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Solar Photovoltaic Energy in Portugal
Environmental Sustainability on the Road to Carbon Neutrality

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Doutoramento em Gestão, na especialidade de Métodos Quantitativos Aplicados à Gestão

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Dezembro, 2021

BUSINESS SCHOOL

Métodos Quantitativos para Gestão e Economia

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Dezembro, 2021

Dedico este trabalho aos meus netos: Jaime, Joana e Tiago. E também à Rosa, que tanto esperou por mim durante estes longos quatro anos…

Agradecimento

Agradeço às minhas orientadoras, Professora Maria João Cortinhal e Professora Mónica Meireles, o apoio incondicional que me deram ao longo deste trabalho. E ao Professor José Dias Gonçalves a valiosa orientação proporcionada durante a parte curricular do doutoramento. Agradeço ainda ao Professor Vítor Sequeira Roldão e ao Professor Helder Coelho por, generosamente, terem recomendado a minha candidatura ao doutoramento.

Resumo

Nesta tese, avalia-se a sustentabilidade ambiental das centrais fotovoltaicas no quadro dos Objetivos do Desenvolvimento Sustentável e desenvolvem-se duas contribuições originais com esse propósito: 1) um método de cálculo da área total futura de centrais implantadas no solo; 2) o cálculo de benefícios e custos ambientais de centrais no solo combinando emissões primárias de GEE, associadas ao fabrico, com emissões secundárias dos solos plantados afetados, no contexto da neutralidade carbónica. O cálculo da ocupação futura conjuga as evoluções temporais da potência instalada e do rendimento dos painéis fotovoltaicos e concretiza-se por uma equação integral linearizada por troços. A área de Portugal continental estimada para 2050 varia entre 29000 e 31000 hectares, valores suficientemente altos para recomendar o planeamento distribuído das centrais solares, evitando-se conflitos de uso do solo. Como resultado intermédio obtiveram-se ainda distribuições da intensidade de uso do solo de centrais fotovoltaicas em Portugal continental. O cálculo de benefícios e custos ambientais recorre à generalização da métrica do tempo de retorno carbónico, CPBT, para incluir tanto as emissões iniciais como as distribuídas pelo ciclo de vida das centrais, estas últimas ajustadas pelo diferimento temporal e pelas reduções planeadas da intensidade carbónica da rede. Produziram-se mapas do CPBT e de outras métricas para Portugal continental, com resolução de 5,5 km^2. O retorno carbónico de centrais de silício monocristalino eliminando florestas de eucaliptos atinge 24 anos (média, 19 anos), valores que recomendam o cálculo sistemático dos benefícios e custos ambientais das centrais fotovoltaicas e a proteção consistente dos sumidouros carbónicos naturais.

Palavras-chave: centrais fotovoltaicas, emissões de GEE, uso do solo, tempo de retorno carbónico, neutralidade carbónica, distribuição geográfica.
Códigos JEL: Q420, Q540.

Abstract

In this thesis, the environmental sustainability of solar photovoltaic (PV) power plants is assessed under the framework of the Sustainable Development Goals. And two original contributions are proposed towards that goal: 1) a method to determine total future land occupation by ground-based PV plants; 2) an evaluation of the net GHG benefits of PV over vegetation-covered land that combines primary emissions from manufacturing and secondary emissions from land-use change, while the electric grid reduces its carbon intensity. Future PV areas were calculated through a piece-wise linear model based on an integral equation incorporating the concurrent growth of both installed capacity and panel efficiency. Total occupation by PV plants in continental Portugal in 2050 was estimated to be 29000 to 31000 hectares, a high value recommending distributed planning of solar PV over the territory to avoid land-use conflicts. Land-use intensity distributions for Portuguese solar PV plants were also calculated. The GHG net benefits of PV plants were addressed by extending the carbon payback time (CPBT) to include initial emissions and emissions distributed over the PV power plants lifetimes. All the distributed emissions were time-adjusted due to their delayed impacts on the atmosphere. Maps for CPBT and other metrics were generated for the whole of continental Portugal, with 5.5 km2 resolution. CPBT reaches 24 years (average: 19 years) for mono-crystalline systems over land previously occupied by eucalyptus forests. These long CPBT values recommend that benefits and costs of solar PV plants are systematically assessed, with natural carbon sinks consistently protected.

Keywords: photovoltaic power, GHG emissions, land use, carbon payback time, carbon neutrality, PV metric maps.
JEL codes: Q420, Q540.

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Abbreviations

cap	per capita
CdTe	cadmium telluride
CF	capacity factor
CFT	carbon footprint
CIS	cadmium indium selenium
CO_2e	carbon dioxide equivalent
CPBT	carbon payback time
EJ	exajoule, 10^{18} joules
EPBT	emissions payback time, same as CPBT
EROI	energy return on (energy) invested
GHG	greenhouse gas
GIS	geographic information system
GWh	gigawatt-hour, 10^9 watt-hours
GWP	global warming potential
ha	hectare, 10,000 m^2
HDI	human development index
J	joule (watt-hour)
kcal	kilocalories or Calories (4.2 kilojoules)
kWh	kilowatt-hour
LCA	lifecycle analysis
LCIA	lifecycle impact analysis
LUI	land use intensity, same as LUE
MDGs	millennium development goals

MJ	mega joule, 10^6 joules
m-Si	monocrystalline silicon, same as mono-Si, m-SI
MVC	mass value carbon
MW	megawatt, 10^6 watts
MWh	megawatt-hour, 10^6 watt-hours
NTG	net to gross energy factor
PEF	primary energy factor
PJ	petajoule, 10^{15} joules
PV	photovoltaic
RF	radiative forcing
SDGs	sustainable development goals
TAWP	time-adjusted global warming potential
TES	total energy supply, same as TPED (total primary energy demand)
TFEC	total final energy consumption
toe	tonne of oil equivalent
ton	10^6 grams, Mg
tonne	metric ton
TWh	terawatt-hour, 10^{12} watt-hours
W	watt (joule/second)
W_{AC}	power in watts delivered as alternating current
W_{DC}	power in watts delivered as direct current

Introduction

This work is about a technology that converts solar radiation directly into electricity: *solar photovoltaics (PV) power*. It intends to discuss how solar PV power contributes to solve a vital contemporary problem: to provide ample energy for societal needs while replacing energy sources that are causing both a potential catastrophic climate crisis and a global ecological crisis. What is at stake is how solar PV power may contribute to the overall pledge of *sustainable development*: to satisfy the social and economic needs of human societies while promoting the preservation, stabilization, and restoration of the Earth-system, on which all life forms rely.

As Vaclav Smil (2017) remarks, any energy transition is built upon the technologies that precede it. This also applies to solar PV power. The technology carries an 'original sin' of harmful emissions handed over by a fossil-fuel based manufacturing industry. This is apparent in the fact that most of its main components, the solar panels, come from countries that are still heavy emitters of greenhouse gases. The emissions embodied in solar PV systems are assigned to the whole energy that solar PV power systems deliver over their lifetimes, defining their *primary* carbon footprints. These are small enough to make solar PV systems *avoiding* or *saving* greenhouse emissions, in most cases, by replacing electricity generators relying on fossil fuels. But considering only primary emissions misses another key impact of solar PV that may drastically reduce its emission-saving benefits: *land occupation*.

Solar PV is a technology that by its own nature occupies large areas of sun-exposed territory. The areas may be over existing structures (rooftops, façades, water reservoirs, etc.) but large *utility-scale* solar PV plants are built over land used for agriculture, forestry, or natural reserves. So, while contributing to 'retire' fossil-fuel energy , solar PV may cause its own social, economic, and ecological problems. One impact, often overlooked, is *secondary* emissions due to land occupation. If land covered by vegetation is occupied by a solar PV plant the natural cover will be fully or partially cut down. This causes emissions not only from the initial clearing but also from the elimination of the permanent *carbon sink* service delivered by plants. For instance, if the land cleared to install a solar PV plant is a forest, secondary plus primary emissions may be enough to cancel the emission avoidance benefits of the power plant.

Solar PV power must then be studied not only for the benefits it brings to sustainable development but also for the trade-offs it imposes, and this is one of the aims of this thesis.

Solar PV energy has enormous potential as an instrument to achieve many of the sustainable development goals. Two factors are seen as determinants for this role: the abundance of the solar resource; and the future predominance of electricity as an energy form.

Solar irradiation is a plentiful energy resource spread all over the world, namely in less developed countries. ESMAP, an assistance program created by the World Bank and dedicated to the promotion of sustainable energy solutions in low and middle-income countries, recently published a *global solar atlas* analysing the solar PV potential of 210 countries (ESMAP, 2021). The atlas presents the theoretical and practical photovoltaic potential of the territory of each country, including the areas more suitable to install PV power plants. In fact-sheets for each country, ESMAP (2021) highlights solar maps, area statistics, and values for socioeconomic indicators: area, population, GDP per capita, human development index (HDI) ranking, share of population with access to electricity, electricity consumption per capita, installed PV capacity, etc.

The study includes a list of countries ranked by their average practical PV potential. It reveals that around 20% of the global population lives in 70 countries featuring *excellent* conditions for solar PV. Middle East and North Africa countries, Sub-Saharan African countries, and Afghanistan, Argentina, Australia, Chile, Iran, and Mexico belong to this 'elite'. In the middle range of PV potential are countries representing 71% of world population, a large group including populous nations like China, India, the United States, Indonesia, and Brazil. At the low end of solar PV potential are 30 countries, with 9% of the global population, a group that is dominated by the European countries, except for southern Europe.

As ESMAP (2021) quickly points out, even bottom of the list countries like the United Kingdom, Germany, and Japan have large installed capacities of solar PV power. So, differences in the solar resource, due mostly to climate and latitude, do not hinder countries from exploiting a permanent, free, and relatively stable energy resource.

ESMAP (2021) presents several interesting correlations between PV potential and socioeconomic indicators. Among others, it highlights that most of the countries with very low electricity access rates also have excellent PV potential; the same happens with countries that score lower in the Human Development Index. Solar PV may then contribute strongly to one of the key sustainable development goals - Energy for All - as detailed in the body of the thesis.

If electricity is likely to be dominant in the global energy system, then solar PV is also likely to play a key role in the system since it provides a direct transformation of solar light into electrical current – of photons into electrons. Bogdanov et al. (2021) present their results of a simulation of the global energy system, from 2015 to 2050, considering all energy technologies (renewable and non-renewable) and their projected costs, for 145 regional energy subsystems, aggregated for nine world regions. They argue that their model has an unprecedented time definition as it can determine how the energy demand of every year in the 35-year interval can be satisfied by the available energy sources at the lowest overall cost.

Discussing their results, Bogdanov et al. (2021) remark that *electricity* - derived at 98% from renewable sources in 2040 and entirely free of GHG emissions by 2050 - can be the *dominant provider of energy services* not only for the traditional power sector (the electrical grid) but also for *heat generation* in households and many industries, for *transportation*, and for *desalination*. This can be achieved by linking solar and wind electricity generation to energy storage, of several types, and by *coupling different energy sectors* with 'power-to-X' technologies, including among others the production of hydrogen by electrolysis, the generation of heat through electrical heat pumps, and the production of potable water through electric desalination systems.

In their cost-optimal, high-electrification scenario Bogdanov et al. (2021) project that the primary energy demand of the whole world *will be satisfied 89% by electricity in 2050*, with zero fossil fuels. They also claim that solar PV will become *the major electricity provider* by 2050: a 'critical role' to be played not only by utility-scale solar PV plants but also by 'prosumers' generating and consuming their own solar electricity while selling the excess to the grid.

Their projections for solar PV power by 2050 are astonishing: *over 60 terawatts of installed capacity*. Wind power, while dominant until the mid-2030s is projected to grow more modestly to about *8 terawatts* in 2050. Hydro electricity, currently the main renewable energy in many countries, plays only a minor role in 2050.

Bogdanov et al. (2021) also determine levelized costs of energy (mostly electricity) for the years until 2050. Their results are reassuring: despite the enormous investments of the energy transition, calculated from projected CAPEX values, the cost of energy stays approximately constant over the 35-year period at 50 to 60 euros/MWh, equivalent to 5 to 6 euro cents per kilowatt-hour. ESMAP (2021) also estimates current levelized costs of electricity generated by utility-scale solar PV in several regions of the world. Their results vary from less than 6 to 10 dollar cents in the Middle East and North Africa, and Sub-Saharan regions, further supporting the role of solar PV in sustainable development.

Portugal is one of the best countries of Europe regarding average PV potential: it is number 100 in the ESMAP (2021) ranking behind Cyprus, Malta, and Spain but in well in front of Greece and Italy, its followers. However, from the 'top four' it is also the country where the recommended area to implement PV power plant is smaller compared to the area of the whole territory. Portugal is also heavily forested. A calculation by the author of the area of *all classes of forests* in continental Portugal using the 2018 release of COS, the Portuguese map of land occupation (DGT, 2019), yields 34,853 square kilometres, i.e., about 39% of the whole continental area.

It is thus concerning that a country so rich in solar resource in most of its territory has also a large part of its territory occupied by forests, agriculture, and protected areas since it means there will be *many opportunities for land-use conflict* and, as noted above, many opportunities for solar PV developments to yield *poor emissions savings benefits* - not to speak of other negative environmental and social impacts.

Discussing the benefits and trade-offs of solar PV power in continental Portugal is, therefore, another general aim of this thesis. It is also the subject for which the author developed two original contributions, summarized in the Abstract, justifying the focus on *solar photovoltaic energy in Portugal* in the title of the thesis.

This document is organized around two central chapters: Chapter 1, "The Quest for Energy and its Consequences" and Chapter 2, "Solar Photovoltaic Power as a Sustainable Technology".

Chapter 1 is mainly a literature review about energy, as used or captured by humans since the appearance of our species.

