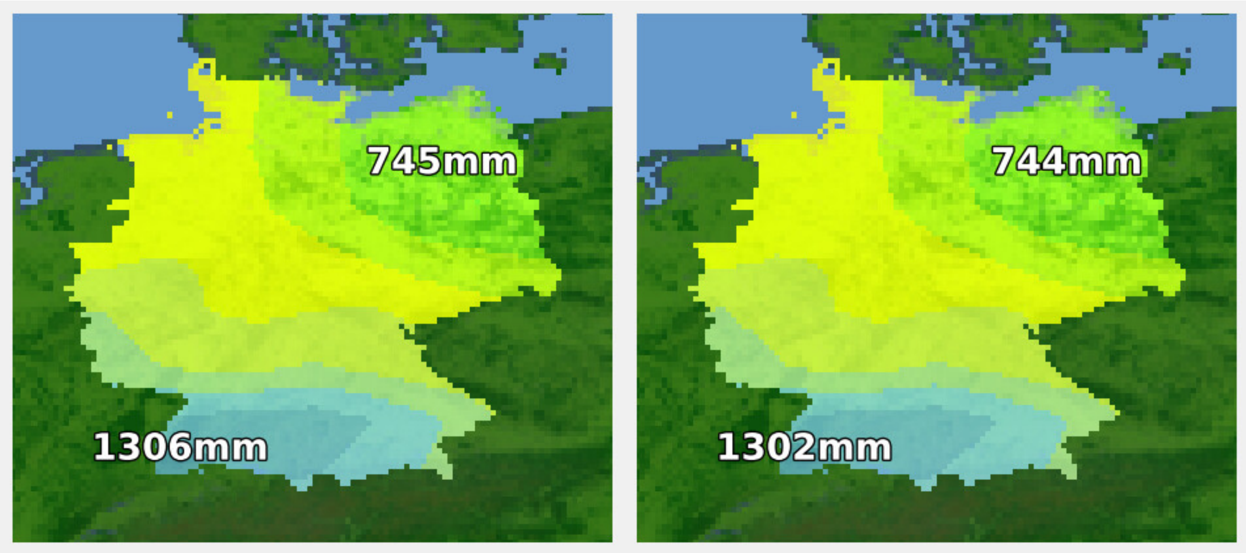


(e) 2020



(f) 2050

Fig. 4.73: Maps of global warming and rainfalls between 2020 and 2100



(a) 2070 (b) 2100

Fig. 4.74: Maps of global warming and rainfalls between 2020 and 2100


Japan

Demography overview

Population in Japan changes as follows:

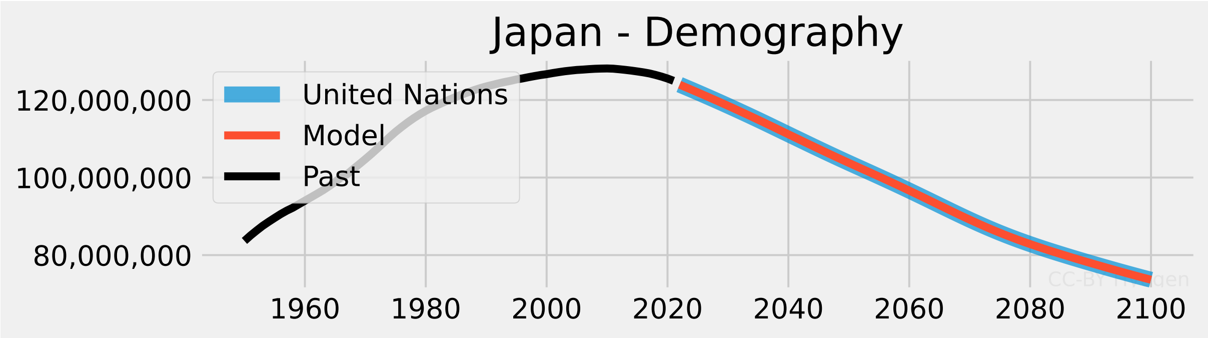


Fig. 4.75: Demography in Japan, UN:[30]

Life expectancy in Japan could evolve as follows:

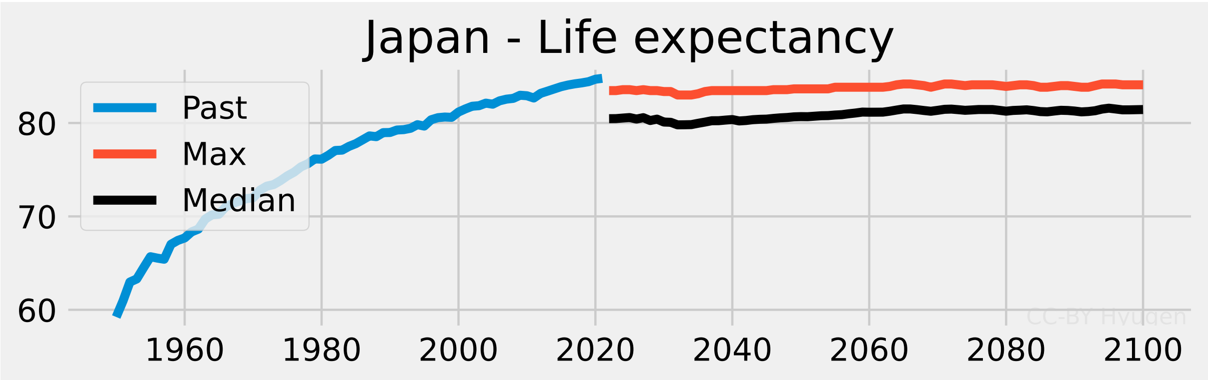


Fig. 4.76: Life expectancy in Japan, UN:[30], max and median from fig. 1.13

Meat consumption of Japan is configured by the user:

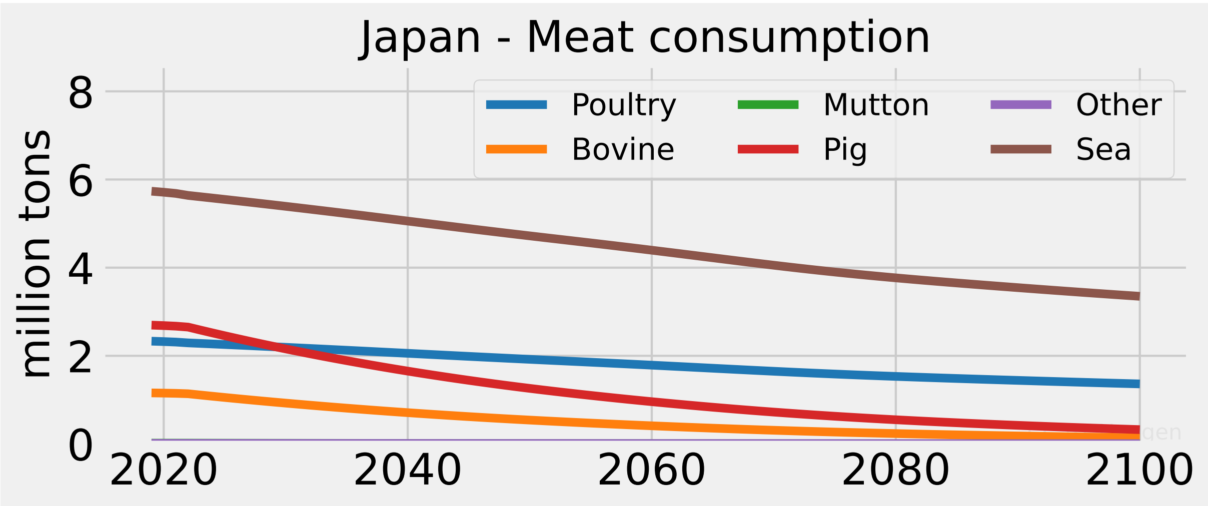


Fig. 4.77: Meat consumption in Japan, initialized with [84]

Climate change impacts on crops can be visualized as follows:

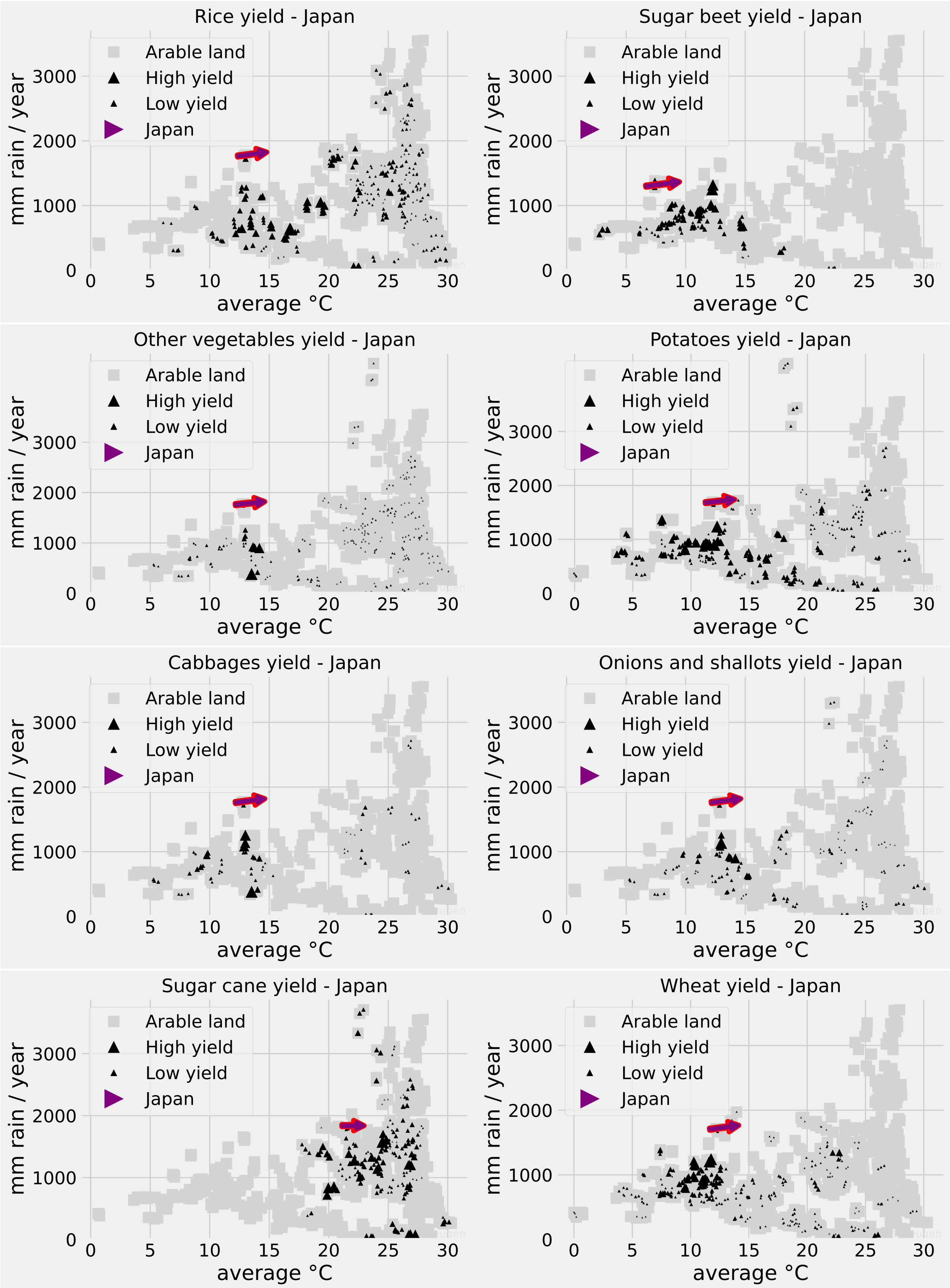


Fig. 4.78: Yields for different crops, arrow represents warming between 2100 and pre-industrial era, yield source:[32]

Energy overview

Changes related to power generation in Japan since 1980 can be presented:

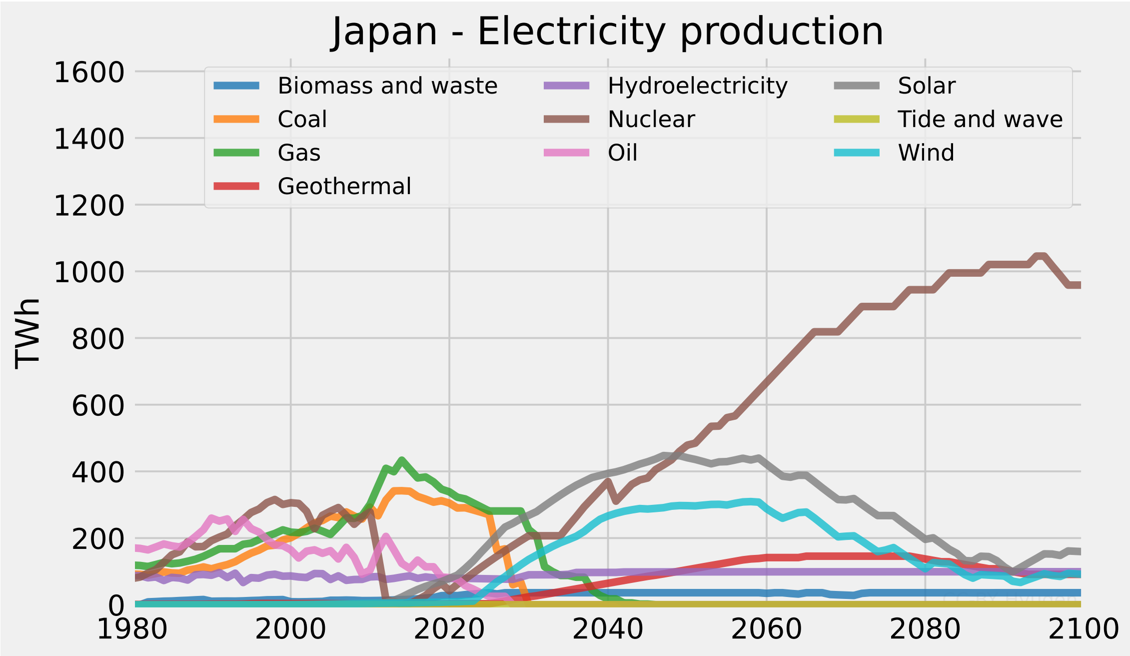


Fig. 4.79: Electricity production in Japan

Changes related to electrical capacity in Japan since 1980 can be presented:

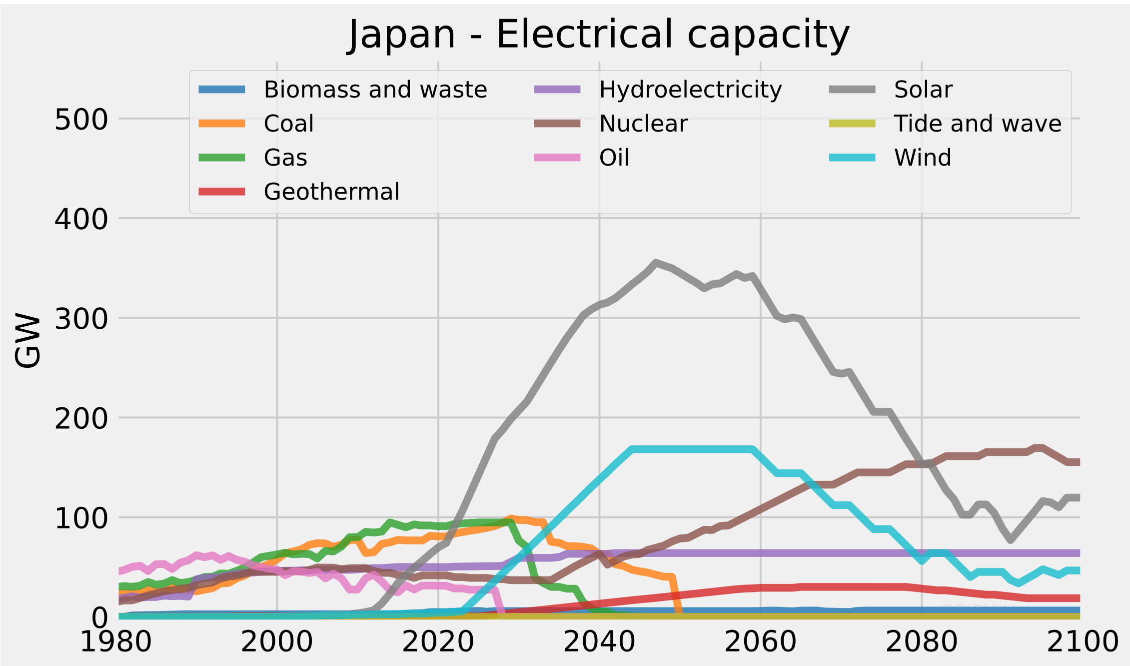


Fig. 4.80: Electrical capacity in Japan since 1980

Estimated capacity factors can be computed for multiple sources of electricity in Japan since 1980:

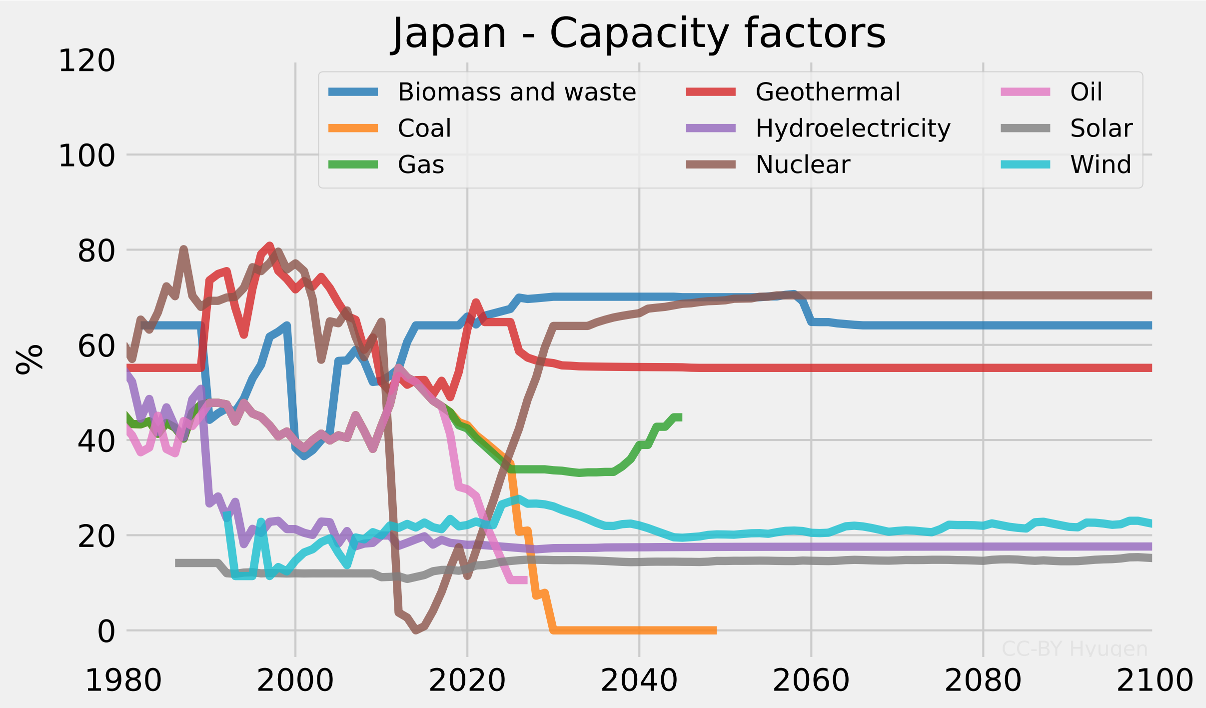


Fig. 4.81: Estimated capacity factors for electricity sources in Japan

Consumption of fossil fuels in Japan evolves as follows:

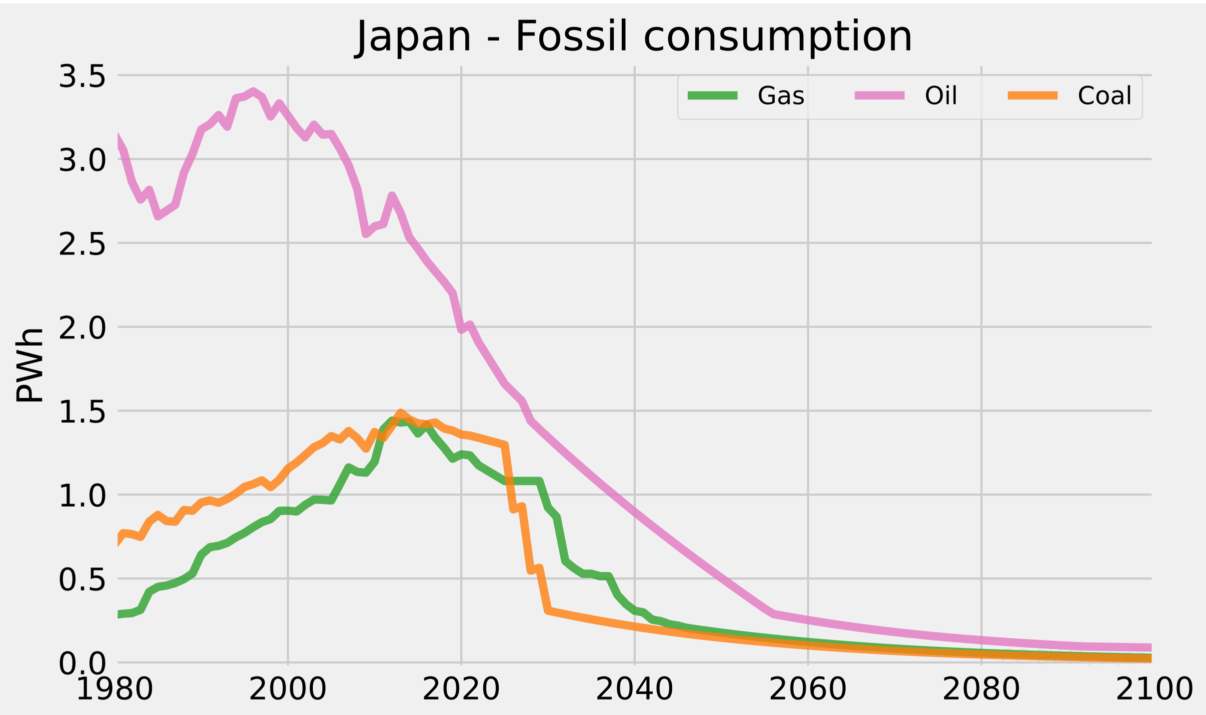


Fig. 4.82: Consumption of fossil fuels in Japan

Useful energy consumption per capita in Japan since 1980 can be compared with the useful energy consumption of other countries:

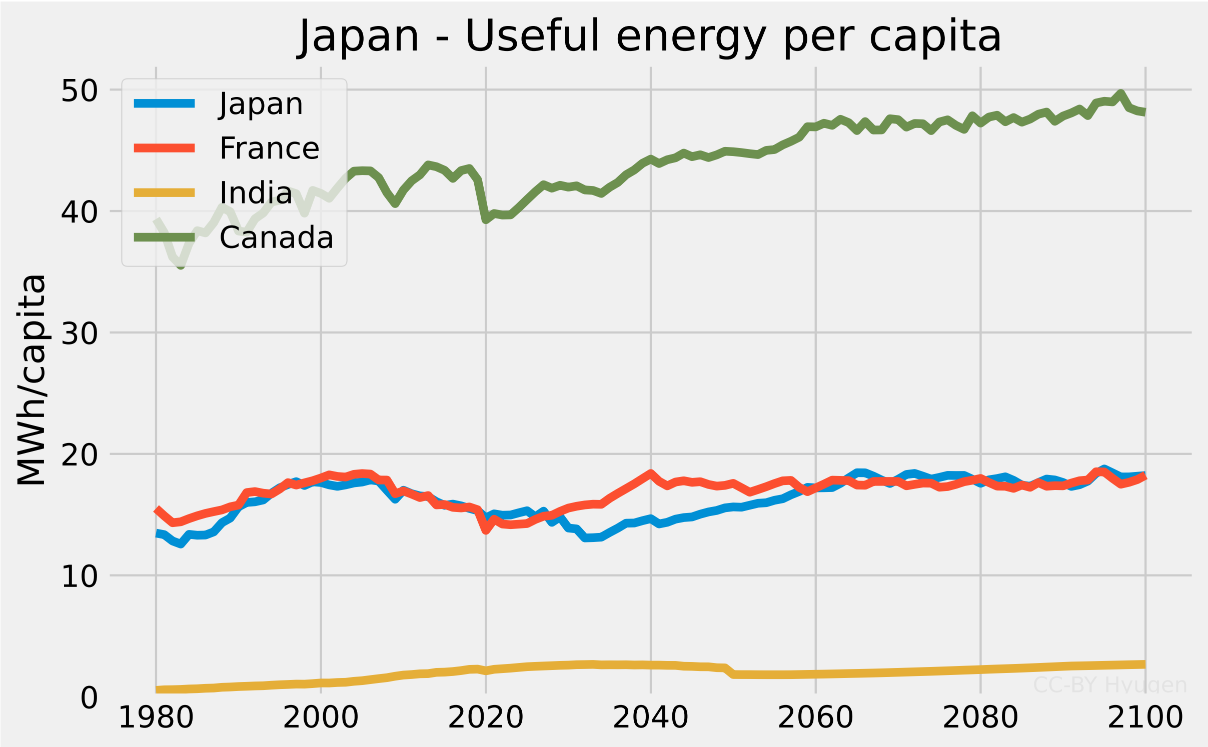


Fig. 4.83: Useful energy in Japan, cumulates electricity production and fossil consumption, ignores electricity imports/exports

Added and removed capacity per source of electricity are represented:

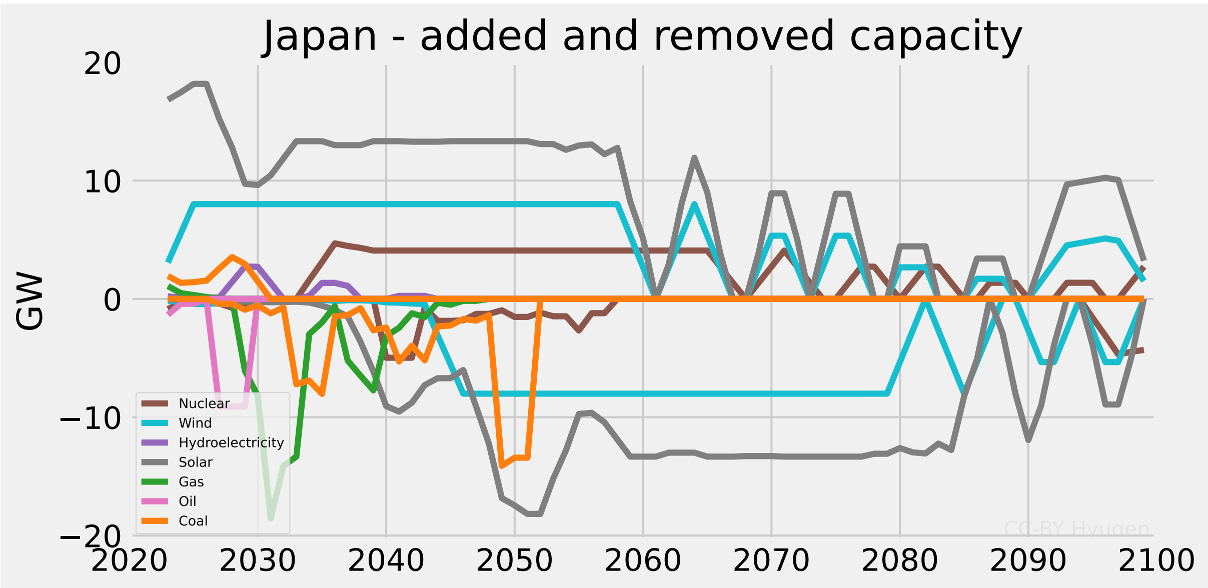
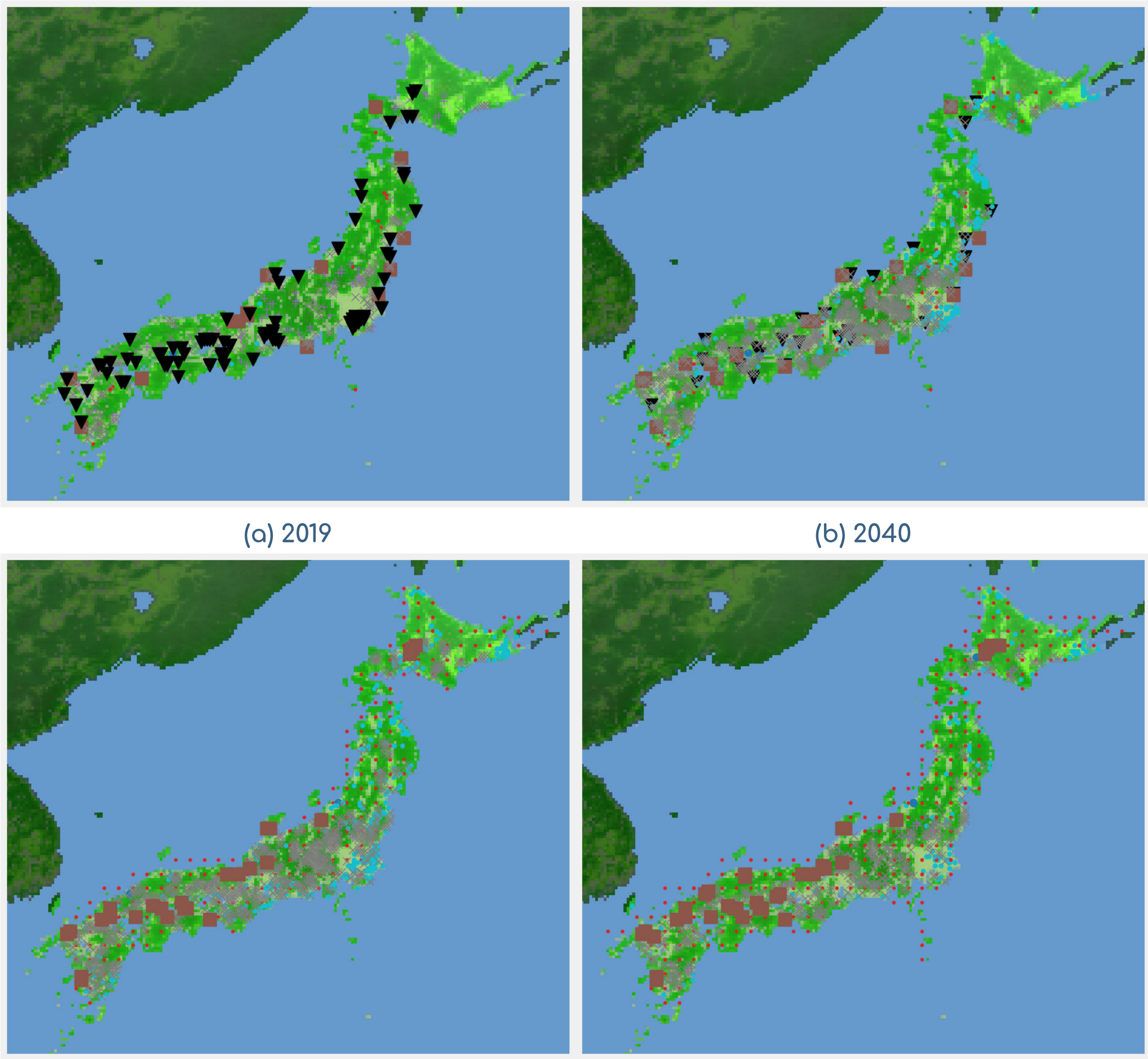


Fig. 4.84: Added / removed capacity per year by electricity source

Power plants are mapped over the country:



(a) 2019 (b) 2040

(c) 2060 (d) 2080

Fig. 4.85: Map of power plants in Japan, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.) , 2019:[55]

Changes related to carbon intensity of electricity in the country are represented in fig. 4.86.

