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April 1, 2021

An Awesome Publisher

* A LaTeX lover

The kaobook class

Disclaimer
You can edit this page to suit your needs. For instance, here we have a no copyright statement, a colophon and some other information. This page is based on the corresponding page of Ken Arroyo Ohori's thesis, with minimal changes.

Colophon
This document was typeset with the help of KOMA-Script and LaTeX using the kaobook class.
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One can see from space how the human race has changed the Earth. Nearly all of the available land has been cleared of forest and is now used for agriculture or urban development. The polar icecaps are shrinking and the desert areas are increasing. At night, the Earth is no longer dark, but large areas are lit up. All of this is evidence that human exploitation of the planet is reaching a critical limit. But human demands and expectations are ever-increasing. We cannot continue to pollute the atmosphere, poison the ocean and exhaust the land. There isn't any more available.

– Stephen Hawking

What I'm saying is the planet is on fucking fire.

– Bill Nye

Preface

I am of the opinion that every LaTeX geek, at least once during his life, feels the need to create his or her own class: this is what happened to me and here is the result, which, however, should be seen as a work still in progress. Actually, this class is not completely original, but it is a blend of all the best ideas that I have found in a number of guides, tutorials, blogs and tex.stackexchange.com posts. In particular, the main ideas come from two sources:

- Ken Arroyo Ohori's Doctoral Thesis, which served, with the author's permission, as a backbone for the implementation of this class;
- The Tufte-Latex Class, which was a model for the style.

The first chapter of this book is introductory and covers the most essential features of the class. Next, there is a bunch of chapters devoted to all the commands and environments that you may use in writing a book; in particular, it will be explained how to add notes, figures and tables, and references. The second part deals with the page layout and design, as well as additional features like coloured boxes and theorem environments.

I started writing this class as an experiment, and as such it should be regarded. Since it has always been intended for my personal use, it may not be perfect but I find it quite satisfactory for the use I want to make of it. I share this work in the hope that someone might find here the inspiration for writing his or her own class.

Federico Marotta

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Introduction 1

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1.1 The Main Ideas

Climate is rapidly changing and starting to impact society. This is only the beginning. While a lot of people have finally realized the dangers human society is in, too many carry an optimism that can be damaging.

The thought often encountered is that of the technology savior. That is, yes, climate change is a problem, but technology is going to find something and we will all be alright. I am not saying this is impossible. A century ago, who could have predicted the scale of the digital world, for example?

However, it is important to note that technology has to follow the laws of physics, and is competing in a inflexible human society. This text aims at helping people consider the big picture, and to not forget the scale and magnitude of the issues and solutions put forth.

Communication is a aspect of science which, I feel, has been degrading fast. I believe that this is due, in part, to the myriad of scientific fields and ultra specialized research, and in part to social media and jumping-to-conclusions journalism. The problem is that it causes people to not realize that success in several fields does not mean success as a whole. Climate change is a problem of physics, geophysics, computer science, material science, chemistry, energetic systems, engineering, economy, politics, social sciences, agriculture, and many more fields.

Only when the big picture is known by the majority of people can a plan be thought of and enacted efficiently. Until then, society is grasping at straws and potentially heading toward the wrong idea, or shutting down development of the right ones.

1.2 What This Text Does

This book focuses on the big pictures. You will not find fancy modeling with multi-line equations and strange Greek symbols and integrals or differential. Plenty of people do that already. Instead, you will be exposed to first-order thoughts pattern.

What this entails is while complex models are great and a useful tools, they often make flawed assumptions to the real world, especially when multiple scientific fields intersects, and especially when future predictions and human society are part of the equations. Some models[1], used as inputs later on, are extremely complex. But our goal in this book is to speak in terms of orders of magnitude.

1: Global Circulation Models notably, also commonly known as Climate Models

Imagine you are very much in love and trying to save up for the wedding of your dreams in a couple years[2].

2: A cheesy example, but bear with me

You could take a complex approach. You figure out exactly how many guests will be there, how many won't be able to come, how many will decide to cancel at the last minute, how many are vegetarian, how many will bring a plus one, etc. This gives you an optimized meal cost. Then you repeat the process for the DJ, finding a super cheap and awesome performer. You look online and find a venue that does a wine bar for a crazy low price, so you go ahed and book it for your date. You got it. Your dream wedding for $12,543. You can even try and optimize your model so that you do not do an open bar in order to add more people to the party.

Fast forward a year or so, you are finally engaged! Congratulations! You're now looking into booking everything on your list. You know exactly how much it will cost after all, according to your complex model. But, calling up vendors, you see that they charge a bit more than they used to. Your awesome DJ is already booked for the date you want, you can only find one that is a lot more expensive now. The cheap venue you had booked went under and is not available anymore, but this other works, even if it's more expensive and not as good. A pandemic hits and everything shuts down[3]. Guest RSVPs and then cancel the day of. All in all, a reasonably common wedding experience. The days after, you realize that you actually paid $19,845.

3: That one is pretty far-fetched, I know!

Your nice, well-thought of, complex model failed you. So would a simple model have helped you save your perfect wedding? No. But it would have made you more prepared for the actual costs by taking a range of potential values, and you may have gotten an approximate value of $18,000. You would have been better prepared and known that you really could do without the ice sculptures.