Section 1.1, "The Energy Exponential" relies mostly on the work of Ian Morris, an historian and archaeologist, who developed a plausible quantification of the energy, per capita, captured by humans, from the beginning of the Holocene period (14000 BC) to actuality (2000 AD). His motivation was not only the study of energy capture by humans but the development of an index for social development, which also contained other characteristics. But as he points out, energy capture is a fundamental, defining factor of civilization - an idea that Morris credits to Leslie White, an author whose work is discussed at the end of the chapter. The 'energy exponential' assembled by Morris is complex but two main inflection points are clearly present: the energy revolutions brought by farming and by industrialization.

Section 1.2, "Towards the Anthropocene" is a long summary of the evolution of human societies regarding their ability to capture energy. It describes how significant qualitative and quantitative changes in energy capture are linked to structural changes in human societies – changes that ultimately lead to higher per capita energy usage and higher population levels. The last part of the section highlights what could be called the three, mutually-reinforcing English *innovations* of the 17th and 18th centuries: *capitalism* - a new economic and social system based on competitive markets; the *steam engine* - an efficient machine to convert heat energy into motion; and *coal* – the fuel that started the long rule of fossil fuels over the global energy system that we still endure today. The environmental changes caused by pre-industrial societies are also addressed, in preparation for the next section.

Section 1.3, "Red Alerts" presents what is underlined by its title: the vast and deep changes that humans have imposed on the climate and on the biosphere. And how they are endangering life on the planet, all species included. The text provides several pieces of evidence about the impacts: the reduction of wildlands to just one quarter of the total land area of the earth; the huge growth in the biomass of humans and domesticated animals, and steep decrease in the biomass of wild terrestrial and marine species; the enormous growth and current size of the global anthropogenic mass, in use and as waste; and the vast emissions of greenhouse gases from the exploration and usage of fossil fuels. It's an alarming description of consequences that are now, hopefully, in the mind of everyone.

Section 1.4, "The Future of Energy Use" raises deeper questions: Why have humans reached such huge amounts of per capita and global energy consumption? Can energy growth provide decent living standards for all, while ending or lessening the profound inequalities between developed and under-developed countries? Can the massive, endless consumption of material resources taken from the planet and from the biosphere be controlled and reversed?

The first question leads to the contrasting views of Alfred Lotka and Leslie White. Was the incessant growth in energy capture by humans an inevitable, unconscious process driven by biological evolution? Or instead, a result of cultural evolution: a strictly social process? The other questions lead to research work and social economic initiatives that may provide solutions under the framework of sustainable development.

Chapter 2 concentrates on the positive and negative attributes of solar PV in view of the sustainable development goals, and how they apply to solar energy in Portugal. It combines literature review and original contributions, ending with a discussion of the opportunities and issues raised by the development of solar PV power in Portugal.

Section 2.1, "Sustainable Development" includes a brief history of the initiatives towards the ideal of sustainable development and, more recently, to the well-defined set of seventeen sustainable development goals (SDGs). It addresses the principles behind the SDGs as well as the monitoring tools for their progress towards completion. A section on the various reasons for criticism is also included. A key part of Section 2.1 presents and discusses a nascent methodology to assess social, economic, and technical initiatives (e.g., large energy projects) that considers the complex network of interlinkages between the SDGs and their targets, which may reinforce or counteract their progress.

Section 2.2, "Is Solar Photovoltaic Power Sustainable?" takes two seminal works on SDG interlinkage assessment, addressing the provision of energy and energy-providing projects, and instantiates them to focus on solar PV power, extending the conclusion to Portugal whenever possible. The two works, by Fuso Nerini et al. (2017a) and Castor et al. (2020a), share principles and literature but in the former results are explicitly presented, while in the latter all results are incorporated in a decision support tool, fully documented. The approach in this thesis was to combine the results of both works plus additional literature review into an explicit assessment. The outcome is a dense, goal-by-goal discussion of the sustainability of solar PV.

Section 2.3, "Environmental Impacts of Solar Photovoltaic Plants" presents and discusses the results of a literature review on the topic. It summarizes works pointing to the positive and negative impacts of large-scale PV power plants and works offering suggestions to mitigate their negative impacts. Some of the articles reviewed provided the motivation for the original work presented in this thesis.

Section 2.4, “Land Occupation by Solar Photovoltaic Plants” summarizes the work presented in a conference paper (reprinted in Annex A1), extending the associated literature review, and discussing limitations and further work. The work contains two main contributions: 1) the measurement of the capacity-based *land use intensity* (LUI), in hectare per megawatt, of the known utility-scale PV power plants in continental Portugal; 2) the development of a novel method to estimate future land occupation of solar PV plants, and its application to Portugal. The results of both contributions are presented and discussed.

Section 2.5, “Solar Photovoltaic Emissions and Returns on Energy and Carbon” summarizes the work presented in a conference paper (reprinted in Annex A2) and other related unpublished results, while also extending the literature review and discussing limitations and further work. The section reports two main contributions: 1) the calculation of the spatial values in continental Portugal of *five* energy and *primary* emissions metrics for the *three* main solar PV technologies (mono-Si, CdTe, CIS); 2) the calculation of the spatial values in continental Portugal of the Carbon Payback Time, an emission metric expressing the return on carbon emissions expected for a solar PV plant replacing energy from the electric grid. The Carbon Payback is calculated considering the technology-linked *primary* emissions and considering, additionally, the environment-linked secondary emissions. The spatial values of all metrics and key intermediate results are presented as maps of continental Portugal in Annex A3. The outcome of both primary and secondary emissions (with the latter resulting from clearing a forest) has deep implications for the assessment of solar PV impacts, which are discussed in the section and the conference paper referred above.

Section 2.6, “Opportunities and Issues of Solar Photovoltaic Energy in Portugal” starts by discussing the present and future of energy use in Portugal, using international and national statistics. Future projections are based on the long-term government Roadmap for Carbon Neutrality 2050 (RNC2050, 2018) and on the medium-term National Energy and Climate Plan 2021-2030 (PNEC, 2019). Solar PV projections are discussed in detail. The section proceeds to a discussion of the opportunities and risks of environmental impacts that the Portuguese territory presents to solar PV development; and to a comparison with other solar-resource rich European countries. It ends with two subjects: 1) how solar PV power has attracted opposition from concerned citizens, environmental organizations, and affected businesses, and the possible reasons for the strength in Portugal of this form of energy, despite the problems it is causing; 2) how poor environmental impact assessment may be related with stronger negative impacts, and how some foreign governments are acting to prevent or mitigate those consequences.

CHAPTER 1

The Quest for Energy and its Consequences

1.1. Exponential Growth

In 2010, Ian Morris, an historian and archaeologist proposed a quantitative measure to assess social development across the ages – a social development index – providing estimates for its value from 14000 BC (the end of the last glaciation) to present times (Morris, 2010). He also differentiated social development for what he identified as the two main geographical “cores” of human society, naming them *West* and *East*.

The cores were defined dynamically, with the western core starting in Mesopotamia and spreading through time to the middle East, north Africa, southern and northern Europe and to the

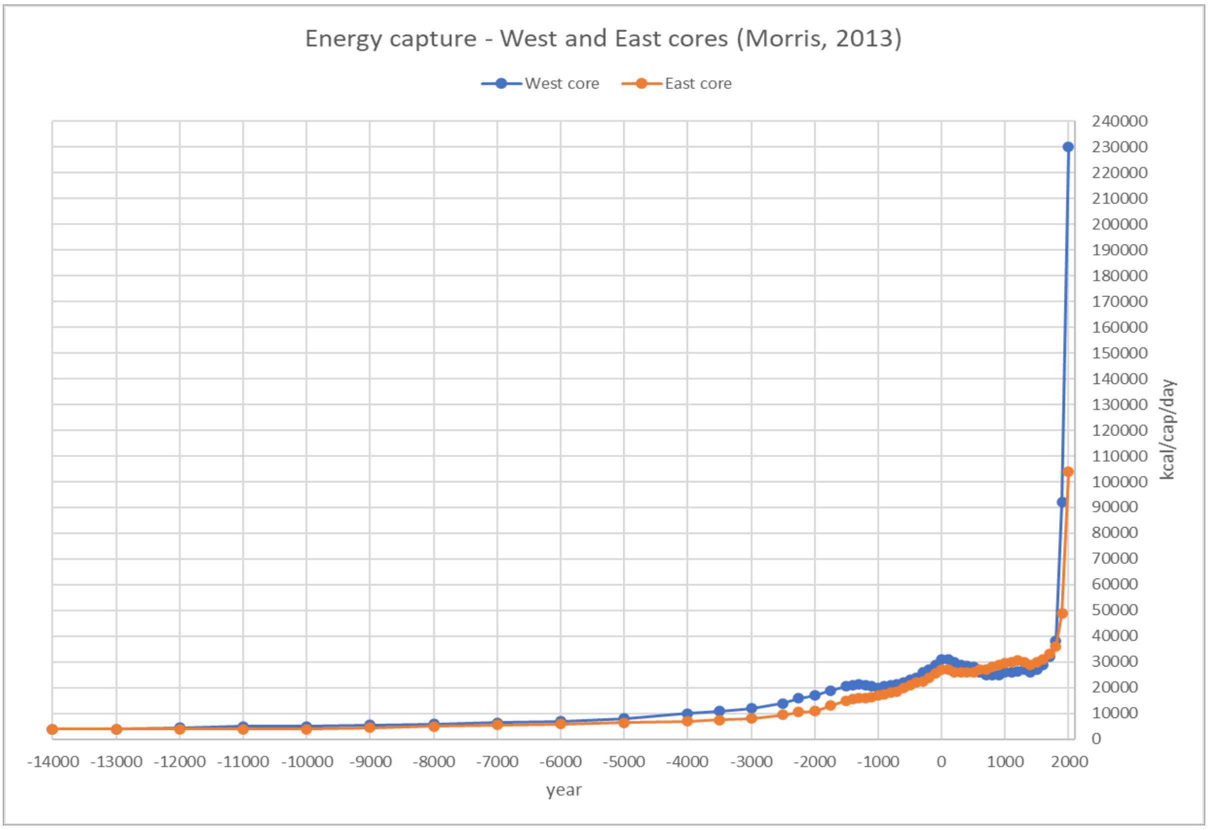


Figure 1.1 - Energy capture from 14000 BC to 2000 AD. Data from Morris (2013).

Americas, from the 16th century onwards. The eastern core was defined as starting in central China between the Yellow and the Yangzi rivers, spreading through time to more regions of China, southeast Asia, south Asia, Korea, and Japan.

Morris (2010) defines social development simply as “a measure of communities’ abilities to get things done in the world”, although he provides a more detailed formulation. His index has four “traits” or attributes: energy capture, organization, information technology, and warfare capability; with energy capture quantified in kilocalories per capita per day (kcal/cap/day). The methodology and results regarding the index are fully discussed in Morris (2013), a follow-up book to Morris (2010).

The detailed estimation of energy capture across sixteen centuries, a central part of his study of social development, is particularly relevant for the subject of this chapter. Figure 1.1 shows energy capture for the full-time scale: from -14000 BC to –4000 BC in intervals of one thousand years, after that in intervals of one or several hundred years. Figure 1.2 details the period from 100 BC to 2000 AD.

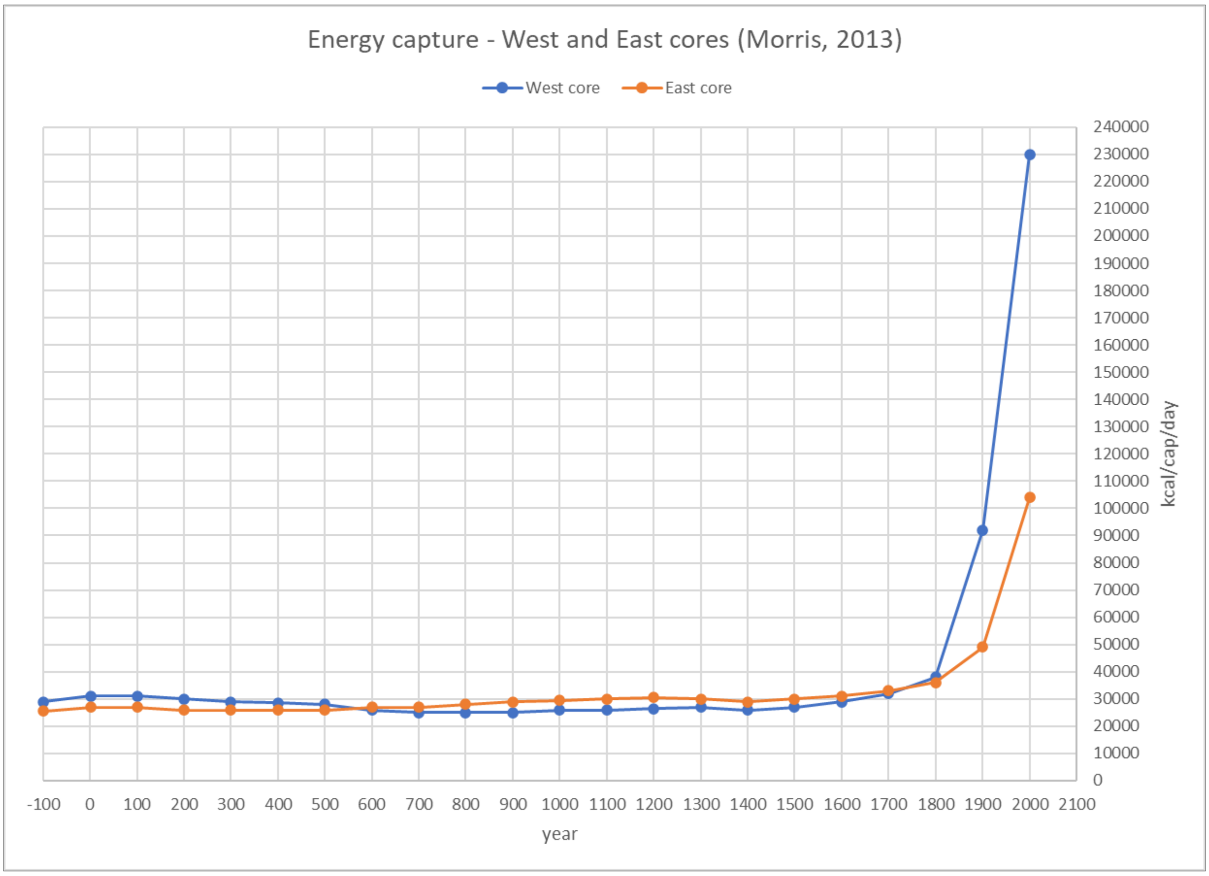


Figure 1.2 - Energy capture 100 BC to 2000 AD. Data from Morris (2013).