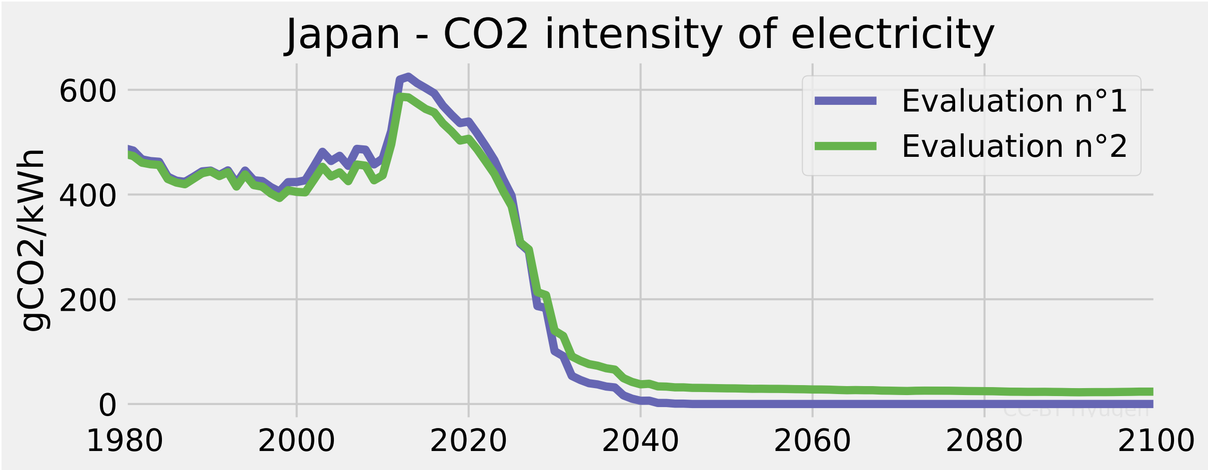


Fig. 4.86: Carbon intensity of electricity in Japan. Details in fig. 3.12

Reserves for multiple elements are included in the model:

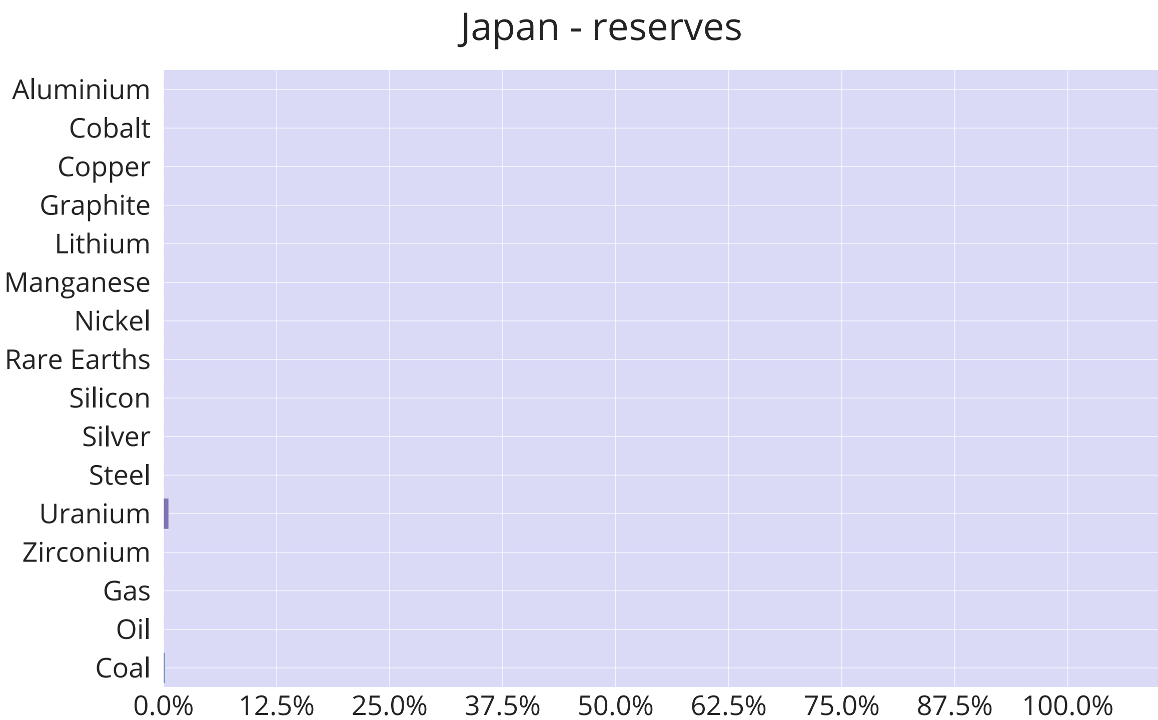


Fig. 4.87: Reserves of Japan as a proportion of the country with the most reserves (proportionally small reserves compared to the largest in the world may not be represented), source:[77]

The number of road vehicles in Japan evolves as follows:

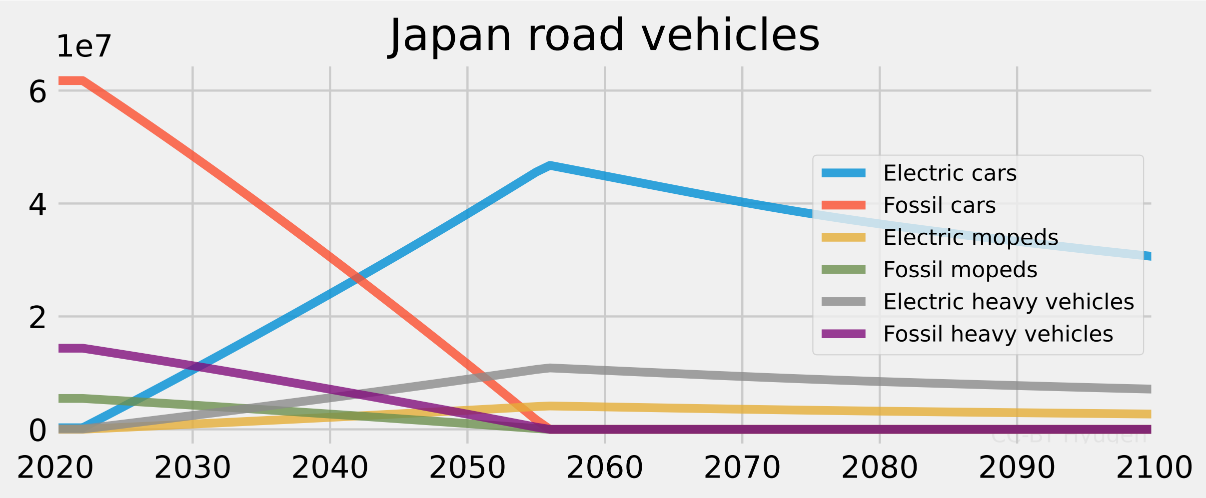


Fig. 4.88: Evolution of road vehicles in Japan. Details in fig. 3.18

Proportion of controllable electricity in Japan is included in the model:

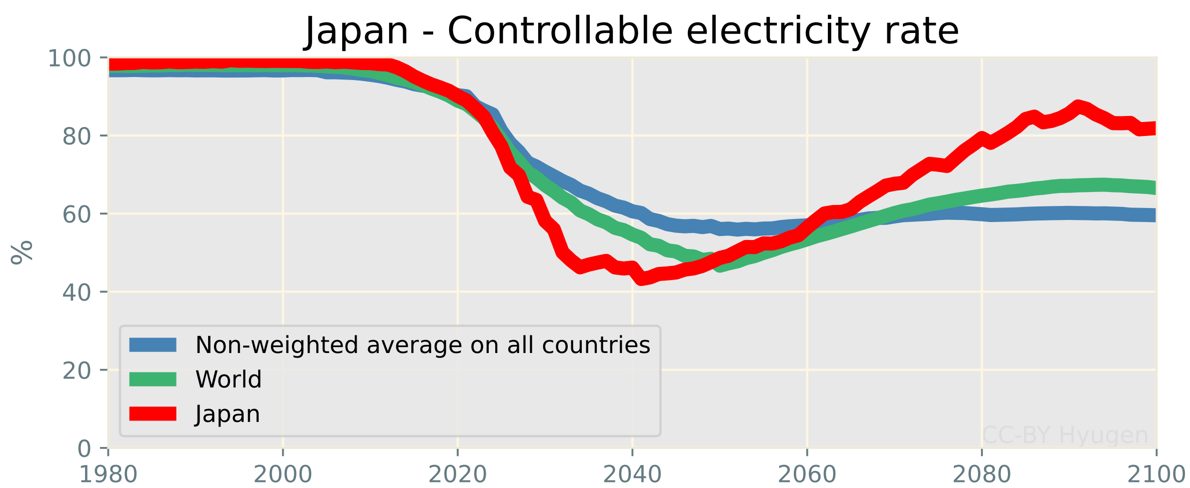


Fig. 4.89: Controllable electricity rate in Japan. Details in fig. 3.17

Power required from storage systems in Japan is modeled:

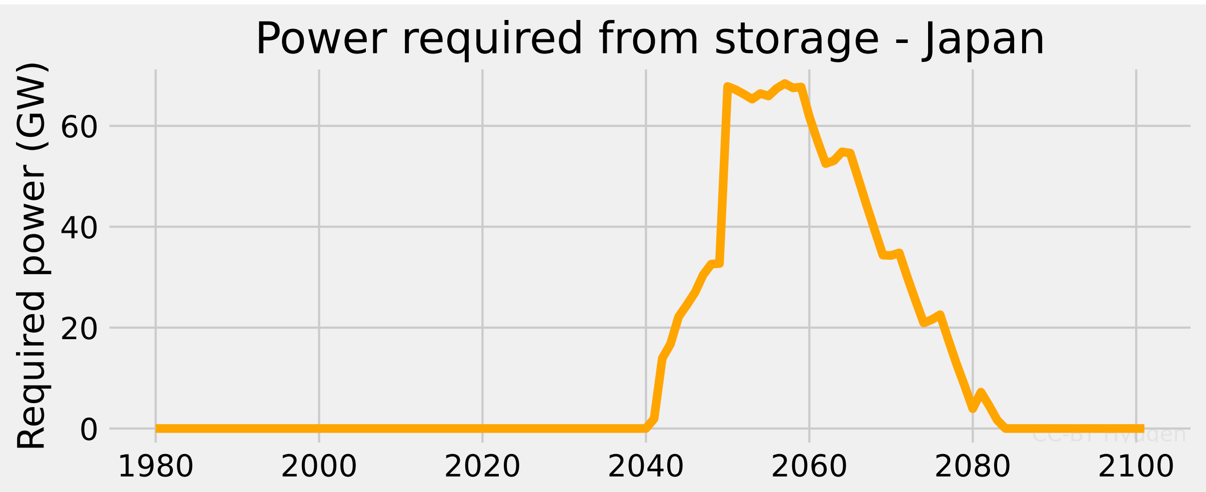


Fig. 4.90: Power required from storage systems in Japan. Details in fig. 3.53

Climate overview

Changes related to CO2 emissions in Japan can be visualized:

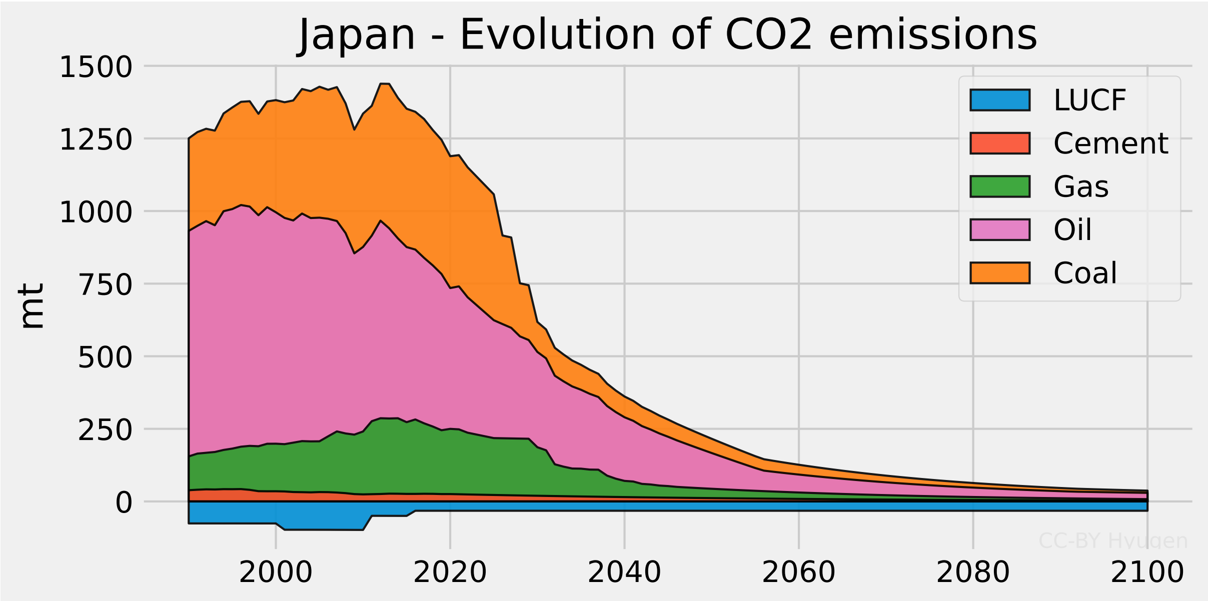
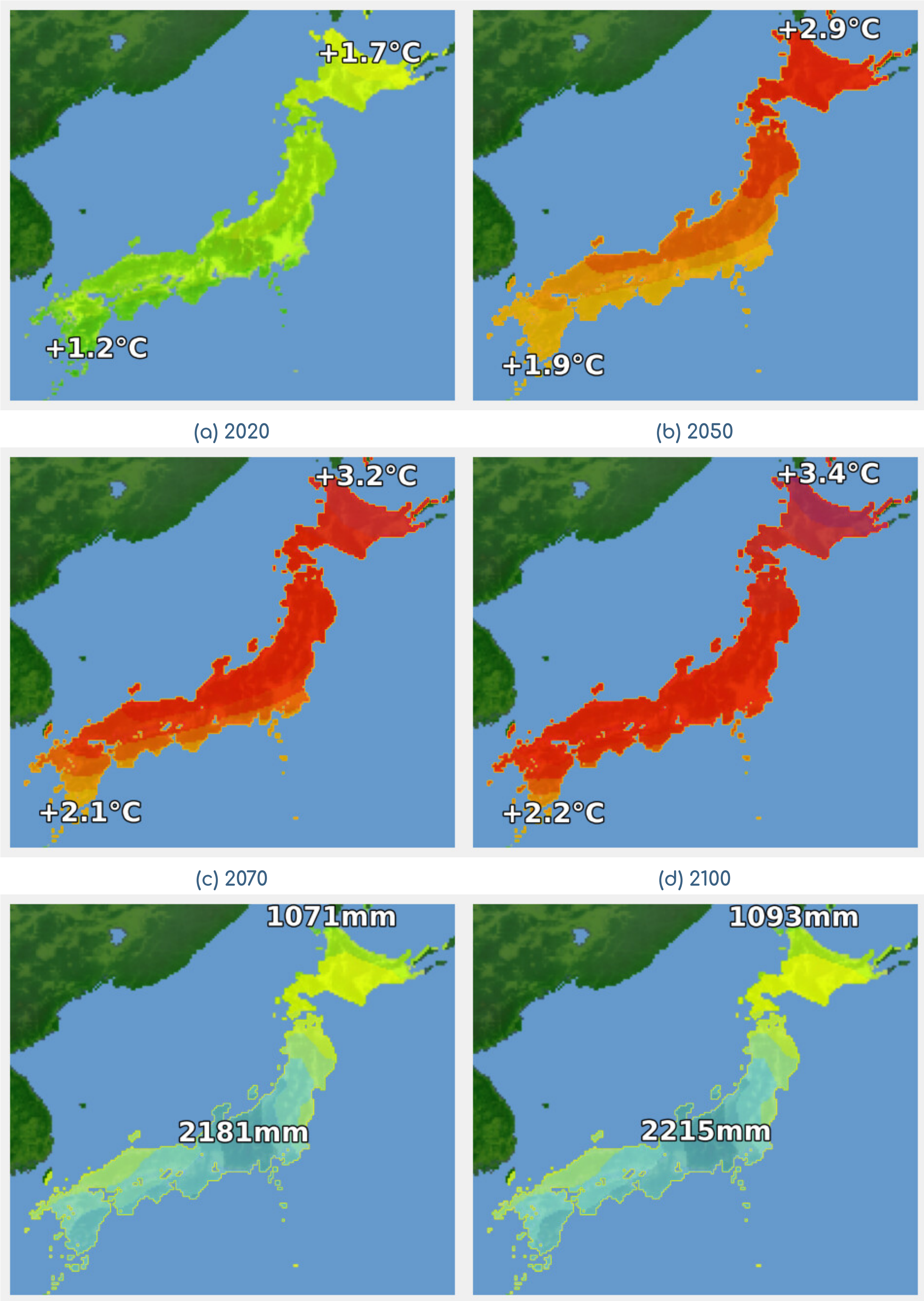


Fig. 4.91: CO2 emissions from Japan, pre-2020 source:[95, 83]

Climage changes in Japan are considered. Warming in the country will range from **+1.9°C** to **+3.5°C** in 2100 compared to pre-industrial era. Average temperature in 2100 weighted by population distribution is **16.7°C** in the model, with an average warming of **+2.7°C** on populations.
Countries which, before global warming, had similar temperatures compared to temperatures in Japan in 2100 are:

Country	Temperatures	Rainfalls (mm)
Bhutan	17.6°C	2111
Morocco	17.5°C	267
South Africa	17.3°C	1031
Peru	17.0°C	1035
Vatican City	16.9°C	583
- Japan	14.0°C => 16.7°C	1908 => 1974
Algeria	16.6°C	310
Uruguay	16.4°C	853
Portugal	16.3°C	709
Iran	16.3°C	287
Australia	15.8°C	761

Table 4.5: Comparison of temperatures of Japan in 2100 with temperatures of other countries before global warming, weighted based on current population distribution. Methodology in section 4.10, based on [57, 62]

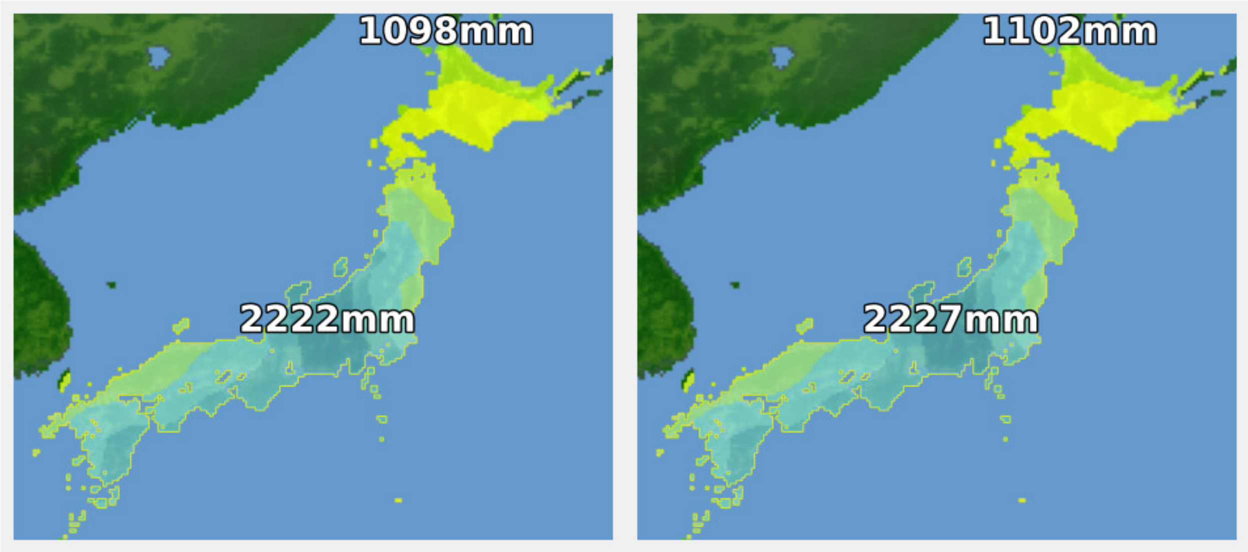


(a) 2020 (b) 2050

(c) 2070 (d) 2100

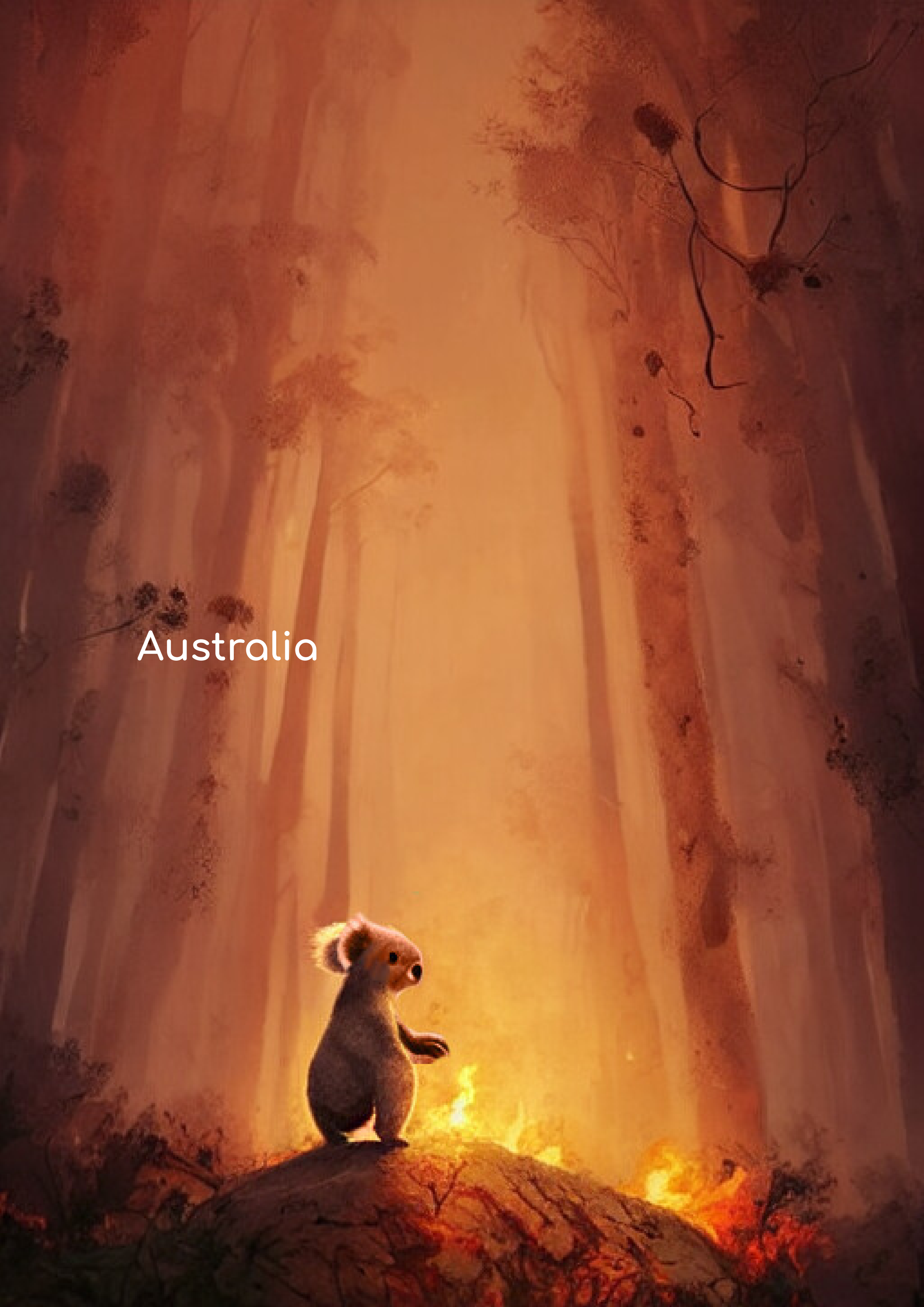
(e) 2020 (f) 2050

Fig. 4.92: Maps of global warming and rainfalls between 2020 and 2100



(a) 2070 (b) 2100

Fig. 4.93: Maps of global warming and rainfalls between 2020 and 2100


Australia

Demography overview

Population in Australia changes as follows:

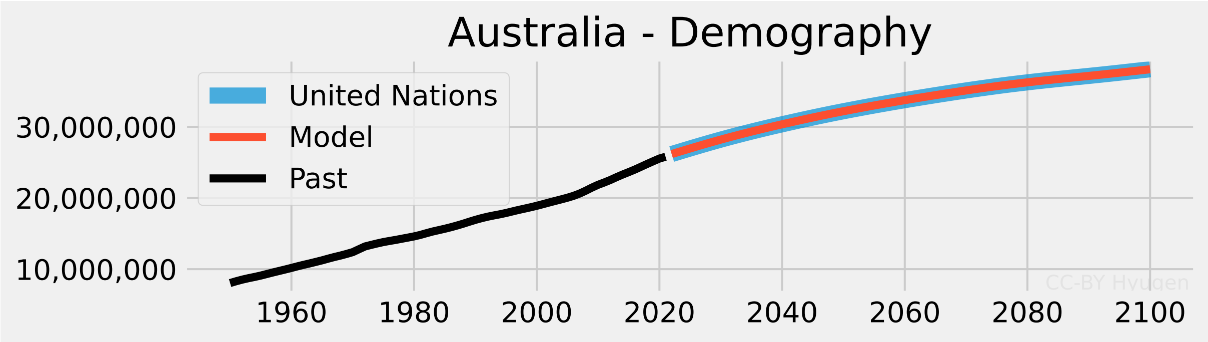


Fig. 4.94: Demography in Australia, UN:[30]

Life expectancy in Australia could evolve as follows:

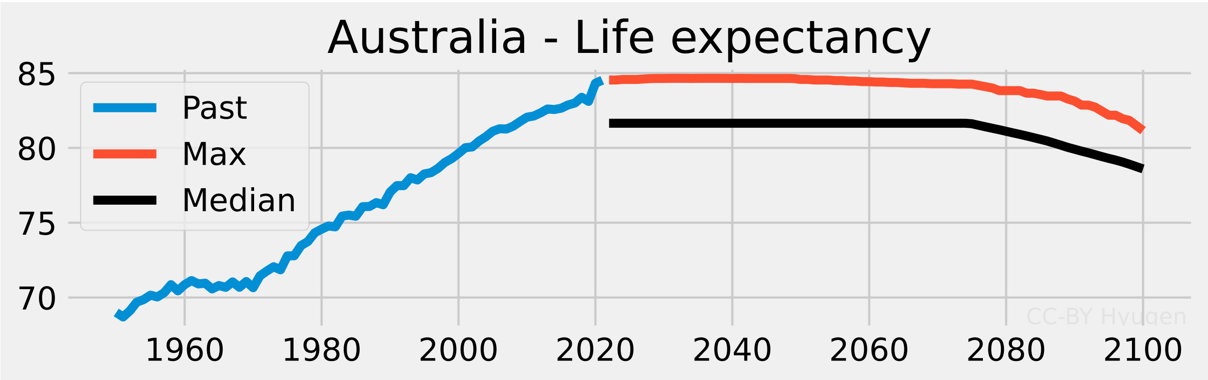


Fig. 4.95: Life expectancy in Australia, UN:[30], max and median from fig. 1.13

Meat consumption of Australia is configured by the user:

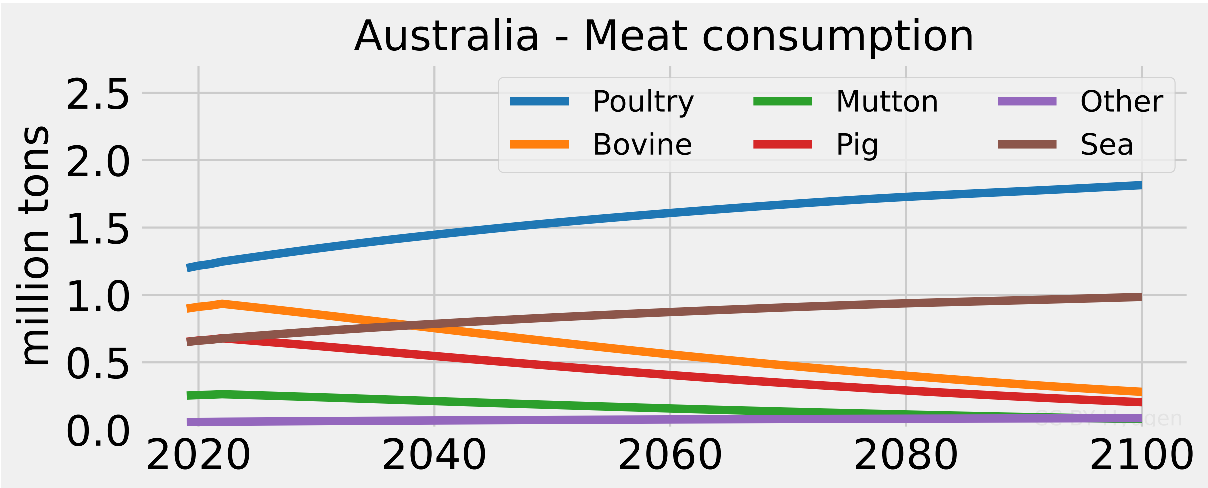


Fig. 4.96: Meat consumption in Australia, initialized with [84]

Climate change impacts on crops can be visualized as follows:

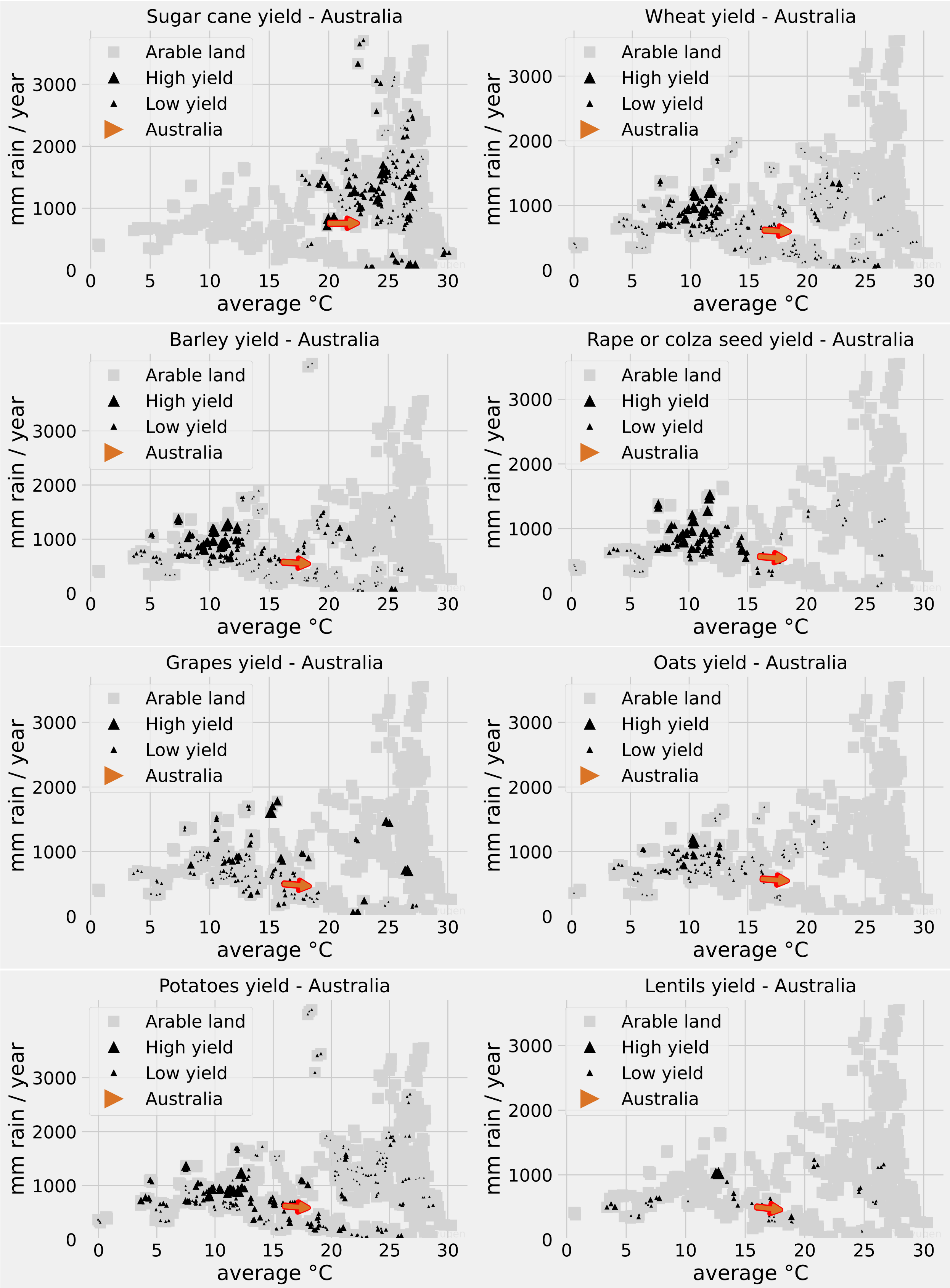


Fig. 4.97: Yields for different crops, arrow represents warming between 2100 and pre-industrial era, yield source:[32]

Energy overview

Changes related to power generation in Australia since 1980 can be presented:

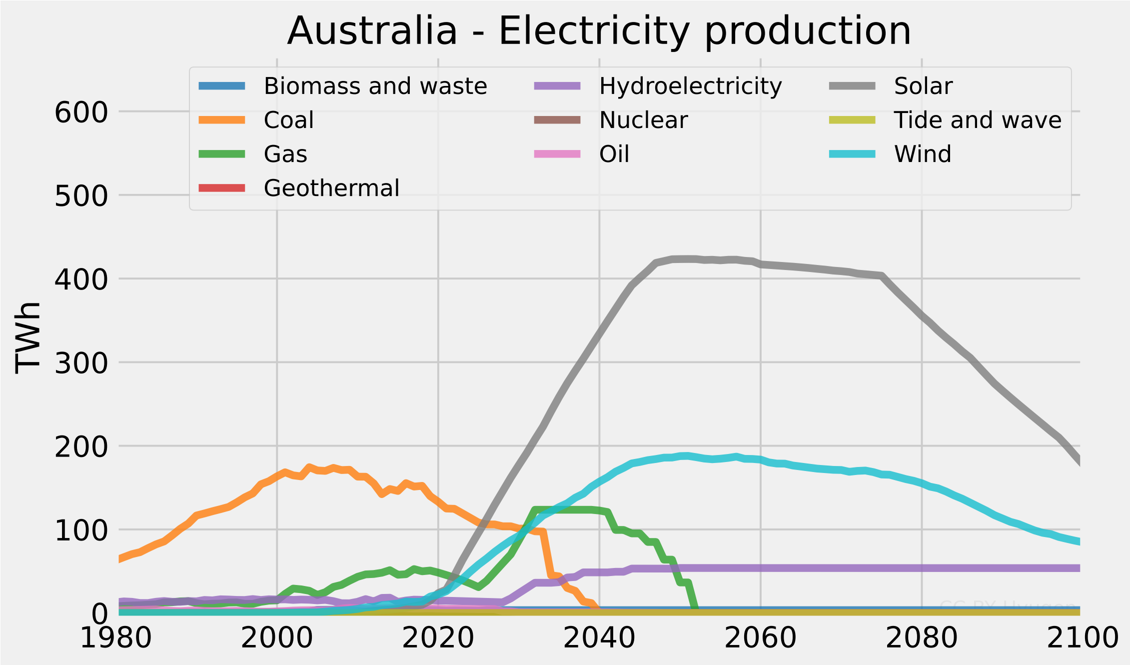


Fig. 4.98: Electricity production in Australia

Changes related to electrical capacity in Australia since 1980 can be presented:

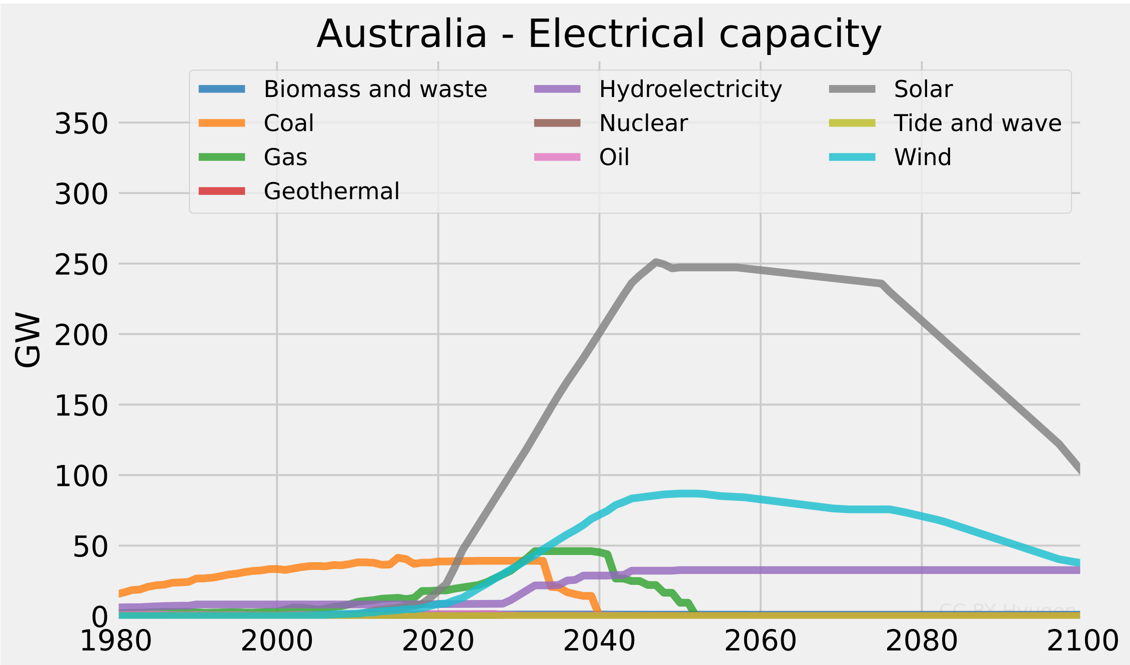


Fig. 4.99: Electrical capacity in Australia since 1980

Estimated capacity factors can be computed for multiple sources of electricity in Australia since 1980:

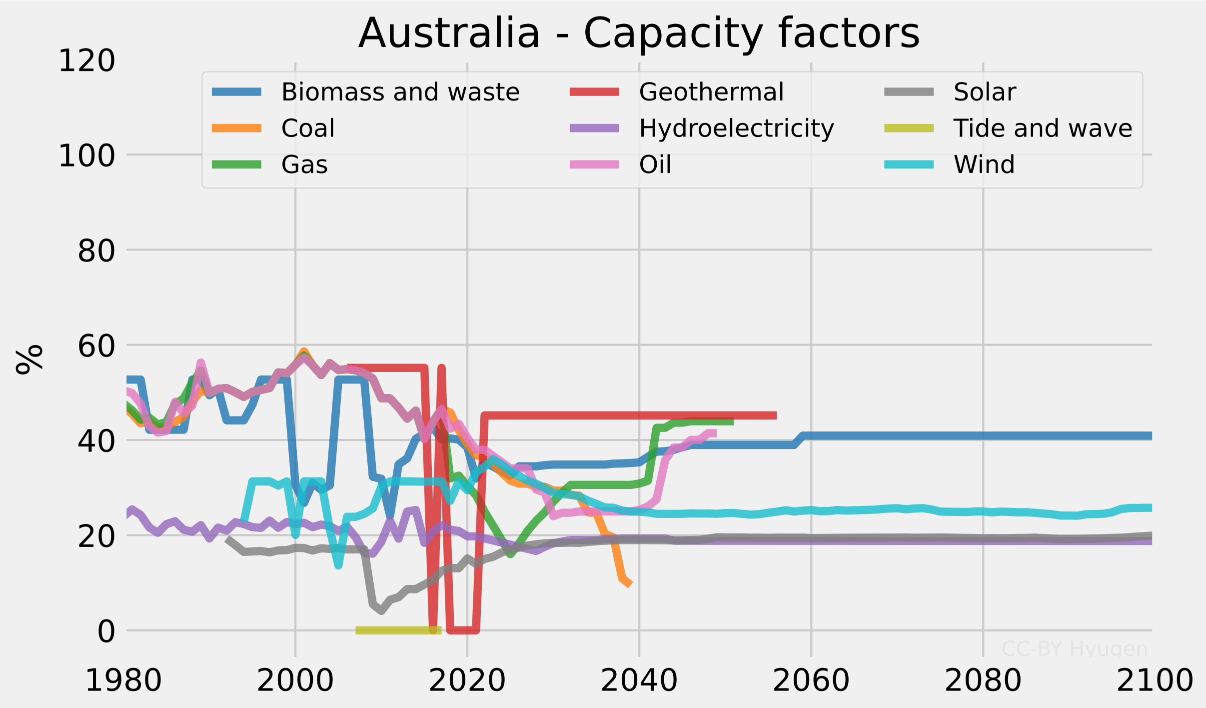


Fig. 4.100: Estimated capacity factors for electricity sources in Australia

Consumption of fossil fuels in Australia evolves as follows:

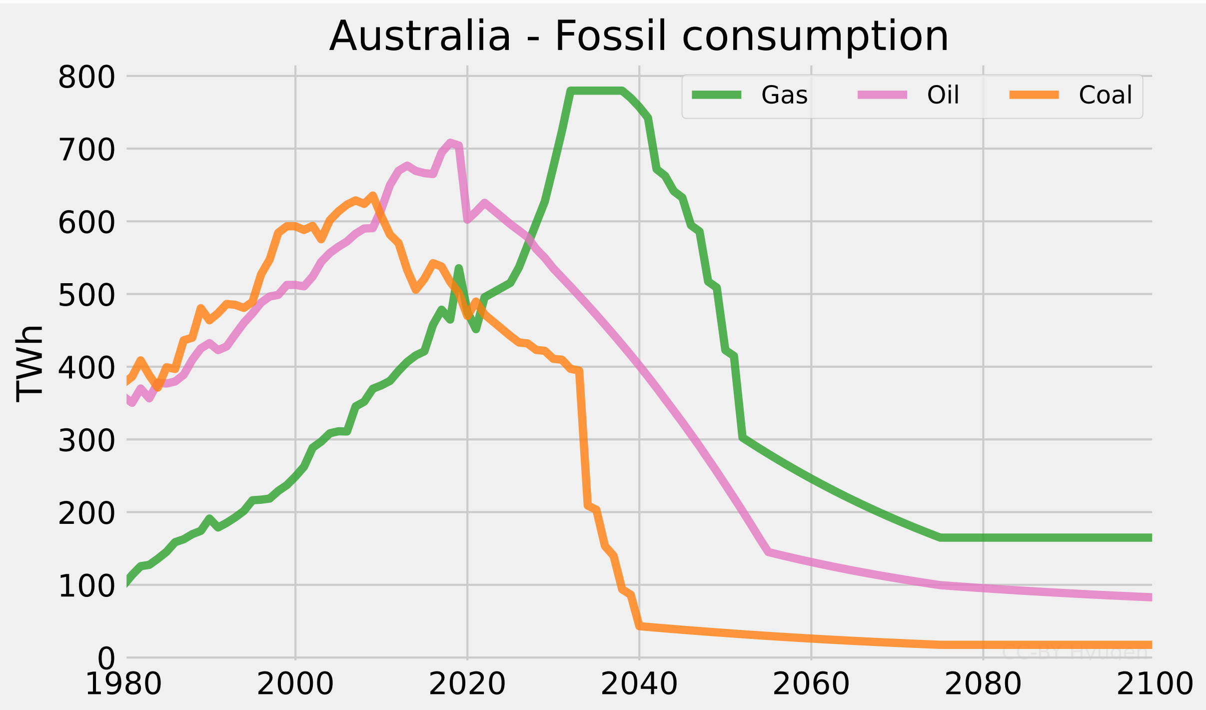


Fig. 4.101: Consumption of fossil fuels in Australia

Useful energy consumption per capita in Australia since 1980 can be compared with the useful energy consumption of other countries:

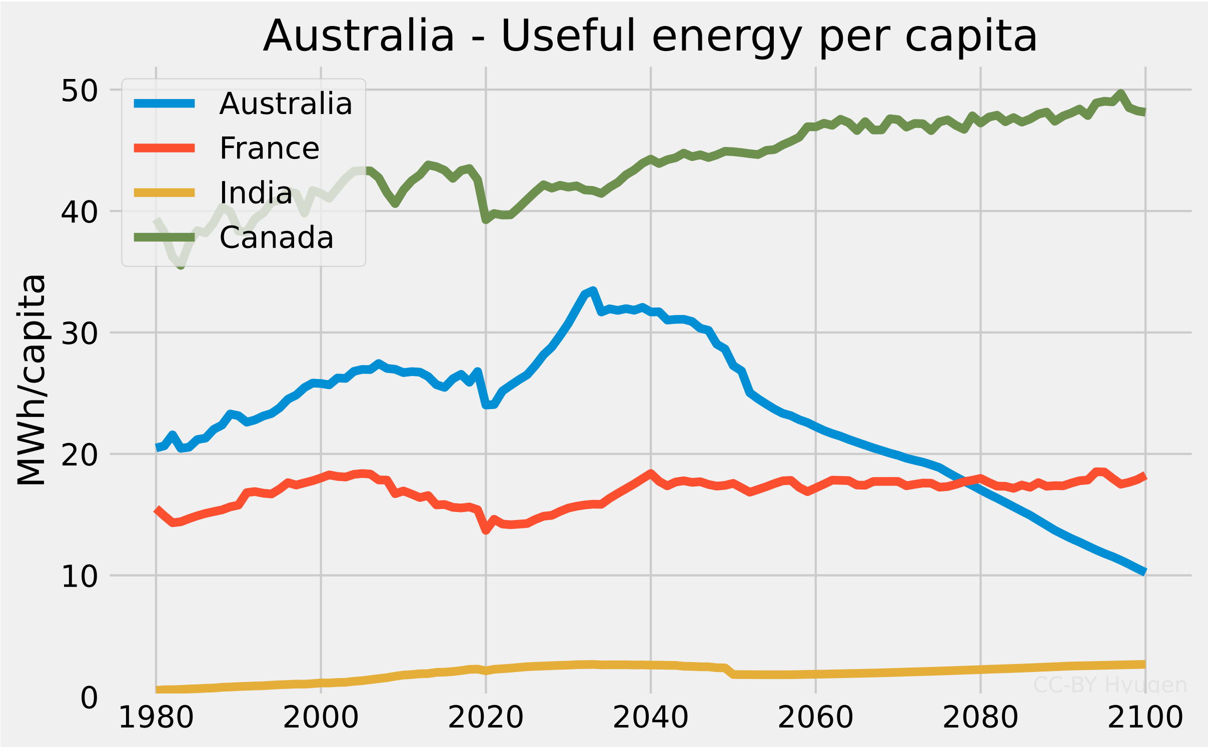


Fig. 4.102: Useful energy in Australia, cumulates electricity production and fossil consumption, ignores electricity imports/exports

Added and removed capacity per source of electricity are represented:

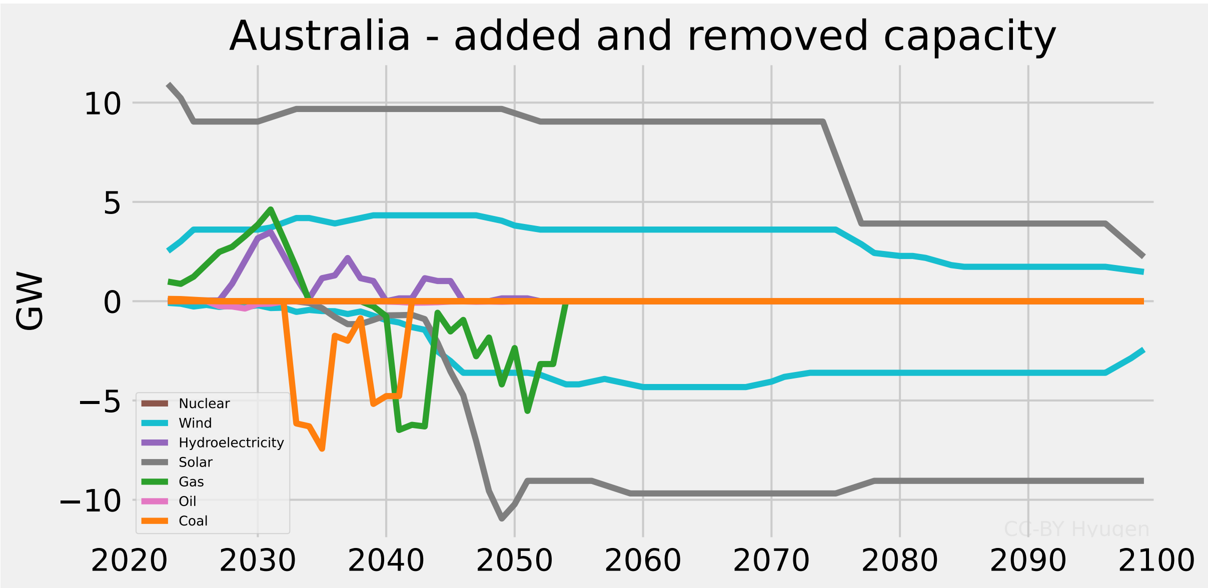
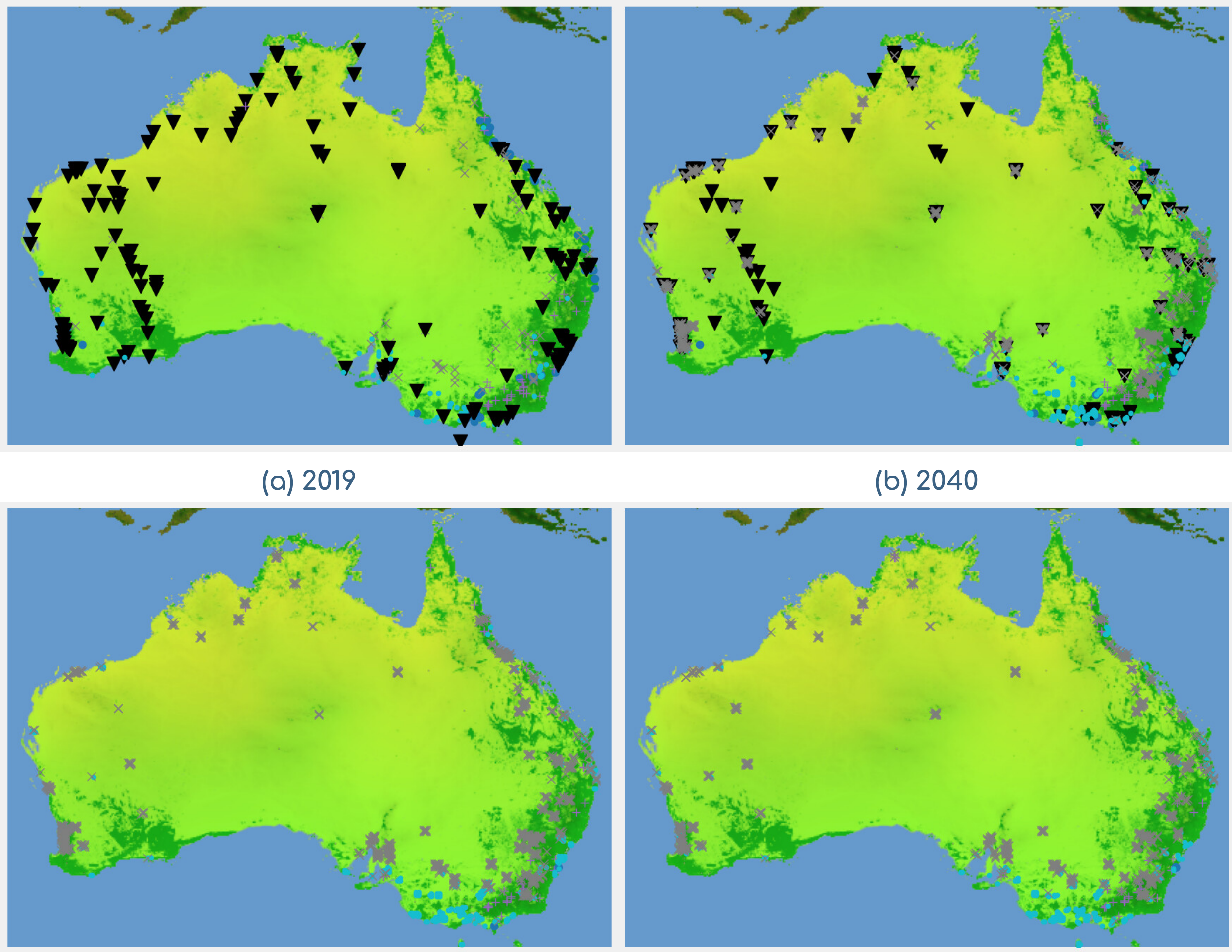


Fig. 4.103: Added / removed capacity per year by electricity source

Power plants are mapped over the country:



(a) 2019 (b) 2040

(c) 2060 (d) 2080

Fig. 4.104: Map of power plants in Australia, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.) , 2019:[55]

Changes related to carbon intensity of electricity in the country are represented in fig. 4.105.

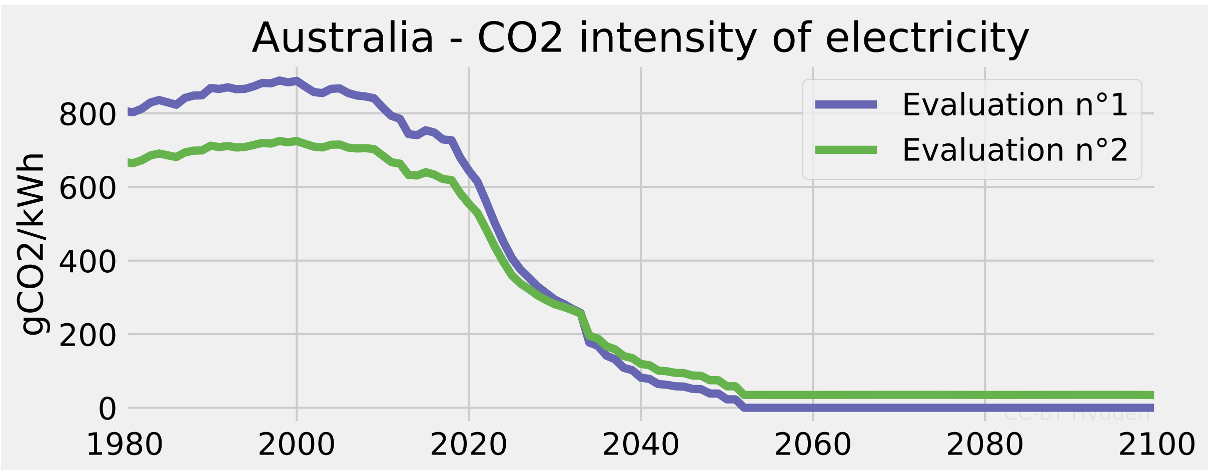


Fig. 4.105: Carbon intensity of electricity in Australia. Details in fig. 3.12

Reserves for multiple elements are included in the model:

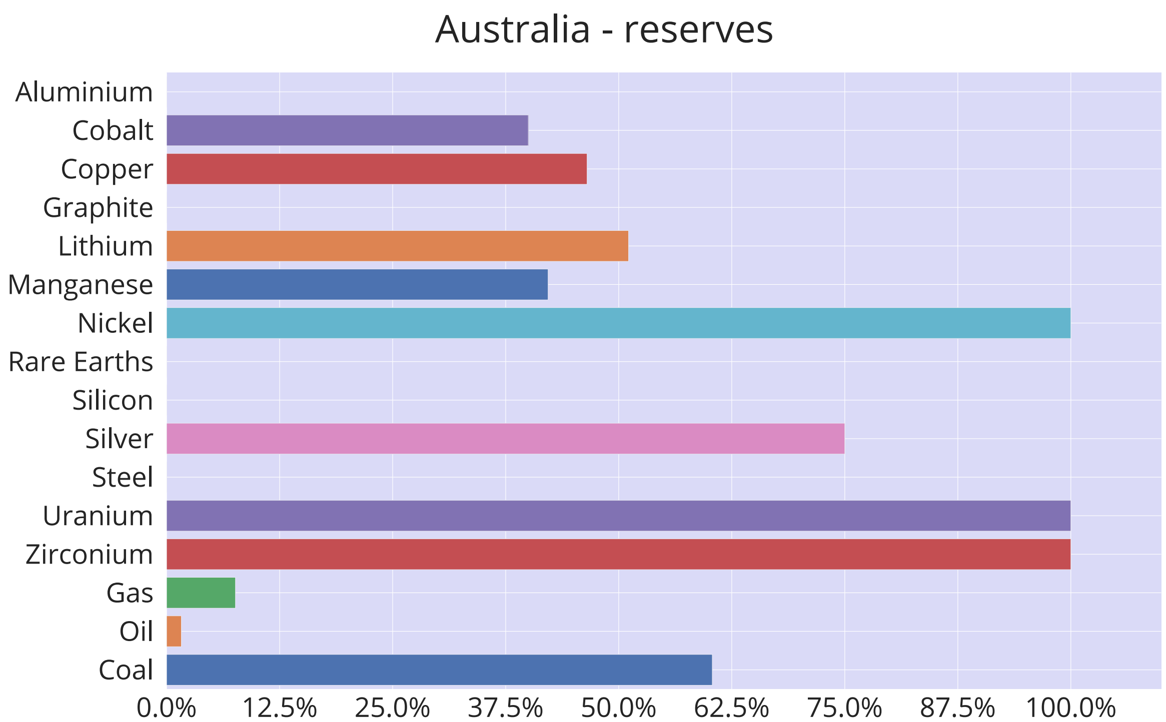


Fig. 4.106: Reserves of Australia as a proportion of the country with the most reserves (proportionally small reserves compared to the largest in the world may not be represented), source:[77]

The number of road vehicles in Australia evolves as follows:

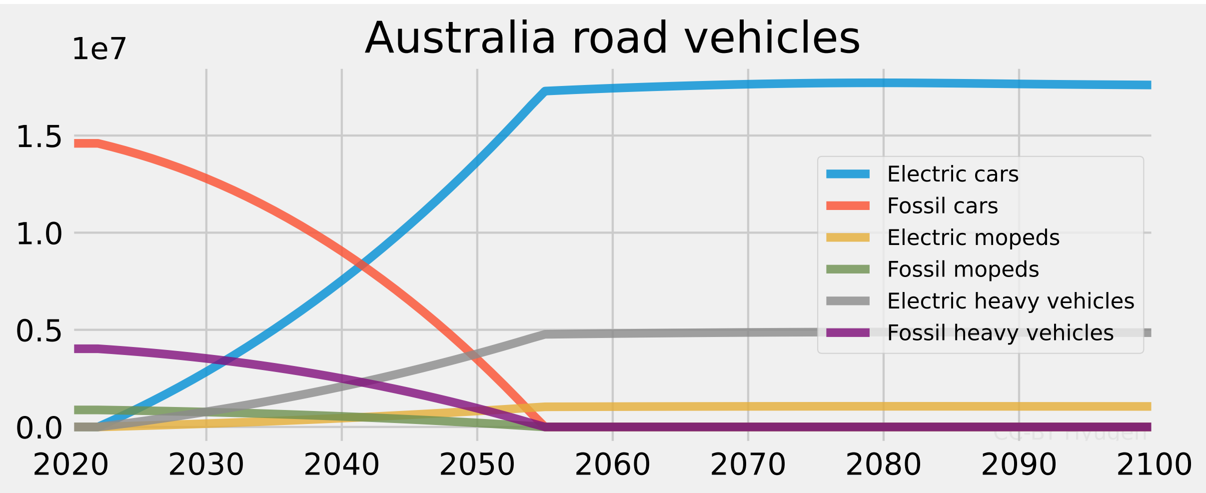


Fig. 4.107: Evolution of road vehicles in Australia. Details in fig. 3.18

Proportion of controllable electricity in Australia is included in the model:

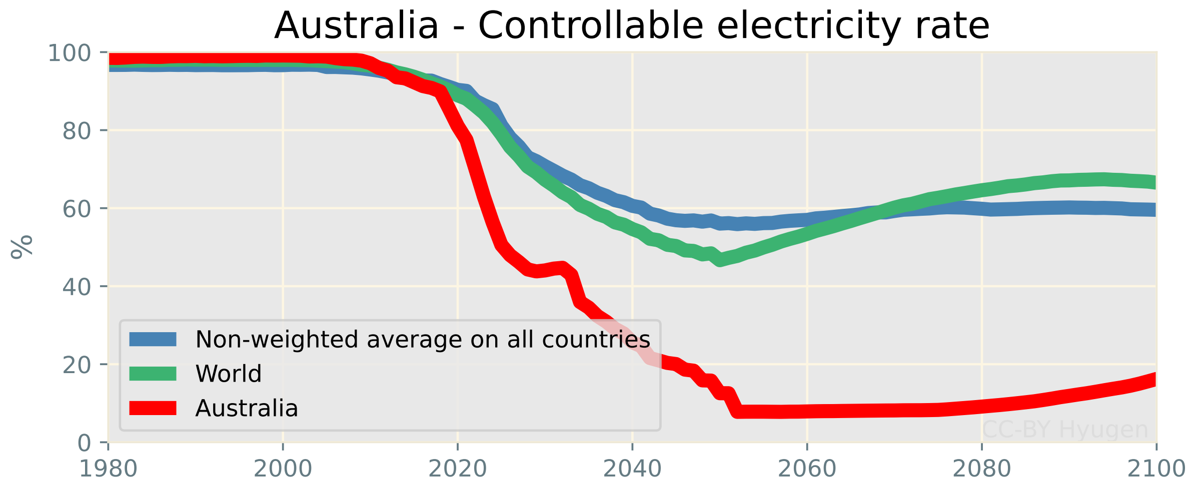


Fig. 4.108: Controllable electricity rate in Australia. Details in fig. 3.17

Power required from storage systems in Australia is modeled:

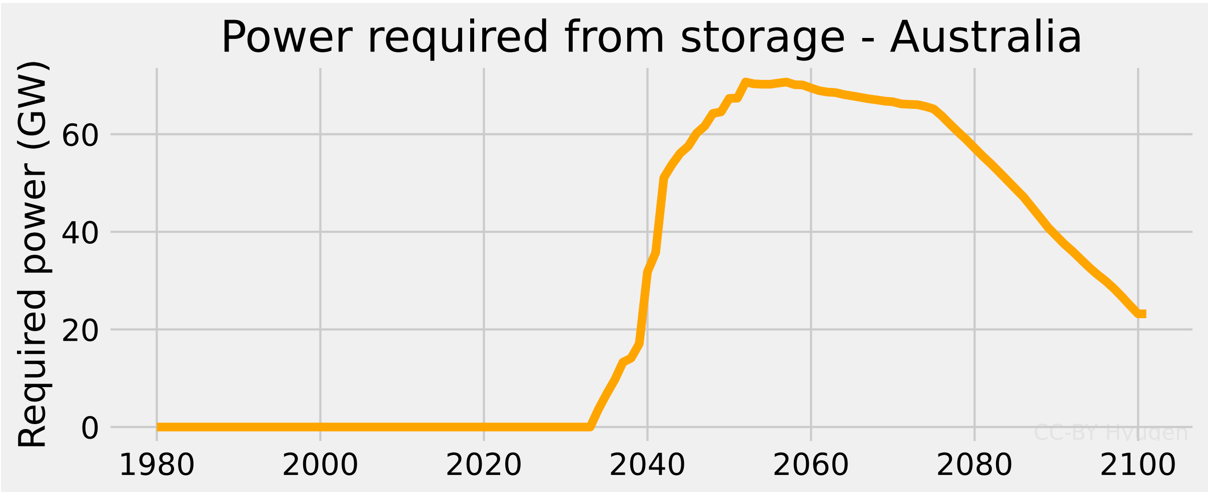


Fig. 4.109: Power required from storage systems in Australia. Details in fig. 3.53

Climate overview

Changes related to CO2 emissions in Australia can be visualized:

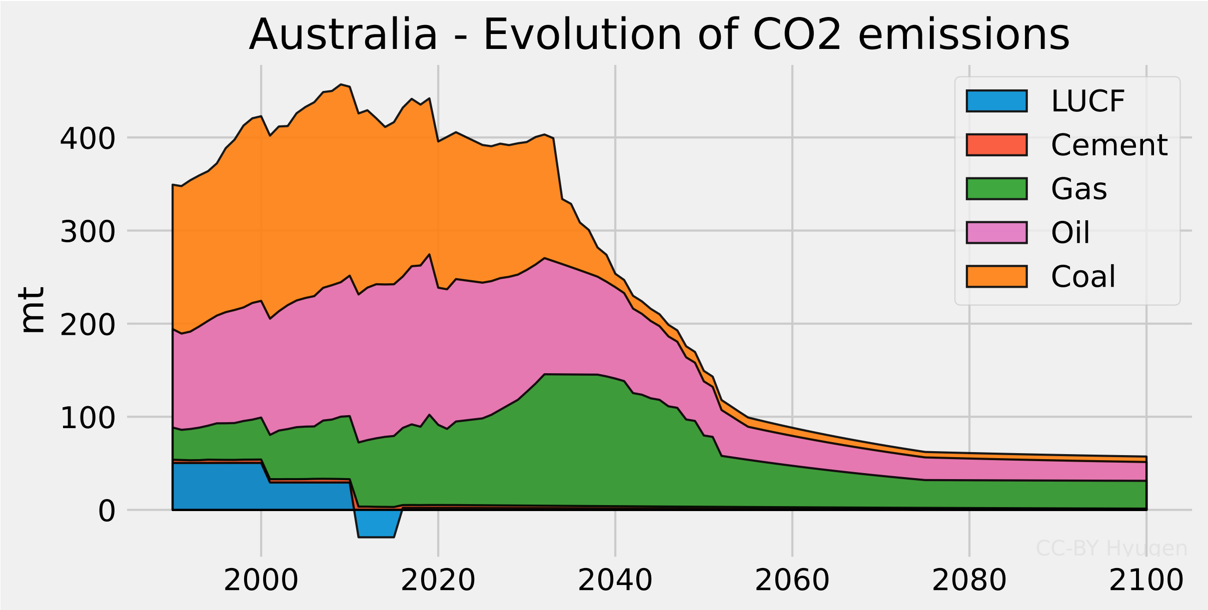


Fig. 4.110: CO2 emissions from Australia, pre-2020 source:[95, 83]

Climage changes in Australia are considered. Warming in the country will range from **+1.3°C** to **+3.4°C** in 2100 compared to pre-industrial era. Average temperature in 2100 weighted by population distribution is **18.1°C** in the model, with an average warming of **+2.4°C** on populations.