Of course, this is not an adequate metaphor for climate change action. At the end of this little story, you still get married, and you still end up happy. The end. I am afraid the situation is a little more bleak when climate change comes into play.

Having said that, this book does aim at giving you an idea of the scale of the problem, and why articles that say that we have the solutions, if only we could just implement them, are most of the times vastly underestimating the magnitudes or misunderstanding the scientific assumptions and shortcomings of the article they report on.

So, we will start by looking back at history, so that we can realize how fantastic fossil fuels are. Once we have done that, we will look at the future, so that we can realize how terrible fossil fuels are. And we will see what various paths forward could mean to the world, assessing the truth of the various energetic transition claims we often see in the news from government or large companies. Finally, from all of that, we will try to assess what any individual can do to help and what one can reasonably expect.

1.3 What This Text Does Not Do

This book does not advocate for or criticize any specific technologies for fun. I may seem that way, as you will see that some ideas unfortunately seem to be shot down by reality, though they are great in theory. Of course, in our demonstrations, we will use only the current known scientific theories, and push it further with optimistic scenarios. We will not count on any timely breakthrough, and we will not consider technologies that are not even being thought of today.

Again, our goal is to stand at the frontier between the real world[4] and the scientific specialty world[5].

We will not explore the technologies in details, as they would and have each taken entire volumes already, but we will briefly recall the basic principles. This will be necessary to show the physical and societal limitations one may run into sometimes.

4: A real world, with real people, most of which do not even have a device to read this text

5: As the physicists often say, let us assume a spherical cow...

Energy and Society

2 Energy History

In this chapter I go over human history with energies, and how energy is a limiting factor. We also go over a 100% renewable world, the past.

3 Energy Impact - The story of modernization

In this chapter I show how energy changed the world.

CLIMATE CHANGE, THE BIGGEST CHALLENGE IN HUMAN HISTORY

4 Greenhouse Effect, a reminder

In this chapter I explain the basics of greenhouse effect.

5 Climate Models

In this chapter I explain the basic of CO_2 emissions consequences and the climate models.

6 Natural Hazards Amplification

In this chapter I show what people can expect, and where things are likely to get bad.

Energies, a varied portfolio

7 Fossil Fuels

In this chapter I show what fossil fuels are and why they were so great and are so terrible.

Renewables 8

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A renewable energy is an energy source that is replenished at least as fast as it can be used. In other words, it depends on the timescale involved, and that timescale needs to be on the human, rather than geological scale. As you know, solar and wind are considered fully renewable. As long as the sun exists, and as long as Earth has an atmosphere, we will have solar radiation and wind mechanical force to potentially harvest. Water is another such resource, with evaporation and condensation (water cycle) taking care of the replenishment of our fresh water reservoirs. Biomass, also known as vegetation, is renewable, up to what can be regrown on the order of the yearly scale.

So, an interesting thing to note is that solar energy is the basis of every single renewable energy source on Earth. The wind exists because of a temperature gradient, caused by the sun irradiance. The water cycle exists because of the evaporation and rainfalls, caused by the warmth brought by the solar rays. The biomass develops by capturing the sun energy by photosynthesis. Only one renewable energy does not depend on the sun, and that is geothermal energy, but the challenges of tapping into that resource are immense. Note that (we will expand on this) current geothermal installation tap into the limited surface flux, not the actual heat reservoir.

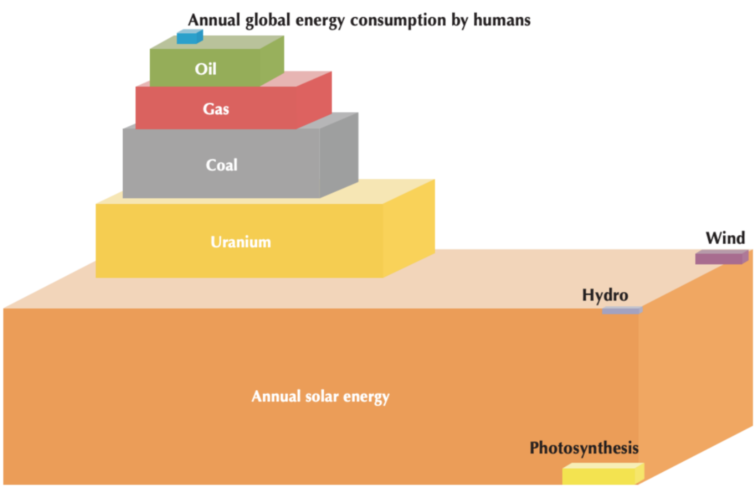
Fossil energies are also replenished over time, but on a timescale that are disqualifying for renewable resources. Nuclear energy is also not a renewable energy due to the finite amount of uranium or thorium notably. However, those resources are vast, which leads some to consider it as a honorary renewable energy due to its capacity at generating a lot of power with little carbon emissions. This is however not technically accurate. Some also equate nuclear fuel with fossil fuels due to the fuel mining necessary. This is also false.