For his estimates of energy capture, Morris (2013) used the framework shown in Figure 2.3, proposed by Earl Cook (1971). Cook differentiated *food* and *non-food* energies. Food energy was subdivided in plant and animal food, the latter including feed given to domesticated animals. Non-food energy was subdivided in home and commerce, industry and agriculture, and transportation.

As explained by Morris (2013) his estimates integrate numerous studies performed by historians and archaeologists and historical accounts and records, when available. He also uses interpolation to estimate intermediate values, with plausibility checks. For 14000 BC, with humans living in huntergatherer groups, he considered 4,000 kilocalories per capita per day to account for food energy and energy associated with simple tools and rudimentary housing. For 2000 AD he kept the same value that Cook (1971) suggested for the US: 230,000 kcal/cap/ day, an astonishingly high value.

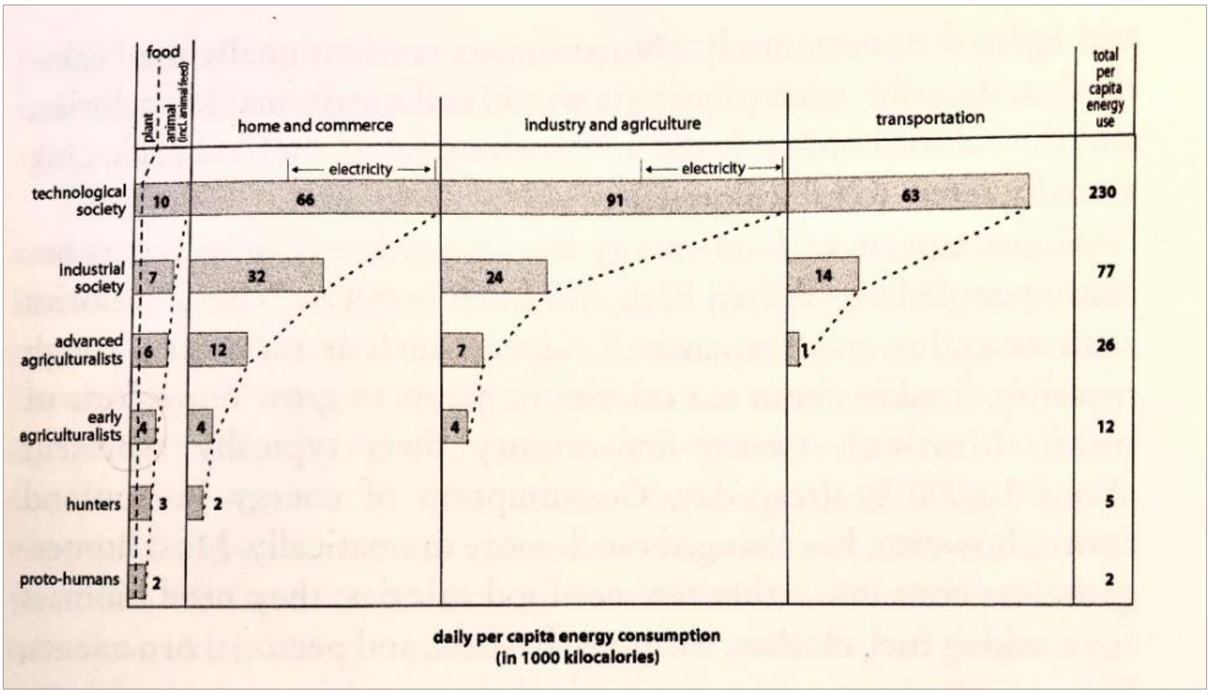


Figure 1.3 - Earl Cooks' energy capture classification and estimates (Cook, 1971).

In broad terms, Figure 1.1 and Figure 1.2 illustrate that energy capture grew very slowly for many millennia, reaching 10,000 kcal/cap/day by the time of the ancient empires of the Middle East (western core). A new high of about 30,000 kcal/cap/day was reached by the time of the Roman empire: 100 AD. Then, following a long period of decay in the western core, energy capture in the eastern core became predominant. In 1000 AD, when the Song dynasty ruled in China, the eastern core had achieved 30,000 kcal/cap/day, the same as imperial Rome in the first century AD. The predominance of the eastern core (mostly China) would continue for seven centuries with energy capture values around 30,000 kcal/cap/day.

This is what Morris calls the *hard ceiling* of energy capture, limited by the productivity of traditional farming. Between 1700 and 1800, with the widespread use of coal, the beginning of the industrial revolution, and the rise of capitalism the western core became predominant again, diverging strongly from the eastern core.

The estimates provided by Ian Morris are values per capita and since the world population also increased exponentially, the combination of both will necessarily show an explosive growth in global energy capture. In the absence of such information, it is possible at least to estimate how much global energy use has grown from 1750 (a reference date for the beginning of the industrial age) to present times.

Figure 1.4 shows estimates, records, and projections of world population until 2100, provided by the United Nations (2019a). The data points are sparser than for energy capture and the estimates only go back to the beginning of our era.

The world had 0.98 billion people in 1750. Per capita energy in 1750 can be found by averaging interpolated values for the year 1750, in the western and eastern cores. The result, using Morris (2013) is 34,700 kcal/cap/day. Multiplying by 365 and by 4.2 (the conversion factor between kilocalories and kilojoules) yields about 53.2 gigajoule (GJ) per capita per year. Since the world had 0.98 billion people

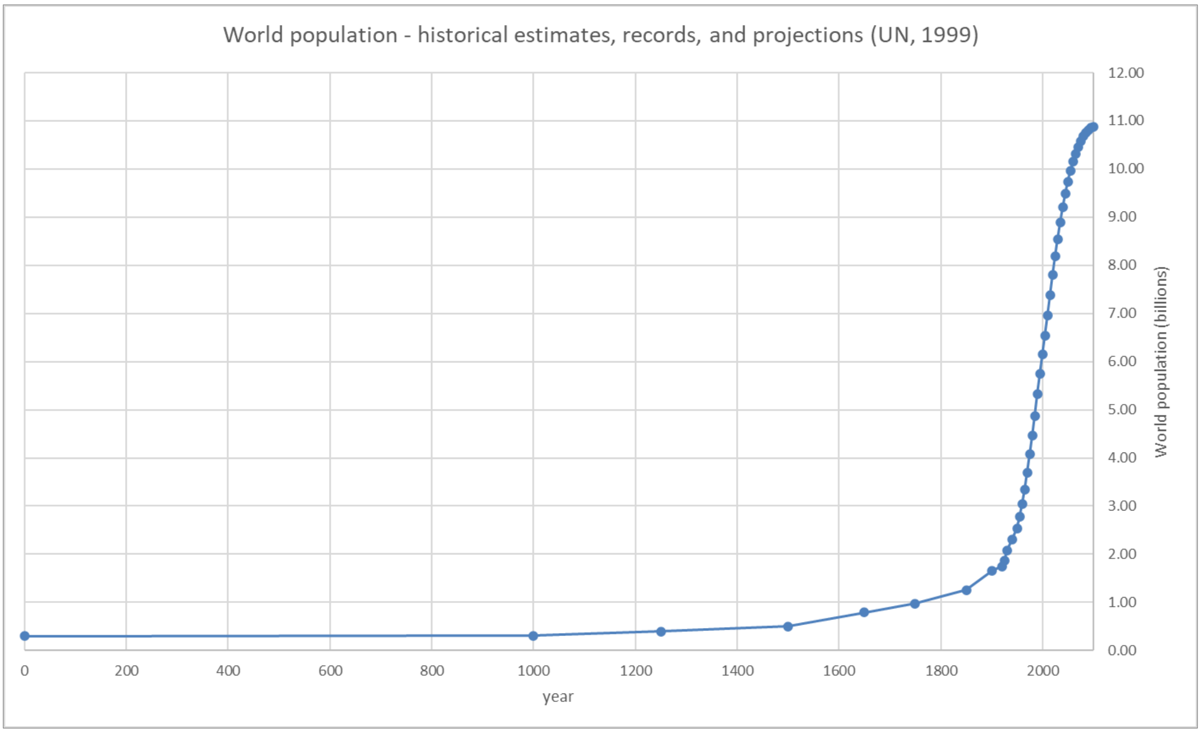


Figure 1.4 - World population: 0 to 2100 AD. Data from UN (2019a).

in 1750 the global energy captured in 1750 was approximately 52 exajoule (EJ).

Regarding present times, the International Energy Agency (IEA, 2021a) provides public-domain values for the total energy supply (TES) of many countries and the world, from 1990 to 2018. Although TES does not include food energy, its value is nowadays very small value compared to the value of non-food energy (which also includes energy inputs for agriculture) and can be ignored. In 2000, according to IEA (2021a) the global TES was about 420 exajoule, so *eight times more* than the energy in 1750, in just two and a half centuries.

A similar calculation can be performed for the United Kingdom. The population of UK in 1750 was 5.89 million people (Thomas & Dimsdale, 2017). Considering the value for the western core, 35,000 kcal/cap/day, and using the same conversion logic as before the UK captured 0.316 exajoule in 1750. The total energy supply for the UK in 2000 was 9.33 exajoule (IEA, 2021a) hence almost *thirty times* *more* in two and a half centuries. The results are summarized in Table 1.1.

Table 1.1 - Total energy capture in 1750 and 2000: UK and World. Values in exajoule (EJ).

	1750	2000	Multiplier
World	52	413	7.9
UK	0.316	9.33	29.5

The energy captured by the world economy has continued to grow in the last two decades: the world´s total energy supply (TES) went from 413 EJ in 2000 to 587 EJ in 2020. However, in their roadmap for net-zero emissions by 2050, the IEA (2021b) forecasts a slow decrease to 543 EJ in 2050. The very high values of daily energy per capita are obviously due to non-food energy: the average food energy requirements remain constant throughout the ages.

It is interesting to compare how individual countries have changed in recent years regarding their TES per capita. Table 1.2, based on data by the IEA (2021a) from 2000 to 2018, converted from *tons of oil equivalent* (toe) to kilocalories, reveals the differences hidden in average global values. For instance, Portugal has decreased its per capita energy use *faster* than the EU-28. Morocco, India, and China were still increasing theirs. The USA had a fast decrease, although starting from a very high value.

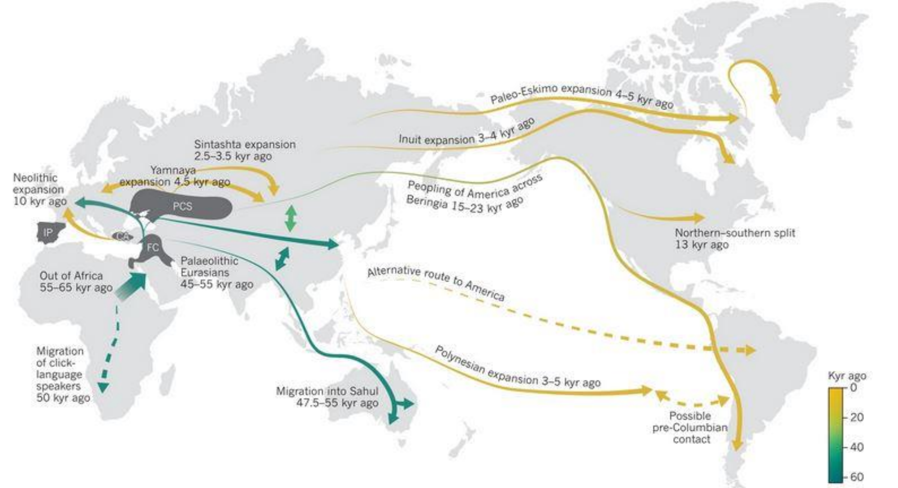
Table 1.2 - Total energy usage of selected countries 2000-2018 (values in kcal/cap/day)

	2000	2018	Change [%]
World	43 836	49 315	12.5
US	221 918	186 301	-16.0
EU-28	95 890	84 932	-11.4
China	24 658	63 014	155.6
India	10 959	19 178	75.0
Portugal	65 753	57 534	-12.5
Morocco	10 959	16 438	50.0

1.2. Towards the Anthropocene

Homo sapiens differentiated from related species (designated as *hominins*) probably between 300,000 to 200,000 years ago, in the middle of the Pleistocene epoch (Stringer, 2016; Lewis & Maslin, 2018). Since those times our species not only persisted, while the other hominin species disappeared, but also prospered to become the dominant species on Earth, with over seven billion individuals and, virtually, complete control over life on the planet.

Early human evolution can be characterized by four main stages: bipedalism, stone tools, brain enlargement, and cumulative culture (Lewis & Maslin, 2018). Hominins originated in Africa, and it was in Africa that many of their evolutive changes have happened. Bipedalism appears in the fossil record as early as 4.4 million years. Stone tools are at least 3.3 million years old - older than the appearance of the genus *Homo*, 2.8 million years ago.