Countries which, before global warming, had similar temperatures compared to temperatures in Australia in 2100 are:

Country	Temperatures	Rainfalls (mm)
Lebanon	19.3°C	434
Jordan	19.2°C	167
Rwanda	19.0°C	1734
Eswatini	18.4°C	1404
Tunisia	18.3°C	240
- Australia	15.8°C => 18.1°C	761 => 733
Syria	17.8°C	330
Bhutan	17.6°C	2111
Morocco	17.5°C	267
South Africa	17.3°C	1031
Peru	17.0°C	1035

Table 4.6: Comparison of temperatures of Australia in 2100 with temperatures of other countries before global warming, weighted based on current population distribution. Methodology in section 4.10, based on [57, 62]

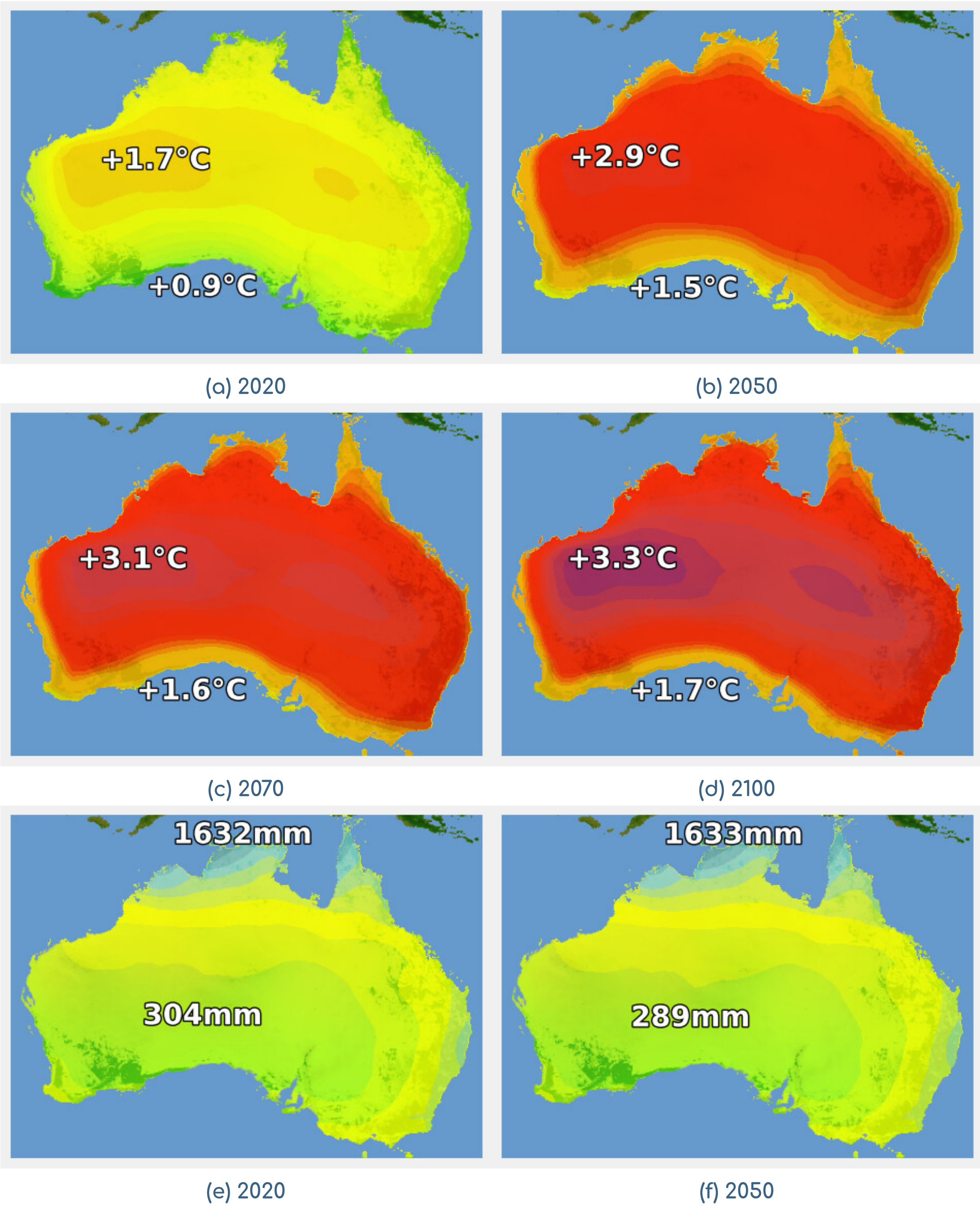
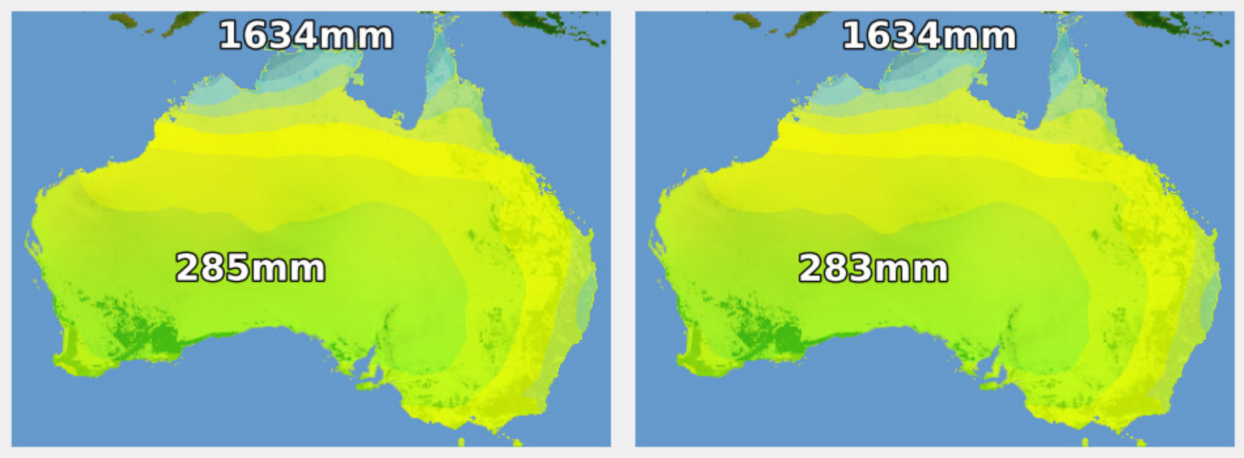


Fig. 4.111: Maps of global warming and rainfalls between 2020 and 2100



(a) 2070 (b) 2100

Fig. 4.112: Maps of global warming and rainfalls between 2020 and 2100

Chapter 5 Economic Aspects

This chapter covers **economic considerations related to energy and climate change**.

Money pays people.

The analysis of climate and energy problems from a financial, economic or monetary point of view can be incomplete because money just pays people. Plans on energy and climate change must be focused on how people can act towards a goal and which constraints they'll have to achieve their projects.

Costs indicated in an energy transition must be interpreted according to these constraints. **Costs cannot be delivered without studying and understanding these constraints**, and they can't be extrapolated from current costs without assessing how these constraints will evolve.

As an example, constraints regarding future costs per kWh of an energy are related to: how controllable that source of energy is, how it can or not replace current energies in future needs, how future needs will evolve, what storage needs and constraints will be, how available this source of energy will be in the future, how many infrastructures will be available to exploit this source, how many minerals required to exploit this energy source will be available, how much manpower will be available to exploit this energy source, how much manpower is required to prepare, organize and maintain the exploitation of this energy source, how and if recycling can be considered for industries linked to this energy source, how this energy source can be transported, how much area is required to develop this energy source, how this energy source is financed and taxed, what needs there are regarding electrical grids, what the cost of usage adaptations would be, which places are the most optimized to exploit this energy globally, etc.

All of these points must be investigated even without considering political or geopolitical constraints. And all costs are also relative to an economic situation, which includes inflation, deflation, employment rates etc., this economic situation being itself conditioned by the situation regarding energy and climate change.

Example: In a deteriorated economic situation with fewer industries caused by the lack of fossil fuels, with a high unemployment rate and a deflation, new low-

carbon energies may become **cheaper, but also less demanded,** due to a lack of needs in energy.
Example: In a situation with a high economic growth and a high use of fossil fuels with a high employment rate, new low-carbon energies may be affordable more easily at first, but a higher growth could be constrained by recruitment difficulties. These difficulties could lead to higher wages, and to **pricier low-carbon energies**.

To reduce climate change, the growth of these low-carbon energies should also not be conditioned by a high use of fossil fuels. **Globally the growth of low-carbon energies has been concomitant with the growth of fossil fuel consumption**.

These constraints can impact the cost of solutions, and how to interpret the cost of a solution. These constraints need to be modeled to be fully included in a plan.

Ultimately, a cost represents a constraint. Air is mostly free to breathe because most people don't need to face a constraint to breathe it. Anticipating a cost is equivalent to anticipating how people can solve a constraint. If there is no constraint for which someone would be needed to access something, this thing is free. If energy is required to face a constraint, the cost to solve this constraint is related to the cost of energy.
Examples: moving objects or people, doing an industrial process, heating or cooling a room, etc.

If a constraint can't be solved, the cost to solve it can be interpreted as infinite.

Examples: wind is free because nobody is required for wind to exist. But wind turbines aren't because all people involved in wind power require salaries. Sun is free, solar panels aren't, and the price of solar energy during the night can be perceived as infinite. The price of solar energy can only be fully interpreted with this constraint. Finally, oil is also free, as no one was paid for oil to exist, only people involved in its access, extraction from the environment and transformation are paid. Money pays people.

Companies or countries aren't directly included in this section which is more focused on people. Countries and companies can only act if people inside these countries and companies act. Implicitly, considerations in this analysis ignore geopolitical constraints, and other constraints which are suboptimal from the usual economic perspective in peaceful conditions (wars, strikes, boycotts etc.)

In a nutshell

The economic analysis of energy and climate change must be focused on constraints to achieve projects rather than costs expressed in a specific currency.
These constraints include: specificities of energy sources, employment, geopolitical considerations, resource availability etc.

5.1 Cost of transition

The cost of the transition refers to **the required economic incentives to reduce climate change and its impacts**. Interpreting this cost requires multiple considerations:

- First, **the transition is not just about CO2 or energy**, it also involves other GHGs and activities: CH4, F-gases, N2O, meat production, air conditioning, rice, agriculture, cement plants, steel mills, etc.
- **In a carbon-based economy, most people are paid to emit GHGs**, because their job is directly or indirectly related to the use of fossil fuels and/or agriculture. IT jobs require hardware, which can only be provided thanks to fossil fuels and electricity. Jobs in tourism directly or indirectly need planes and cars. Selling objects or resources requires the use of fossil fuels to transport these objects, etc. Virtually all jobs emit GHGs directly or indirectly, and people are paid to continue to do these jobs
- The cost of the transition must be compared with the cost of non-transition
- The cost of transition cannot be fully interpreted outside the technical constraints related to that cost in a specific global and local economic situation

Based on the second point, the cost of the transition could be $0, as it doesn't cost any money to stop paying people. And if people, industries, services, shops etc. are not paid, they won't continue their activity, and they won't emit GHGs for this activity.

The cost of the transition isn't just about choosing the cheapest option to reduce GHGs, it implies the constraint to preserve current economic activities.

5.1.1 Cost of non-transition

The cost of transition can only be compared with the cost of non-transition. The cost of non-transition involves multiple aspects.

Current situation

Not removing fossil fuels is the default short-term natural behavior of the economy. Globally, based on current energy consumption, tax-free fossil fuels without geopolitical constraints are cheaper compared to other energies without subventions, if they were to be demanded as much as fossil fuels for the same uses (see fig. 5.1). Because of that and from a limited perspective, it can be considered that non-transition is the cheapest short-term option. No new incentives are required so that business as usual continues. Thus, the short-term cost of non-transition can be $0. In a short-term analysis, the cost related to future energy and climate problems can be ignored.
During last decades, energy abundance thanks to the availability of fossil fuels in relatively stable climatic conditions has driven the global economy, which includes

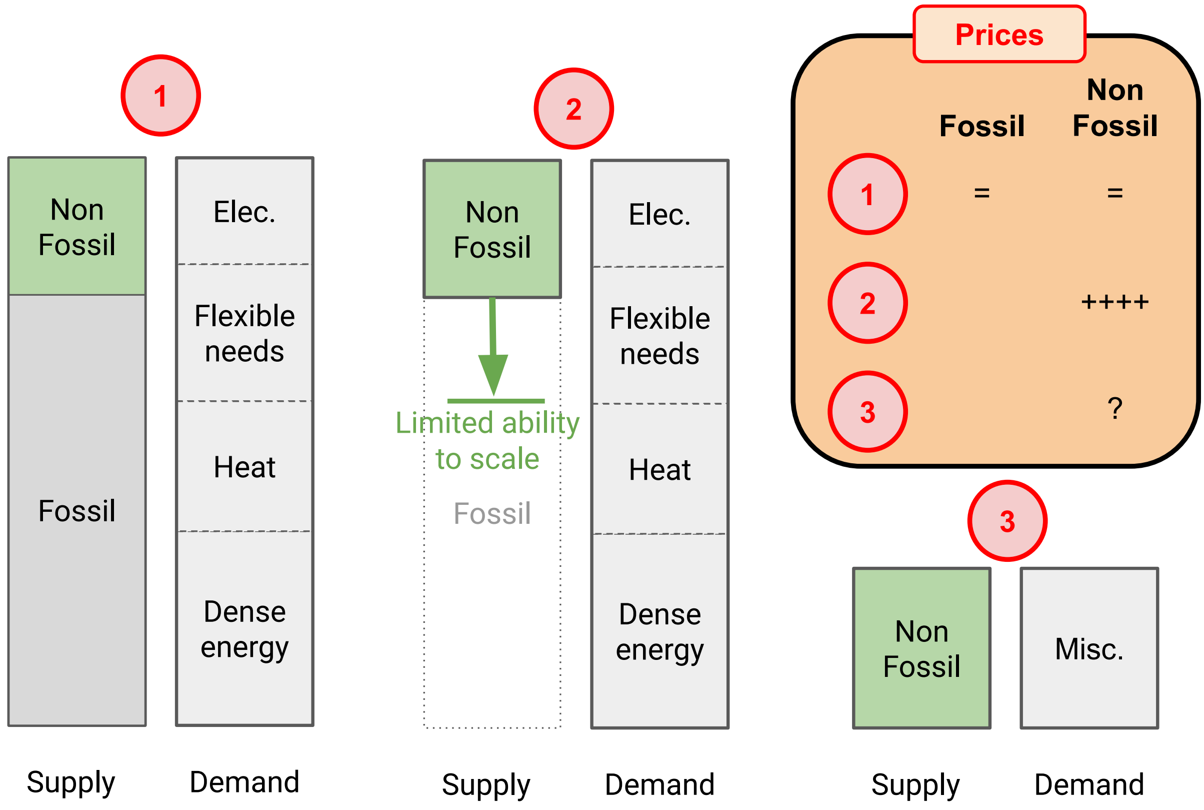


Fig. 5.1: Evolution of supply and demand in a context of rapid fossil fuel phase-out. The breakdown of demand is arbitrary, categories may overlap. Scaling demand down would be required to maintain prices in situation (2), this perspective is also limited. Interpreting prices in situation (3) is difficult.

the production and the consumption of products and services in the world. Not transitioning led the world to the current global economic situation, with an increased life expectancy in all regions of the world which developed thanks to fossil fuels.
Life expectancy is an important indicator because it reflects the development of a country. The economic development refers to the ability to answer people's needs. It can be considered that the first need of humans is the need to survive (which includes needs for food, water, health, safety, home with stable temperatures etc.). Life expectancy can also be measured easily with little risks of frauds and the value is convenient to compare between countries.
The perspective that was just described is however limited.

Pollution

Fossil fuels have direct adverse effects on health. Burning coal, oil and gas emits pollutants, including fine particles, which are responsible for millions of deaths and disabilities over multiple years in the world [17]. Because of that, and because of prices, some countries started a transition from coal to gas, which is another less CO2-intensive fossil fuel.
The cost of non-transition implicitly includes the cost of pollution from fossil fuels. Because the world has continued an economic development based on fossil fuels for 200 years with increased life expectancies, this development is still glob-

ally considered as more beneficial than reduced pollution. However, this consideration can change for specific countries or cities. Alternatives to coal are available in some countries and an equivalent development with less adverse health effects would also be considered as more beneficial from an economic perspective. Adverse health effects on workers have direct negative consequences on the ability of these workers to develop the country.

Depletion of resources

The current situation is based on a finite stock of fossil fuels.
New reserves can be found. However, these reserves required millions of years to form. In a finite world with finite reserves, fossil fuel consumption can't grow indefinitely, and can't even stay constant indefinitely except to a level below or equal to the natural renewal level of these fuels, which is very low for fossils.
Moreover, the harder it is to exploit these reserves, the pricier energy will be if society's needs stay constant. Geopolitical constraints can also increase when fewer countries have oil or gas available.
The depletion of fossil fuels is to be considered in the cost of non-transition. This reduced availability can vary per country and regions of the world.
Lack of fossil fuels can have multiple impacts on an unprepared economy. It can cause inflation at first. High demand and low supply results in higher prices for energy. In controlled economies, inflation and demand can be reduced with higher interest rates, which can have a negative impact on activity. Low supply and high prices means that some industries will stop operating because it's not profitable for them anymore, which can result in lower demand, and in lower prices in declining economies.
Non-transition implies higher economic instabilities due to the depletion of fossil resources.

Climate change

Even without constraints related to pollution and lack of fossil fuels, climate change is alone able to have disrupting consequences on economies. Energy is the basis for the operation of machines, food is the basis for the operation of humans. The consequences of the lack of energy are structural for an economy because machines run the economy. The same idea applies to food because humans also run the economy.
Climate change is already having consequences on food production in multiple regions of the world. Consequences can increase non-linearly with average global warming. 50-year events can be 5 times more frequent compared to 1850-1900 with +1°C, 14 times more frequent with +2°C, and 39 times more frequent with +4°C [4].
These events can greatly impact crop yields. With lower yields, food supply cannot be guaranteed in all regions of the world, which can result in famines over the world.
These famines can damage all activities and can have negative impacts in all regions of the world, directly or indirectly. A lower supply of food in one place can create a greater demand for imports, which can create pressures on food prices in other places.
Moreover, consequences of climate change are long-term regarding the warming caused by multiple GHGs, and multiple consequences, such as rising seawater, are very long term. In order to consider the cost of an impact, one must consider the

duration over which this impact is applied. Emitting GHGs now can have negative impacts over multiple centuries, benefits from using fossil fuels now must be considered in light of the pluri-centennial negative consequences it'll have in the future.
In a more complete analysis, climate change can also have positive impacts on some specific indicators locally [96]. Cold regions of the world will be warmer, which implies lower energy consumption for heat and a higher yield for multiple crops in these regions. However, these positive aspects can be balanced by two points. Human lifestyle habits and cultures depend on hundreds of years of history, changes in cultures to adapt to a new climate may not be fast enough to truly profit from the regional benefits climate change could bring in a limited number of regions. Secondly, not all species on which humans depend can adapt at the same speed. These species include trees, plants, animals etc., which are used in agriculture, food systems, buildings, pharmaceuticals, etc... Positive impacts for a limited number of human activities can be balanced by negative impacts on other activities. A changing climate reduces the ability for humans in all regions of the world to profit from cultural habits used to survive more easily in the previous climate.
The cost of non-transition must include the negative impacts of climate change over multiple centuries.

Depending on the point of view and the time horizon, business as usual can be considered as a very cheap or a very expensive option. This report is oriented towards a long-term analysis which doesn't allow neglecting costs associated with non-transition.

5.1.2 Cost of transition

The cost of a non-transition can be used to estimate the benefits of the transition. However, because non-transitioning is an optimal short-term strategy from an economic perspective, transitioning requires incentives. These incentives are classified as financial, legal, or moral.

- **Financial incentives** include paying emitters to reduce their GHG emissions, changing their production methods, taxing emissions of GHGs, etc.
- **Legal incentives** include using the law to limit GHG emissions from multiple emitters, through legal requirements to produce and use machines that don't consume fossil fuels, by limiting or forbidding some products, etc.
- **Moral incentives** include boycotts, strikes, promotion of less GHG-intensive behaviors, etc.

Energy transition

Energy transition refers to the removal of fossil fuels from the total energy used. The usual goal is to replace these fossil fuels with other low-GHG alternatives.
Two related problems emerge:

- Firstly, **alternatives may not be as "qualitative"** (in terms of energy) as fossil fuels. They can be harder to extract, to transport, have a lower energy density, require storage systems, etc.

- Secondly, **alternatives globally require more investments than fossil fuels**. If alternatives were by default more interesting than fossil fuels, no energy transition plan would be required as organizations would by default switch to other energies. Instead, observations show that fossil fuel consumption has continuously increased globally over the last decades.

For the first point, if society's needs regarding the quality of energy stay the same, energies with a by default lower quality require even more investments to compensate for their lower quality.

Example: oil is already a highly dense stored energy. However, electricity can't be stored and needs to be converted into another form of energy (chemical in batteries or hydrogen, gravitational potential in pumped-storage hydroelectricity), with losses.

The first point includes usage reduction, which will be discussed in the next subsection. Comparisons regarding the price of energy need to account for the different properties of the different sources of energy. Otherwise, it's assumed that society's needs will seamlessly adapt to the quality of available energies, which can't be guaranteed.

The second point includes multiple considerations. Research and engineering are still important to improve alternatives to fossil fuels, this includes:

- larger and easier to install wind turbines for offshore projects,
- solar panels with a higher efficiency,
- more secured and efficient nuclear power plants,
- more successful geothermal projects with less earthquake risks,
- more efficient and secured dams in more difficult places, etc.

While the efficiency of thermal energies for multiple applications is limited by Carnot's law, other laws applies to other sources of energy (Betz's law for wind turbines, Shockley-Queisser limit for single p-n junction solar panels) with different perspectives regarding how a better efficiency per power plant can be reached, and how fast these new power plants can be produced and installed.

For solar panels, NREL publishes a graph of the State of the Art (SOTA) over time (fig. 5.2).

Even with an increased efficiency or safety in theory, **the ability to industrialize a solution is not guaranteed**. While the efficiency for SOTA solar cells approaches 50%, the efficiency of new solar panels on the market is between 15% and 20% [98]. Similar constraints apply to all sources of energy which, while being more efficient on paper in some cases, can suffer from delays and industrialization difficulties.

Without artificially penalizing fossil fuels, and/or without advantaging alternatives, alternatives to replace fossil fuels won't develop as fast globally. **They can however develop locally due to lower costs thanks to specific local conditions for**

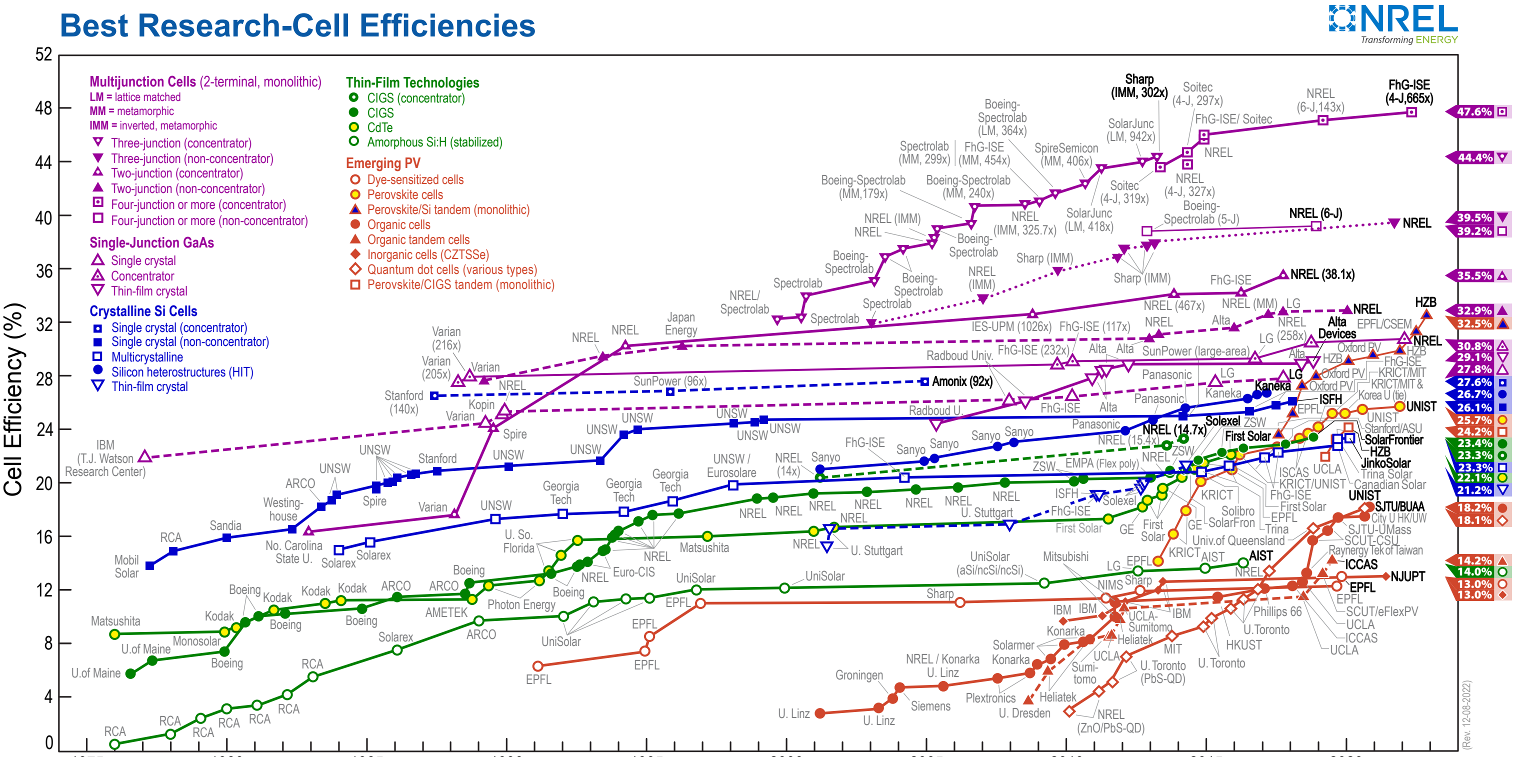


Fig. 5.2: State of the art (SOTA) cell efficiency of solar panels over time, source: [97]

a limited number of systems: geothermal energy when it's easily available, hydroelectricity in regions with strong water flows, wind turbines in regions with intense winds, nuclear energy in countries with a high level of expertise on this energy, solar panels in regions with a high insolation, etc.
The most economical and efficient way to operate regarding this situation seems to **give the most financial, legal and moral incentives to the most appropriate energies per region**, which can be evaluated with a holistic planning.

Historical examples: geothermal energy in Iceland, hydroelectricity in Sweden, nuclear energy in France, wind energy in Denmark, etc.

Empirically, with the hypothesis that most of the previous energy systems did not receive major incentives related to climate change, **hydroelectricity, nuclear energy and wind turbines seem to be the three most economically efficient ways to produce energy outside of fossil fuels**, with a high growth for wind turbines and, recently, solar panels. These energy sources are **the most producing low-carbon electricity sources in the world**. For electricity, biofuels, geothermal energy and energy from tide and waves can either develop in more limited conditions and/or are still limited globally which indicates a lower natural economic interest in these sources.
Outside of electricity, the ability of other energy sources to replace fossil fuels also has limits, but each source must be investigated based on local availability and ability to exploit these sources.

All these considerations regarding the cost of alternatives are limited by rules which go beyond standard economic analyses. In appendix B, it is shown that solutions with a low EROI can at first grow thanks to fossil fuels, before decreasing. These constraints are not represented in the short-term cost of these products, which should therefore not receive financial incentives solely based on this cost. Costs represent the short-term constraints regarding access to a product. Long-term constraints, plans and investments need to be **deeply investigated** outside the short-term cost to avoid unanticipated negative situations, as described in appendix B, appendix C and appendix D.2.

Energy sobriety

If energy transition refers to the removal of fossil fuels, it is also possible to remove these fuels without replacing them at all, or without replacing them with as-qualitative alternatives.
The cost of a complete system based on intermittent energies needs to be added to the cost of storage to be compared with current situations. If society's needs adapt and reduce when there is no energy available, the cost of storage can be ignored or reduced.
Less qualitative alternatives that don't produce as much energy when needed have increased competitiveness in scenarios with a highly flexible consumption of energy.
The idea of regulating needs is already applied in some situations. To avoid power outages during peak demands of electricity, because production at a specific time is limited, countries or energy companies can finance the temporary interruption of an industrial process, or make electricity prices higher during some hours. Needs can be reduced in this situation. How far this idea can go needs to be investigated per country depending on uses, industries, and population's acceptance of these constraints.

Reforestation and afforestation

Deforestation is mainly caused by the need for agricultural lands ([11] 9.2.1), which are used to produce food for humans (or for animals which produce food for humans). This need is high in the hierarchy of human needs, which means that it appears difficult to make a plan on reforestation that would go against this need.
However, not all foods require the same amount of land. Different crops have different yields. And different animals require different surfaces per unit of food they produce (directly, or indirectly through the crops they consume).
Paying for reforestation in a place requires the guarantee that another won't be deforested in order to keep producing as much food globally. Thus, the world must globally engage in a less land-intensive diet before plans regarding reforestation and afforestation can get to their full efficiency. Figure 5.3 shows the unanticipated impact of a reforestation strategy.

Food

Foods emit GHGs by the use of transports they require, industrial processes, deforestation, enteric fermentation, anaerobic decomposition related to rice, nitrogenous fertilizers, etc.
All these points may change partially with different types of incentives. Regarding transports, incentives related to energy transition and sobriety apply, as well as less

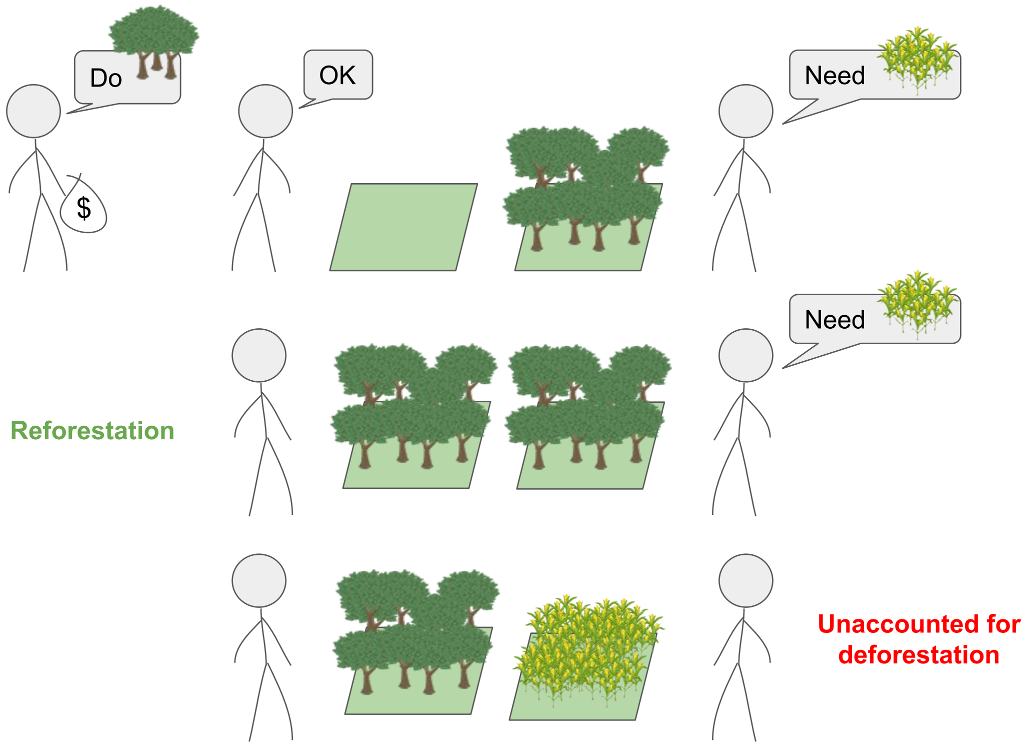


Fig. 5.3: Unanticipated consequences on land use may reduce the efficiency of reforestation strategies

international trades of food when it can be produced locally. Addressing enteric fermentation requires incentives towards a less CH4-intensive meat production and consumption. Food types which emit the most CH4 per kg are bovines, lambs, and pigs. Poultry and most crops emit less CH4. This consideration also applies to rice production. The constraint related to fertilizers seems harder to overcome alone. Reduced animal product consumption can reduce N2O emissions, as well as improved efficiency and reduced food loss and waste [99]. Incentives relative to all of these options are able to reduce future changes in climate.

In a nutshell

The transition to reduce climate change is related to energy systems, food systems, and other industries.

- Non-transitioning implies multiple uncertainties on food production or on the long-term availability of fossil fuels. The impact of climate change is not linear with the number of additional degrees of global warming.
- The energy transition implies both more investments and the acceptance of more constraints on access to a dense and permanently available energy.
  The transition in food systems and land use is constrained by cultural habits regarding food consumption and population growth.

5.2 Efficiency and Jevons effect

The role efficiency can play on climate change could be limited. When the cumulative use of a product (for example a fossil fuel) impacts climate, efficiency can have a positive impact only if it's not compensated by an increased consumption of the product.

Example: if planes are more efficient, they consume less jet fuel, which makes plane tickets more affordable, which increases the demand for airplane trips, which can raise the global consumption of fossil fuels from planes, despite the increased efficiency.

This is the Jevons effect.