Renewable energies are not all equal, both in terms of their capture or their efficiency, as well as localized variability. As a quick illustration, hydroelectric power is a renewable energy because of the water cycle replenishing the reservoir. However, at the same time, its capture and transformation to electricity is limited in terms of scale due to a limited number of siting locations available in the world. The resource itself (water) is thus renewable, but the means of capture is not.

Understandably, renewable energies have been touted as the savior for humanity for as long as we have known that fossil fuels were a problem, which is, as we have noted previously, much longer than people tend to realize. The main reason for this is two-fold. They seem to be getting back to a natural order of things, a less industrialized period, and the theoretical potential is incredible and dwarf (for solar notably) any other energy source. In a little under two hours, enough solar energy strikes the Earth to power our world society for a year.

It is consequently tempting to think that it is a simple matter of capturing it. But that capture is everything but simple.

Today, if you were to think about it quickly, or ask almost anyone in the streets, the question "What is renewable energy?", the first two responses by far would be "solar" and "wind". In reality, those account for a tiny fraction of the renewable energy mix, which is dominated by hydroelectricity and by the biomass. Right now, you should not really picture a solar panel or a wind turbine, but a dam or a forest, especially historically.



Source: National Petroleum Council, 2007, after Craig, Cunningham and Saigo (republished from IEA, 2008b).

Figure 8.1: Representation of the potential energy from different sources.

8.1 Biomass

Biomass energy is limited by the deforestation rate. In other words, in order for the biomass energy to be considered renewable, one must not deplete the forests at a higher rate than photosynthesis replenish them.

8.2 Solar

Direct heating from sun irradiance through windows is a big natural use. Having houses that are able to do that is important, but retrofitting is not really an option. Solar heating of air or water can also be a use of solar energy, notably for showers or house flooring. Finally, the electrical conversion through photovoltaic panels can be done.

8.3 Wind

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

8.4 Hydroelectricity

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8.5 Geothermal

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

9 Nuclear

In this chapter I will explain what nuclear is.

10 Carbon Capture

In this chapter I discuss carbon capture, at the source and from the atmosphere.

Energy Storage 11

In this chapter I discuss several energy storage technologies, from batteries to pumped storage and compressed air.

12 Electrical Transmission Grid

In this chapter I talk about the grid

First Order System Assessments

The Transition Needs 13

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In this chapter I will assess the situation as it is for several representative countries, each representing a different economical, geographical and energetic contexts.

France France will be taken to represent Europe as well as a large existing nuclearized electricity grid.

United States of America The USA will be considered due to its socio-economic importance, and its varied geographical and energetic landscape.

Brazil Brazil will also be used as a case study, a large South American country powered notably by hydroelectric power.

China China has an immense impact on the world, and is today one of the main source of carbon emission[1].

Nigeria Nigeria will represent the continent of Africa, due to its large and vastly under-electrified population.

1: We will come back to that, but keep in mind that this is very misleading, and that it wildly depends on how you define the CO2 footprint

Those five countries should give us a pretty good idea of the sheer scale of the challenge awaiting us in this transition. It is important to remember that one country alone will not make a difference. The atmosphere and consequently the climate does not care where the carbon came from, and a gram of carbon from Cambodia is worth exactly the same as a gram of carbon from Iceland. The transition must be global.

We will first assess the energy need to transition the electricity grid, and then the energy requirements. Electricity and energy are two different things, as we discussed earlier. Once we know how much energy we need, we will assess the magnitude of the costs of doing so with different scenarios. We will finally look at the feasibility of those scenarios and try to see what the important takeaways might be.

When the media discuss energy transition, I feel that they often misrepresent, or don't explain enough, what they mean. There is a very large difference between electricity and energy. Electricity encompasses only the electric power uses, such as what allows a home outlet to charge a phone, plug a fridge, etc. Energy consists of all of the electricity as well as transportation and heating.

When using gas to power a car or to heat a location, a lot of the energy is lost in the process. Electricity would allow you to be a lot more efficient. Consequently, the electrification of the transportation and thermal sector implies a better efficiency and less consumption, translating to a lower power needed.

In the following, we will make two things distinct:

Energy Transition

Energy transition is the removal of all energy from fossil fuels, to be replaced with non carbon-emitting sources.

Electricity Transition

Electricity transition is the removal of all energy from fossil fuels from the electrical grid. In other words, the gasoline powered cars can stay, the coal and gas plants have to go.

For the five countries discussed earlier, we look at the electricity transition, accounting for potential population electrification in developing countries. We do not directly look at the energy transition, as we will see that even simply the electricity part is a major challenge.

13.1 France

The data for the current electricity generation mix in France is obtained from the public electricity transmission operator (RTE, 2020) and displayed in Table Table 13.1, with the share of installed capacity in Figure Figure 13.1 and the share of production in Figure Figure 13.2 on the following page.