Some migration routes remain under debate. For example, there is still some uncertainty regarding the migration routes used to populate the Americas. Genomic data are limited in their resolution to determine paths of migration because further population movements, subsequent to the initial migrations, may obscure the geographic patterns that can be discerned from the genomic data. Proposed routes of migration that remain controversial are indicated by dashed lines. CA, Central Anatolia; FC, Fertile Crescent; IP, Iberian Peninsula; PCS, Pontic–Caspian steppe.

Figure 1.5 - *Homo sapiens* migrations (Nielsen et al., 2018).

Homo erectus, which appeared 1.9 million years ago, was the first hominin with an enlarged brain: 80% larger than predecessor species and about two thirds the size of modern humans' brains. They were the first hominins known to have migrated out of Africa to Eurasia, about 1.8 million years ago. And hold the record of the most long-lived hominin species lasting from 1.8 million BC to about 70 thousand BC. *Homo heidelbergensis* appeared 600,000 to 700,000 years ago in Africa and Europe and is considered a direct successor of *Homo erectus*. They may have been the ancestors of Neanderthals (*Homo neanderthalensis*), Denisovans (*Homo denisovan*, a recently found branch of Neanderthals), and *Homo sapiens* (Stringer, 2016).

Between 100,000 and 50,000 years ago, *Homo sapiens* started migrating out of Africa, eventually reaching all places in the world (Nielsen et al., 2018). During this process all other hominin species in existence, like the Neanderthals in western Europe and *Homo erectus* in eastern Asia have disappeared. The reasons are unknown and may have involved competition for resources and war, although there was also cross breeding of humans with Neanderthals and Denisovans. The diagram of Figure 1.5 taken from Nielsen et al. (2018) displays likely routes and dates of ancient *Homo sapiens* migrations.

1.2.1. Hunting and gathering

Until the appearance of agriculture, about 10,000 years ago, hominins were foragers (hunter-gatherers), meaning they fed themselves by hunting wild animals, gathering wild plants, and fishing, with no deliberate attempt to domesticate the exploited resources, i.e., changing their gene pool (Morris, 2015).

The development of tools and weapons, the control of fire, the enhanced mobility provided by bipedalism, and the persistent knowledge enabled by cumulative culture led to evolutive changes in hominins. Changes in diet toward energy rich foods have been associated with a reduction in the digestive tract diverting the body energy saved to an enlarged brain. The human brain needs 20-25% of resting energy compared to 8-10% in other primates and just 3-5% in other mammals. The small intestine also evolved to adapt to high quality, energy-dense foods, like meat and nuts. Humans have 56% of their gut mass in the small intestine and 17-25% in the colon, while existent non-human primates have more than 45% of the gut mass in the colon and only 14-29% in the small intestine (Smil, 2016).

Hunting of large animals required the development of tools and weapons. A large variety of special hand-held stone tools (bifacial hand axes, picks, and cleavers) appear in the fossil record from 1.2 to 0.1 million years ago. A near complete wooden spear found in an elephant skeleton was dated 115,000 to 125,000 years ago. Finds of *throw spears* (to be thrown with the help of a spear thrower) were dated from 400,000 thousand to 380,000 years ago. Stone points attached to wooden spears existed already 500,000 years ago (Smil, 2016).

The earliest dates for the controlled use of fire are unknown although there are records of cooked food as early as 1.9 million years ago. By 30,000 to 20,000 years ago, however, the use of fire was widespread (Smil, 2016). Domestication of fire marked a significant change in hominin society. It expanded the types of food that could be used, and the amount of energy extracted from them. It was useful to keep large predators, poisonous animals, and mosquitoes away. The light and warmth also allowed hominins to move into colder regions (Lewis & Maslin, 2018). Fire was also used as an engineering tool: humans were using heat to treat stones as early as 164,000 years ago (Smil, 2016). Controlled burning of landscapes clears vegetation, encouraging grasses and in turn the easy-to-hunt animals grazing on them (Lewis & Maslin,2018). There is evidence for the controlled burning of vegetation in South Africa as early as 55,000 years ago (Smil, 2016).

1.2.2. Foraging societies

Reliable information about past foraging societies comes mostly from the observation of contemporary hunter-gatherers. Foragers live in small groups or bands linked by kinship with high mobility in search of food resources. The bands are part of larger groups of hundreds to ensure a viable breeding population. In abundant environments, particularly those with rich marine resources foragers can live permanently in groups of several dozen or hundreds of people. Many foraging societies in energy-rich environments reached levels of complexity usually associated only with later agricultural societies, with permanent settlements, high population densities, large-scale food storage, social stratification, elaborate rituals, and incipient crop cultivation (Morris, 2015; Smil, 2016).

1.2.3. Environmental impact of hunter-gatherers

Hunter-gathering seems at first incapable of causing large environmental impacts due to the size of the foraging population and the vastness of natural resources. Two examples, however, show that the impacts can be profound. The first is the use of controlled fire to turn woodland into grassland illustrating how the actions of a small group can change entire ecosystems (Lewis & Maslin, 2018). The other example is the disappearance of large animals that occurred by the time *Homo sapiens* migrated out of Africa: the so-called *slaughter of the megafauna*. Quoting Lewis & Maslin (2018): "As soon as early second-wave *Homo sapiens* migrated into a new region, they started to systematically hunt populations of large animals – defined as over 40 kgs in weight – called megafauna (…). At the same time, about half of all large-bodied mammals worldwide were lost, 4 per cent of all mammal species. The losses were not evenly distributed: Africa lost 18 per cent, Eurasia 36 per cent, North America 72 per cent, South America 83 per cent and Australia 88 per cent of their large-bodied mammals. The greatest losses were on continents that did not have ancestral hominins species present. The culprit, it appears, was us". This conclusion is disputed, however: other causes, like climate change and food chain alterations could also have been responsible for the Pleistocene extinctions (Smil, 2016). A study by Broughton & Weitzel (2018) for North America, correlating populations of humans and megafauna concluded that the extinctions of mammoths, sabre-toothed cats, and horses were consistent with hunting by humans in the Clovis period (13,150 to 12,850 years ago); while the extinctions of mastodons and Shasta ground sloths were consistent with climate change in all places except one, where both hunting and climate change were the likely cause.

1.2.4. Rise of agriculture

Agriculture appeared after the end of the last glaciation (14000 BC) as the ice receded and the Earth got warmer, enabling the domestication of plants and animals. Domestication implies the alteration of the gene pool of the exploited resources by selective breeding, leading them to evolve into entirely new species, which can only go on reproducing themselves with continued human intervention (Morris, 2015).

It can be argued that the origin of agriculture was driven by both natural and social factors, including population growth. During the late Palaeolithic the climate was too cold and CO_2 levels were low, but these conditions changed with subsequent warming during the Holocene. Agriculture, which would be impossible during the Pleistocene, would become "mandatory" in the Holocene - an argument strengthened by the fact that between 10000 and 5000 BC, domestication of plants and

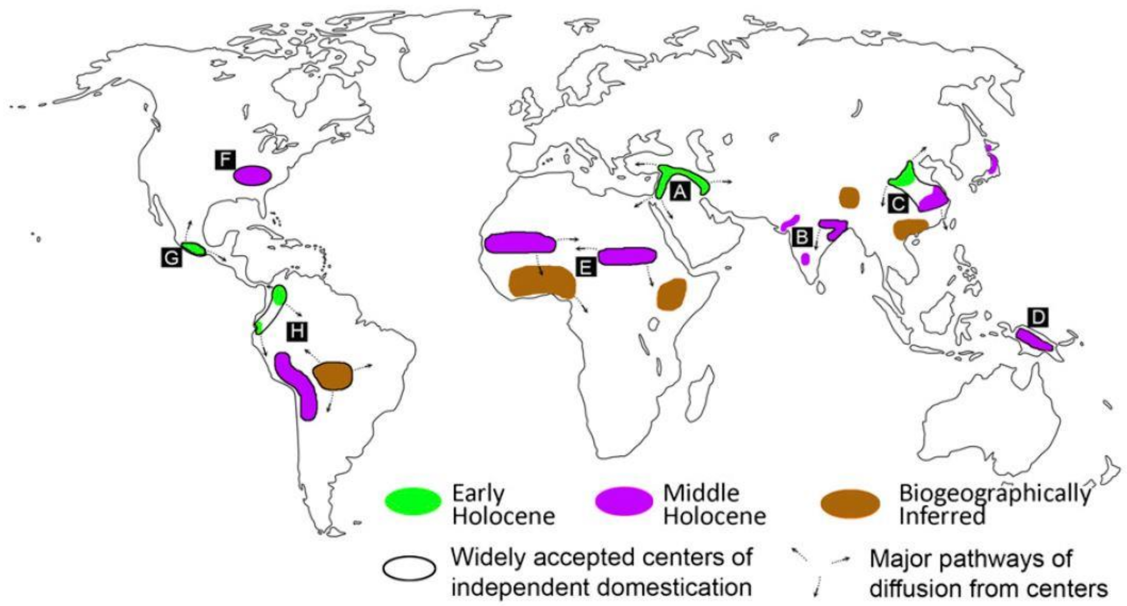


Fig. 1. A map depicting likely centers where the domestication of at least one plant or animal took place. Black outlines surround the most widely accepted independent centers of domestication, and sources of major diffusions of domesticates are indicated by arrows. Green and purple regions, respectively, are those where the domestication process took place during the late Pleistocene to early Holocene transition (12,000–8,200 B.P.), and in the middle Holocene (8,200–4,200 B.P.). Brown regions represent areas where, at present, the evidence for domestication is interpreted based upon the presence of domestic forms indigenous to these regions found outside of their native distributions. Letters *A–H* correspond to those listed in Fig. 2. Additional detail and references associated with each region are found in the *SI Text*.

Figure 1.6 - Domestication centres and epochs (Larson et al., 2014).

animals evolved independently in several locations across Asia, America, and Africa (Smil, 2016). The diagram of Figure 1.6 from Larson et al. (2014) displays the locations of the known or inferred domestication centres. Larson et al. (2014) list the plant and animal species that were ultimately domesticated, stressing the *gradual* nature of the process: a species is first exploited for hundreds or thousands of years, then managed for another long period still without any morphological traits of domestication, and finally changes into a fully domesticated species. In the Fertile Crescent (Southwest Asia) wheat, barley and lentils, and sheep, goats and pigs were, respectively, the first plants and the first animals being domesticated, a process starting 12,000 years ago. Only *twenty-two animal species*, including the silkworm insect, and only *fifty-three plant species* have been domesticated by agricultural societies (Larson et al, 2014). These numbers illustrate how challenging the process was, since there are about 350,000 vascular plant species and, after the megafauna extinctions, 150 large terrestrial mammals (Lewis & Maslin, 2018). Note that dogs were domesticated by foragers prior to the appearance of agriculture.

1.2.5. Farming societies

Foragers and farmers formed quite distinct societies. Foragers exploited wild species that they did not attempt to domesticate, lived in small groups, and were constantly on the move; while farmers domesticated their exploited resources, lived in large (often very large) groups, and moved around little. As noted by Morris (2015): "In foragers' mobile but tiny bands, the places change but the faces stay the same; in farmers' static but big villages, the faces change but the places stay the same". Farming societies had many variations but can be classified in three main types: horticulturalists (or 'food cultivators'), agrarian states, and city-states.

Horticulturalists were small groups that practised hunting and gathering but also domesticated some plants and animals, as it still happens nowadays with some Latin American tribes. Agrarian states were large, hierarchical farming societies, like the Qing dynasty in China (1644-1912), Ottoman Turkey (1299-1922), and some Western Europe nations with their colonial settlers in the 18th century. Classical Athens (500 to 336 BC) and medieval Venice (697 to 1797 AD) are examples of city states of the farming era (Morris, 2015).

Farming substantially increased the amount of energy available to society. As population grew in the agricultural cores, people moved in search of new farmland with their domesticated plants and animals - slow migrations taking agriculture to the rest of the continents. Great rivers like the Euphrates, the Tigris, the Nile, the Indus, and the Yellow River enabled irrigation, transport, and communication. The increased crop yields and economic integration led to the establishment of nearby cities with populations in the tens of thousands or even hundreds of thousands. Access to sea enabled further development: the Roman agrarian state took control of the whole Mediterranean basin in the early centuries of the current era, with the population of Rome reaching one million people (Morris, 2015).

Early farming required higher human energy inputs, but it could supply higher population densities and provide a more reliable food supply. It often took the form of shifting agriculture: cultivation of plot of land followed by a fallow period. Where scarce precipitation made cropping unrewarding or impossible, nomadic pastoralism was (and still is) an effective alternative. The evolution of agriculture can be seen as a continuing effort to raise land productivity, i.e., to increase digestible energy yield to accommodate larger populations. The diets of all traditional peasant societies were overwhelmingly vegetarian, depending on staple crops, particularly grains.

The intensification of farming supported higher population densities, but it also demanded more energy expenditure, for direct farming activities but also for critical supportive measures like the digging of wells, the building of irrigation channels, roads, and food storage structures, and the terracing of fields. These improvements also required more energy to make a larger variety of tools and simple machines, powered by domestic animals or by water and wind. Keeping domestic animals, in turn, required more intensive cropping to produce feeds. The increasing scale of such activities eventually demanded *hierarchical coordination* and *supra-local management* leading to the formation of large, stratified agrarian states with wealth accumulation and much higher social inequality than in foraging groups (Smil, 2016; Morris, 2015).