Other more indirect effects apply. To ensure the absence of increased consumption thanks to a higher efficiency is complex, as increased consumption may not always be directly visible at the same place. Globally, CO2 emissions per capita have stayed approximately constant in the world since 1960 at around 5 to 6 tCO2/capita (fig. 1.11), higher efficiency of a product that would impact global CO2 emissions per capita has not been observed yet.
In a context where a limited supply of fossil fuels is available on the planet with a high demand, a higher efficiency which would cause a reduced consumption somewhere can be compensated with an increased consumption elsewhere. This increased consumption can help agriculture in countries with limited food safety, which can drive an increase in population, which can itself drive an increased consumption of fossil fuels. The ability to anticipate such effects while only considering gains in efficiency in a specific region of the world seems limited.

In terms of economy, Jevons effect can be associated with economies of scale. Economies of scale implies that producing more objects reduces production costs per object, which encourages mass production to maximize profits. **Removing the Jevons effect implies to not profit from an economy of scale**, which can be financially suboptimal and counter-intuitive for a company.

Example: If a limited amount of fossil fuels is available in the world to produce an object, and if a company can produce twice as much for a slight increase in fossil fuel consumption, not doing so would result in lost markets in a context of high demand and high competition. Companies which would not profit from this situation will lose markets and disappear.

An unregulated economy with free competition and strong demand encourages economies of scale and Jevons effect.

In a nutshell

Increased production may compensate for increased efficiency, which minimizes the ability to use increased efficiency for climate change or energy.

5.3 Supply, demand and limits of transition

A basic concept in economy is **supply and demand**. In a competitive market, the price of an object depends on how much of this object is supplied, and how much is demanded. High supply and low demand means low prices. Low supply and high demand means high prices.

This concept can have **many impacts on energy transition**. High prices in a context with high demand and low supply serve as an incentive to raise production in order to satisfy needs. However, raising production may face limits. These limits include: finite resources, pricier exploitation of a resource, inability to raise production fast enough, inability to exploit resources fast enough, inability to industrialize a process fast enough, inability to recruit enough people, etc.
These examples apply to all alternatives to fossil fuels, and to fossil fuels themselves.

Example: let's imagine a country which would want to massively finance an existing wind power industry to accelerate transition. At first, wind power industries don't employ enough people, they don't have a large enough supply chain, they don't have all the processes to quickly scale etc. After financing this company, it'll be able to recruit, scale up its industrial processes... **up to a certain limit**. Above this limit, the company won't be able to recruit as many people, it won't have enough of the required materials to produce and connect wind turbines, it'll need to maintain existing wind turbines, it'll need to recruit for their dismantling, for their recycling if a recycling is required, etc. This consideration applies in different ways to all energy sources.

In order to efficiently finance these companies, these limits should be anticipated. Above this limit, financing these companies creates **a risk of inflation**.

Example: There would be a high demand for wind turbines, a low supply because of production constraints, which would result in higher prices.

In other words, putting an infinite amount of money in a solution will not result in an infinite availability of this solution, because money can't push constraints indefinitely. Evaluating these limits correctly matters in order to not overfinance or underfinance a solution.

In a nutshell

All scenarios, with or without transitions, contain limits. These limits can impact the cost and/or availability of energy and food. Anticipating these limits to finance solutions reduces economic risks.

5.4 Inflation and production reduction

Inflation could play a major role in the transition.
Inflation can in part be controlled by governments and monetary policies.

- High inflation reduces benefits made during previous situations (the value of savings diminishes) and makes earning money from work more interesting than living off one's savings.
- On the contrary, low inflation, or deflation, at first benefits to savers and to people who earned money during previous economic situations, which penalizes current workers compared to savers.

Low interest rates are used to encourage activity and reduce risks of deflation. High interest rates are used to limit risks of excessive inflation. Large central banks (for dollar, yuan, euro...) have an inflation target of 2$\sim$3%.

In order to limit GHG emissions with standard economic rules, emitting GHGs must become pricier than not emitting GHGs. A usual method to do so is by implementing a carbon tax, or more generally a carbon price.
Ideally, fossil fuels and activities relying on them would become pricier, while low-carbon alternatives would benefit from such measures by not being impacted by these taxes. However, because of the central role fossil fuels have in today's economy, raising their prices can have multiple unwanted impacts. Fossil fuel inflation can spread throughout the economy.

Examples: It can reduce benefits workers made by making their commute more expensive. It can reduce benefits for companies, which may suffer from competition from countries that would not be applying such measures.

Alternatives to fossil fuels, when available, must be promoted to raise the efficiency on such taxes.

Proposition: the idea is **to describe a very simplified economic situation for individuals, in which climate change would partly be solved by reducing consumption and changing production**.
This analysis doesn't depend on a specific currency.
In the proposed situation, central banks lower interest rates and raise inflation to finance low carbon alternatives to fossil fuels, while not being fully able to replace them.

An individual earns 3000 per month in this context, pays 1000 per month for a house, 1000 per month for daily highly important needs (eating, water, heating/cooling house etc.), and 1000 per month for diverse less important needs (newer clothes, electronics, hobbies, holidays, etc.).
The reduced production should not affect highly important needs which are required for survival. However, the reduced production could affect secondary needs.
For secondary needs, because they are secondary, they could be almost entirely removed. Implicitly, the analysis only considers GHG-intensive secondary needs. Also for an already built house, if one stops paying it, the house remains as it is except for the cost of maintenance, which are included in "secondary needs".

How could the situation of this person be materialized with economic constraints?

- **Situation 0**: At first, it can be hypothesized that inflation impacts all parts the same way. If the salary of this person follows inflation, the global consumption stays the same.

Now, in next situations, inflation is higher for some parts, which can change how the person is able to consume the different kinds of products. Next situations assume that salary doesn't follow inflation and stays at 3000. Only "similar amounts" of products are compared.

- **Situation 1**: the "same amount" of house costs 1500, the same amount of primary needs ("food", etc.) costs 1000, and the "same amount" secondary needs ("hobbies", etc.) costs 1000. In this situation, it's assumed that the person will choose to continue to pay the house 1500, continue to pay primary needs for 1000, and pay hobbies 500 instead of 1000. This situation can be politically unstable because, as explained earlier, that person could just stop paying the house and the house could still meet housing needs. Rents and debts related to real estate don't satisfy a primary need and could be considered as optional by those who pay them.
- **Situation 2**: the house costs 1000, food costs 1500, hobbies cost 1000. It's assumed the person will reduce consumption of "hobbies" and only pay 500.
- **Situation 3**: the house costs 1000, food costs 1000, hobbies cost 1500. It's assumed the person will reduce consumption of "hobbies" and only pay 1000.
- **Situation 4**: the house costs 1000, food costs 3000, hobbies cost 1000. It's assumed the person will stop paying the house and hobbies.

In all situations, it's assumed people will reduce optional consumption of products during inflation with a constant salary. However, **a situation with stagnating salaries does not benefit to workers**. In order to transition, one could choose to **give more incentives to workers in order to raise wages and benefits, and to encourage hiring in industries which are required to decarbonize**.

This brings new situations, one of which could be:

- **Situation 5**: salary is 6500, house costs 2000, primary needs cost 4000, secondary needs cost 1500. It's assumed the person will pay the house and primary needs, and reduce consumption of products which are non-necessary.

In situation 5, salaries are higher, and there is a different inflation for all products. This situation satisfies two constraints:

1. It allows the use of inflation to encourage working in low-carbon industries.
2. It forces reducing consumption of non-essential GHG-intensive products.

This situation is able to reduce consumption and encourage changes in production. **This situation involves, however, extreme levels of inflation**.

Two situations are possible regarding more usual levels of inflation, either it's high enough to encourage work, or it's too low, which is less beneficial to workers and more beneficial to savers. In a situation with low or negative inflation and high interest rates, activity is by default reduced and borrowing money is harder. However, even in this situation, it's not impossible to finance a transition, but the distribution of wealth to encourage work must be directed by governments by using financial and / or legal penalties and benefits (such as taxation). In a situation where more money doesn't come from central banks to finance the transition, incentives must come from changes in the distribution of existing money.

> **In a nutshell**
> Inflation, how it is managed, and the sectors it affects can impact how the transition is implemented and how it is perceived.

5.5 Economic indicators

Multiple economic indicators are used to evaluate the economy of countries: GDP, growth, inflation, employment rate, salaries, etc.
How these indicators are measured and what they include can vary over time and between countries. How they can be interpreted can also vary depending on the country, on its age pyramid, on its social protection, etc. Methods to uniformize and compare these indicators exist, but **they are limited in what they can or do correct.**

Because of the limitations of these indicators, it is considered in this report that using them in plans for energy and climate change makes these plans less interpretable.

More robust indicators are considered to be: detailed energy production, life expectancy, measured pollution, climate, population aged between 18 and 60, etc. These indicators aggregate less subjective considerations regarding what they measure, and they can more easily be used to compare multiple countries and different time periods. The interpretation of all indicators still requires a global context.

Chapter

6 Social aspects of the transition

The following scenario is considered: the most optimized plan to solve climate change and to solve issues regarding energy supply and other sources of GHGs is available, **but changes in behaviors are still required to realize this plan**.

In this situation, **public opinions still need to be mobilized to accept changes which could be experienced as a reduced standard of living**.

Many plans already exist in multiple countries regarding climate change, and climate change itself has been a well-known issue in the most polluting countries for multiple decades. These countries have already signed multiple agreements regarding how they can reduce their CO2 emissions. However, globally, CO2 emissions have continued to increase. In a global economy where all countries depend on others at some level, this global increase can be interpreted as the responsibility of all countries.
In this chapter, responsibilities are discussed, and constraints which come from social considerations are evaluated.

The climate problem can be decomposed in 3 steps to solve it:

- **Studying the physical problem is the first step**, which is the responsibility of scientists and IPCC
- **Finding solutions "on paper" is the second step**. This step can be done thanks to researchers, scientists, politicians, economic actors, engineers, civil society, etc.
- And **spreading, producing, and adapting these solutions in the real world is the third step**. This step requires approval and actions from civil society and industries in order to fully develop.

This report is mostly related to the 2nd step. The DEC model copies or accepts results of other papers for the 1st step, and includes a very limited amount of constraints from the 3rd step. This 3rd step can be the hardest of all 3.
For the 1st step, there is a rather broad scientific consensus on the physical basis of climate change. The 1st step can be considered as "solved" (solved enough to start working on the second step).
For the 2nd step, there is no global consensus on how to solve the issue. Some countries are willing to use nuclear energy, others made it illegal. Some countries are

willing to impact a limited number of economic activities for the transition. Others only want a transition if it can be done in a context of increased economic growth. However, even with the 1st and 2nd steps achieved, the 3rd step is still required to do the transition. Multiple points which can be considered as important are detailed for this 3rd step to succeed, including: **(1) the hierarchy of human needs, and (2) the fairness of demanded efforts**.

6.1 Hierarchy of needs

The hierarchy of human needs refers to how people prioritize actions they feel are the most necessary for them. This hierarchy differs for everyone and is always changing.

Example: if someone is hungry, eating has a high priority. This person eats. After which "eating" is not high anymore is the hierarchy of needs of this person.

This hierarchy depends on the moment in time, on culture, age, gender, habits, education, experience, etc.

The hierarchy of needs is an important concept for climate and energy issues, it helps to evaluate how realistic a plan to solve these problems is.

Example: let's say a plan is based on the idea that people will consume less of all kinds of food in order to free up land for reforestation. One can evaluate this plan based on a hierarchy of needs. If the author of such a plan agrees that, in a hierarchy of needs he or she assumes coherent, short-term food needs are more important to people than long-term climate problems, this author should agree that the proposed plan can be in conflict with this hierarchy of needs.

The hierarchy of needs is subjective and can change based on culture and education. Younger people could prioritize climate change more, or traveling more, or eating meat more; older people could prioritize safety more, or health more, etc. Authors of different plans all explicitly or implicitly assume a specific hierarchy of needs when making a plan. Perhaps people will volunteer for drastic changes to preserve climate, perhaps they'll want to keep growth, perhaps they absolutely want to have children no matter the context, perhaps they're willing to sacrifice taking planes but aren't willing to reduce their red meat consumption, etc.

Previous works regarding how humans prioritize their needs include the Maslow's hierarchy of needs [100]. It's assumed that there isn't only one possible hierarchy. In Maslow's hierarchy, physiological needs are the most important. They include food, water, rest and living in tolerable temperatures. In the current situation, fossil fuels help to satisfy all these needs in the short term. Fossil fuels are used to produce and transport food and fertilizers. Fossil fuels are used by machines to sanitize water. Houses and apartments are built with machines that use fossil fuels, which are also used to heat and cool homes.

However, in the current situation, the climate also helps to satisfy these needs. In multiple countries, the climate provides stable conditions for crops to grow, for

rivers not to dry up, for living and resting efficiently without being too hot or too cold.
Fossil fuels also help to satisfy needs which are higher in the hierarchy, **the problem is to safeguard the satisfaction of future high priority needs, while minimizing impacts on the satisfaction of current needs**. It's understandable that future needs, when compared to current needs of the same category, have a lower priority.

Example: If a person is hungry now, this person won't keep food aside, and not eat it, to satisfy its future hunger in 1 year.

However, it's not clear how priority is managed between future high priority needs, and current low priority needs. It's not clear how traveling now in order to visit other countries (while emitting GHGs to do so) is to be compared with how future generations will be able to satisfy their need for food. The answer to this problem seems more controversial than in the previous situation, where only high priority needs were compared.

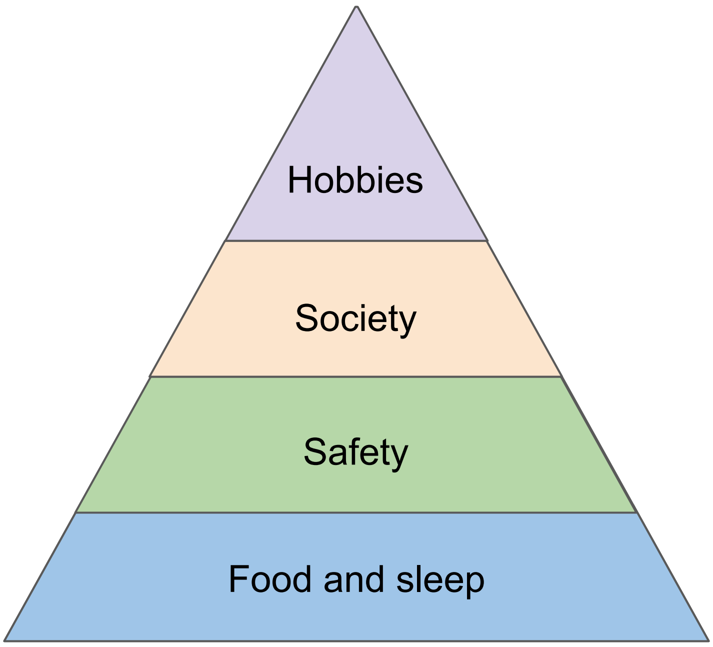


Fig. 6.1: Example of a simplified hierarchy of needs, high-priority needs are the basis of the pyramid

6.2 Fairness of efforts

Another constraint related to social behaviors is identified. **Even with a perfect and global understanding of climate change, its consequences, and a perfect global plan, the demanded efforts in the plan must be perceived as "fair" in order to be efficiently deployed**. What "fair" fully means is highly subjective and depends on people, countries, cultures, etc.
This constraint could be linked to the hierarchy of needs with the following condition:

demanded changes in a plan regarding high priority needs of a person should not exceed demanded changes regarding low priority needs of another person. This idea can be based on the Universal Declaration of Human Rights, stating that **"All human beings are born free and equal in dignity and rights"**.

Example: a plan cannot state that people will fully accept the right someone has to take a private jet for leisure activities (secondary need) exceeds the right of another person to access food (primary need), in a context where both activities currently require fossil fuels whose consumption must be limited to reduce climate change.

It can be considered that some situations are already unfair regarding the aforementioned issues. Secondary needs are already prioritized first in some situations, while primary needs of other individuals have a lower priority. **A plan can't be based on the idea that this situation can or will fully change, as it seems unrealistic and highly optimistic**. It's also not possible to wait for this situation to fully change before taking action for the climate. Otherwise, as an example, the whole world would constantly be waiting for the richest person to act, which could permanently block action by just not taking action on climate change. All less privileged people could present the situation as follows: they are required to act, but this more advantaged person won't act, so they won't act. Which is understandable, as it would put these people in a worse situation while the most advantaged person would keep a more comfortable situation.

Fairness isn't considered a limit to action, but it's considered that an unfair strategy can and will reduce motivation for action. How fair the demanded action is can be interpreted between all actors: younger and older generations, richer and poorer populations, highly developed and less developed countries, etc.
In order to be coherent, the demanded effort should be distributed in a way that would be considered as "fair" by the largest number of entities involved in the transition.

6.2.1 Country level

The usual highest level of decision-making is at the country level. Thus, the fairness of efforts can be evaluated per country.

A first consideration is the responsibility of a "seller" country for emissions on its ground which serve to produce for another "buyer" country. Which country is responsible? Would the emissions occur if the buying country didn't need the product/service which caused the emissions? Perhaps these products would be sold to other countries. Perhaps they wouldn't. Would the "seller" country put everyone out of work if they didn't export to the "buyer" country, rather than changing the production (but still producing) to satisfy internal needs? The "buyer" country usually cannot decide to change the sources of energy of the "seller" country in order to have a more climate-friendly production. But this "buyer" country can decide not to buy these products. **Both countries are considered responsible for these emissions, the accounting method should depend on the end goal of the analysis.**

Another consideration usually refers to the "historical responsibility" of emitters.

This debate about historical responsibility involves a moral assessment about how past emissions should impact the distribution of effort today. This is a complex issue because it implies many considerations over multiple decades. Some of them can be listed:

- **Almost all populations of the world benefit from past emissions**. These past emissions in a limited amount of countries served to develop machines, cars, boats, fishing industries, education, research, health industries, methods to increase crop yields etc. which are used everywhere now and profit to everyone. Without these past emissions, these industries wouldn't exist, and no one would be benefitting from them now.
- Total emissions of these countries in the past even over a long time period are limited compared to current emissions. One year of emissions from fossil fuels now (37 GtCO2 approx.) is equivalent to 15 years of emissions from fossil fuels in 1900 (2 GtCO2 approx.[1]). However, in these countries, **emissions per capita reached very high levels in the past.**
- If all countries and people wanted to experience the economic benefits of having the same per-capita emissions from fossils a country such as the United Kingdom had in 1900 (10t CO2 per capita[2]), 10*8b = 80Gt of CO2 would be emitted from fossil fuels, doubling current emissions. This situation would be beneficial to no one in the long term because of climate change. Even if it is unfair that all countries can't reproduce what others did regarding fossil fuels, it's also less damaging for all countries, and more alternatives to fossil fuels are developed now than what was available at the time.

These considerations do not mean that effort shouldn't be distributed based on current levels of wealth, which can be correlated with historical responsibility. These considerations also do not mean that developed countries shouldn't primarily help less developed countries.

6.3 Cultural solutions and constraints

Finally, it's considered in this report that all countries and people have different cultures and that **many solutions regarding how to deploy a plan rely on these cultures.**

Some cultures are highly adapted to current climate and energy issues. In some cultures, eating red meat isn't encouraged, using a lot of fossil fuels and energy for secondary needs is considered as unnecessary. Religions also define moral rules which can include being hostile to avarice. Political parties or leaders are also involved in promoting or discouraging some behaviors based on debates, ideas and laws they pass and promote.
Some cultures are very close to nature and cohabit with other species, without the need to expand indefinitely.

[1] https://www.carbonbrief.org/analysis-which-countries-are-historically-responsible-for-climate-change/
[2] https://ourworldindata.org/co2/country/united-kingdom

Some trends in architecture, urban planning and industries are also involved in promoting some behaviors. These trends can promote overconsumption, gigantic constructions, having larger houses or flats, owning multiple cars and houses, and cities can be built around the necessity to own large cars. On the other hand, **other trends can also promote minimal consumption of products, sobriety in the displayed wealth, and extravagant behaviors can also be perceived as ridiculous.**

There is no absolute truth regarding which trends are good or not, because this report doesn't consider there is an absolute way to evaluate all behaviors no matter what the goal is. It's considered that if current behaviors can't be fully decarbonized, efficiently solving climate change requires a new hierarchy of needs and changes in some cultures. **Fortunately, because more virtuous cultures already exist, individuals can freely draw inspiration from these existing cultures to guide these changes.**

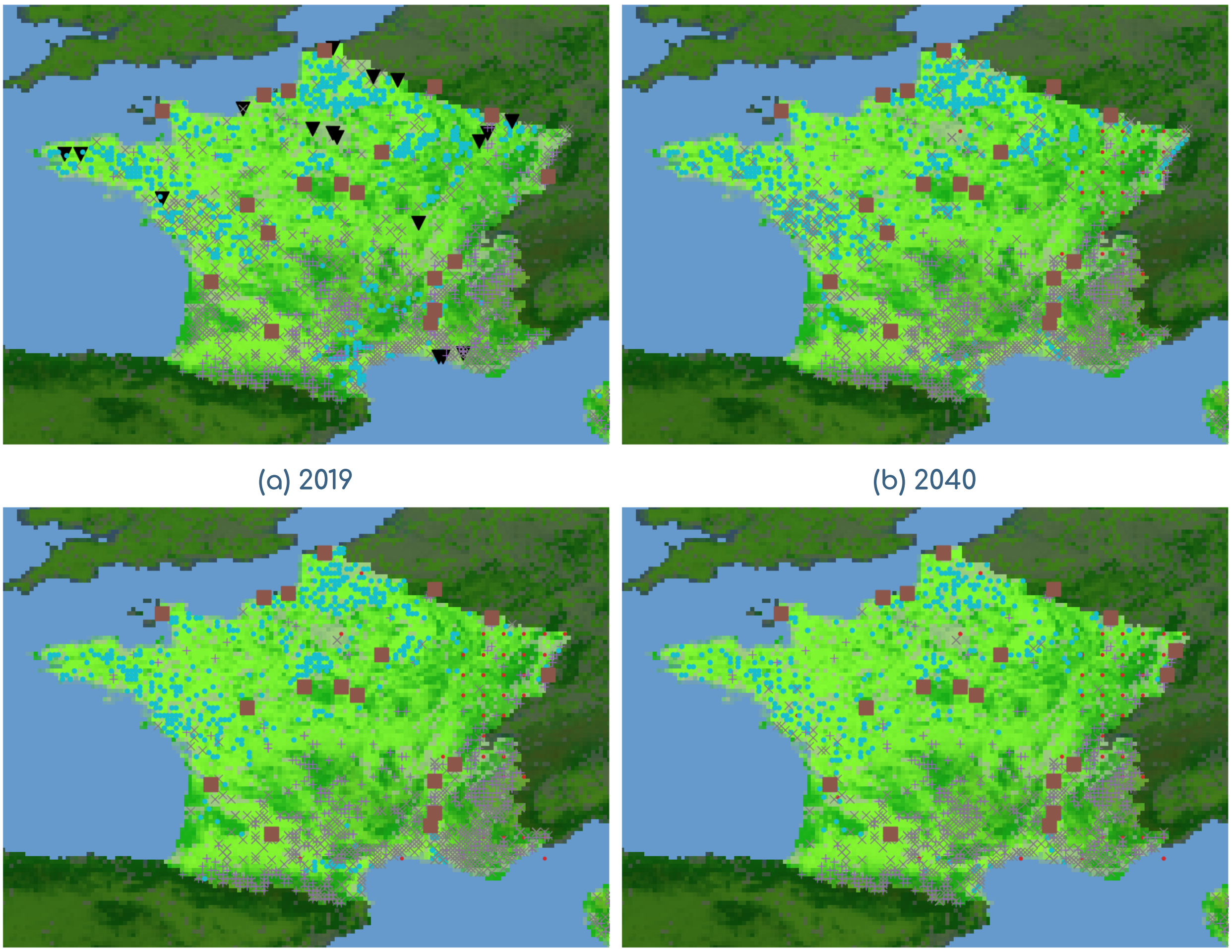
In a nutshell

The concrete implementation of a plan must not be overlooked in the conception of a plan, it requires global acceptance and coordination towards its realization.
Changes required to reduce global warming must be consistent with a hierarchy of human needs and must be perceived as fair.
Many cultures coexist in the world, it is possible to draw inspiration from cultures which are already more prepared to face future energy and climate issues.

Appendix

A Step-by-step example for energy in France

The model is applied per year and per country. Some detailed results of the model for France can be presented. These results depend on a specific configuration.



(a) 2019 (b) 2040

(c) 2060 (d) 2080

Fig. A.1: Locations of power power plants in France in the model, colors: Coal(v), Gas(v), Geothermal(.), Hydroelectricity(+), Nuclear(square), Oil(v), Solar(x), Wind(.)

N°	Step	Coa	Gas	Geo	Hyd	Nuc	Oil	Sol	Win	Tot
1	Remove old plants									
2	Add planified plants									
3	Estimate capacity factors									
4	Useful energy: 953 TWh									
5	Init. based on past	19	21	1	8	25	11	5	7	47
6	Config. multipliers	19	21	4	8	25	11	11	13	47
7	Climate strategy	-	21	4	8	25	11	11	13	47
8	Gas substrategy	-	0	4	8	25	0	11	13	47
9	Physical limits	-	0	4	8	25	0	11	13	47
10	Nuclear limits	-	0	4	8	25	0	11	13	47
11	Demography limits	-	0	4	8	25	0	11	13	47
12	Education limits	-	0	T	8	T	0	11	13	47
13	Total limits	-	0	0	8	0	0	11	13	-
14	Locate on map									
15	Schedule future plants									

Table A.1: 2023 - Steps to anticipate future electricity production afer 2023, values are expressed in TWh and represent how much future production the country can anticipate to add, Coa=Coal, Nuc=Nuclear, Hyd=Hydroelectricity, Win=Wind, Sol=Solar, Geo=Geothermal, Tot=Total, T=(Training is required before start)

Multiple steps are required:

- The first step is to remove power plants which reached the end of their life
- Newly completed power plants are added (Step 2),
- their production is estimated (Step 3)
- Then, the model evaluates future sources of energy during a planning phase (Step 4-13), details are presented in chapter 2. Based on the total useful energy of 953 TWh, the model evaluates other values.
- Because France doesn't produce a lot of geothermal energy, a training phase is required (Step 12). France also didn't construct nuclear reactors during a long period, a re-training phase is also required for nuclear energy (Step 12)
- Based on the DEC model, in 2023 France can anticipate to add 8 TWh of hydro-electricity, 11 TWh of solar panels and 13 TWh of wind turbines for future years (values used in the model also depend on capacity and capacity factor). This total is below the maximum "Tot" that can be added of 47 TWh, so there are no further restrictions on these values during the planning phase.
- The model evaluates where these power plants will be located (Step 14) and the construction starts in the model (Step 15)

Likewise, results for 2028 can be provided in table A.2.

Nuclear and geothermal power plants can now be built for future years as the training phase was completed. However, the total limit of TWh can be exceeded. In this situation, the ability to add solar panels is reduced. Solar panels have the lowest capacity factor of all sources in France, which explains its lower priority compared to other low carbon alternatives, as configured by the user.

N°	Step	Coa	Gas	Geo	Hyd	Nuc	Oil	Sol	Win	Tot
1	Remove old plants									
2	Add planified plants									
3	Estimate capacity factors									
4	Useful energy: 1014 TWh									
5	Init. based on past	19	21	1	8	25	11	5	7	52
6	Config. multipliers	19	21	4	8	25	11	11	13	52
7	Climate strategy	-	21	4	8	25	11	11	13	52
8	Gas substrategy	-	0	4	8	25	0	11	13	52
9	Physical limits	-	0	4	0	25	0	11	13	52
10	Nuclear limits	-	0	4	0	25	0	11	13	52
11	Demography limits	-	0	4	0	25	0	11	13	52
12	Education limits	-	0	4	0	25	0	11	13	52
13	Total limits	-	0	4	0	25	0	9	13	-
14	Locate on map									
15	Schedule future plants									

Table A.2: 2028 - Steps to anticipate future electricity production after 2028

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Appendix

B Elasticity of energy systems with a low empirical EROI

B.1 Theory

Elasticity is the ability for an element to deform and then return to its initial shape. This section deals with the elasticity of electricity production (TWh). A rupture happens when the element goes back to its initial situation in an uncontrolled way, without the ability to deform again.

For electricity production, starting from an initial situation S0 (fig. B.1), an energy E is used to install new capacity, and to increase the production to a situation S1. Because of constraints C applied on the system, S1 is unstable, and the system tends to go back to S0 if not enough energy E is used to maintain S1. **A rupture happens when constraints are too strong and not enough E can be used anymore**. This puts the system in a situation S2 which is similar to S0, except the system can't go back in S1 again.
Applied constraints C are a function of the distance between S1 and S0. Energy E raises the distance between S0 and S1.

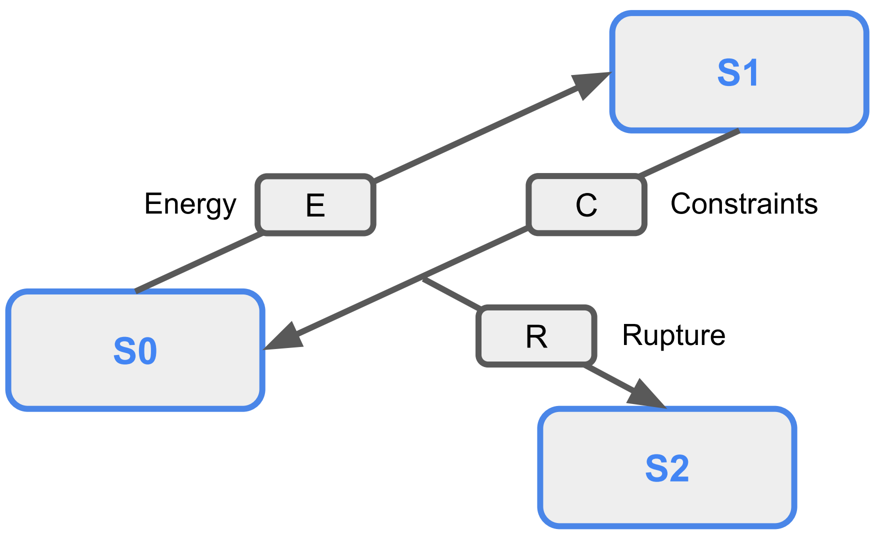

Fig. B.1: States of a system under constraints, which can grow with energy and rupture

The energy available E to increase electricity production is a function of energy production, which includes and is not limited to electricity production. Low EROI sources of energy need more energy invested than others to produce energy. This appendix analyzes which constraints are applied for low EROI sources compared to high EROI sources.

B.2 Motivation

This "elasticity" analogy is operated for the following reasons: **S0 is the current situation of the energy system**, which can be assimilated to the total amount of energy (TWh) produced for the current year. S1 is a situation in which a lot of low EROI solutions are installed, massively increasing electricity (TWh) produced for future years at first. S1 can be assimilated to the total amount of TWh in 20~30 years.
An elastic phenomenon happens between S0 and S1 because of multiple constraints: All installed capacities have a lifespan after which they're not usable anymore, this constraint reduces power generation. All installed capacities depend on finite resources, once resources are less available, a constraint is applied. All installed capacities need energy to be renewed, if less energy is available, E is less available, which is equivalent to a constraint being applied.

In a simple way, currently a lot of fossil energy is needed to install solutions which may not be producing a lot of electricity compared to energy invested, and which have a short lifespan of 20~30 years. This is situation S0. Fossil energy E is currently available to raise electrical production for these low EROI sources. This is situation S1. But, in 20~30 years from now, there will be constraints C, which are: less fossil energy available for climatic and/or depletion reasons, and end of life of previously installed low-EROI solutions.

A rupture happens if, after this period, E is not available anymore. Under these circumstances, situation S1 is unstable, and the system goes back to S0, or to S2 if E can't be used anymore.

B.3 Algorithm

The aforementioned system can be represented with a simplified algorithm available in table B.1, at the end of this appendix.

B.4 Results

Based on the given parameters, for a "very low" EROI, production decreases continuously. For a "high" EROI, production increases continuously. **However, for a low/intermediary EROI, production starts to raise before declining**. Basically the proportion of energy dedicated to renew the energy system multiplied by the EROI must be larger than 1 to increase energy production.

With an EROI of 1:10, 10% of current energy production are required to renew current energy production. With 1:5, 20% are needed. With 1:50, 2% are necessary. The

EROI does not need to be under 1 for an energy system to decline as 100% of the energy produced is not used to re-produce energy.