Table 13.1: 2020 electricity data for France

Type	Installed Capacity (GW)	Energy Produced (TWh)	Load Factor (%)
Nuclear	61.4	335.4	62.4
Coal	2.9	1.4	5.5
Petroleum	3.4	1.7	5.7
Natural Gas	12.6	34.5	31.3
Hydroelectric	25.7	65.1	28.9
Solar	10.4	12.6	13.8
Wind	17.6	39.7	25.7
Biomass	2.2	9.6	49.8

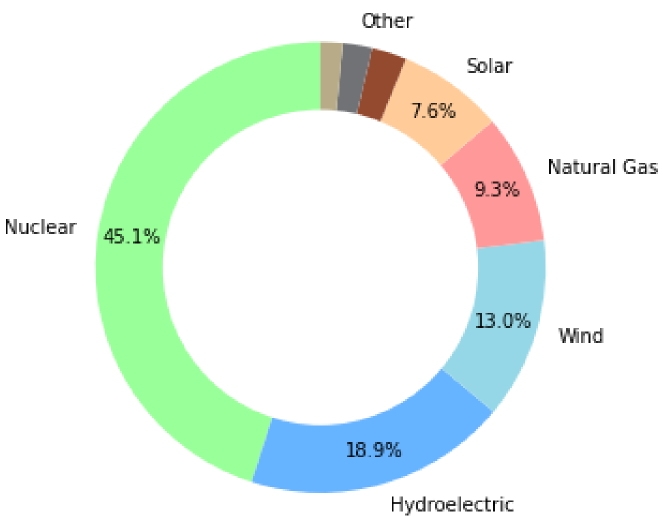

Figure 13.1: Share of installed power capacity per energy in 2020.

We can note that 2020 has been an atypical year in France and the world in general[2], with the lowest electricity consumption of the past couple decades. This explains the load factor of nuclear notably being lower than it used to be. This can be seen in the 2019 data shown in Table Table 13.2 on the next page, given here for comparison.

2: You don't say!

Table 13.2: 2019 electricity data for France

Type	Installed Capacity (GW)	Energy Produced (TWh)	Load Factor (%)
Nuclear	63.1	379.5	68.7
Coal	3.0	1.6	6.1
Petroleum	3.4	2.3	7.7
Natural Gas	12.2	38.6	36.1
Hydroelectric	25.6	60.0	26.8
Solar	9.4	11.6	14.1
Wind	16.5	34.1	23.6
Biomass	2.1	9.9	53.8

It is important to consider that while some load factors are artificially reduced[3], some are physically limited[4]. France proves to be a good benchmark for a real world case study of nuclear at a large scale, as the lower load factor (in the 60-70% range, compared to values in the 90% neighborhood for countries such as the USA, as we will see later) demonstrates the ability of nuclear energy to "load-follow". On the other hand, production of electricity from solar and wind installed capacity is cheap and even close to free[5], so a lower value here would be dictated almost entirely by physical limitations in the current market-driven grid.

3: Nuclear and thermal power plants suffer in part from having to follow the load, and in part due to a market effect

4: Wind, Solar, and Hydroelectric generate power only when the wind is blowing, the sun is shining, and sufficient water level is in a reservoir

5: Solar and wind indeed do not have any fuel cost, though they do have some maintenance costs

Load Follow

Load-Following is the act of quickly adapting the production to the demand by ramping up or down the output of the power plant.

The global demand in France was 473 TWh in 2019 and dropped to 449 TWh in 2020[6].

6: Impact of lockdowns and a slower economy. Interestingly, one can note that this is lower than the electricity produced in 2019 (537.5 TWh) and in 2020 (500TWh). France is a net exporter of electricity

In the near future (horizon 2050), it is likely that due to the electrification of the transportation sector and of the heating sector, the electrical demand in France would rise, though the energy demand would decrease. It is difficult to predict the average use of electricity of a French person then, but we can imagine that better efficiency would imply a lower

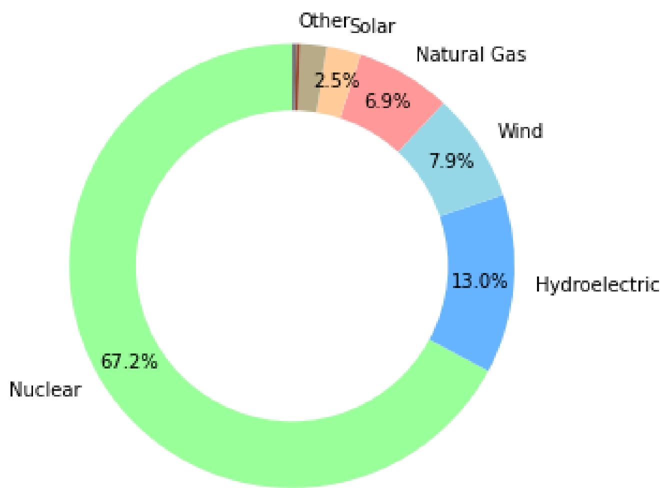

Figure 13.2: Share of 2020 production per energy.

consumption.

We will assume two main scenarios:

- Nuclear Scenario
- 100% Renewable Scenario

The Nuclear Scenario will consider that we expand the nuclear program in France to cover 100% of the electrical demand. The 100% Renewable Scenario phases out both fossil fuels and nuclear energy from the electricity generation mix. In those scenarios, we are not electrifying the car fleet in the country.

Of course, those scenarios are an exaggeration of what the near future may look like, but it will be interesting to compare their respective viability[7].