1.2.6. Trade development and colonial expansion

By increasing their capture of non-food energy farming societies were able to produce surplus, region-specific goods (tools, cloth, ceramics, jewels, animals, raw materials) that could be exchanged with nearby villages or traded with neighbouring states. In his detailed account of trade throughout history, Bernstein (2008) describes several *great trade systems in the agrarian era*. In Mesopotamia, for instance, there was trade of copper for grain in the third millennium BCE, involving sources of copper in Anatolia and in the Persian Gulf. Imperial Athens, in the 5th century BCE is another example. Attica, the territory ruled by Athens had poor soil; barley was the only grain that could be produced locally. To satisfy the tastes of its wealthy population the city-state imported wheat from Egypt, from Sicily (which had a rich volcanic soil and was under Athenian control) and from the Black Sea, where many Greek colonists had settled. Wheat was exchanged by the sophisticated craft goods and expensive crops produced by Athens: pottery, textiles, olive oil, and wines. The trading network required continuous military control of several straits in the Aegean Sea and dangerous navigation in cloudy weather. Ultimately, the fight with the other Greek city-states led to the Peloponnesian war, which ended the imperial rule of Athens.

Another extensive trade network carried the spices of India and several East Asian islands to Europe, its last leg controlled by Venice and Genoa in the thirteen century AD. The largest part of the network, reaching the remote locations where pepper, cinnamon, nutmeg, mace (a co-product of the nutmeg fruit), and cloves were produced was dominated by Muslim traders. Venetians and Genoese collected the spices in Alexandria, distributing the expensive, luxury items to European clients. The Italian city-states had not many products to exchange for the lucrative spices, except textiles and glass artifacts; but had strong fleets that could *collect and deliver slaves* from the Black Sea, a “merchandise” sought by the Muslim Mamluk dynasty ruling the Middle East. The Muslim-dominated spice trade would be strongly disrupted in the early 16th century by the Portuguese, with the opening of the Cape of Good Hope route to Indian Ocean.

The Portuguese spice trade involved other trade circuits. For instance, by dominating East Africa's most important ports they established a triangular trade: African gold was used to pay Indian spices and the gold was bought in Africa with Indian textiles. After the Dutch took control of the spice trade in the late 16th and the 17th centuries, the Portuguese found another lucrative marine trade: buying silk in China and selling it in Japan against Japanese silver, then used to pay for Chinese silk (Bernstein, 2008).

1.2.7. Environmental changes of the agrarian age

Trade chains contributed to the spread of better agricultural techniques and adoption of new crops. The changes were, almost always, very gradual and coexisted with traditional farming practices that persisted for several millennia (Smil, 2016).

The arrival of Columbus to Mesoamerica (1492), the first voyage of Gama to India (1498) and the visit of Cabral to Brazil (1500) happened almost simultaneously being ultimately responsible for the diffusion of new crops from the Americas in Europe, Asia, and Africa; and of new crops and animals from the Old World in the New World – the *Columbian Exchange*, a bidirectional, relatively fast process with far-reaching consequences. The worldwide adoption of potatoes, corn, tomatoes, and peppers, and the cultivation in the tropics worldwide of pineapples, papayas, vanilla, and cacao trees all resulted from the conquest of America by the Iberian powers. In the opposite direction, crops and animals travelled to the Americas where they were new: sugar cane, pigs, cattle, horses, and later spices from East Asia (Ferrão, 2015; Lewis & Maslin, 2018; Smil, 2016).

With the soldiers and colonists came diseases, like smallpox and measles, for which the humans of the Americas (which had separated from their Eurasian ancestors maybe 20,000 years ago) had no immunity. The effects of the diseases were devastating for native Americans, causing millions of deaths and helping the colonial powers take control (Diamond, 1999). Lewis & Maslin (2018) argue that the Eurasian diseases probably killed 50 million people. This led to a drastic reduction in the cultivated area in the Americas causing *natural regrowth* of forests and woodlands, which acted as carbon sinks leading CO_2 in the atmosphere to fall. The CO_2 fall, observed in ice cores, started several decades after the Spanish and Portuguese colonists had arrived in America. The reduction in carbon dioxide, the authors claim, is the first geographical sign of climate modification by humans and marks the beginning of a new geological period, the Anthropocene. There is no agreement, however, about the event marking the beginning of the Anthropocene (Lewis & Maslin, 2018).

The adoption of agriculture may also have caused long-lasting effects on the climate. The Early Anthropogenic Hypothesis (EAH), proposed by Billl Ruddiman in 2003, argues that the sustained increase in atmospheric carbon dioxide and in methane observed in ice cores 7,000 and 5,000 years ago, respectively, are not consistent with the naturally occurring values of previous interglacial periods, and must then have anthropogenic causes. According to the EAH, deforestation linked to agriculture

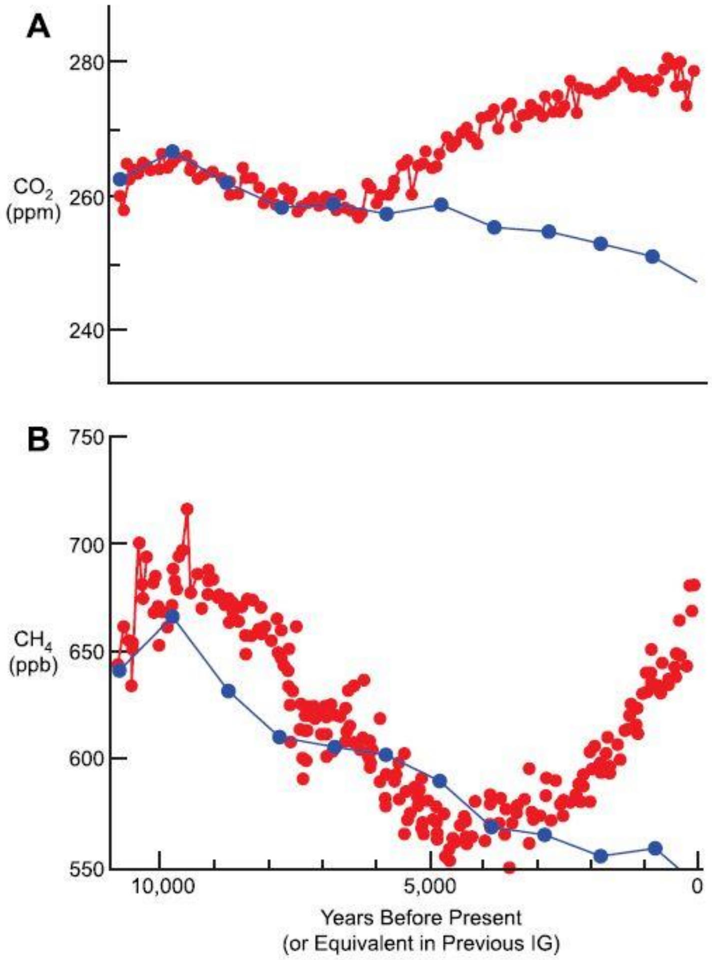


Fig. 1. Comparison of Holocene trends (red) of CO_2 (A) and CH_4 (B) to averaged values (in blue) for previous interglaciations, from Ruddiman et al. (2016). Based on Dome C data in Monnin et al. (2001) and many papers by EPICA Community Members (2004).

Figure 1.7 - Carbon dioxide and methane anomalies in the Holocene (Ruddiman et al., 2020).

was responsible for the increase in carbon dioxide. And intensive rice paddy farming in East Asia and livestock care were responsible for rise in methane levels (Ruddiman et al., 2020; Lewis & Maslin, 2018). The anomalies in the level of the two greenhouse gases, illustrated in Figure 1.7 represent anthropogenic increases until pre-industrial times of about 40 parts per million (ppm) and 100 parts per billion (ppb) in carbon dioxide and methane, respectively.

As detailed by Ruddiman et al. (2020) the EAH caused a long controversy but, the authors claim, has been reinforced and clarified by new, independent findings. A restructured model can explain the observed increase in CO_2 by the net results of increased emissions due to deforestation, decreased emissions due to natural carbon capture, and a reduction in carbon capture by the ocean due to its warming. Regarding methane, seventy per cent of its anomaly can be explained by rice paddy cultivation in Southeast Asia, from India to Japan, with the remaining most likely due to emissions by livestock.

The implications of the EAH are far-reaching. In interglacial phases CO_2 levels are high at the start of the interglacial and then slowly decrease until orbital conditions create conditions for a new glacial (Maslin, 2016; Tzedakis et al., 2012). In the middle of the Holocene interglacial the levels of GHG increased due to anthropogenic causes. According to Tzedakis et. (2012) the next glaciation would probably start when CO_2 levels reached 240 ppm, which means that the anthropogenic emissions of the last 7,000 years (Cf. Figure 1.7) delayed the onset of the next glaciation. If Ruddiman et al. (2020) are right, the emissions created *sustained conditions for farming* by stabilizing the climate from mid-Holocene onwards.

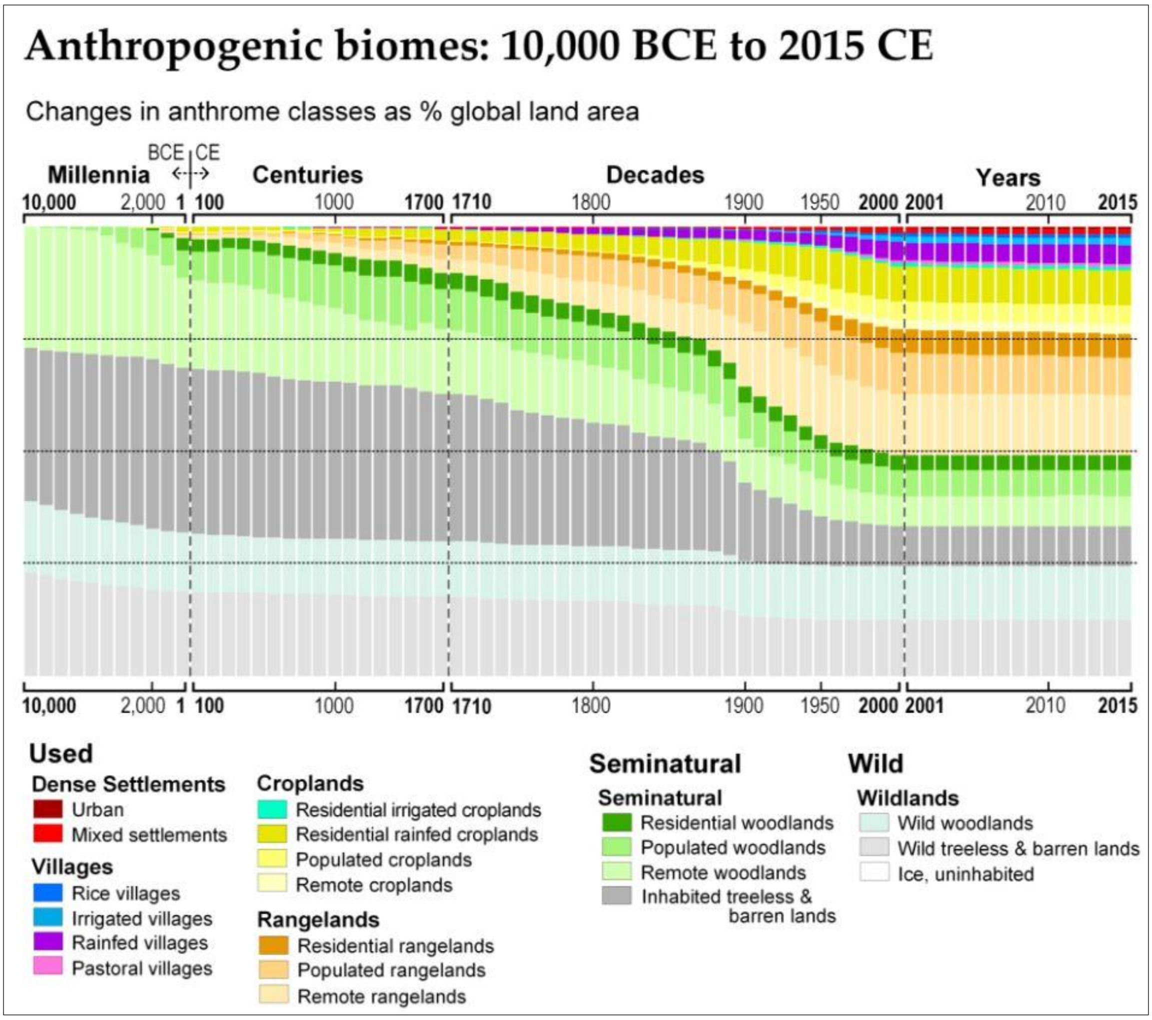


Figure 1.8 - Anthropogenic biomes 10 000 BC to 2015 AD (Ellis et al., 2020).

The overall impact of agriculture on the planet is apparent in Figure 1.8, a diagram from Ellis et al. (2020) featuring an historical and geographical database of land use encompassing twelve thousand years, 10000 BC to 2015 AD. Anthropogenic biomes (*anthromes*) are landscapes shaped by humans for their use, like settlements, cropland, and pastures. The anthromes in Ellis et al. (2020) are classified in major types: dense settlements, villages, croplands, rangelands, semi-natural lands, and wild lands. The first three are the anthromes strongly shaped by humans, while seminatural areas correspond to forests and woodland inhabited and exploited by humans. Wildlands are areas undisturbed by humans. Under the six main classes are twenty-two land use classes based on criteria like population density, urban density, crop and irrigation types, and cropland and pastureland dominance. In their paper, Ellis et al. (2020) present and discuss the classification algorithm, their sources and overall methodology. Considering the time span of traditional farming (10000 BC to 1700 AD) it is apparent that *cropland and rangeland have increased at the expense of woodland and wildland*. In 10000 BC woodlands occupied about 60% of the terrestrial land area and wildlands 40%. In 1 AD, settlements, villages, cropland, and rangeland occupied already 2.6%, with woodlands and wildlands occupying 64.2% and 33.2%, respectively. In 1700 CE, settlements, villages, croplands, and rangelands occupied already 10%, with woodlands and wildlands occupying 50.7% and 31.3%, respectively. Since woodlands, tree and treeless, were also inhabited, humans in 1700 AD occupied already 60.7% of the land on Earth (Ellis et al., 2020).