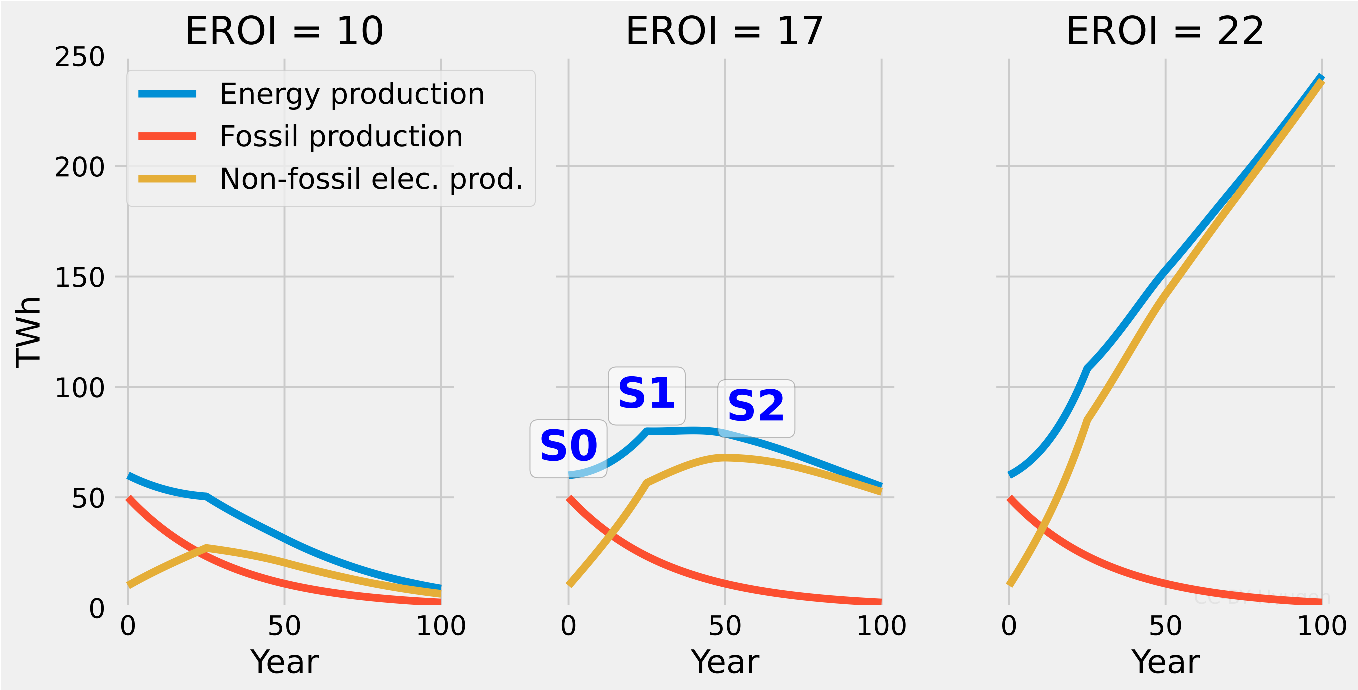

Fig. B.2: Simulated evolution of energy production per year for different EROI during a fossil fuel phase-out, as modeled in table B.1, analysis is limited to energy from fossils and non-fossil electricity

Numbers used should be considered as a simplified representation of reality.

- For "very low" EROI solutions (=10), non-fossil electricity production grows at first, but energy production is never maintained.
- For "very high" EROI solutions (=22 in the simplified model), energy production increases continuously.
- **For "low" EROI solutions (=17), an increase in energy production can be observed, before being followed by an infinite decline.**

How fast the decline occurs depends on the configuration.

EROI=17 is a risky position in which countries don't realize at first they're engaging in an unstable situation. The point of this section is to warn on this possibility. Even in the EROI=10 situation, low-carbon electricity production can raise at first thanks to the consumption of fossil energy.
In the DEC model, an empirical version of the EROI is indirectly used because the model measures how much new power plants a country can add based on its energy production. Thus, **the aforementioned constraints are included in the DEC model.** If useful energy production declines (including from fossils), the ability to add new power plants is reduced.

B.5 Discussion

Adding to the previous points, it is also important to consider **the real EROI of low-carbon solutions in a world without fossil fuels**. Because fossil fuels can't be replaced while keeping the same ability to use energy (because of limits on electric motorization, batteries, etc.), the EROI of low carbon solutions could change if their renewal is also based on low carbon solutions. **Current EROIs are computed in a world where the vast majority of energy production comes from fossil fuels.**
It is also important to estimate which proportion of the energy production is and could realistically be dedicated to the renewal of the energy system.
Labor-intensivity of solutions is also an important unconsidered parameter in the DEC model. Even with the right EROI, if a solution doesn't scale well and requires a large workforce to be maintained, the ability to use energy to produce more energy will be hindered. In order to use energy to produce more energy, energy is required, but people and machines also are. If fewer people and/or fewer machines are available compared to what was anticipated in the energy sector, a higher EROI is required to maintain the system.

```
#init
fossil_systems, elec_systems = [50], [10] #Energy unit (TWh for example)
Sy = [fossil_systems[0]+elec_systems[0]]
prop_nrj_for_new_nrj = 0.05 #proportion of energy available to increase energy prod
elec_lifespan = 25#years
fossil_reducpyear = 3#percent
eroi_of_loweroi = 17 #EROI of the "low" EROI solution
max_y = 100 #Number of years to compute
year_range = range(1, max_y+1)

#compute eol for already installed production (presupposed same lifespan)
delta_elec = [0]*(len(year_range)+elec_lifespan+1)
for y in range(1, elec_lifespan+1):
    delta_elec[y] = -elec_systems[0] / elec_lifespan

#production future years
for y in year_range:
    #amount of energy available for energy transition
    energy_for_elec = Sy[-1] * prop_nrj_for_new_nrj

    #compute how much energy will be added during the next years
    added = energy_for_elec * eroi_of_loweroi / elec_lifespan
    delta_elec[y] += added
    delta_elec[y+elec_lifespan] -= added

    #compute next states
    elec_systems += [elec_systems[-1]+delta_elec[y]]
    fossil_systems += [fossil_systems[-1] * (1-fossil_reducpyear/100)]
    Sy += [fossil_systems[-1]+elec_systems[-1]]
```

Table B.1: Simplified algorithm for energy transition and EROI in Python

Appendix C EROI example: Solar panels and hydrogen in Belgium

This appendix presents a hypothetical strategy regarding the installation of solar panels in Belgium.

The estimated capacity factor of solar panels in Belgium is 13%. In Egypt, the capacity factor would be 23%[64].

EROI of solar panels is a still under study topic [24, 25, 26, 23]. Solar panels are recent in the field of mass production of electricity. They represented approximately 0.2% of world's electricity production in 2010 and 3% in 2019 [12]. All studies regarding solar panels in a context of mass production are recent, and empirical well-studied knowledge on how they perform in real situations is still limited and evolving.

The EROI of solar panels depends on energy invested and energy return. The energy return depends on the capacity factor of solar panels during their lifetime. The capacity factor of a solar panel depends on sunshine, maintenance, temperatures, wear etc. Because of that, solar panels are more energy-efficient in some countries or locations. Multiple estimates for the EROI of solar panels in Belgium and other places are proposed:

Location	EROI	Source	Date of study
Belgium	7	[101]	2018
World/Other	6.56 / 6-12	[102, 103, 104]	1995-2010
Switzerland	7.5	[26]	2016
South of Europe	19	[105]	2012
South of Europe	19 / (8.3) / 9.5 / (19)	[24, 105, 29, 106, 107]	<=2015

Table C.1: EROI for solar panels, methodologies differ for each study, an EROI of 19 in Spain approximately corresponds to an EROI of 13 in Belgium based on estimated capacity factors [64].

Based on these studies, an approximate EROI of 10 is used in this appendix for solar panels in Belgium.

In order to maintain societal habits with intermittent energies, countries would require storage capacities. The current strategy of Belgium regarding hydrogen storage is evaluated[1]. The strategy states that hydrogen could be used to "store excess capacity and return it during shortages". The strategy also says that hydrogen "is less efficient for road transports but has advantages regarding weight and sizes, and the market will find an optimum regarding different technologies".

If hydrogen is used to "store excess capacity and return it during shortages", it's understood that electricity is stored as hydrogen (PtG, Power to Gas), and then hydrogen is converted back as electricity. In order to convert electricity into hydrogen, an electrolyzer can be used. **Efficiency of electricity to hydrogen conversion is approximately 65% (60-70%, [108, 109])**, depending on technology used, loss, need for compression or liquefaction of hydrogen etc. Conversion of hydrogen back to electricity can be done with Internal Combustion Engines (ICE), with an efficiency of approximately 40% (30-60% [110]). Which means that **approximately 26% of the original power is delivered back from the storage system**.

Purposefully, the proposed strategy is not the most optimized solution, yet it isn't excluded from official strategies. In this situation, because approximately 75% of the original power is lost, the original EROI is divided by 4. **During this situation, the EROI of solar panels would be 2.5, without considering the energy required to build and to run the electrolyzer, the ICE, etc.** Furthermore, while solar electricity can at first be added to the grid without increasing electrical interconnections too much, the more intermittent capacity is added to the grid, the more interconnections are required to exchange some of the excess production with other places. **Adding and maintaining these interconnections also requires energy**, or it requires workers, which require energy directly or indirectly to live.

With an EROI of 2, 50% of the energy produced in a country must be dedicated to the energy system in order to maintain energy production. This hypothetical strategy can be continued by adding more losses. For example, a system would be even less efficient with a seasonal storage system, with hydrogen produced from solar panels during summer, which would serve electric vehicles during winter, as more losses would apply. The more complex the system is regarding storage or transport of energy, the less credible it is from an EROI perspective. Complexity implies more changes and transfers, and changes imply loss of energy. Constraints in terms of industrialization and employment also need to be considered.

The goal of the strategy matters for climate change. The stated goal in the previously referenced strategy in Belgium is to "reduce GHG emissions". **Reducing GHG emissions globally is not the same goal as guaranteeing energy independence, reducing GHG emissions for a specific country or guaranteeing energy to citizens and industries without changing habits**.

If the sole goal of a country is to reduce GHG emissions, this country can consider cooperation with other countries to invest in the most optimal solution globally. If the EROI of solar panels in Belgium is approximately 10 without storage, 3 with storage, and 20 in Egypt without storage, for Belgium to invest in storage seems less efficient regarding energy and CO2 emissions than investing in solar panels in Egypt, Lebanon, Morocco, or any other sunnier country which would produce more low-

[1]https://economie.fgov.be/sites/default/files/Files/Energy/hydrogene-vision-et-strategie.pdf, [French] October 2022 version

CO2 energy starting from the same investment.

In all circumstances, Jevons effect must be considered and avoided. **To reduce climate change, additional low-CO2 energy sources should only replace high-CO2 energy sources and not be added to existing high-CO2 energy sources.**

Appendix

D Lethality of energy production

Lethality of energy production relates to how many people could die or get seriously injured because of the production of energy. In this report, only deaths are considered. Different conventions are used to estimate these values. Deaths from pollution such as deaths from fine particles are considered in multiple papers [17, 37], while very indirect or difficult to estimate consequences such as the impact of climate change or wars for energy are not. In order to normalize data, "Deaths per TWh of energy produced" is used, data is averaged over the whole world. Because data for all energies is harder to use and to compare, this analysis is focused on electricity generation.

Electricity source	Values used in DEC	Data source
Coal	32.720	[37]
Oil	18.430	[37]
Biomass and waste	4.630	[37]
Gas	2.821	[37]
Nuclear	0.487	appendix D.1
Hydroelectricity	0.024	[36]
Wind	0.035	[36]
Solar	0.019	[36]
Geothermal	0.016	[36]
Tide and wave	0.000	Not enough data

Table D.1: Deaths / TWh of electricity produced in the model

D.1 Nuclear energy health impacts

D.1.1 Methodology

For nuclear energy, Sovacool et al. [36] estimated 0.0097 deaths/TWh, and Markandya et al. [37] estimated 0.074 deaths / TWh. Because deaths from the use of nuclear energy is usually considered a controversial subject, and because numbers constantly evolve due to new production and new accidents, **this section proposes to re-evaluate deaths per TWh of nuclear electricity.**

Considering the current perception of risks for nuclear energy in multiple countries, the goal of this analysis is **to propose an upper threshold for nuclear risks**. This goal implies to always take highly pessimistic assumptions. This strategy means that an analysis on the numbers used in this report could systematically propose lower numbers with reasonable arguments, yet accept the numbers used in this report as an extreme and pessimistic simplification.

The methodology can be decomposed into **multiple steps**:

- **List historical events** which could lead to the death of individuals because of nuclear energy
- Identify **how individuals might die directly or indirectly** from these events
- Re-compute or re-use estimates from multiple sources on the number of victims from these events
- **Take the highest number of deaths for each event**
- Compute how much nuclear electricity was produced over time and divide the total number of death by the total electricity production.

Events must be entirely and only related to civil power generation. For example, events such as the Windscale fire are excluded because, in this example, the main purpose of the reactor was to produce weapons-grade plutonium. Same for Kyshtym as the disaster happened in 1957, the reactor used to produce military plutonium was taken out of service in 1961[111]. Mailu-Suu is not considered for the same reasons.
Events for the whole fuel cycle are included (mining > enrichment > use > disposal) as long as the data is available. Deaths from the industry outside of specific large-scale events aren't anticipated to have a major impact on the result (regular work accidents, etc.), these deaths are also not included in numbers used for most other sources of electricity. A larger list of events can be found in [112] (appendix D).

Sovacool et al. [36] explicitly included 3 events: Chernobyl, Fukushima and Kyshtym. **The events and places included in this report are: Chernobyl, Fukushima, Three Mile Island and Tokaimura (1999).**

Three causes of death are identified:

- **Short-term deaths**: it includes all deaths which are directly related to how the event happened during the first days, and deaths from acute radiation syndrome (ARS). It includes: deaths from explosion, deaths from a fire, deaths from falling debris etc... Short-term deaths are easily counted and should not require a statistical analysis.
- **Long-term deaths**: it includes all deaths from the dispersion of radioactive elements in the environment. Long-term deaths are not easy to count and often require a statistical analysis
- **Evacuation-related deaths**: it includes all deaths which would be directly or indirectly related to mandatory evacuations. Self-decided evacuations are not included.

This methodology is limited as other measures could be included. For example, undesirable economic events and stress affect the health of individuals [113, 114]. Injured people can also have a shorter life expectancy. Years of life lost could be used instead of evaluating how many people died, or an equivalent death toll could be evaluated based on this number. More precise statistical analyses would require more time, and aren't considered as relevant to build a first estimate that would be comparable with other sources of energy, **for which values also depend on approximations**.

The exposition to radioactive elements can cause a "long-term death". Radioactivity is measured in Sievert. To estimate how a population was affected by radiations after an event, researchers provide a collective dose for this population. This quantity is expressed in person.Sievert (or man.Sievert). 1 man.Sievert could mean that 1 man received 1 Sievert, or that 2 men received 0.5 Sievert, or that 100 men received 10 mSv. Assuming that health consequences are statistically the same in these 3 situations is a simplification based on the Linear no-Threshold (LNT) model. Because of that, using man.Sievert to compute cancer deaths "should be avoided"[115]. It is a simplification. However, as explained above, the proposed analysis is based on pessimistic simplifications, and will directly or indirectly use man.Sievert if necessary to estimate cancer deaths with the LNT model.
Based on International Commission on Radiological Protection (ICRP), the **"detriment adjusted nominal risk for cancer and heritable effects" is estimated at 5.5% per Sievert** ([115], table A.4.4). The value used for DDREF is 2, lower values for DDREF can be found in the literature[116] which would result in higher estimates on death tolls. This 5.5% estimate can be likened to the risk of death from cancer after radiation exposure of a population, this is a simplified interpretation.

The real risk value depends on the age of individuals, their wealth, the type of exposure, the evolution of medical processes, and much more information which won't be used in this simplified analysis. Values used by ICRP are based on the Life Span Study (LSS), a long-term cohort study of health effects in the Japanese atomic bomb survivors in Hiroshima and Nagasaki. The lethality fraction per cancer is based on data from at most 2007 (some data date back to 1980[117]), numbers may have changed since then.

D.1.2 Evaluation

Data used in the analysis are presented:

Event	Source	Information	Value
Chernobyl	UNSCEAR 2000V2J [118]	Short term deaths	31
Chernobyl	WHO [119]	Long term deaths	4000
Chernobyl	UNSCEAR 2008V2D [120]	Long term deaths	9000
Chernobyl	OWID nuke [121]	Short term deaths	31
Chernobyl	OWID nuke [121]	Long term deaths	385
Chernobyl	Sovacool [36]	All	4056
Chernobyl	Hirschberg1998 [112]	Short term deaths	31
Chernobyl	Hirschberg1998 [112]	Long term deaths	32700
Chernobyl	From results in UNSCEAR2020V2B [122]	Long term deaths	19800
Chernobyl	From results in torch2016 [123]	Long term deaths	22000

Chernobyl	UNSCEAR2020V2B [122]	Evacuated	340000
Chernobyl	UNSCEAR2020V2B [122]	Workers	600000
Fukushima	Sovacool [36]	All	573
Fukushima	UNSCEAR 2013V1A [124]	Short term deaths	0
Fukushima	UNSCEAR2020V2B [122]	Long term deaths	0
Fukushima	Hoeve2012 [125]	Long term deaths	1100
Fukushima	Hoeve2012 [125]	Evacuation deaths	600
Fukushima	Tsuboi2021 [126]	Evacuation deaths	2326
Fukushima	Fukushima authority [127]	Evacuation deaths	2259
Fukushima	From results in UNSCEAR2020V2B [122]	Long term deaths	1760
Fukushima	Authorities measurable [128]	Long term deaths	1
Fukushima	UNSCEAR2020V2B [122]	Evacuated	88000
Fukushima	UNSCEAR2020V2B [122]	Workers	21000
Three mile isl.	Hatch1990 [129]	Long term deaths	0
Three mile isl.	From results in NRC [130]	Long term deaths	0
Three mile isl.	Based on common knowledge	Short term deaths	0
Tokaimura1999	No source	Short term deaths	2
Tokaimura1999	No source	Evacuation deaths	0

Table D.2: Events, sources and information used in this report, methodology differs, this list is not hierarchical. All = All deaths.

"From results in" means the value is not provided in the source, and that data from the source were re-used to compute the value. Data can include collective exposure. "No source" indicates that no official source was found. The value 0 is used if no data to indicate that someone died or could die because of the event was found.

Only the maximum value among all sources is kept. When data is not available, it can be estimated based on data from other events: evacuation deaths from Chernobyl are calculated based on the proportion of evacuees considered deceased after the evacuation around Fukushima, which are all considered as deceased due to the nuclear event in this report, because of the **pessimistic simplification**.

Event	All	Short-term	Long-term	Evacuation
Chernobyl	41717	31	32700	8986
Fukushima	4086	0	1760	2326
Three mile island	0	0	0	(0)
Tokaimura1999	2	2	(0)	0

Table D.3: Estimated maximum amount of deaths per event used in this report

It is considered in this report that estimating a higher death toll would be difficult, based on current calculation methods. As an estimation based on this methodology, at most **45805** died because of civil use of nuclear energy. It's estimated that **93964** TWh of nuclear electricity have been produced in the world before 2022 ([12, 21, 20]). The lethality of civil nuclear energy is estimated to be **0.49** deaths/TWh, in this report, based on this methodology.

Provided numbers should only be used as **the maximum possible death tolls from these events**, based on a **simplistic statistical meta-analysis** with the aforementioned parameters.

D.1.3 Difficulty of the analysis

The provided analysis aims at being highly pessimistic. Multiple aspects made this analysis more difficult to produce.

Numbers may differ between different sources, causes are:

- Parameters of the LNT model (value of the DDREF)
- Estimating how many people really died because of the event related to nuclear energy and not because of another event. Example: evacuations and trauma related to Fukushima's tsunami, which would still have happened without nuclear energy involved
- When there is a statistical evaluation, a confidence interval may be given. Depending on the application, one could consider the worst case, the best case or the average case
- The evolution of scientific methods of calculation and of scientific data
- Changes in the way collective exposure is calculated
- Searching how many people died because of radiation exposure based on health records, rather than statistical estimates

Multiple events were not made public directly by authorities or involved companies, which makes analyses harder to do. Chernobyl was hidden by the USSR government. Tokaimura event of 1997 was hidden by the company [131]. This constraint is even worse for events related to the military use of nuclear energy, though they are not included in this analysis, but even considering if they could be included or not is a difficulty.

Analyses of evacuation fatalities are limited for multiple events, including Chernobyl. This subject is under-investigated, the main focus of most analyses is on radiation deaths. Consequences of evacuations may exceed radiation deaths if populations were not evacuated [125]. Under-reaction and hyper-reaction of authorities both are risks.

There is no official estimate of the death toll due to both radiations and evacuations after an event, with a detailed and standardized methodology from a recognized international organization. This death toll could be disputed as it could come from a statistical analysis, but it could serve as an official basis for risk assessments.

For nuclear electricity to be as lethal as fossils in electricity production, the number of deaths new nuclear accidents should do is estimated to be **219,267** for Gas and **3,028,702** for Coal.

D.1.4 Interpretation

Multiple major points are needed to interpret the results.

- Results of this analysis always considered the worst possible numbers within the considered hypotheses

- Newer nuclear disasters could happen in denser areas
- Newer nuclear reactors take into account previous accidents to improve safety

Multiple events which exposed population to large amounts of radiation were not included because they were related to military nuclear projects (Mailu-Suu[132], Windscale fires, Kyshtim[133, 134]...). Including these events would not change the numbers significantly. This appendix is not focused on all events related to nuclear industries, but only to the civil use of nuclear energy.

The provided analysis is based on a DDREF of 2, using a DDREF of 1 could approximately double the numbers on long-term deaths, which would not change the rank of nuclear energy compared to fossil fuels / PM2.5 emitters.

D.1.5 Conclusion

Even an extremely pessimistic evaluation of nuclear energy indicates that it is at least 10 times less lethal per TWh of electricity produced than the use of coal or oil. **Nuclear energy phase-out while coal, oil or gas could be replaced by this energy can't be justified from a health perspective, even without considering the health damages caused by fossil's driven climate change.**

D.2 German 2000-2019 strategy on electricity

Between 2000 and 2019, German strategy regarding power production included a nuclear phase-out. This section compares the German strategy on electricity generation between 2000 and 2019 with a hypothetical strategy where instead of reducing electricity production based on nuclear energy, Germany reduced electricity production based on coal.
Each nuclear electricity removal in TWh is replaced with a coal removal in TWh.

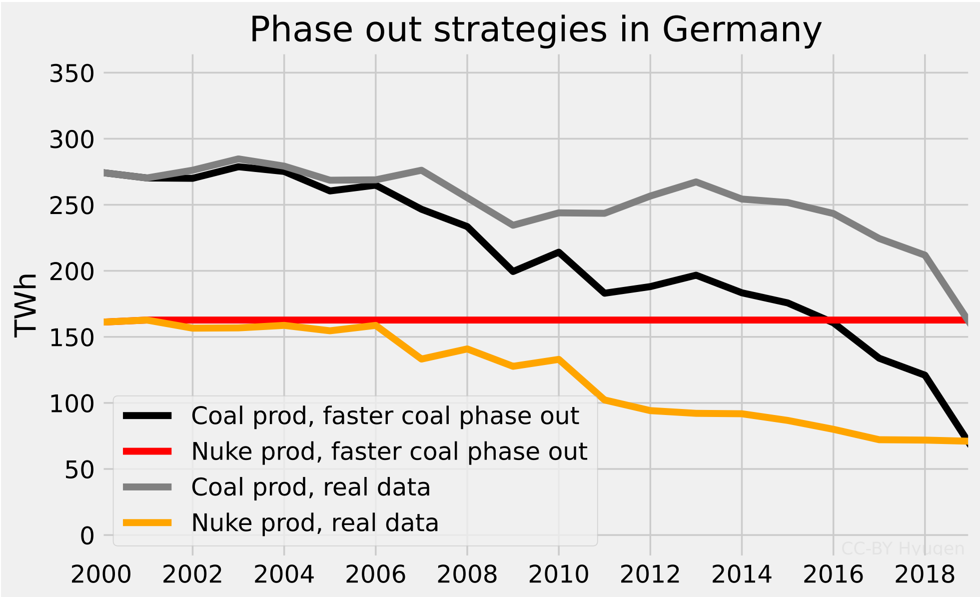

Fig. D.1: Comparison of the actual nuclear phase-out strategy with an alternative hypothetical faster coal phase-out strategy in Germany

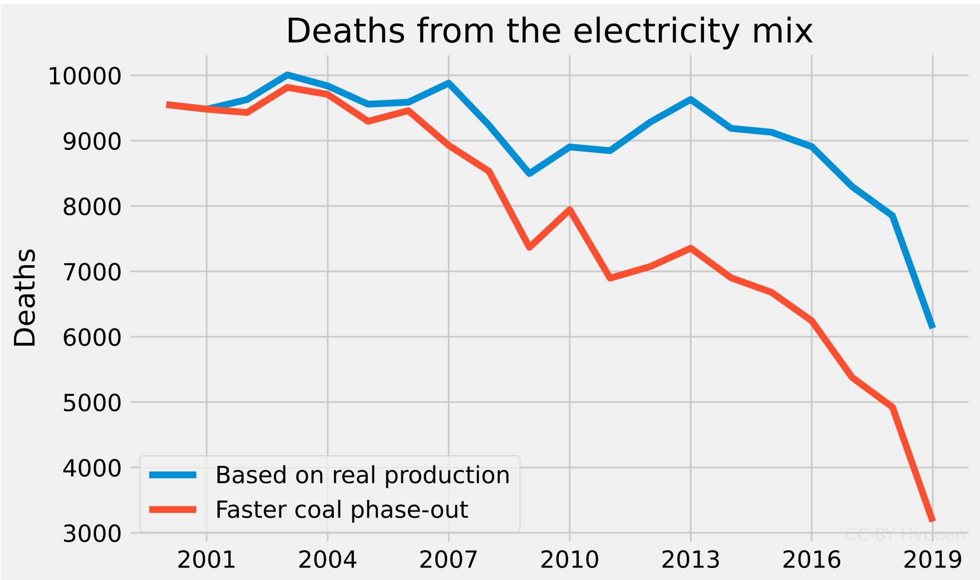

Fig. D.2: Deaths per year in Germany because of the electricity mix, all sources of electricity are included based on deaths per TWh in appendix D, comparison of historical data with a faster coal phase-out scenario

Based on this comparison, it can be estimated that **27298** people would not have died in Germany by causes related to the use of coal energy, if a faster coal phase-out occurred in place of a nuclear phase-out. This number is **6** times the estimated number of deaths from Chernobyl by WHO.

D.3 Re-evaluation of lethality from fossils

Based on [17] deaths related to the use of fossil fuels can be re-approximated. [17] indicates that coal contributed to "over half" of 1.05 million people deaths due to PM2.5 in 2017. Approximately **9156** TWh of electricity were produced by coal in 2017 [12].
Using approximations, 500000 deaths / **9156** TWh = **54** deaths / TWh of coal electricity. This is a quick approximation, more than half of deaths were caused by coal and not all coal is used to produce electricity.
This value is consistent with results from [37] (33 deaths/TWh) in order of magnitude. A more in-depth analysis with primary energy from fossils [12], PM2.5 per country per cause from [17] and deaths from PM2.5 per country from [35] in 2019 gives **13.8** deaths/TWh for coal (primary energy) and **5.7** deaths/TWh from cumulated PM2.5 emissions from gas and oil (primary energy).

Parameter	Value
PM2.5 Deaths	
- from coal	**655946**
- from oil and gas	**567596**
Energy consumption (TWh)	
- Coal	**47656**
- Oil + Gas	**100065**
Deaths per TWh	
- Coal energy	**13.8**
- Oil+gas energy	**5.7**
- Coal electricity (x3 energy)	**41.3**
- Oil+gas electricity (x3 energy)	**17.0**
Markandya et Wilkinson ([37])	
- Coal electricity ([37])	32.72
- Oil electricity ([37])	18.43
- Gas electricity ([37])	2.82

Table D.4: Re-evaluation of deaths from fossil fuels, cumulated from data per country from [35, 17, 12], 2019, PM2.5 data are not differentiated between PM2.5 from gas and from oil

These values are consistent with values from [37]. 1 electric TWh of coal requires approximately 3∼4 TWh of coal energy (multiply deaths/TWh by x3). For oil/gas, a x3 multiplication can be applied for the same reason.
These values do not include other causes of death due to the use of fossil fuels: climate change, mine explosions, smog, etc. These values are provided as a complementary analysis and are not used to estimate deaths from energy in this report.

Appendix

E Carbon offset

E.1 General considerations

Carbon offset refers to the reduction of GHG emissions an entity can make in order to compensate emissions from its activities. Carbon offset is not included in the DEC model. How relevant are carbon offset strategies regarding climate change? This analysis is focused on CO2 emissions. If all CO2 emissions were offset for one year, net anthropogenic CO2 emissions for that year would be 0.

Under this consideration, for this analysis, there are two ways to guarantee that an offset is valid. The offset must either reduce emissions in an activity by the exact same amount it created in another activity, during the same time period. Or, the offset must add means to absorb CO2, such that the addition of these means offsets the emissions from the activity and from the process which created this mean.

Examples of invalid offsets in this consideration: protecting a forest from deforestation, adding low-carbon electricity sources without reducing the use of high-carbon energy sources, offsetting past emissions, reforesting somewhere while deforesting as much elsewhere, increasing the energy efficiency of a system, reducing emissions of a process, not accounting for all emissions of a process which tried to create an offset, etc.

While these examples can help in not emitting even more CO2, they don't guarantee a net removal of CO2 emissions throughout the world. Jevons paradox is to be considered, efficiency (including carbon efficiency) can increase consumption, which can also increase CO2 emissions.

Approximately 40 +/- 2.9 net GtCO2 were emitted in 2021[95], including approximately 4 GtCO2 coming from Land-Use Change (LUC). In order to offset emissions, one should consider the entirety of these emissions and not just the part coming from fossil fuels. Land use change is currently a source of CO2 emissions. Offsetting strategies include CO2 removal, **which can be done with biosequestration, which includes reforestation and afforestation.**

Because of seasonal changes, CO2 absorption in the world varies during each year as it is presented in fig. E.1. Seasonal changes are caused by photosynthesis and decomposition of organic matter [135, 136, 137]. Variations in CO2 concentration depend on the location [138, 139]. Local variations can be impacted by human activities and higher or lower local photosynthesis [140, 138]. Range of variations goes approximately from 2ppm (Samoa) [141], to 10ppm [138], with 5 ppm at Mauna Loa [139].

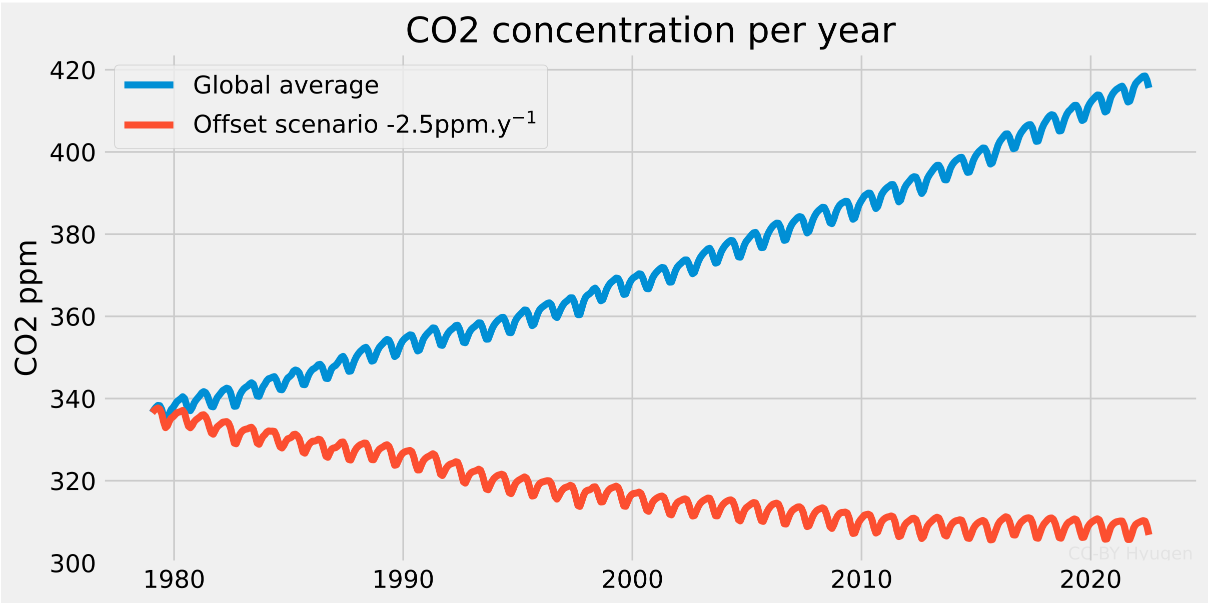

Fig. E.1: CO2 concentatrion per year in the world with seasonal variations [82], a hypothetical offset scenario of -2.5ppm per year starting from 1980 is represented, stability is observed for last years in this scenario, pre-industrial CO2 concentration was approximately 270ppm[142]

This section checks orders of magnitude involved in a world carbon offset strategy with minimal reduction of emissions. CO2 concentrations rose by approximately 2.5ppm per year in recent years[139]. In order to compensate this increase without changing human activities, one would need a strategy to decrease concentrations by 2.5ppm per year (represented in fig. E.1 starting from 1980). The globally averaged ability of the planet to absorb CO2 because of seasons is evaluated at around 4.45ppm per year [82]. In a stable situation, the same amount is also emitted each year due to seasons.
The required reduction in CO2 concentrations to compensate for emissions represents 56% of the world's ability to absorb CO2 due to seasons. An offset strategy would need to reproduce this effect, each year, permanently. This seasonal absorption is caused by seasonal changes in the impact of the sun on the whole biosphere, which is composed of billions of plants, trees, etc. Reproducing this effect, or a significant portion of this effect, seems unlikely in a context where land-use changes (LUC) done by humans is currently emitting CO2 and not absorbing it.