7: Note that no scenarios involving fossil fuels for electricity generation are acceptable, as the end goal is to transition to low carbon energy sources

In both scenarios, we can assume that, as a first order approximation, the entire energy capacity need will stay constant and be met by the given resources, that is, the entire annual consumption of 473 TWh. We will come back to this number when the time comes.

13.2 United States of America

This gives the information (2020 and future) for the USA

13.3 Brazil

This gives the information (2020 and future) for Brazil

13.4 China

This gives the information (2020 and future) for China

13.5 Nigeria

This gives the information (2020 and future) for Nigeria

Technology Costs

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In this chapter I will go over estimating the technology costs, per unit of energy installed and produced, for the low carbon options and their necessary ancillaries[1].

1: We will come back to that, but there is debate on the "low" part of "low carbon" for some of the technologies

Low Carbon Energies

As a reminder, those low carbon energies are:

- Wind
- Solar
- Water
- Nuclear
- Biomass

Storage is the necessary ancillary for 100% non-controllable renewable scenarios.

Technology costs can be difficult to account for fully. For example, renewable energy, due to their decentralized nature and their high output variability, require significant, and often considered separately, transmission grid upgrades. As we will discuss, storage becomes prevalent in 100% Renewable scenarios. And finally, the costs vary a lot by location, even within a single country, and over short periods of time.

14.1 Nuclear

Nuclear costs data varies a lot by country, depending on the workforce, the red tape, the NIMBYsm (Not In My Backyard) delays, the political will, and other considerations. Some projects are utter failures, while other seem quite successful. Hinkley Point C Power Plant, in the UK, is predicted to be four times more expensive than the identical Taishan Power Plant in China[2].

2: It is an important point that we will have to consider later on. This demonstrates less a nuclear problem and more a loss of competence at building large ambitious projects

The prices are obtained for advanced nuclear reactors as well as small modular reactors from the EIA.

We see that the capital cost is estimated at around $6,100 per kW for both systems. The cost of dismantling a reactor is estimated to be between $600 and $1,500 per kW[3]. Historically, hazardous waste industrial facilities dismantlement in different industries has been shown to cost around 10% of the capital cost, which validates our estimated range further despite the lack of actual data points. A value of $1,000 per kW of dismantlement will be used. Keep in mind that this cost is not as big as one would think in the grand scheme of transition, and that even tripling it would not impact the conclusions we will get at.

3: In France, EDF is estimating the cost at $350 per kW. Maybe, maybe not. I would not bet on it. At the same time, the UK is estimating the cost at up to $3,200 per kW. Again, maybe, maybe not. And again, I would not bet on it

The lifetime of a nuclear plant can be taken as 60 years. It typically ranges from 40 to 80 years, with 40 years being very pessimistic, and 80 years requiring significant upgrades over the years.

14.2 Gas with Carbon Capture

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14.3 Solar

We use the research from the National Renewable Energy Laboratory (NREL) for the cost of photovoltaic storage data. They also compute the cost of a photovoltaic and storage combined installation, but we will for now ignore those results, as we will want to account for those separately at a grid level (Feldman, 2021).

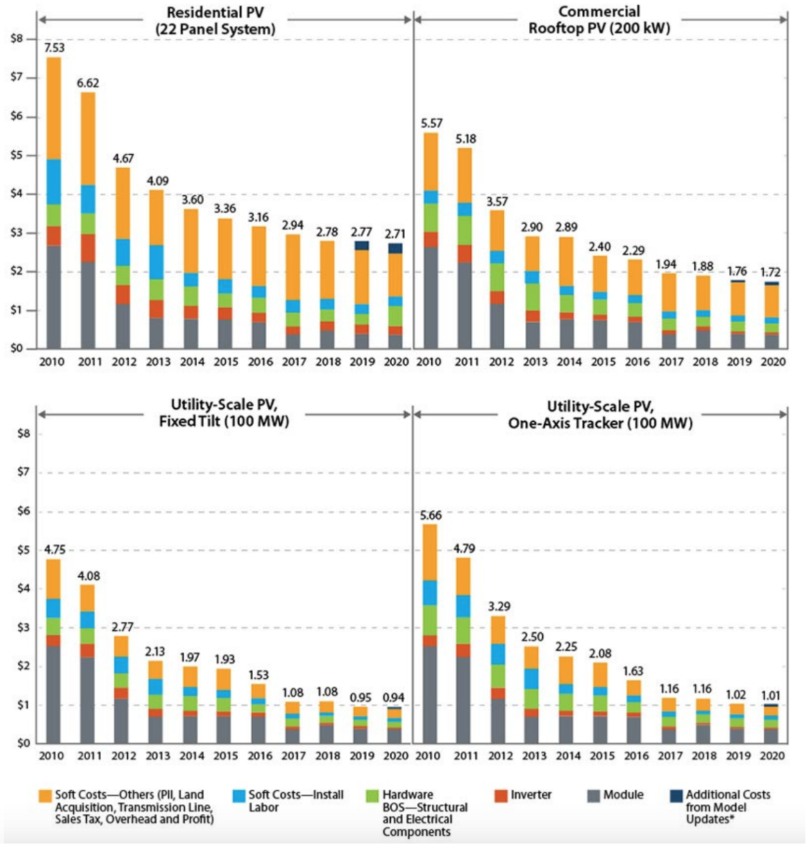

Figure 14.1: Evolution of photovoltaic costs over the last decade, for several system sizes ($/W).