1.2.8. The origin of capitalism

In the 16th century the two main western powers, Portugal, and Spain, were extending and consolidating their trade networks and colonial conquests, following the Tordesillas world division of influence zones. But trade, everywhere, continued to be based on the *agrarian social and economic structures* of the countries involved: farmers working the land for subsistence and elites (imperial bureaucracies, kings, feudal landlords, chieftains, etc.) appropriating for themselves surplus value from the farmers' production, through political and military power.

In England, however, aristocratic landowners were enforcing a *new type of property relationship* with their dependent farmers, which would change forever the exploitation of natural resources and ultimately create industrial capitalism and market economies worldwide. This historical transformation was clarified less than fifty years ago by the works of Robert Brenner (1976) and Ellen Meiksins Wood (2002), which have argued convincingly against all the previous attempts to explain the rise of capitalism, like the strong development of trade, bourgeois revolutions, growth of the cities, and the technological developments of the industrial revolution. The origin of capitalism is *agrarian*, they asserted, an *agrarian capitalism* starting in England, and only in England, a country that had very specific conditions for its inception.

According to Wood (2002), an exceptionally large proportion of land in England was owned by *landlords* and worked by *tenants*, who leased the lands from their aristocratic owners with rents dependent on market conditions, i.e., not fixed by law or custom. A growing number of tenants was therefore subjected to market imperatives: they were required to specialize for the market and to produce competitively, simply to guarantee access to the land and ensure their means of subsistence. On the other hand, landlords in England controlled a large proportion of the best land but they did not enjoy the *extra-economic powers* on which other landlords (like French aristocrats) depended for its wealth: they depended on the productivity of their tenants, rather than on coercive powers to squeeze more surplus out of them. Thus, both direct producers and landlords came *to depend on the market* in historically unprecedented ways just to secure the conditions of their own self-reproduction.

The result was a new historical dynamic: a process of self-sustaining development, new competitive pressures that required productivity increases, and the reconfiguration and further concentration of landholding. Both landlords and tenants depended on being successful in the market since the former relied on the profits of the latter for their rents (Wood, 2002).

The enhancement of productivity by means of innovative land use and techniques was named *Improvement*, a word rooted in the medieval English word for profit. Improving the lands implied new or better methods and techniques of farming but also new forms and conceptions of property, and the elimination of old customs and practices that interfered with the most productive use of land. One example were common lands, where grazing and firewood collection were allowed. Between the sixteenth and eighteenth centuries landlords exerted growing pressure to extinguish customary rights through *Enclosure*, the physical fencing of their properties - a socially disruptive practice opposed on several occasions by the Tudor and Stuart kings of England. A first major wave of enclosures occurred in the sixteenth century to drive commoners off lands that could profitably be used as pasture for sheep farming, an increasingly lucrative activity. But whether for sheep or cropping, the enclosures continued, becoming a major source of political and social conflict until they eventually became a prerogative of the Parliament in the 18th century (Wood, 2002).

1.2.9. Industrial capitalism

In his major work, *The Great Transformation*, first published in 1944, Karl Polanyi (1957) addresses the rise of industrial capitalism in England – the Industrial Revolution - and the subsequent establishment, worldwide, of what he calls a *market society*, based on a *self-regulated* market encompassing all human activities. While he was not aware of the agrarian capitalism characterized by Wood (2002), Polanyi (1957) also points to the practice of enclosure as an enabler of industrialization and industrial capitalism in England. He argues that enclosures strongly raised the value of the land, saying that: "where cultivation was maintained employment did not fall off, and the food supply markedly increased". And that "the yield of the land manifestly increased, especially where the land was let".

The conversion of arable land to rangeland for sheep farming destroyed habitations and restricted employment but "cottage industry was spreading by the second half of the fifteenth century, and a century later it began to be a feature of the countryside. The wool produced on the sheep farm gave employment to the small tenants and landless cottagers forced out of tillage, and the new centres of the woollen industry secured an income to a number of craftsmen" (Polany, 1957). And the development of the woollen industry led to the establishment of the cotton industry, "that vehicle of the Industrial Revolution" (Polanyi, 1957).

The Industrial Revolution of the 18^{th} century was for Polany a repetition, about 150 years later, of the social disasters brought by the enclosures. An "almost miraculous" improvement in the tools of production was accompanied by a "catastrophic dislocation of the lives of the common people, threatening the life and well-being of the British countries". Already in an early phase "the labouring people had been crowded together in new places of desolation, the so-called industrial towns of England; the country folk had been dehumanized into slum dwellers; the family was on the road to perdition; and large parts of the country were rapidly disappearing under the slack and scrap heaps vomited forth from the 'satanic mills'".

Such was the human degradation brought by the social conditions under the Industrial Revolution that it was condemned by "writers of all views and parties, conservatives and liberals, capitalists and Socialists" (Polanyi, 1957).

There were many interacting causes for the Industrial Revolution: the expansion of markets, the presence of coal and iron, the humid climate favouring the cotton industry, the multitude of people dispossessed by the new eighteenth-century enclosures, the existence of free institutions, and the invention of new machines. Polany (1957) argues that *one basic change*, the establishment of a *market economy*, underlies all the characteristics of the Industrial Revolution, and insists that *once elaborate machines and factory plants* were used for production the "idea of a self-regulating market system was bound to take shape". This contrasts with what Wood (2002) asserts: that the essential factor in the origin of capitalism is the establishment of *market-dependent property relationships* and not any technological factor. For Polanyi, since elaborate machines are expensive, they do not pay unless large amounts of finished goods are produced. The flow of goods must be reasonably assured, and production must not be interrupted for lack of the primary goods necessary to feed the machines. For the machine owner this means that *all factors involved must be on sale*, including the land and human labour, i.e., they must be available in the needed quantities to anybody prepared to pay for them (Polanyi, 1956).

But both Polanyi (1957) and Wood (2002) stress that the *market system* is unprecedented in the history of economic systems and that *before capitalism* markets were no more than *accessories of economic life*.

1.2.10. Market economy and market society

Polanyi (1956) is crystal clear in his definition of a market economy: "an economic system controlled, regulated, and directed by market prices; order in the production and distribution of goods is entrusted to this self-regulating mechanism." And that: "accordingly, there are markets for all elements of industry, not only for goods (always including services) but also for labour, land, and money, their prices being called respectively commodity prices, wages, rent, and interest".

For Polanyi, a self-regulating market requires the institutional separation of society into an economic and a political sphere. Normally, the economic order is merely a function of the social order but nineteenth-century society saw a singular departure of the old order: *a market economy could only exist in a market society*.

While pointing to the devastating social effects of liberal capitalism, Polanyi does not mention how it works. Following Wood (2002), market systems imply *intense competition* between the owners of the means of production which form the industrial capital. Capitalists (owners of machinery, factory plants, etc.) must compete in the market for their finished goods and services, for raw materials and intermediate products, for rented land, for money loans, and for labour.

And since human labour is the ultimate source of value, capitalism depends on improving the productivity of labour by technical means due to the imperatives of competition and profit maximization, hence encouraging the improvement of productive forces. The laws of motion of capitalism compel people to enter the market, to reinvest surpluses and to increase production efficiency by improving labour productivity: the laws of competition, profit maximization, and capital accumulation (Wood, 2002).

The "improvement of productive forces" by capitalism due to the "imperatives of competition and profit maximization" has certainly generated incessant technological and social progress. However, and partly because of that same progress, a high price has been (and is being) paid by the natural environment.

1.2.11. Fossil fuels rule the world

Vaclav Smil (2017) remarks that: "fundamentally, no terrestrial civilization can be anything but a solar society dependent on the Sun's radiation, which energizes a habitable biosphere and produces all of our food, animal feed and wood". This solar energy flux is used both directly and indirectly. Solar irradiation (insolation) provides heat and light to living places. But is also indirectly responsible for the cultivation of field crops and trees, the harvesting of plant material, and the conversions of wind and water flows into useful mechanical energy. Wind and water flows are almost *immediate* transformations of solar radiation, resulting from atmospheric pressure differences and from the water cycle, but the conversions of solar radiation to food, animal feed, and biomass fuels involve delays - equivalent to *energy storage* - which may range from days to years.

Fossil fuels are also stored energy coming ultimately from the sun, but the time scales are much longer. Peat and coals result from the alteration of dead plants; hydrocarbons (oil and natural gases) from more complex transformation of the remains left in the sea or lakes of phytoplankton, zooplankton, algae, invertebrates, and fish. The transformation is very slow: from a few thousand years for the youngest peat to hundreds of millions of years for hard coals. Pressure and heat are the dominant transforming processes, resulting in fuels with high carbon and low water contents, and high energy densities (Smil, 2016).

Following Smil (2017) for the contents of this section, otherwise indicated: while preindustrial societies used renewable energy sources, industrial societies make extensive use of fossil fuels, *energy stored for thousands or millions of years*. Using them required qualitative improvements that were essential for the energetic foundation of industrial societies.

A first class of improvements was the invention, development, and mass-scale diffusion of *new ways to convert fossil fuels into mechanical energy*: steam engines, internal combustion engines, steam turbines, and gas turbines.

A second class of improvements was the invention of processes to *transform raw fossil fuels*, like producing metallurgical coke from coal, refining crude oils to produce liquid fuels and non-fuel materials, using coal and hydrocarbons to synthesize new chemicals.

A third class of inventions enabled fossil fuels to *produce electricity*, an entirely new kind of commercial energy. Any solid, liquid, or gaseous fuel could be burned, its released heat used to convert water into steam, and the steam used to rotate generators and produce electricity. However, since the very beginning of electricity generation, the kinetic energy of water, rather than that of expanding steam, was also used to produce electricity. And later advances added to this class forms included electricity generated in geothermal plants, by nuclear fission, and most recently, by large wind turbines and photovoltaic cells or concentrated solar radiation.

Coal exploration and steam engines had parallel, mutually reinforcing developments. Although coal had been used on a small scale since the beginning of the current era, England was the first country to shift from plant fuels to coal during the 16^{th} and 17^{th} centuries due to wood shortages, which led to increases in the cost of fuelwood, charcoal, and lumber. The shortages increased in the 17^{th} century due to growing demand for iron and timber requirements for shipbuilding. Domestic coal extraction increased to satisfy the growing demand: almost all the country´s coal mines opened between 1540 and 1640. Coal was extracted from underground mines with deeper pits requiring water pumping. Energy was also needed for mine ventilation, for hoisting the coal from deep shafts, and for its distribution. These needs were powered by water wheels, windmills, and horses, while coal mining itself was energized by heavy human labour.

The first steam engine with a significant diffusion was designed by Thomas Newcomen in 1712 to pump water out of coal mines. Coal from the mine heated a boiler that generated steam, which by expanding in a cylinder pushed a piston powering the water pump in a continued cycle. Although very inefficient, Newcomen engines began to spread in the coal mines after 1750. James Watt designed and patented an improved design in 1769, which was successfully commercialized for many years by Watt and his business partner, Mathew Bolton.

The first engines of the 18th century delivered only reciprocating movement, suitable for pumping, but before 1800 there were designs delivering *rotary motion*. Commercialization and widespread adoption of steam engines advanced slowly since they had to compete with waterwheels and water turbines. Only Watt´s largest units matched the most powerful existing waterwheels, but the location of waterwheels was inflexible while steam engines could be sited with much greater freedom, particularly near ports or along canals, where cheap transport by ships or boats could bring the necessary fuel.

The full impact of steam engines came only after 1840 with the rapid construction of railroads, steam ships, and installations as a centralized producer of kinetic energy, transmitted by belts to individual machines in manufacturing enterprises. For land transportation steam engines were heavy and the only practical way of using them was to put the vehicles on rails. Intense competition after 1800 led to the installation of small private railroads but the first public railroad opened only in 1830. Regarding waterborne transportation, the first commercially successful steamships came only in 1802 in England and 1807 in the United States.

As Smil (2017) points out: "the steam engine apogee came more than one century after Watt's improved patent: by the early 1880's its widespread use adoption had laid the energetic foundation of modern industrialization, and the affordable availability of such concentrated power transformed both manufacturing productivity and long-distance land and marine transportation".

But steam engines lost their dominant role in the 20th century as *steam turbines* rapidly replaced them in electricity generation, and *internal combustion engines* provided a new *prime mover* to energize road transport - light, powerful, and affordable.

Large-scale oil extraction and utilization were concentrated in a few decades of the late 19th century. During the 1860, the United States, Canada, and Russia had already new, growing oil industries. Still before 1900 oil discoveries were also made in Romania, Indonesia, and Burma. In 1908 came the first major Middle East discovery, Trinidad in 1913, and Venezuela in 1914. Most discoveries were of hydrocarbon fields that contained crude oil *and* natural gas, but the gas was usually discarded because without compressors and steel pipes it could not be easily transported.

Crude oil extraction was supposed to produce a more affordable source of energy for lighting but less than 25 years after its US beginnings, *commercial electricity and light bulbs* began to offer a superior alternative.

For transportation, though, and despite the early development of electric vehicles, the *high energy density* of liquid fuels refined from crude oil (gasoline, kerosene, fuel oil) and their easy portability made them the superior energy source. The development of the internal combustion engine (ICE) where fuel is burned inside the cylinder where the acting piston is located, proceeded very rapidly.

The first commercial 4-stroke engine was patented in 1877 by Nicolaus August Otto, still using coal gas as fuel. But starting in 1883, Gottlieb Daimler and Willem Maybach developed ICEs powered by gasoline that could move carriages. Their company supplied engines to other car manufacturers, namely to Emile Levassor, which in 1891 designed an innovative automobile that was not merely a 'horseless carriage'. Finally, Henry Ford introduced in 1908 his affordable, mass-produced Model T, opening the way for automobiles to become means of personal transportation.