Because of these considerations, in this report, it's considered that **carbon offset strategies cannot compensate the entirety or a significant part of current anthropogenic CO2 emissions.**

LUC is and has been a non-negligible net emitter of CO2 during the last decades. **For it to become a net absorber, a strategy would need to first reduce LUC emis-**

sions, in a context where LUC emissions could raise because of climate change ([143], A.3).

E.2 Carbon capture plants

This section reviews the potential of the "Orca" carbon capture plant in Iceland[1]. The Orca plant claims a capture capacity of **4000 tons of CO2** per year with 2650 kWh (2000heat + 650elec) per ton of CO2 for a scale up version of their system[2]. The company employs 200+ employees over the world.

Assumptions and approximations are used.

In this analysis, it's supposed that 100 people per year are directly or indirectly required to prepare, finance, build, manage, promote, maintain and run a similar version of that plant, with the aforementioned parameters, in the US. Only 900 kWh out of the 2650 kWh are considered, assuming heat can be provided without additional energy, by using a nearby thermal source or a thermal power plant for example. A thermal power plant would need approximately 2700=3*900 thermal kWh to produce 900 kWh of electricity with 33% efficiency and 1800 kWh of heat. With a 27% efficiency, >650 elec and 2000 heat kWh would be available.

When 900 kWh of electricity are consumed, 1 ton of CO2 is removed. The carbon intensity of electricity in the US is estimated at 393 gCO2/kWh in 2019 (US electricity production:[12, 19], CO2 per kWh per source:[85]). The plant would emit 393*900 = 0.35 tons of CO2 per ton absorbed = -35% efficiency. Computations will assume the plant needs 100 people to exist. Emissions per capita can be estimated at around 15 tCO2/capita in the US in 2021[3]. Supposedly, employees working for this company are highly qualified, the company declares itself as the "market leader in the field" with "a latest funding round exceeding USD 650m", which is approximately 2∼3 million invested per employee. Higher incomes correlate with higher CO2 emissions [144, 145, 146]. In order to compute emissions from employees involved in this project, it'll be loosely estimated that they emit 2 times more CO2 than the average citizen, being part of a high-income group. Based on these assumptions, employees running the plant would emit in total: 100 employees * 15tCO2 * 2 = 3000t CO2 per year, reducing the efficiency of the plant by 3000/4000 = -75% efficiency.

The cumulative efficiency reduction of the plant is -35-75=-110%. It implies that under the proposed considerations, **such a plant in a high carbon energy mix does not contribute to reduce CO2 concentration.** Such a plant virtually makes more sense in Iceland because Iceland produces a lot of low-carbon electricity and heat. In a low-carbon mix, the energy consumed by these carbon capture plants could be considered as a reduction of efficiency of low-carbon solutions, which means that these sources of energy would need an even higher EROI to keep energy production stable. Emissions would be reduced in a more direct way if the low-carbon energy

[1]https://climeworks.com/roadmap/orca
[2]https://grist.org/technology/orca-the-largest-carbon-removal-facility-to-date-is-up-and-running/
[3]https://ourworldindata.org/co2/country/united-states

produced was used to replace fossil fuels rather than to absorb CO2.

A conventional life-cycle analysis is provided by [147], stating an efficiency of approximately 90% with the Iceland energy mix. Emissions from employees required to run the plant aren't considered.

Appendix

F European - African: solar strategy

This appendix introduces **a hypothetical strategy in which European and northern African with middle eastern (AME) countries cooperate to decarbonize electricity production**. The practicality of such strategy in real world conditions is not fully investigated. This strategy is presented to encourage reflection on international cooperation to decarbonize.
The DEC model is currently not configured to propose such strategy.

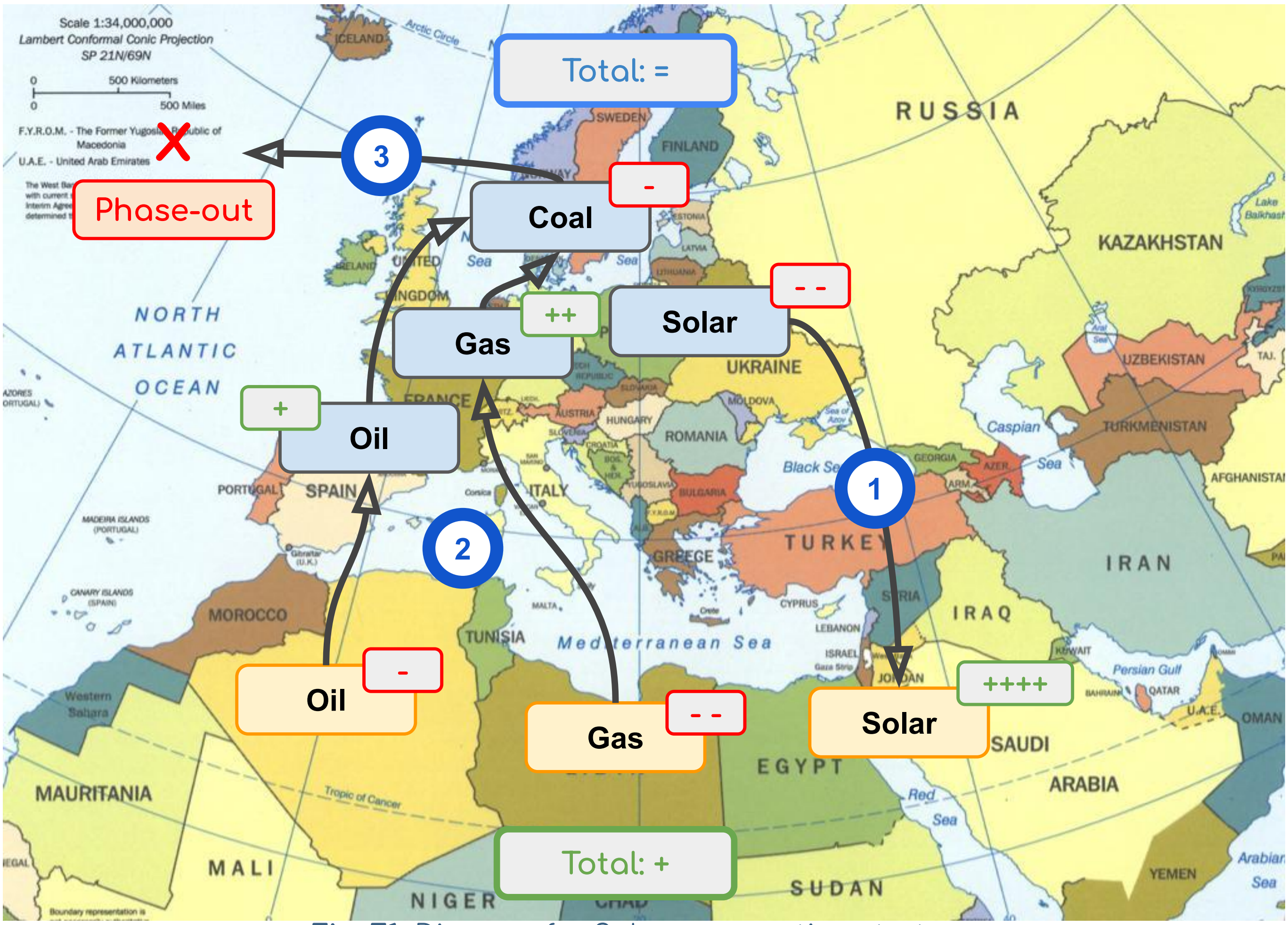

Fig. F.1: Diagram for Solar cooperation strategy

This strategy tries to optimize how solar panels are used over Europe and AME. Following details contribute to the analysis:

- Europe has a lot of solar capacity installed compared to countries in Africa and Middle East [12]
- Solar capacity factor in Europe is lower than in Africa and Middle-East [64]
- Europe uses coal, this coal emits more CO2 per TWh than gas [12, 11]
- Europe is able to replace a part of its coal with gas
- Northern African countries and middle-east countries use a lot of gas to produce electricity [12]
- Solar panels can partly replace fossil fuels

Based on these observations and assumptions, **a strategy in which solar panels which would be installed in Europe are instead installed in sunnier countries is proposed**. These solar panels will produce more electricity. This surplus could serve low-carbon development for these countries. The non-surplus part would be traded to Europe as Gas and/or Oil equivalent. And Europe would use this Gas/Oil to remove Coal from its electricity mix. This strategy is presented in fig. F.1.

Parameters of such a strategy are analyzed. This analysis includes countries in a broad way, without political or industrial constraints. Any smaller scope of cooperation can still be considered. Countries included in "Europe" are all countries in the European Union in 2022. Countries included in "Africa / Middle East" (AME) are: **Algeria, Morocco, Tunisia, Libya, Egypt, Saudi Arabia, Iran, United Arab Emirates, Kuwait, Qatar, Israel, Oman, Bahrain, Jordan, Yemen.**

The model computes the average capacity factor for solar panels in AME countries. The model computes the production solar panels which are currently installed in Europe would have per year (wear included) if they were instead installed in AME countries, based on their capacity and based on the estimated capacity factor.

Results are applicable for future solar panels.

The model computes how much of gas and oil in AME countries could be replaced.
The model estimates:

- additional production of solar electricity AME countries will receive thanks to sunnier conditions
- how much gas AME countries could give in exchange to European countries
- how much coal European countries could remove thanks to the given natural gas

Results are presented in table F.1.

Result	Value
Europe solar capacity factor (%)	12 %
Est. AME future solar capacity factor (%)	22 %
Europe solar prod (TWh)	123 TWh
Est. AME solar prod with EU capa (TWh)	229 TWh
AME prod gas/oil 2019 (TWh)	1351 TWh
AME prod gas/oil 2019 (TWh), max to replace	405 TWh
Europe, est. solar production removed (TWh)	92 TWh
Europe => AME, solar capacity given (GW)	107 GW
AME, est. solar production added (TWh)	187 TWh
Average net added production / year (TWh)	87 TWh
Coal production removed in Europe (TWh)	100 TWh
Proportion of European coal removed (%)	24 %
Non-emitted CO2 (mt)	34 mt

Table F.1: Results of European - AME solar strategy, detailed computations include solar panels wear and production per year

Results show that under the aforementioned assumptions, **an additional low carbon amount of energy is produced, coal production is removed from Europe, and CO2 emissions are reduced globally**. The strategy is neutral regarding the amount of gas consumed and solar capacity installed. CO2 emissions per zone are ignored, only global CO2 emissions are considered.

The analysis can be extrapolated for all energy sources and all countries in order to find a global optimum, depending on practical energy transfer constraints which can vary greatly for industrial or political reasons. Gas is notoriously harder to transport than oil. Where CO2 is emitted is not considered for climate change, which implies that global cooperation is meaningful.

Appendix G Model design

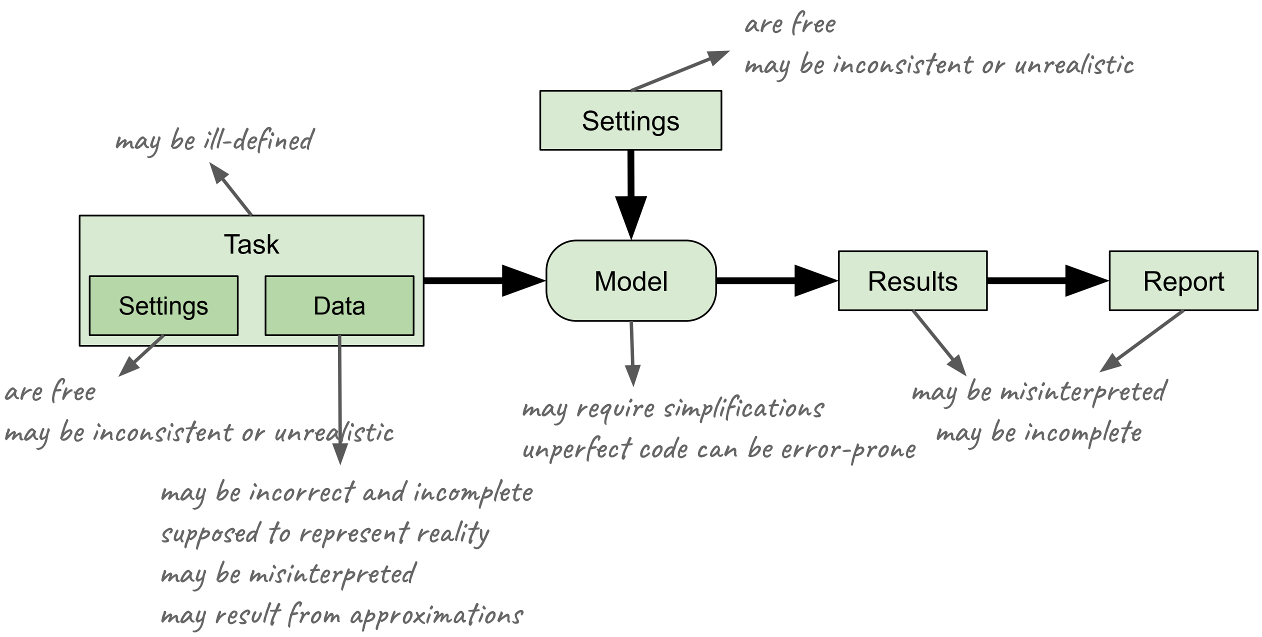

Fig. G.1: How the DEC model is designed, including the flaws of all similar models

Under this design, results that could be interpreted as invalid could come from: errors in the code, ill-defined task, inconsistent settings from the user, incorrect, incomplete or misinterpreted data from external sources, etc.

- The modeler is responsible for the task and the model.
- The data providers are responsible for the data they publish. The modeler is responsible for how this data is used by the model.
- The user is responsible for the settings.
- The user and the modeler are responsible for the results.
- The author is responsible for the report.

For this report, the author is also the modeler and the user. This doesn't imply that the modeler provides the most accurate settings for the model.

Appendix

H List of model parameters

This following list only details the most important parameters of the model.

Parameters	Description
energy.allow_nuclear_energy_switch	Allow countries which forbid nuclear energy to re-allow it after constraints
.......cars_battery_kwh_required	KWh per battery for average passenger cars
.......climate_strategy	Strategy for new fossil power plants
.......construction_delay	Delay per source to construct new power plants
.......controllability_strategy	Defines constraints on intermittent sources
.......controllability_tolerance	Tolerance for controllability strategy
.......daebe_gas_new_end_date_delta	Destroy All Elec-coal Before Elec-gas (DAEBE), delay for delayed EOL of Gas PP
.......degradation_per_year	Solar/Wind production decrease per year
.......demography_strategy	Defines target on useful energy per capita
.......density_limit1800x3600	Density limit per tenth of degrees to consider a place as populated
.......destroy_all_eleccoal_before_ele ....cgas	DAEBE, if gas EOL, remove coal instead
.......education_delay	Per source delay to train workers on a technology
.......education_strategy	Defines if an education is required before starting power plants construction

.......electric_vehicle_lifespan_years	Lifespan of E.V.
.......electricity_loss	Losses of electrical production
.......ev.battery_props	Proportions of battery types per year
..........heavy_ev_kwh_multiplier	Battery capacity requirements for heavy vehicles (bus, etc.) as a multiplier of cars needs
..........verylight_ev_kwh_multiplier	Battery capacity requirements for very ligh vehicles (mopeds, etc.) as a multiplier of cars needs
.......f2delayforallowelec	Delay per fossil before end of new fossil power plants
.......f2delayforallowglobal	Delay per fossil before reduction of consumption from other uses
.......fossil_to_datetoendelec	New max end date for all fossil power plants, reschedules EOL
.......fossils_reducing_threshold_for_ ....forced_allow_nuclear	Authorize nuclear energy if hard fossil phase-out
.......gas_substrategy	Defines if future gas PP are only allowed when coal is to be replaced
.......generator_loc	Defines rules to place new power plants
.......hydroelectric_feasible_ratio	Ratio to penalize optimistic hydroelectric estimates
.......lifespan	Lifespan of power plants per energy source
.......minimal_examples_required_decli ....ne.default	Number of (country,year) to use as an example to define maximal limit on energy decline pace
.......minimal_examples_required_growth	Number of country/year to use as an example to define maximal limit on energy growth pace
.......minimal_n_generators_for_example	Minimal number of real power plants to use as examples
.......minimal_prod_absolute_qualified ...._twh	Minimal production from a source to be considered as qualified for that source
.......minimal_prod_percentage_qualified	Minimal percentage of total production in a country so that this country is qualified on that source
.......source_to_destroymultiplier	How fast compared to historical phase-out new fossil phase-out can go

.......source_to_newcapaprodmultiplier	How fast the model can install a source of electricity compared to historical growth of that source
.......nuclear.educ_delay_reduction_if ...._underconstr	Reduces education delay if an NPP is currently under construction in country
..............minimal_n_reactors_to_q ....ualify	Number of reactors to have under construction in the last years to be qualified
..............minimal_n_years_to_qual ....ify	Last years considered to evaluate qualification based on recent construction of nuclear reactors
..............minimal_generator_mw_to ...._consider	Only consider large enough reactors
.......nuclear_strategy	Strategy regarding nuclear power: all, permissive, restrictive, none
.......physical_strategy	Care or ignore world production limits regarding hydroelectricity installations, geothermal energy etc.
.......prodcapa_strategy	Strategy regarding the use of production or capacity as the maximum reference for growth of electrical sources
.......qualification_prop_year_range	Proportion of considered years in which the countries is above thresholds of production to be considered qualified
.......qualification_year_range	Number of years to consider while establishing if a country is qualified on an electrical source
.......ratio_on_delay_to_fossildestruc ....tion	How fast fossil phase-out in electricity is performed considering fossil_to_datetoendelec
.......recycling_rate	Recycling rate per source per year (with interpolations)
.......stop_newfossils_island	Delayed date to stop fossils on isolated islands
.......storage.availability_factor	Maximum availability factor per source to consider at a given moment for storage needs
.......subsampling_geothermal_map	Resolution subsampling used to evaluate location of geothermal power plants

.......total_strategy	Strategy regarding limits on total amount of power plants which could be planified per year
.......transition_refusal_fossil_thres ....hold	Threshold on proportion of useful energy per capita compared to 2019 to consider transition is refused
.......year_when_u235_not_required_new ...._nuclear	Year from which future nuclear projects won't consume uranium reserves
future.fgas_multiplier	Per-capita evolution of f-gas emissions
.......foodtype_to_multiplier	Per-capita per-food evolution of consumption
.......fossilroad_to_elecroad	How much E.V. to add when one fossil vehicle is removed
.......fosusage_to_minimal_limit	Minimal non-replaceable production per fossil fuel per usage
.......lucfsource_to_multiplier	Evolution of GHG emissions from LULUCF
.......n2o_multiplier	Per-capita evolution of N2O emissions
.......simulation_end_year	Last year of the simulation
.......source_to_ch4multiplier.Waste	Per-capita evolution of CH4 emissions from waste
.......source_to_co2multiplier.cement	Per-capita evolution of CO2 emissions from cement
.......source_to_so2multiplier.industr ....y_misc	Evolution of SO2 emissions from industries
.......usage_to_reduction.boats	Evolution of fossil energy consumption from boats
.........................rest	Evolution of fossil energy consumption from unspecified activites
.......vehicle_to_multiplier	Evolution of the number of vehicles per year per capita

Table H.1: List and description of important parameters of the DEC model

Appendix I
Configuration example


```yaml
demography:
    linear_model:
        min_ratio_2019_2100: 0.5
        pop_threshold_reducratio: 1000000

    complex_v2:
        deaths_knn: 12
        newborn_age_ref: 2
        newborn_thresholds_min: 0.03
        newborn_thresholds_max: 0.97
        newborn_randomforest_n_estimators: 40
        migrations_multiplier: 1
        deaths_multiplier: 1
        newborn_multiplier: 1
        linear_confidence_scenario:
            linear_attraction: 0.02
            year_coef: 6
        linear_confidence_start_scenario:
            max_dy: 40
            lsc_exposant: 4
        y2poptarget_specified:
            max_dist_eval: 60

    life_expectancy_target: 75
    best_le_knn: 31


energy:
    n_days: 365.25
    density_limit1800x3600: 0.2
    hydroelectric_feasible_ratio: 0.333

    cars_battery_kwh_required: 50
    electric_vehicle_lifespan_years: 15

    electricity_loss: 0.1

    lifespan:
        Nuclear: 60
        Wind: 20
        Solar: 25
        Hydroelectricity: 150
        Gas: 40
        Coal: 60
        Oil: 50
        Tide and wave: 100
        Biomass and waste: 40
        Geothermal: 50

    construction_delay:
        Nuclear: 8
        Wind: 2/12
        Solar: 2/12
        Hydroelectricity: 6
        Gas: 3
        Coal: 3
        Oil: 3
        Tide and wave: 3
        Biomass and waste: 3
        Geothermal: 3

    degradation_per_year:
        Wind: 0.016
        Solar: 0.007

    education_delay:
        Solar: 0
        Wind: 1
        Hydroelectricity: 3
        Gas: 3
        Coal: 3
        Oil: 3
        Biomass and waste: 5
        Tide and wave: 5
        Geothermal: 5
        Nuclear: 8

    minimal_prod_percentage_qualified: 0.05
    minimal_prod_absolute_qualified_twh: 1
    qualification_year_range: 30
    qualification_prop_year_range: 1/3

    nuclear:
        educ_delay_reduction_if_underconstr: 1/2
        minimal_reactor_mw_to_consider: 500
        minimal_n_reactors_to_qualify: 2
```

```yaml
        minimal_n_years_to_qualify: 15

    maximal_usable_twh_per_capita: 1e-4

    minimal_examples_required_growth:
        Solar: 3
        Wind: 3
        Hydroelectricity: 5
        Gas: 5
        Coal: 5
        Oil: 5
        Biomass and waste: 5
        Tide and wave: 5
        Geothermal: 5
        Nuclear: 5

    minimal_examples_required_decline:
        default: 3

    minimal_n_reactors_for_example: 2
    min_capa_ratio_country_reactors: 0.001

    storage:
        availability_factor:
            Nuclear: 0.9
            Geothermal: 0.8
            Biomass and waste: 0.9
            Gas: 0.9
            Oil: 0.9
            Coal: 0.9
            Hydroelectricity: 0.5

    ev:
        heavy_ev_kwh_multiplier: 7
        verylight_ev_kwh_multiplier: 1/10

        battery_props:
            y2020:
                NMC622: 0.3
                NMC111: 0.4
                NMC811: 0.1
                NCA: 0.1
                LFP: 0.1
                LTO: 0

            y2030:
                NMC622: 0.1
                NMC111: 0.1
                NMC811: 0.2
                NCA: 0.1
                LFP: 0.5
                LTO: 0

            y2050:
                NMC622: 0.1
                NMC111: 0
                NMC811: 0.2
                NCA: 0
                LFP: 0.7
                LTO: 0

    recycling_rate:
        Lithium:
            y2022: 0.001
            y2030: 0.1
            y2050: 0.4
        Uranium:
            y2020: 0.02
            y2030: 0.1
            y2040: 0.2
        Aluminium:
            y2020: 0.5
        Copper:
            y2020: 0.5
        Steel:
            y2020: 0.5
        Concrete:
            y2020: 0.1
        Cobalt:
            y2018: 0.1
            y2040: 0.3
        Silver:
            y2020: 0.15
        Graphite:
            y2020: 0.05
        Manganese:
            y2020: 0.1
        Nickel:
            y2010: 0.7
        Rare Earths:
            y2020: 0
            y2039: 0
            y2050: 0.1
        Silicon:
            y2020: 0
        Zirconium:
            y2020: 0

    subsampling_geothermal_map: 5

    powerplant_loc:
        rank_needs_margin_m: 1.2
        max_need_met_mult_fp: 10
        max_length_to_keep: 3000
        max_worst_multrank_r: 1
        windsolar_rankneeds_m: 0.1
        windsolar_rankneeds_mpn: 3
        windsolar_neg_mpropkm2: 0.3
        windsolar_mpropp: 0.3
        windsolar_effratio_excl: 0.5
        maw_worst_effiency_m: 1.3
        frate_degp10p: 0.05
        agee_max_prop: 0.6

        needs_location_m: 2

    controllability_tolerance: 0.05
    usefulEpcapita_tolerance: 0.1
    usefulEpcapita_analysis_delay: 30
    usefulEpcapita_analysis_toomuch_excess: 5
    min_newprod_prop_to_start_learning: 0.001

    physical_strategy: 'care'
```

```
    prodcapa_strategy: 'mod_specific'
    controllability_strategy: 'free'
    demography_strategy: 'lifeexpectancy'
    education_strategy: 'learn_first'
    climate_strategy: 'delay'
    total_strategy: 'nofossils1st'
    nuclear_strategy: 'restrictive'
    year_when_u235_not_required: 2050


    gas_substrategy: 'only_to_replace_coal'


    f2delayforallowelec:
        Coal: 5
        Gas: 15
        Oil: 15
    f2delayforallowglobal:
        Coal: 5
        Gas: 15
        Oil: 5
    stop_newfossils_island: 2080
    fossil_to_datetoendelec:
        Coal: 2050
        Gas: 2060
        Oil: 2060
    ratio_on_delay_to_fossildestruction: 2/4
    modes_with_history_limits: ['Coal']
    destroy_all_eleccoal_before_elecgas: True
    daebe_coal_y_delay: 60
    daebe_gas_new_end_date_delta: 2
    transition_refusal_fossil_threshold: 0.7
    mode_to_newcapaprodmultiplier:
        Solar: 1
        Wind: 1
        Total: 1
    mode_to_destroymultiplier:
        Coal: 3
        Gas: 3
        Oil: 3

future:
    demography_model:
        method: 'predict_nextpop'
        method_kwargs:
            migration: True
            scenario: linear_confidence_start
            strict: None
            y2poptarget: None

    energy_model:
        name: complex_constraints

    source_to_co2multiplier:
        cement: 0.98

    source_to_ch4multiplier:
        Waste: 1

    foodtype_to_multiplier:
        Bovine: 0.98
        Poultry: 1
        Mutton: 0.98
        Pig: 0.98
        Other: 1
        Sea: 1

    source_to_so2multiplier:
        industry_misc: 0.98

    #misc
    temperature_randomness: False
    enable_heatwave_deaths: False

    #co2/ch4 from lulucf
    lucfsource_to_multiplier:
        unloc: 0.98
        loc: 0.98

    #n2o
    n2o_multiplier: 0.99

    #fgas
    fgas_multiplier: 1

    #vehicle parameters
    vehicle_to_multiplier:
        fossil_road: 0.98
        elec_road: 0.997215
        fossil_planes: 0.95

    fossilroad_to_elecroad: 0.98
    fossilroad_to_elecroad_mode: 'replaceratio'
    keep_vehiclepcapita_constant: True
    raise_vehiclepcapita_whenpeopledie: False
    static_percentage_fossilroad: True
    mult_static_percentage_fossilroad: 1.02


    reserve_multiplier:
        Coal: 1
        Oil: 1
        Gas: 1
        Uranium: 1
        Lithium: 1

    usage_to_reduction:
        rest: 0.97
        boats: 0.99

    fosusage_to_minimal_limit:
        Oil:
            rest: 0.05
            fossil_planes: 0.02
        Coal: {'rest': 0.05}
        Gas: {'rest': 0.05}


    simulation_start_year: 2019
    simulation_end_year: 2100
```

Appendix J Climate model

J.1 Pipeline

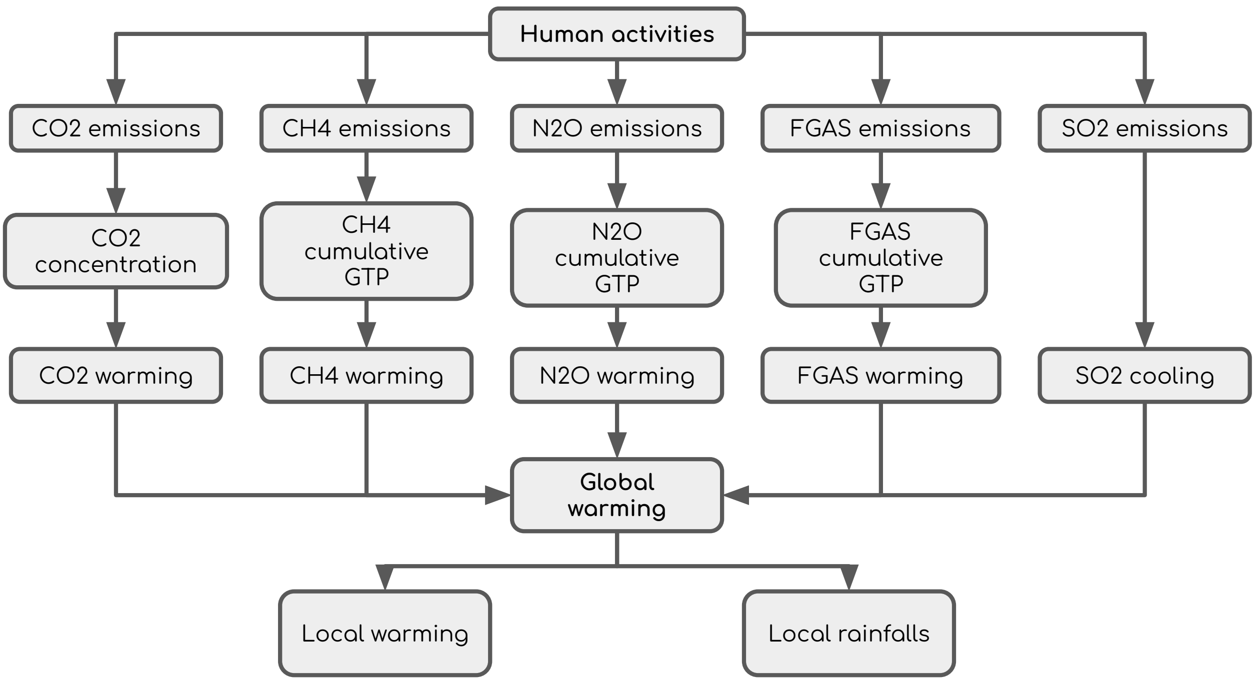

Fig. J.1: Climate model used in the DEC model

The pipeline of the climate model used in DEC is not related to physical causality but to data availability. The goal of the DEC model is not to build a physically accurate climate model. A statistical climate model which can quickly and accurately reproduce a physical climate model is sufficient for the main task.
It's considered in this model that the average warming caused by CO2 can be approximated with CO2 concentrations. And that the local warming in different places can be approximated from the global warming.

J.2 Local warming for large cities

Local warming are approximated with linear models trained on main SSPs:

$$warming_{lat,lon} = a_{lat,lon} * global\_warming + b_{lat,lon}.$$

Data and linear models can be visualized:

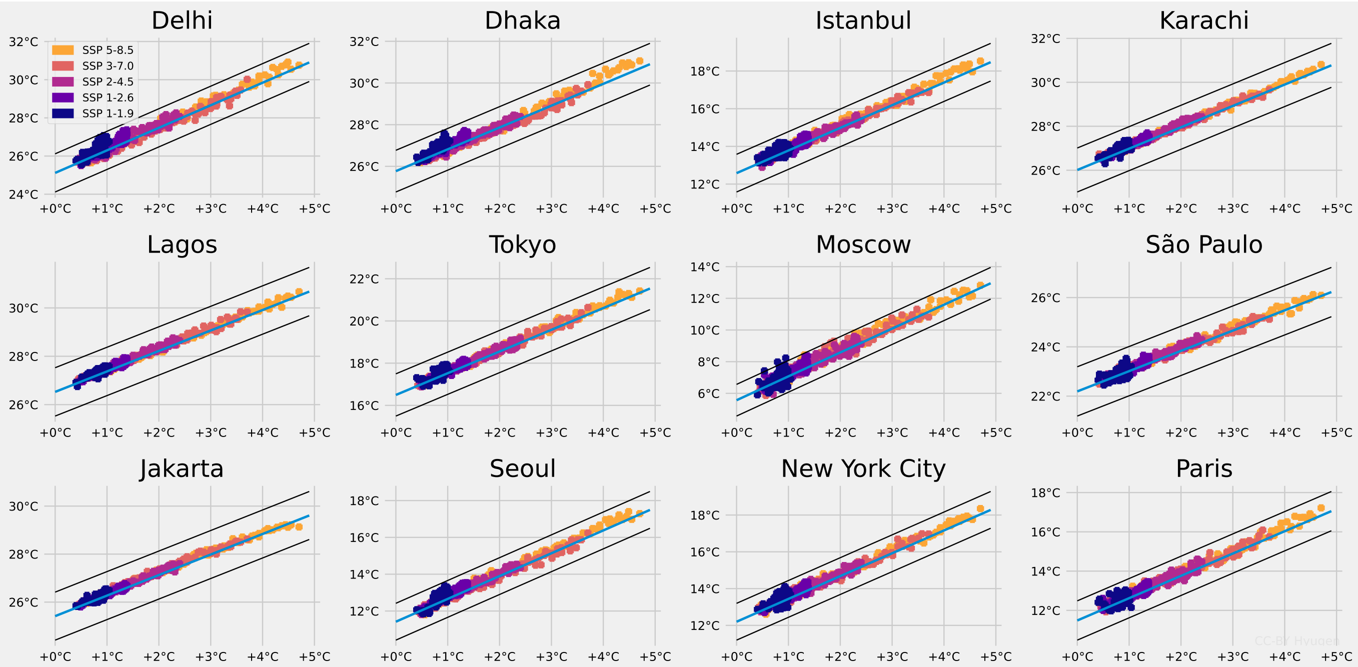

Fig. J.2: Possible local temperatures (year average) for large cities as a function of global warming, DEC climate model is represented with the blue line, black lines = +/- 1°C, SSPs: [57]

J.3 Possible global warming with linear models

Multiple scenarios of gas emissions can be tested with the models developed for DEC.