What Figure Figure 14.1 on the preceding page shows is that while the cost of installing a solar panel went down significantly over the past decades, most of the easy optimization has been done and the rate of price reduction is quickly decreasing, showing an exponential trend[4].

4: In my experience, this is often glossed over in the media by simply saying that the prices for solar keep going down. Technically true, I will admit that, but nuance is always important

We can note that utility scale is separated into two main categories, a fixed tilt (your panel does not move) and a one-axis tracker (your panel follows the sun). The gain in load factor of the latter category is often offset by the cost difference. In this study, we will focus on the fixed tilt, while keeping in mind that a few optimizations could be done, without changing the overall conclusions.

So, what we can conclude from Figure Figure 14.1 on the previous page is that, indeed, the costs of solar energy have plummeted even in the last decade. However, we are reaching a limit that will be difficult to break through.

Consequently, in this calculation, we will assume that the current price of solar (remember, it is location dependent) is $940 per kW, and that we can only realistically expect few gains over the next decades.

The lifetime of a solar installation is around 25 years. Of course, it does not fail exactly at 25 years. But degradation rates are a non negligible issues, so even if it lasts a bit longer, the gains are not enormous. We can tweak this value to test the sensitivity later on.

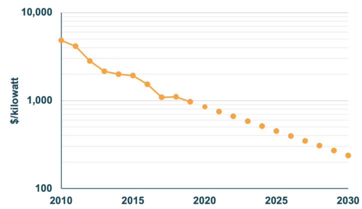

Figure 14.2: An interestingly optimistic view of the future...
Solar energy manufacturing, installation and maintenance will be absolutely free before the end of the century according to some. A good reminder to be careful with your extrapolations, and the use of logarithmic scales.

14.4 Wind

The wind costs have not been falling as sharply as solar in recent years. As can be seen in an NREL report on 2019 costs, onshore wind turbines will set you back around $1,436 per kW, and offshore wind turbines around $4,077 per kW (Stehly, 2020). It is indeed a lot more complicated to build and maintain an offshore turbine, due to the harsh ocean environment. There is a clear upside to that though, as the wind is more constant and drastically increases the load factor.

The lifetime of a wind turbine is around 25 years, give or take a few, and a little less for an offshore wind turbine, due to the harsher conditions.

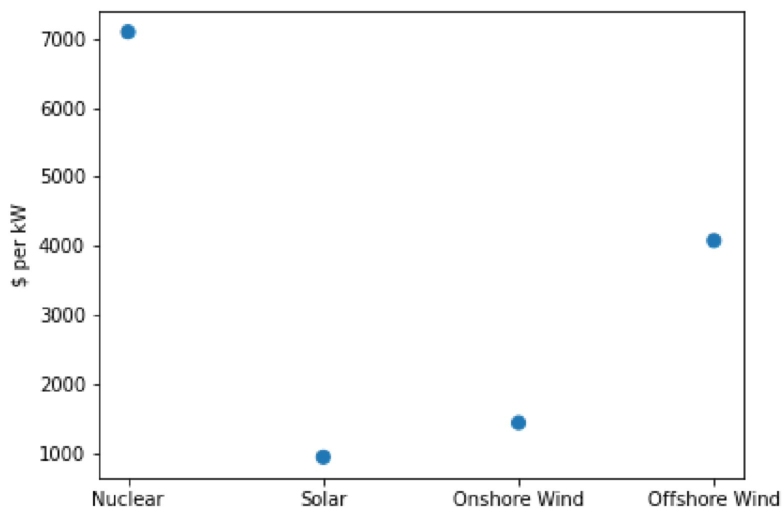

Figure 14.3: 2020 capital costs estimate to install various technologies.

Figure Figure 14.3 on the preceding page shows a damning picture for nuclear doesn't it? It is simply too expensive, several times the cost of solar and onshore wind, and even offshore wind project would be way cheaper. This is what most people, from media to politics, base their financial estimates on. And it is technically true.

But, and you knew a "but" was coming, this is misleading. Why is it misleading? Two main reasons:

- Lifetime
- Controllable energy

A nuclear power plant has a much longer lifetime than a renewable plant[5]. Even though, per kW, your cost is way cheaper, you do need to install several times as many kW over a long enough period of time.

5: Except hydroelectricity!

On top of this, nuclear energy is a controllable energy. You turn down the dial, you have less power. You turn it up, you have more power. Solar and Wind are non controllable energy sources. We do not decide when the sun will shine or when the wind will blow. Interestingly, with the sun, we have a pretty good idea of the production times, as we know for a fact that no energy will be output at night. But cloud cover varies (fast) and we are simply not able to model it currently, and probably never will. Wind has a higher load factor, as seen previously, but the variations are quite important and unpredictable.

Controllable versus Non Controllable

A controllable energy is an energy that you control. You can decide how much power you will output and (relatively) quickly adapt to the demand consumption quick changes.

A non controllable energy is an energy that you do not control. If it's sunny, you have some, and the amount you get depends on how sunny it is, not on a button you turn. If it's not sunny, you are out of luck and must wait until the sun (or the wind) comes back to turn your TV back on.