ICEs were also key factors in the birth of modern aviation. In 1903, the Wright brothers achieved the first flight by a self-propelled plane using a very light, gasoline-powered engine. The development of airplanes was so fast that by 1914 the major powers had nascent air forces, which were deployed and enlarged in World War I.

An important innovation, patented in 1892, was the design by Rudolf Diesel of a new type of internal combustion engine. Diesel engines were heavier but more efficient than gasoline-powered engines and could use cheaper fuels. They became the choice for ships, electricity-generating stations, locomotives, trucks, buses, and later also passenger cars.

Natural gas remained for decades a minor contributor to global energy supply: in 1900 it supplied merely 1% of all fossil energies and by 1950 its share was still about 10%. Afterwards, three major demand trends lifted its global share in 2020 to almost 30% of all fossil fuels (Ritchie & Roser, 2020; Smil, 2016).

The smallest but very important new market was the use of natural gas as both feedstock and fuel for the synthesis of ammonia (used in fertilizers) and to produce plastics.

The largest new global market has developed in response to high levels of air pollution experienced in most Western cities during the industrialization of the post-war period: replacement of coal and fuel oil by natural gas for industrial, institutional, and household heating and cooking, eliminating emissions of particles and almost eliminating sulphur dioxide generation.

The latest trend boosting natural gas use has been the generation of electricity by gas turbines and combined-cycle gas turbines, increasing the overall process efficiency up to more than 60%.

The commercial use of electricity resulted from the works of many European and American scientists and engineers during the latter part of the 18th century and the first six decades of the 19th

century. A fundamental step was the demonstration by Michael Faraday (1791-1867) that mechanical energy can be converted into electricity to generate alternating current (AC), and vice versa, opening the way for the practical introduction and conversion of electricity not dependent or limited by heavy, low energy density batteries.

But decades had still to pass before this possibility was turned into a commercial system. The reason was that the introduction of electricity required the invention, development, and installation of a *whole new system* to generate it reliably, to transmit it safely over long-distance transmission, and to convert it efficiently to deliver the final forms of energy desired by users.

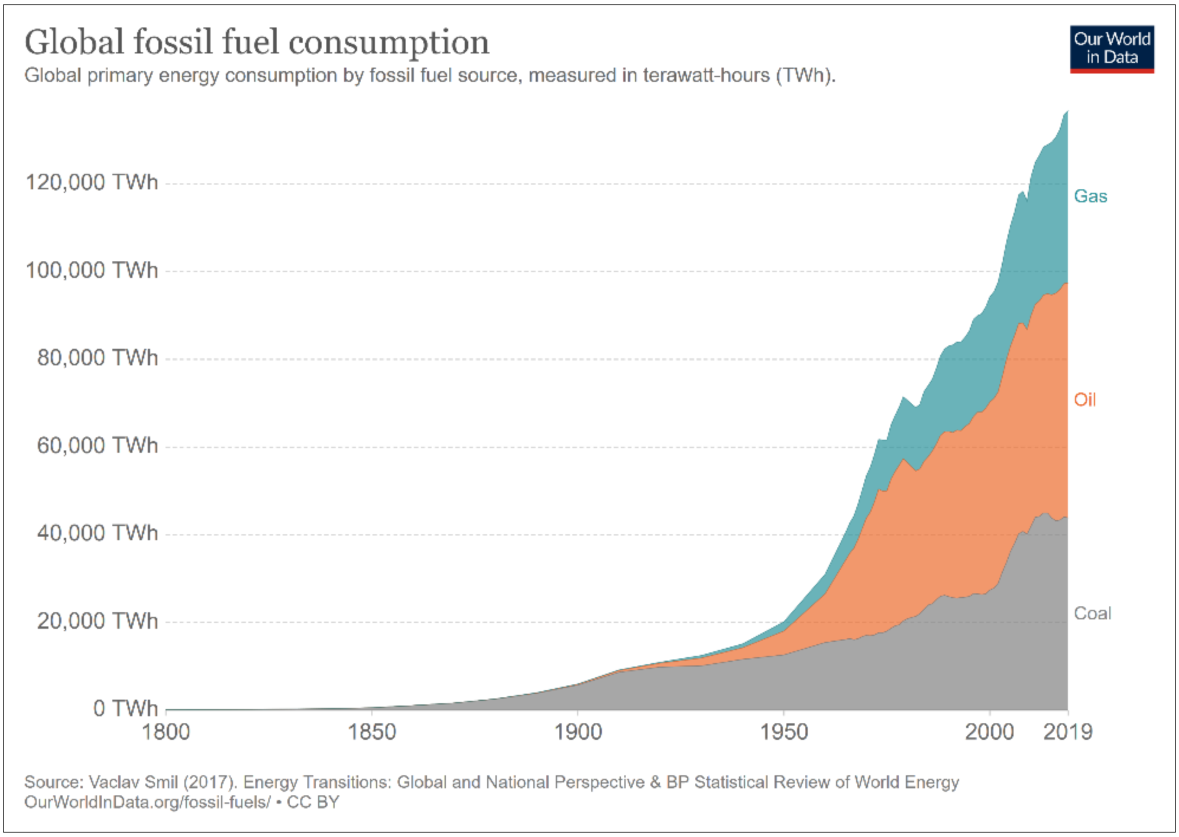


Figure 1.9 – Historical consumption of fossil fuels Ritchie & Roser (2020a).

Commercialization of electricity began with the quest for new sources of light. Arc-lights powered by electric dynamos illuminated famous public places in Paris and London, spreading in the 1880's to many European and American cities. But in 1879, Edison presented a superior alternative: *a durable carbon filament incandescent lamp*.

Edison succeeded in putting entire practical systems of commercial systems of electrical lighting in place. The first coal-powered electricity-generating plant was built in London by one of Edison's companies, having started activity in 1882. The "Edison system of lighting" used direct current (DC). This limited the long-distance transmission of current, which requires high voltages to minimize transmission losses due to cable electrical resistance. Later inventions - unrelated to Edison and strongly opposed by him - included electric transformers (1885), steam turbines (1888), AC electric motors (1882), and high voltage AC transmission (1890's), all leading to the kind of electric networks and systems that are still in use today.

Hydroelectricity generation began in 1882, concurrently with thermal generation. The first large AC station was built at Niagara in 1895 and had a capacity of 37 MW. In the 30's there was further development in the US and URSS, with much larger capacities, like the Hoover Dam in 1936 (2.08 GW), and the Grand Coulee Dam in 1941 (6.8 GW).

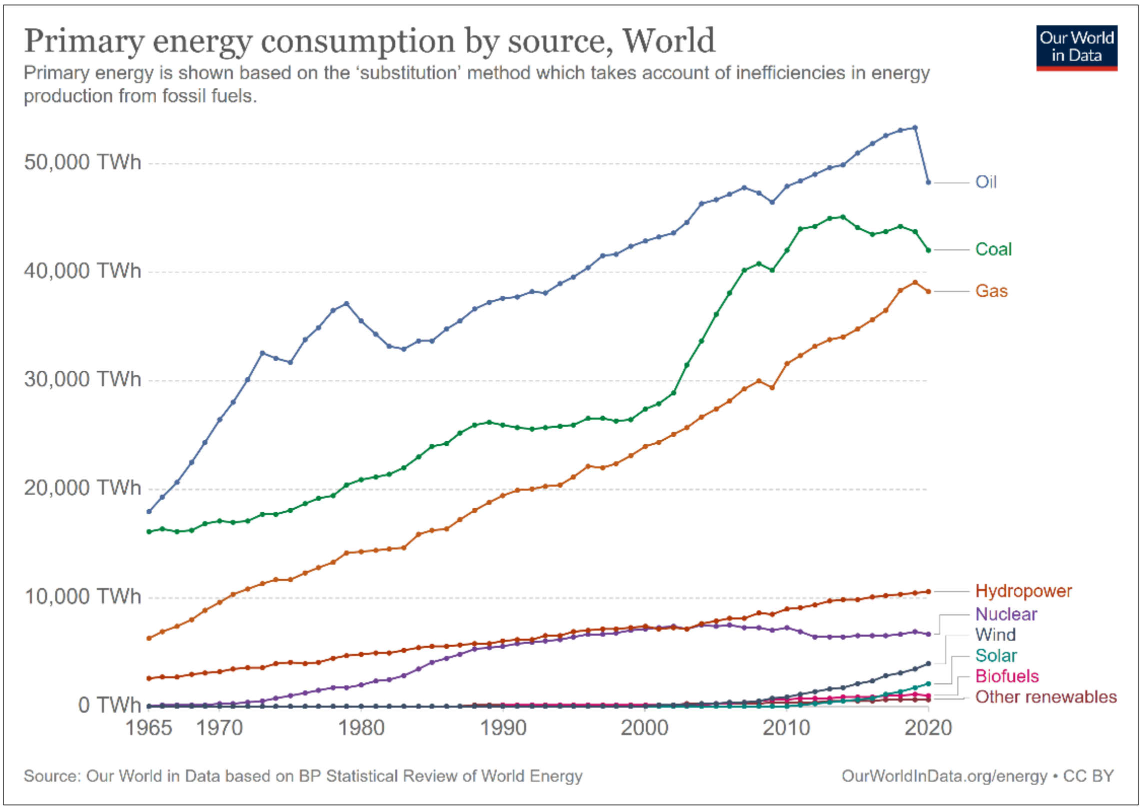


Figure 1.10 – Fossil fuels vs. low carbon and renewable energies (Ritchie & Roser, 2020b).

After three post-war decades, hydropower was the source of nearly 20% of the world's electricity, with large projects in Brazil, Canada, USSR, Congo, Egypt, India, and China. In most countries the construction of new projects slowed down or stopped since the 1980's although not in China: the very large Three Gorges dam, with a maximum capacity of 22.5 GW, was completed in 2012. In 2020, the share of world's electricity coming from hydropower was 16.85% (Ritchie & Roser, 2020).

After World War II, a new major way arrived to raise steam for thermal electricity: nuclear fission. American nuclear reactors were first used for the propulsion of submarines and later reconfigured for commercial electricity generation. The first nuclear power stations started operating in the UK in 1956 and in the US in 1957. In 2015, there were 437 nuclear power stations that supplied 10.7% of the world's electricity (Smil, 2016). In 2020, the share was 10.12% (Ritchie & Roser, 2020). But energy from nuclear fission is either being discontinued or remains stagnant in Western countries. Of the 67 reactors under construction in 2015, twenty-five were in China, nine in Russia, and six in India.

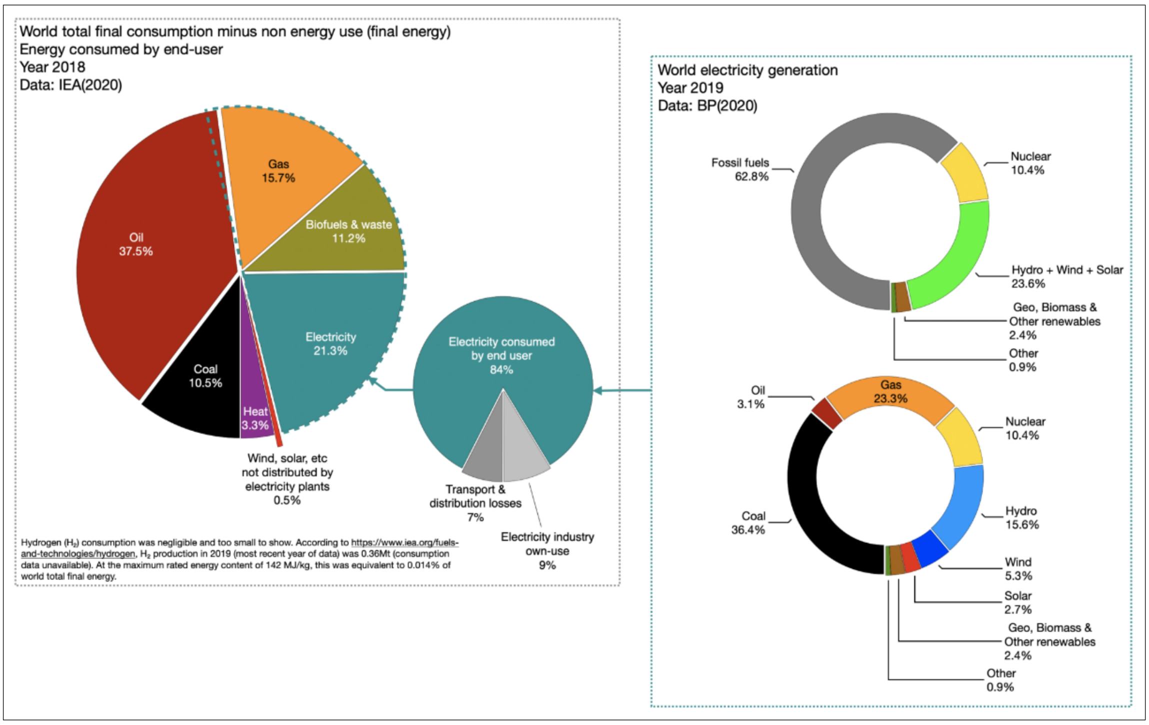


Figure 1.11 – Electricity share in final consumption and generation sources (White, 2020).

Despite the changes in prime movers since the beginnings of fossil fuel use - with the end of steam engines and the appearance of new sources of energy like hydroelectricity, nuclear power, wind turbines and solar power - *fossil fuels kept growing exponentially* and remain by far the main sources of primary energy.

Figure 1.9 from Ritchie & Roser (2020) illustrates the growth of the three main fossil fuels since 1800; and, how coal remains a key source of energy in the present. In 2019, coal, oil, and natural gas were 35.7%, 39.2%, and 29,7%, respectively, of the total fossil fuel consumption.