A Business As Usual (BAU) scenario where emissions continue to increase linearly can be included for different gases. There is also a scenario where emissions stay the same, a scenario where emissions suddenly drop to 0, and a scenario where the forcing caused by the gas remains constant.

Multiple of these scenarios are not realistic. A test can evaluate what would happen to global warming in the DEC model if SO2 emissions suddenly dropped to 0 while emissions from other gases would continue to increase. This scenario is not realistic because SO2 emissions are partly caused by the same activities that also cause the increase of other gases.

Scenarios are displayed in fig. J.3 to see some extreme cases of in the model.

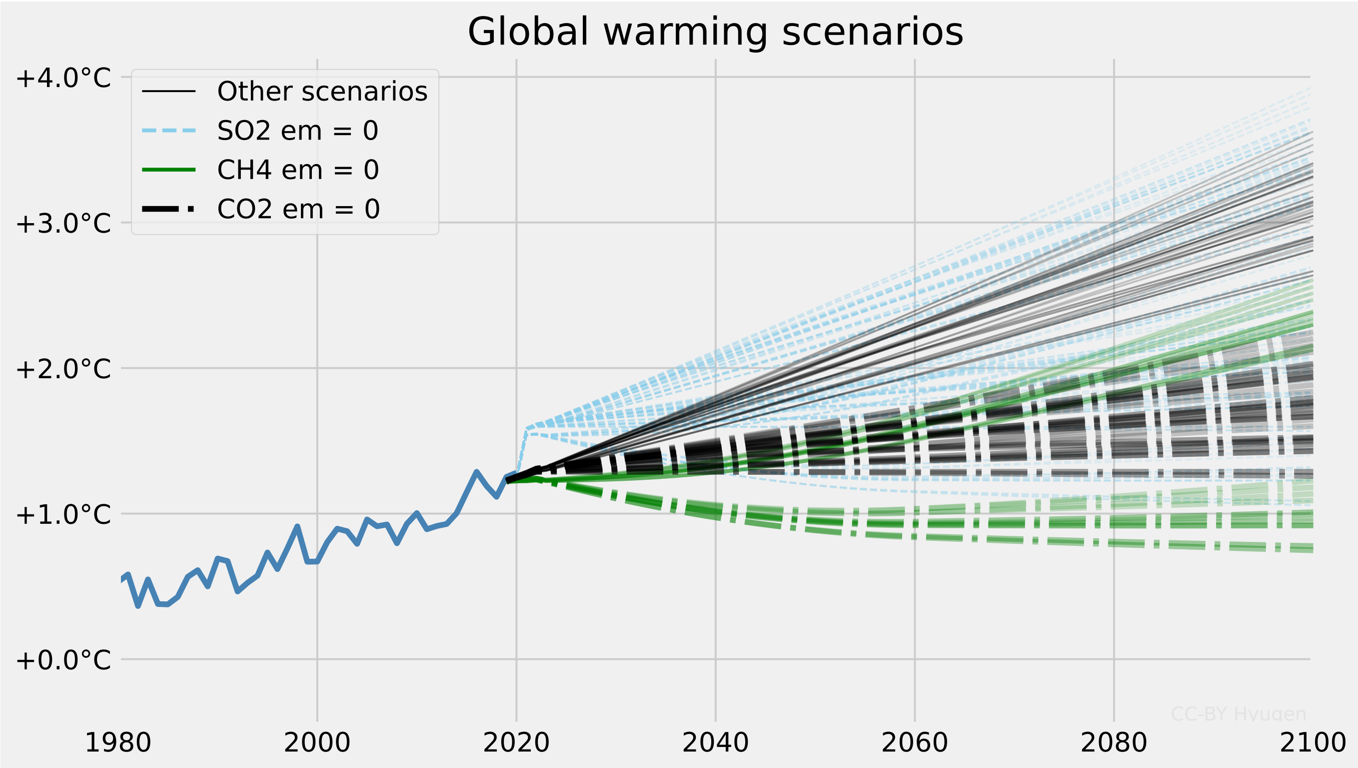

Fig. J.3: Multiple global warming scenarios with variations of CO2, CH4, N2O, F-Gases and SO2. Based on models used in DEC (which are constrained based on [4] and [6], ch1, fig1.5, p65). Realism of scenarios is not considered. For this plot, at most, gases emissions continue to increase linearly. At least, gases emissions instantly drop to 0.

Appendix K Transports

How vehicles are used vary per country. Assumptions made to estimate which vehicles people used and how much they use them per year and per country are detailed. These assumptions are used to estimate needs for electrification of transport.

K.1 Proportions of cars, mopeds and trucks

The proportion of cars, mopeds and trucks is imported from sources or estimated per country. This value is used to estimate resource needs. For most countries, source is [148] (OECD, IPF countries), and otherwise [149] (for India, China, Indonesia and Brazil).

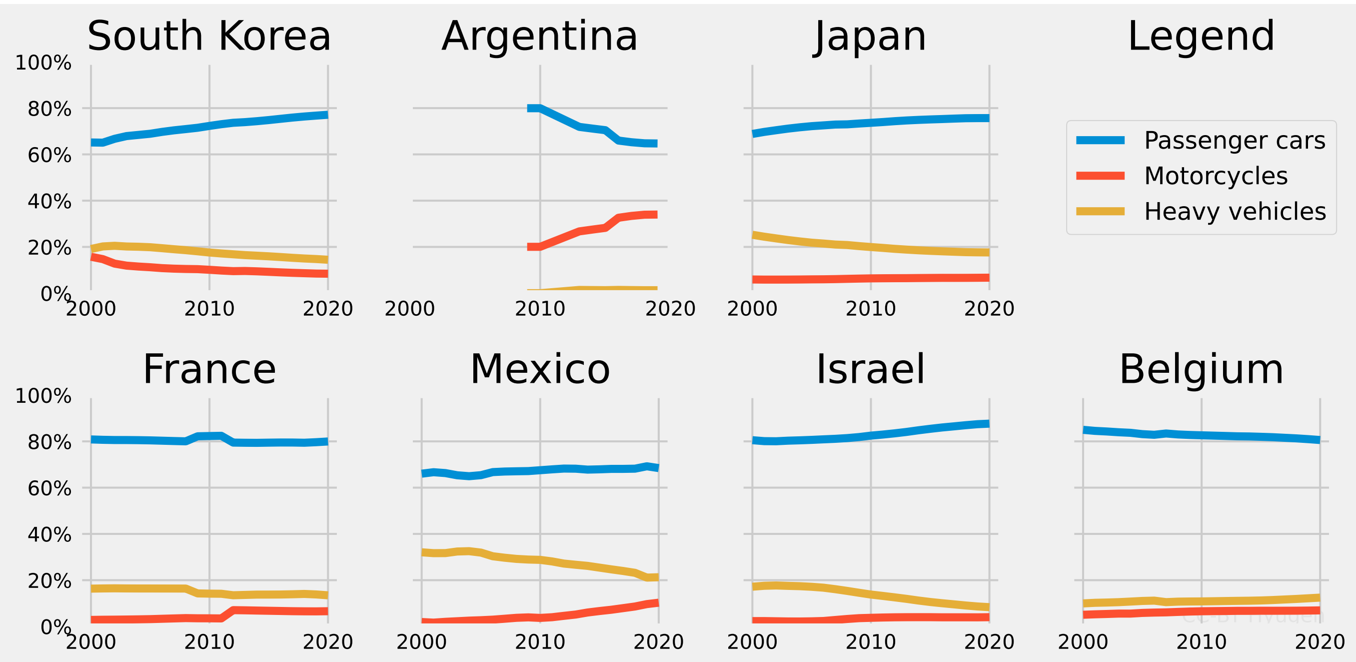

Fig. K.1: Proportions of each vehicle type per country per year, [148]

Countries in the dataset include **78%** of 2019 oil consumption. For other countries, proportions are estimated based on the amount of oil energy per capita for each country.

K.2 Distance traveled per year for passenger cars

The average distance (km) traveled per year and per country for passenger cars is estimated or imported from sources. This value is used to estimate electricity needs for transport in multiple countries.

Country	Distance traveled (km per year)	Source
United States of America	22954	[150]
Canada	18000	[151]
Russia	17500	[152]
South Korea	16023	[153]
Turkey	14236	[154]
Republic of Austria	13699	[155]
Germany	13602	[155]
Finland	13600	[156]
Netherlands	12849	[155]
People's Republic of China	12377	[157]
France	12223	[155]
Sweden	12110	[158]
Norway	12000	[159]
India	12000	[160]
United Kingdom	11909	[161]
Mexico	11413	[162]
Greece	10786	[155]
Spain	10591	[155]
New Zealand	10000	[163]
Portugal	9878	[155]
Japan	9300	[164]
Poland	8607	[155]
Italy	8464	[155]

Table K.1: Distance traveled for passenger cars in the world

Countries in the dataset include **73%** of existing cars. The distance traveled per car per year for other countries is estimated based on a linear regression on the number of cars per person. The model uses approximations. Results for countries outside the dataset should not be used for a detailed analysis. The distance traveled per year by cars for most countries is 13000 km +/- 4000km.

Appendix L Productivity per land used

Land use is a concern for diffuse energy sources such as wind and solar energy. This appendix presents estimates and data on energy density for wind and solar energy.

L.1 Solar productivity per land used

The productivity of solar panels per occupied surface is estimated based on multiple sources. Results can be visualized in fig. L.1.

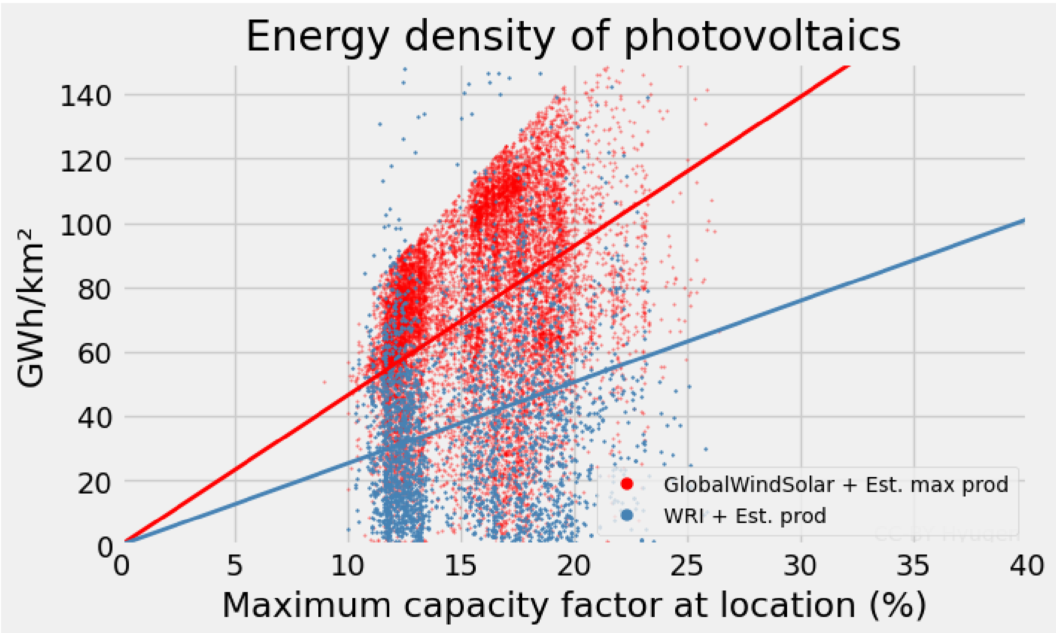

Fig. L.1: Electricity generation per unit area per year as a function of theoretical max capacity factor at that location. Each point represents a set of solar panels. WRI / Est. prod: [55, 12], 2019. GlobalWindSolar: [65], Est. max prod / capacity factor: [64]. Lines are non-weighted regression without fit intercept

Results show that solar panels' productivity depends on a large range of parameters apart from the theoretical capacity factor for their given location. The land energy productivity of solar electricity is estimated to be between 10 GWh / km² to

100 GWh / km². The productivity of an installation per km² depends on the quality of the installation, the quality and technology of solar panels, their maintenance, their age, climatic hazards, climatic randomness, etc. The maximum theoretical capacity factor can only be achieved in an optimal situation and is not representative of the average situation over the life of the panel.

Based on empirical data, a surface productivity of solar panels can be estimated for all locations on the planet. Based on this estimate, it is possible to evaluate (from a theoretical point of view) proportion of each country that should be covered so that they would produce 100% of their electricity with solar energy.
Comparison of results can be done with [165].

Country	DEC	World bank ESMAP [165]
Mexico	0.23%	0.1%
France	1.62%	1%
Singapore	58.62%	
Belgium	6.84%	
Japan	5.45%	
Ethiopia	0.02%	

Table L.1: Proportion of the country's land to fill up with solar panels to produce 100% of 2019 electricity with solar panels (%)

L.2 Wind productivity per land used

In order to estimate productivity per occupied surface for wind turbines, wind speed is used. Wind speed isn't the sole required parameter to estimate their productivity. Empirical capacity factors from [55, 12] are correlated with wind speeds ([67], gwa3_250_wind-speed_100m).

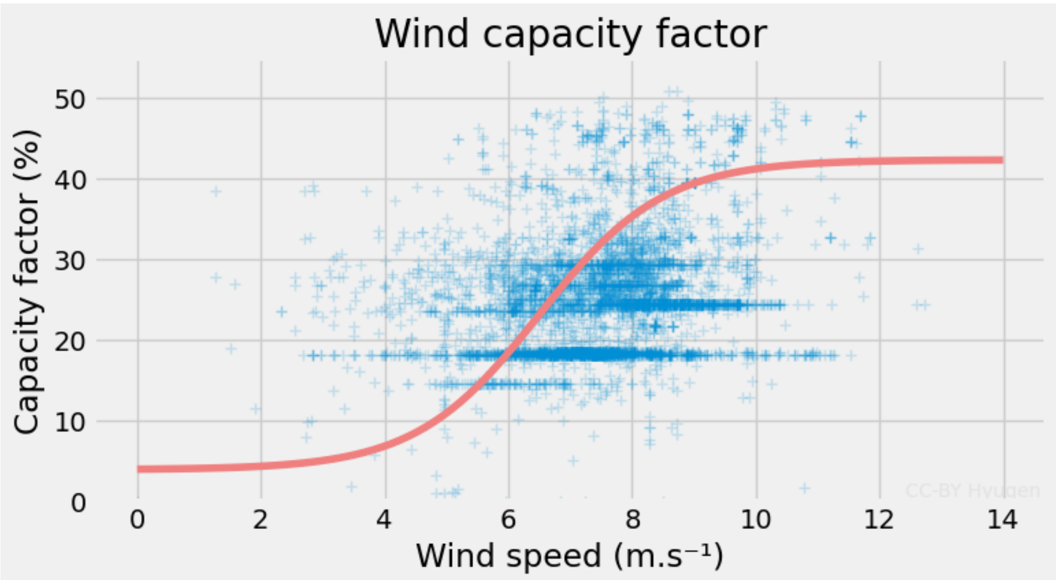

Fig. L.2: Capacity factor as a function of wind speed. Each point represents a wind farm. Capacity factor is estimated based on capacity [22] and production [12] per country, per wind farm [55] for year 2017. Curve detailed below.

An equation of the capacity factor as a function of wind speed is evaluated and used (year average, wind speed expressed in m.s^{-1}) :

$$cf = (tanh((windspd - 6.5) * 0.5) + 1.2) * 1/5.2$$

The capacity factor for all locations on the planet is re-estimated based on wind speed and empirical data. Based on the estimated capacity factor, a theoretical maximum production for wind turbines in [65] is evaluated. These results allow computing the empirical energy productivity of land used for wind turbines in [55] and the theoretical productivity of the land used for wind turbines in [65].
Productivity for some onshore and offshore wind farms is manually computed, and includes data from other sources on offshore wind farms [166], to assess the results. Estimating how much land is used for wind farms is relatively subjective as there often is a possibility to densify an installation. This could however not make sense for economic reasons, topological reasons or for productivity reasons because the wind will be disturbed after passing through some turbines. Assessing how much of an area with wind turbines is "full" of wind turbines is partly subjective.

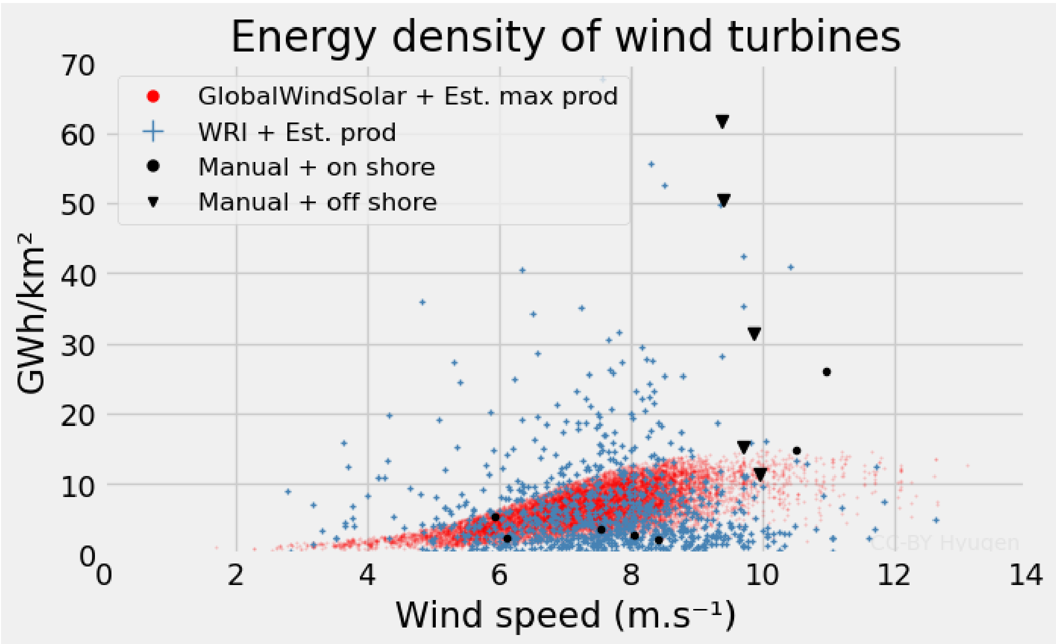

Fig. L.3: Electricity generation per unit area per year as a function of wind speed. Each point represents a wind farm. Blue points include data from [55] with production from [55, 12] and surface estimates from [65]. Red points include data from [65] with production estimates based on wind speed and capacity factor. Manual estimates are based on production from [55, 12] and surface estimates based on satellite imagery

The land energy productivity of onshore wind is estimated to be below 20 GWh/km², approximately 2 to 10 times lower than solar.

Appendix M Environmental and human constraints for nuclear energy

M.1 Map of environmental constraints for nuclear reactors

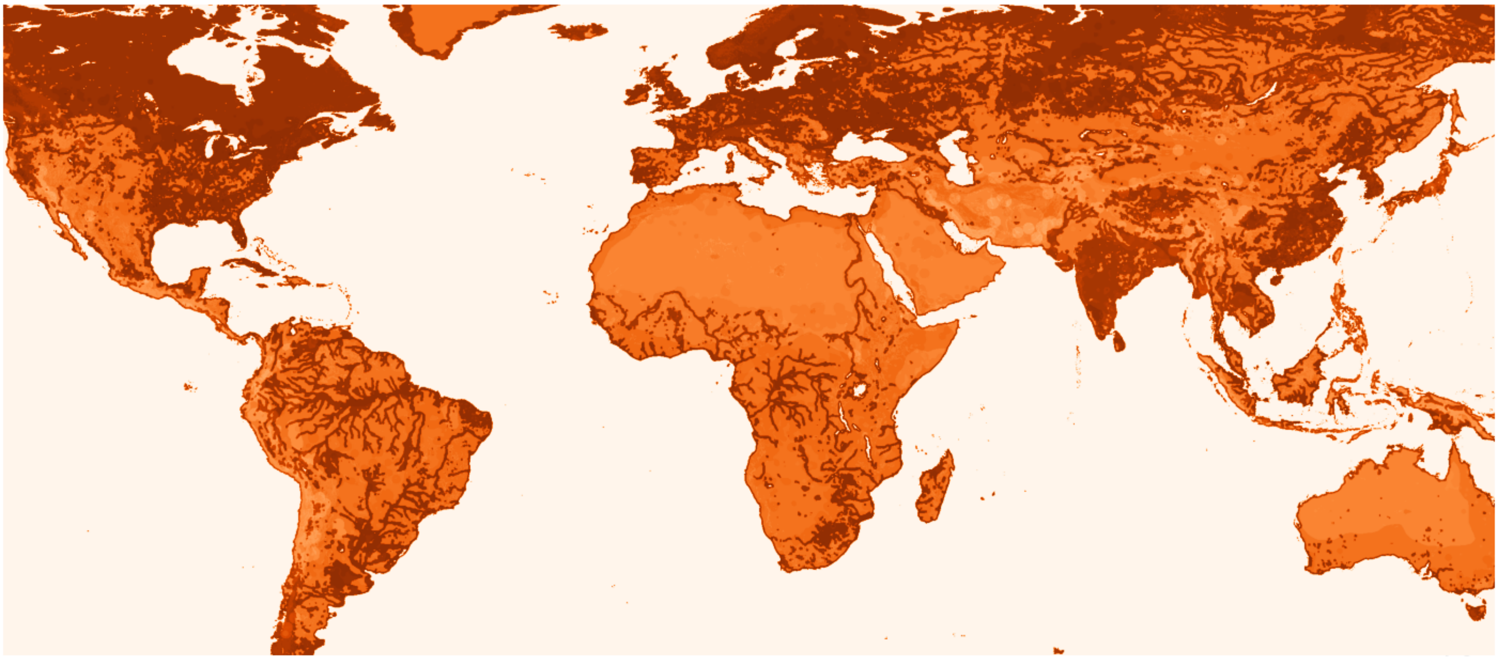

Fig. M.1: Environmental constraints for nuclear reactors, darker colors are associated with less environmental constraints

Details for this map are provided below.

M.2 Nuclear reactors with the highest environmental constraints

Name	Country	Score	Constraint(s)
...	...	...	...
CRUAS	France	47	floods
Harris	USA	47	floods
Waterford 3	USA	47	floods
Fangchenggang	China	47	rain
Koeberg	South Africa	45	pop density
Indian Point 2	USA	45	pop density
Indian Point 3	USA	45	pop density
Fangjiashan	China	45	pop density
Qinshan 2	China	45	pop density
Ling Ao	China	42	rain, pop density
DAE RAJASTHAN	India	40	air temperature
R.A.P.S.	India	40	air temperature
Ohi	Japan	40	mountains
Tsuruga	Japan	40	mountains
Mihama	Japan	40	mountains
Chasnupp	Pakistan	40	air temperature
ASCO GR	Spain	40	mountains
Bushehr	Iran	40	air temperature
Bilibino	Russia	40	mountains
KAIGA	India	37	rain, mountains
DOEL 4	Belgium	35	too close to city, pop density
N.A.P.S	India	35	air temperature, pop density
Kashiwazaki Kariwa	Japan	35	earthquake
Ikata	Japan	35	earthquake
Sendai	Japan	35	earthquake
Higashi-Dori	Japan	35	earthquake
Hamaoka	Japan	35	earthquake
Kanupp	Pakistan	35	air temperature, pop density
Diablo Canyon	USA	35	earthquake
KAKRAPARA	India	34	floods, rain, air temperature
TARAPUR	India	32	rain, air temperature, pop density
M.A.P.P.	India	32	rain, air temperature, pop density
Daya Bay	China	32	rain, mountains, pop density
Onagawa	Japan	27	earthquake, tsunami
Tokai Daini	Japan	27	earthquake, tsunami
Fukushima Daina	Japan	27	earthquake, tsunami
Kuosheng	Taiwan	27	earthquake, rain, pop density
Chinshan	Taiwan	27	earthquake, rain, pop density
Tomari	Japan	25	earthquake, mountains
Maanshan	Taiwan	22	earthquake, rain, mountains
~~CIVAUX~~	~~France~~	~~0~~	~~nowater~~
~~CN COFRENTES~~	~~Spain~~	~~0~~	~~nowater~~
CEFR	China	-5	pop density, nowater
~~Krsko (NEK)~~	~~Slovenia~~	~~-10~~	~~mountains, nowater~~
Palo Verde	USA	-10	air temperature, nowater

Table M.1: Environmental constraints per nuclear reactor, lower score means higher constraints

Reactors with wrong estimates are crossed out. The spatial resolution used for water presence is such that thin rivers may not be seen by the model, which will consider

that there is no water in this place. Data for CEFR (China Experimental Fast Reactor) is uncertain. Constraints on proximity to a city may be incomplete. Simplifications are applied.
The estimation method is non-official, weights are based on perceived constraints, based on IAEA constraints indicated in [69].

Constraint	Weight	Data source
Earthquake	-15	[70]
Tsunami	-8	[71]
Floods	-3	[72]
Rainfall intensity	-3	[73]
Volcano	-10	[74]
Small island	-10	[66]
Mountains	-10	[66]
Air temperature	-10	[5]
Population density	-5	[61]
City proximity	-10	[66]
Water presence	+50	[66]

Table M.2: Weight per environmental constraints

Each constraint uses a binary mask over the whole world with 0.1° resolution. If an existing reactor is located where the binary mask has the value "True", the weight is applied. Values of the binary mask are defined based on specified data and based on metrics for current nuclear reactors. It implies that **most of the constraints are relative to the worst environmental conditions for existing reactors**, which doesn't imply these conditions are not compatible with new nuclear reactors as counter-measures can be applied to reduce risks, but this possibility is not considered in the model.
A merge of all masks can be observed in fig. M.1.

M.3 Restrictions for legal or security reasons

The model can also be configured to restrict nuclear energy for reasons related to human behaviors.

Country	Reason
Yemen	security
Iraq	security
Democratic Republic of the Congo	security
Switzerland	phase-out
Taiwan	phase-out
Denmark	law
Ethiopia	security
Nigeria	security
Germany	phase-out
Uruguay	law
Belgium	phase-out
Somalia	security
Mozambique	security

Chad	security
Mexico	security
Iran	security
Vietnam	declaration
South Sudan	security
Australia	law
Ukraine	security
Mali	security
Republic of the Congo	security
Italy	law
Syria	security
Cameroon	security
Niger	security
Israel	security
Central African Republic	security
Colombia	security
Republic of Austria	law

Table M.3: Nuclear energy possible restrictions related to human behaviors

Security reasons imply recent wars, military coups, war threats or threats to use nuclear energy for military reasons (except current nuclear states). Countries may have a planned phase-out, countries may have entirely forbid nuclear energy by law, or by declaration of their leader. Security reasons should not be interpreted as guidelines but as an estimation of constraints if a specific configuration is used. **These considerations can be entirely ignored and re-configured in the model.**

M.4 Observed delays between start of construction and commercial operation

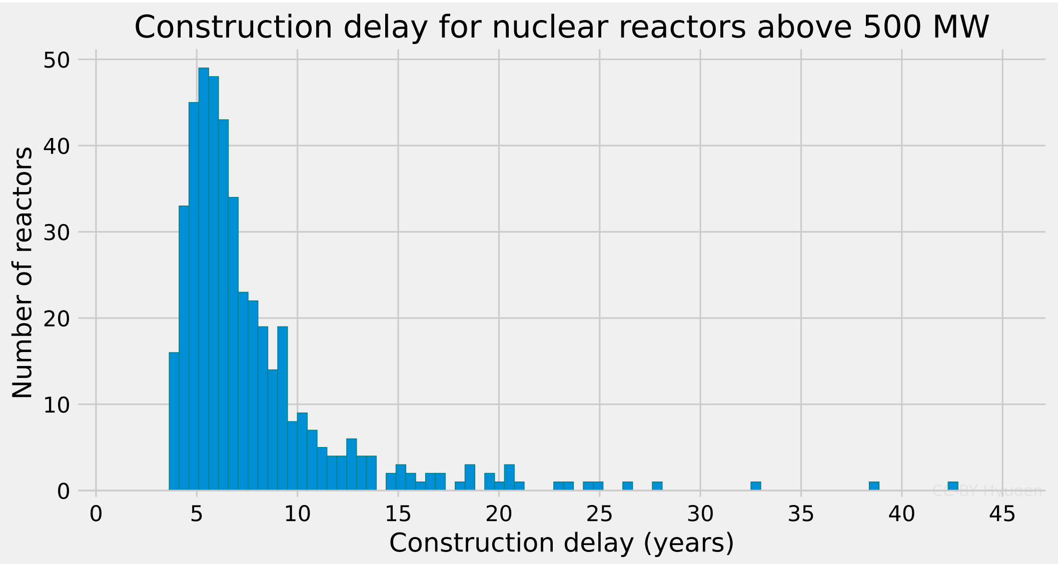

Fig. M.2: Observed construction delays for nuclear reactors above 500MW [167]

The empirical construction delay of nuclear reactors is computed and displayed in fig. M.2. This delay does not include the preparation phase.

M.5 Closure reasons and risks

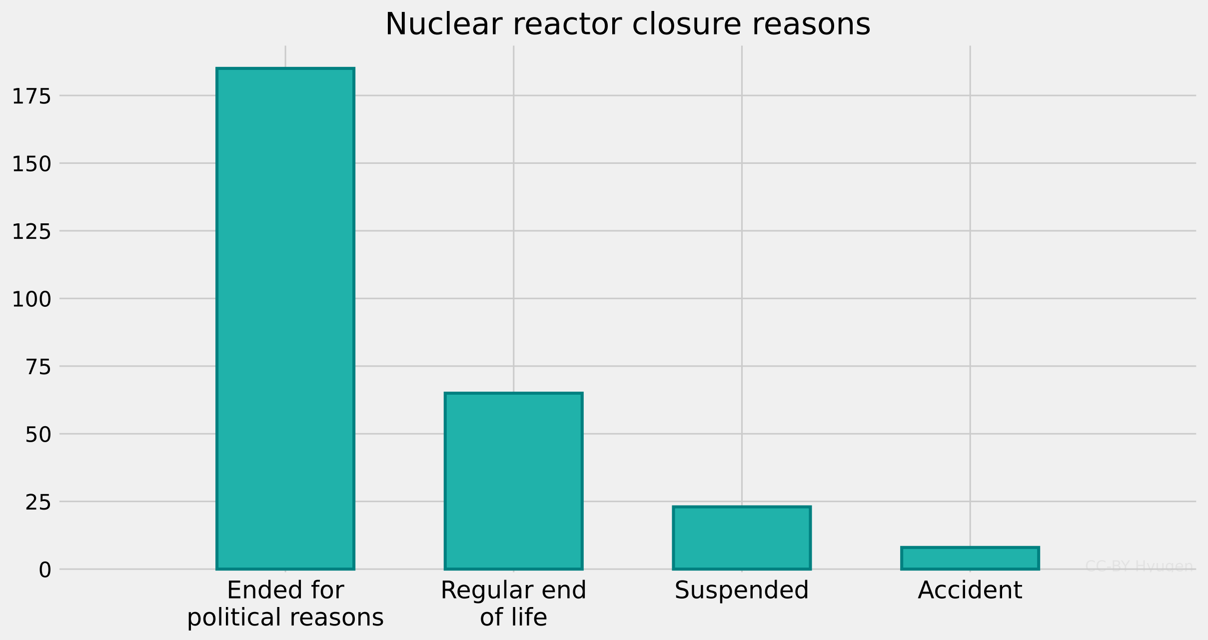

Fig. M.3: Empirical risks for nuclear reactors

Risks for nuclear reactors involve **any event that could cancel standard operation or repairs of a reactor and definitely stop the plant**.

Closure reasons for most of nuclear reactors were reviewed. Political reasons include: closing nuclear reactors instead of fossil fuel power plants (coal, gas, oil) while the reactor could continue to work, closing nuclear reactors for cost reasons in a context where fossil fuels are cheaper (closing nuclear reactors to use gas instead because gas would be cheaper), closing nuclear reactors for excessive security constraints in a context where alternatives such as coal are kept and are more deadly, closing nuclear reactors after a vote, after a political opposition or after protests. Political reasons do not include: closing >40y.o. nuclear reactors by substituting them with a low-carbon alternative, closing nuclear reactors which had issues by substituting them with another more recent nuclear reactor, closing nuclear reactors which had issues and an independent authority stated that the reactor couldn't be repaired for industrial reasons. Accidents include meltdowns, fires, etc. Suspended reactors may include political suspensions. Military reactors are not included.

Main estimated risks on standard nuclear reactors operations are: 85.6% for the political risk, 10.6% for the suspension risk and 3.7% for the accident risk. There is also a risk for nuclear reactors planned or under construction to be cancelled for political reasons. There is a lack of data to measure this risk.

Conflicts of interest

This report was not funded and did not receive grants.
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