What this means is that one cannot simply compare the cost of nuclear energy with the cost of solar or wind energies, as the metrics are not measuring the same things. It is the same units, $ per kW, but the respective kW are two very different things depending on their ability to be controlled.

There is one thing that I would like to point out, and here is as good a place as any. The low (and falling) cost of manufacturing of solar panels and wind turbines is, in part, due to easy and cheap energy sources for industrial activities, provided by fossil fuels. While I am not quantifying that value, it is not that far-fetched to see that removing that access may impact the manufacturing costs negatively, especially during a transition phase.

Levelized Cost Of Electricity

You will sometimes see the term LCOE, which stands for Levelized Cost of Electricity. What this metric does is account for time in the comparison, so that the lifetime discrepancy is corrected for.

A lot of people takes the LCOE at face value, and argue that it is the value to consider. In the current energy mix, this is correct. However, the controllability difference is still not considered, and at high enough penetration of renewable (and any 100% renewable scenario), this does not hold true anymore from a purely physical point of view. You can install as many solar panels as you want, when it's night time, you get zero power, which you cannot afford in modern society.

14.5 Storage

Now, we have seen the cost of installing solar and wind energy. Is that enough? Well, if we consider a 100% Renewable scenario, we need a way to efficiently dispatch electricity to cover the varying demand.

As mentioned previously, we are going to make an assumption that I am convinced you will tend to agree with. We do want a cleaner world[6], but we still want Netflix, we still want a choice of clothes, we still want our phones, we still want our burgers, we still want to turn on the lights whenever we want to, we still want to be able to take the train or the car to go places,. . . In short, we still want a world at least similar to the one we are living in today. Sure, we can and will likely have to make some sacrifices and be more aware of what we can do on a day to day basis, be mindful of when to do the laundry or turn on the oven. But comfort is not going away without a fight. Additionally, I personally hope the impoverished of the world[7] will have access to a better life and rise to a level of comfort at least somewhat similar to us today, which means access to energy.

6: We actually need it

7: The ones who will be disproportionately affected by climate change, remember. . .

So, assuming this, and accounting for a 100% renewable energy world, it is easy to see that to meet our needs, the means of production will have to become controllable. This is where energy storage comes into play.

We will consider multiple options, from the proven pumped storage stations to the highly hyped battery energy storage system[8]. Pacific Northwest National Laboratories (PNNL) data will be used as reference. Interestingly, they give a value in 2018 as well as an estimated projection up to 2025. In this report, we will consider the more advantageous 2025 values given (Mongird, 2019).

8: Often simply called "batteries" or "grid-scale batteries" in the news articles you may have come across

For a battery energy storage system, out of the multiple options available (Sodium-Sulfur, Li-Ion, Lead Acid, Redox Flow, . . .), the cheapest is selected, that is Li-Ion, at $1,446 per kW and $362 per kWh. The lifetime of such batteries is 10 years, maybe 15 years could be doable by 2025.

Energy storage: kW versus kWh

Recall the energy storage section for the difference between the cost per kW (power capacity, what you can store) and the cost per kWh (energy capacity, what you can get back)

Let's now look at the more classical options, namely pumped storage stations (PHS) and below-ground compressed air energy storage (CAES). According to the same PNNL report, pumped storage clocks in at a cost of $2,638 per kW and $165 per kWh, while compressed air storage is given at around $1,669 per kW and $105 per kWh. The lifetime of a pumped storage station has been estimated to be around a century, while a compressed air storage system is given at 25 years.

While compressed air storage is cheaper, the conversion ratio, or in other words the losses incurred by the storage and restitution of the energy is much lower.

Consequently, we will for now consider the best storage technology on the long term, which is the pumped storage hydroelectric solution. It is coincidentally the only one that has really been used at a non-negligible scale and for a long time. We will come back to the other technologies later on.

14.6 Grid

The grid network is very often overlooked. It is now a cost that is folded into an energy source technology, despite the fact that it depends strongly on what energy is being used.

Those costs are extremely difficult to project, especially for a 100% renewable system for which no data point exists. Studies (IER, 2019) have shown a cost roughly a third of the investment in the production means themselves (solar panels, wind turbines). However, countries currently developing it, such as Germany, have seen an actual cost impact on production of 100%. In other words, 1 dollar spent on the installed renewable capacity required another dollar invested onto the grid infrastructure.

In this study, we will consider the value above of one-third of the investments made, which correspond to roughly $500 per kW renewable installed. A sensitivity analysis will also be performed to see the impact of modifying this parameter.

14.7 Summary

Table 14.1: 2020 technology costs estimates

Technology	Capacity Installation	Storage Installation	Grid upgrades
Nuclear	$7,100 per kW (25y)	Not Applicable	Not Applicable
Solar	$950 per kW (25y)	$165 per kWh (100y)	$500 per kW (50y)
Onshore Wind	$1,436 per kW (25y)	$165 per kWh (100y)	$500 per kW (50y)
Offshore Wind	$4,077 per kW (25y)	$165 per kWh (100y)	$500 per kW (50y)

15 A Renewable Solution?

In this chapter I will go over computing the amount of capacity to install, the amount of storage to install, the impact to expect on the grid, and the impact of a renewable mix versus what we will end up computing, a homogeneous system.

A Renewable Problem 16

In this chapter I will go over the costs needed for 100% Renewable scenarios and compare with the cost of a Nuclear scenario over the course of 50 years and a century.

A Bigger Renewable Problem 17

In this chapter I will go over the physical limitations of 100% Renewable scenarios, from pumped storage locations and scale to batteries materials mining and photovoltaic and wind land area constaints.

A path forward?

18 The Nuclear Problem

In this chapter I tackle the issue of nuclear power, from siting to proliferation to fear and waste.

19 The World Needs

In this chapter I scale the renewables scenario to the world, with current assumptions and social assumptions

We are under severe time constraints, and it is important to consider, from what we talked about previously, that continued economic growth is not a fact of nature, and is extremely dependent on energy. Peak oil is approaching quickly, and some countries have passed it already, which notably means that it is likely any energetic transition will have to take place in a recessive context. Investment will not be available in the same way. Conflicts, devastation, migrations on a scale never seen before may also happen due to the climate change very impact, with much stronger hazards, as discussed in a previous section.

We have shown that what is needed, by default of being the only option, is nuclear and renewables, and energy storage for localized use only.

Nuclear "reinstallation" will take time, and we can use that time to ramp up to a good penetration of renewable and make progress. Something is better than nothing, as long as there is a plan.

20 Mental Health – Coping with the situation

In this chapter I mention who we can blame (nobody really), what one can do, what carbon accounting is and how to reasonably use it to better the world.

Fossil fuels replacement is absolutely daunting. Writing off options is the worst thing one can do, it takes a village, and we've been on the clock for a while already. But investments need to be made coherently from a unified front.

- Meditate
- Vote, with your voice and your wallet
- Do not go into the fight with a blindfold and one hand behind your back. Nuclear is important.
- Renewable energies are also important, due to their deployment speed, but do not aim for 100% renewable, as storage is not a scalable savior and we will get stuck
- Change your habits, be ready to not be able to watch Netflix at 1am or accept that your electricity may go out at any time.

Appendix

A

Heading on Level 0 (chapter)

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

A.1 Heading on Level 1 (section)

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Heading on Level 2 (subsection)

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Heading on Level 3 (subsubsection)

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Heading on Level 4 (paragraph) Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

A.2 Lists

Example for list (itemize)

- First item in a list
- Second item in a list
- Third item in a list
- Fourth item in a list
- Fifth item in a list

Example for list (4*itemize)

- First item in a list
  - First item in a list
    - First item in a list
      - First item in a list
      - Second item in a list
    - Second item in a list
  - Second item in a list
- Second item in a list

Example for list (enumerate)

1. First item in a list
2. Second item in a list
3. Third item in a list
4. Fourth item in a list
5. Fifth item in a list

Example for list (4*enumerate)

1. First item in a list
    a) First item in a list
        i. First item in a list
            A. First item in a list
            B. Second item in a list
        ii. Second item in a list
    b) Second item in a list
2. Second item in a list

Example for list (description)

First item in a list
Second item in a list
Third item in a list
Fourth item in a list
Fifth item in a list

Example for list (4*description)

First item in a list
    First item in a list
        First item in a list
            First item in a list
            Second item in a list
        Second item in a list
    Second item in a list
Second item in a list

B

Fonts Testing

B.1 Font Sizes

The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

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The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

The quick brown fox jumps over the lazy dog.

B.2 Font Families

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

The quick brown fox jumps over the lazy dog. Medium.

The quick brown fox jumps over the lazy dog. Bold.

The quick brown fox jumps over the lazy dog. Upright.

The quick brown fox jumps over the lazy dog. Italics.

The quick brown fox jumps over the lazy dog. Slanted.

The quick brown fox jumps over the lazy dog. Small Caps.

`Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift - not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.`

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`The quick brown fox jumps over the lazy dog. Italics.`

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The quick brown fox jumps over the lazy dog. Small Caps.

Greek Letters with Pronunciations

Character	Name	Character	Name
α	alpha *AL-fuh*	ν	nu *NEW*
β	beta *BAY-tuh*	ξ, Ξ	xi *KSIGH*
γ, Γ	gamma *GAM-muh*	o	omicron *OM-uh-CRON*
δ, Δ	delta *DEL-tuh*	π, Π	pi *PIE*
ϵ	epsilon *EP-suh-lon*	ρ	rho *ROW*
ζ	zeta *ZAY-tuh*	σ, Σ	sigma *SIG-muh*
η	eta *AY-tuh*	τ	tau *TOW (as in cow)*
θ, Θ	theta *THAY-tuh*	υ, Υ	upsilon *OOP-suh-LON*
ι	iota *eye-OH-tuh*	ϕ, Φ	phi *FEE, or FI (as in hi)*
κ	kappa *KAP-uh*	χ	chi *KI (as in hi)*
λ, Λ	lambda *LAM-duh*	ψ, Ψ	psi *SIGH, or PSIGH*
μ	mu *MEW*	ω, Ω	omega *oh-MAY-guh*

Capitals shown are the ones that differ from Roman capitals.

Alphabetical Index

preface, v