Figure 1.10, also by Ritchie & Roser (2020) shows how oil, coal, and gas have been contributing to primary energy consumption since 1965, and *how much larger* are their current shares when compared to those of low-carbon and renewable energy sources. Note that the shares of renewable energies have been adjusted by a factor representing the efficiency losses of the transformation of fossil fuels. Without the correction, the shares of the low carbon and renewable energies would still be lower.

Regarding electricity - primed to become the main source of energy in the future - the graphs of Figure 1.11 by Shane White (2020) show the relatively small share of electricity in the total final consumption of world energy (21.3%). And that fossil fuels are still globally responsible for 62.8% of electrical generation.

1.3. Red Alerts

If no other information was available, the environmental changes brought by the industrial age, could certainly be hinted from the diagram by Earl Cook of Figure 1.3 and from the amazing growth in human population since the 19th century, pictured in Figure 1.4. In Cook's diagram, energy capture per capita per day in "technological societies" is almost nine times more than that of "advanced agriculturalists". The breakdown of energy use is also telling – from one to the other stage there were enormous growths in industry and agriculture, and transportation. Even food energy consumed per capita is now three to four times the biological requirement.

The availability of fossil fuels - a gigantic stock of very old, stored energy – was obviously behind the jump in energy capture. But while the fuels were mostly extracted from underground *holes* the consequences of their use were to be felt all over the Earth's *surface*, including the sea and water bodies and the enveloping atmosphere.

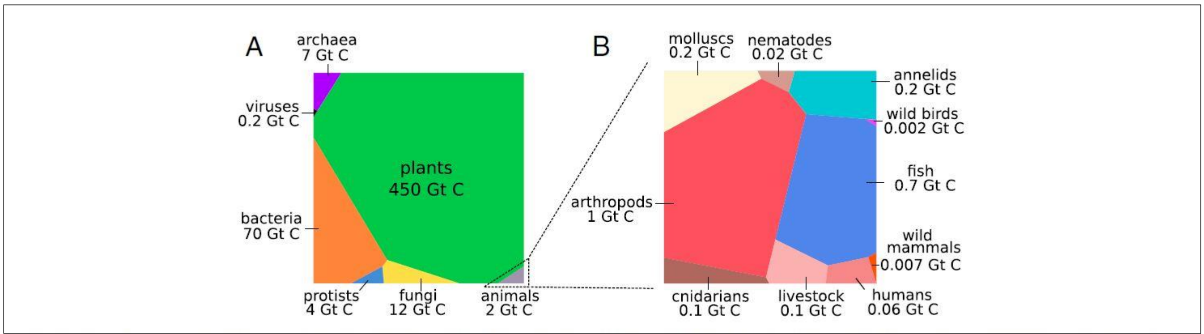


Figure 1.12 - Global biomass on Earth (Bar-On et al., 2018).

First evidence: as it can be seen from Figure 1.8 from Ellis et al. (2020), from the late 18th century onwards there were marked increases in land used for dense settlements and villages, cropland, and rangeland (pastureland) with a relative reduction in seminatural areas. Rangelands currently occupy a little more than a quarter of the terrestrial surface of Earth, while wildlands have been reduced to about one quarter.

Second evidence: a global survey of biomass on Earth performed by Bar-On et al. (2018) whose results are summarized in the Voronoi diagrams of Figure 1.12. The areas of the polygons are proportional to the mass of each taxon analysed and their mass is expressed in gigatonnes (Gt) of carbon (C), which makes it independent of water contents and other chemical components.

Compared to other kingdoms (like plants, bacteria, and fungi) animals have a small global mass (2 Gt C), and within animals (diagram on the right) the share of mammal biomass is only 8.4%. However, significantly, the mass of *wild mammals* is just 0.007 Gt C, one order of magnitude *lower* than the biomass of humans (0.06 Gt C) while the mass of livestock (0.1 Gt C), dominated by cattle and pigs, is one order of magnitude *higher* than the biomass of humans.

The biomass of domesticated poultry, dominated by chickens, is about 0.005 Gt C while the biomass of wild birds is only 0.002 Gt C.

Bar-On et al. (2018) also estimate the impact of humans on other biota over time by comparing current biomass values with historical estimates. For example, the biomass of mammals before the mega-fauna extinction (mentioned in Section 1.2.3.) is estimated at 0.02 Gt C. The present-day biomass of wild mammals, 0.003 Gt C, is approximately *seven times* lower. Exploitation of marine mammals, like whales, resulted in a *fivefold* decrease in marine mammal global biomass: about 0.02 Gt C to 0.004 Gt C.

But while the total biomass of wild mammals (both marine and terrestrial) decreased by a factor of six, approximately, the total mass of mammals increased four times, about 0.04 Gt C to 0.17 Gt C, due to the vast increase of the biomass of humans and associated livestock. Mankind also impacted fish stocks, a decrease of about 0.1 Gt C in the remaining total biomass in fisheries.

Regarding plants, their biomass *may have halved* relative to its value before the start of human civilization. The total biomass cultivated by humans is estimated at 10 Gt C, about 2% of the existing plant biomass (Bar-On, 2018).

It is easy to conclude that some of the land-use changes of Figure 1.8 can be related with the changes in biomass reported by Bar-On et al. (2018), namely the increase in rangelands providing feed to livestock, and the decrease in forested areas cleared for agriculture.

Third evidence of the profound changes brought by the industrial age: the growth and current size of global human-made *mass* (buildings, infrastructure, objects, and waste) as reported by Elhacham et al. (2020). The authors define *anthropogenic mass* as being formed by concrete, aggregates (like gravel and sand), bricks, asphalt, metals, wood used for paper and industry, glass, and plastic, incorporated in objects and structures *in use*; and *anthropogenic mass waste* or simply *waste* as man-made items that have been demolished, taken out of service, or discarded, including abandoned buildings and solid waste in landfills.

The diagrams of Figure 1.13 by Elhacham et al. (2020) illustrate the growth of anthropogenic mass and its components since 1900 (left side); and the growth of anthropogenic mass and of waste (right side). The diagrams also show global biomass as solid green lines, measured in teratonnes (Tt) of *dry weight* using data from Bar-On et al. (2018), together with the estimated *crossover* dates between anthropogenic mass and biomass. The biomass is shown in *dry weight*, i.e., excluding water, which is about two times the carbon weight; and in *wet weight*, i.e., including water, which is about two times the dry weight (Elhacham et al., 2020). Both biomass values and crossover years have uncertainties expressed by normal distributions: the dashed green lines and the deviations correspond to one standard deviation. Elhacham et al. (2020) remark that for the last 100 years anthropogenic mass has been doubling every 20 years and that now accumulates at a rate of 30 Gt per year, based on the average for the past 5 years. This corresponds to each human on Earth generating more than his body weight in anthropogenic mass *every week*. The diagram of Figure 1.14 also from Elhacham et al. (2020) (with biomass in dry weight) is also a telling illustration of how humans have changed the planet.

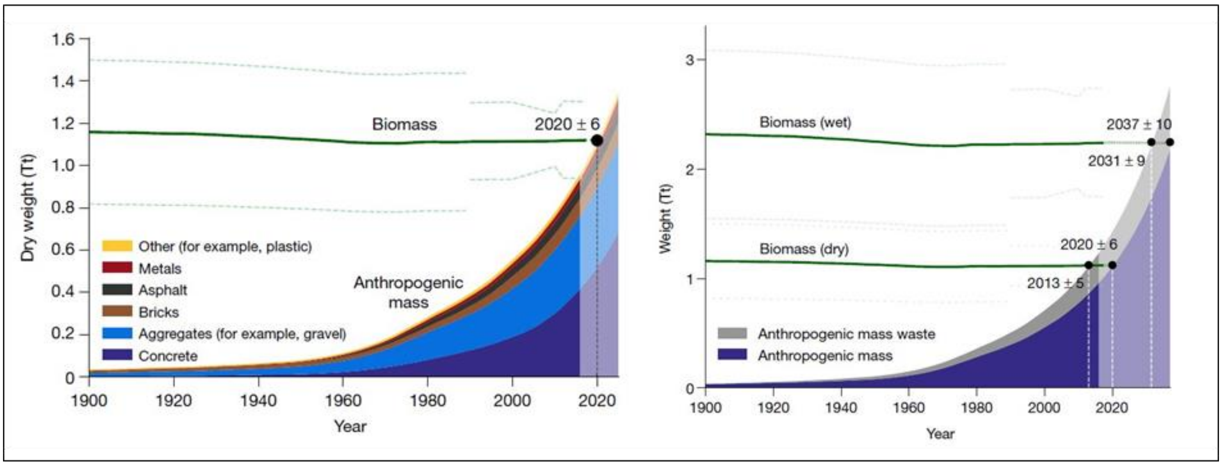


Figure 1.13 - Growth of anthropogenic mass and waste since 1900 (Elhacham et al., 2020)

Figure 1.14 - Masses compared (Elhacham et al., 2020)

Last evidence of human impact on the planet but certainly not the least: the atmospheric emissions from fossil fuels and other human activities.

Figure 1.15 shows on the left the carbon dioxide emissions from the three fossil fuels associated with energy, transportation, and industrial production, since the beginning of industrialization. And on the right on the same time scale the consumption of coal by the main consumer countries. Both graphs are by Ritchie & Roser (2020). It is apparent from the graphs that coal has become nowadays the largest contributor to emissions, taking over oil by the beginning of the 21st century, and that India and China are now the largest emitter countries – as other countries are reducing coal consumption. Note that the default emission factor for the combustion of coal (the “dirtiest” of fossil fuels) is equal to 98,300 kg CO_2/terajoule, while the same factors for crude oil and natural gas are 73,300 and 56,100 kg CO_2/terajoule, respectively (IPCC, 2006).

While carbon dioxide is the main contributor to the greenhouse effect there are other emissions of greenhouse gases (GHG). Figure 1.16 presents the contributions of the main greenhouse gases to total emissions in 2016 (Ritchie & Roser, 2020). Methane (CH_4) is emitted by ruminant livestock, rice

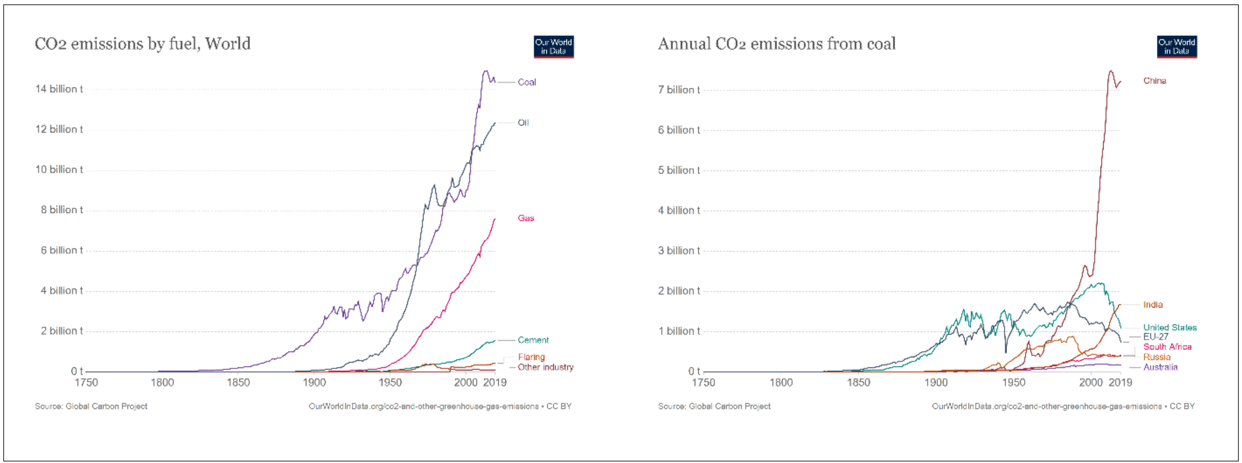


Figure 1.15 – Emissions from fossil fuels. Coal-using countries (Ritchie & Roser, 2020c)

cultivation, burning of biomass, waste in landfills, and fugitive emissions during oil and gas extraction. Emissions of nitrous oxide (NO_2) result from applying nitrogen fertilizers to the soil, increasing the production of NO_2 by soil microbes since not all the fertilizer is taken by the plants. Excess fertilizer running off to the sea has also severe impacts on marine life. The *F-gases* are a group of fluorinated compounds resulting from industrial processes. All these gases have a much stronger greenhouse effect than carbon dioxide.

The comparative effects are expressed by a global warming potential (GWP), calculated by the amount of warming created by a tonne of gas over 100 years divided by the amount of warming

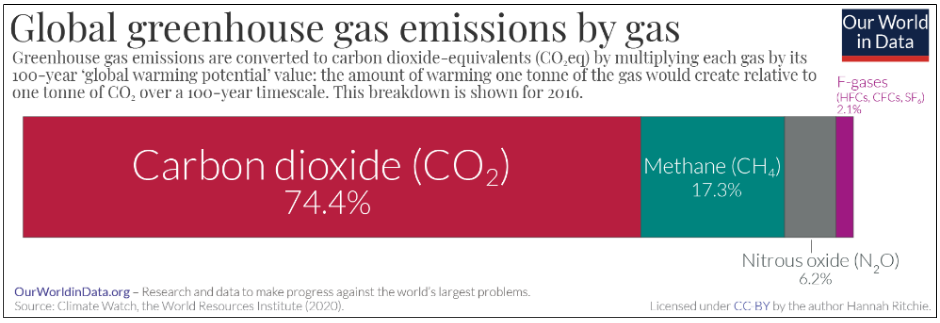


Figure 1.16 – Shares of global GHG emissions by gas (Ritchie & Roser, 2020d)

created by one tonne of carbon dioxide over the same 100 years.

One tonne of methane over one century (ignoring climate feedbacks) would generate 28 times the amount of warming as one tonne of carbon dioxide, its GWP being thus 28. For nitrous oxide, the

GWP value is 265. All the fluorinated gases *have GWPs well over 10,000* although their global emissions are comparatively very small.

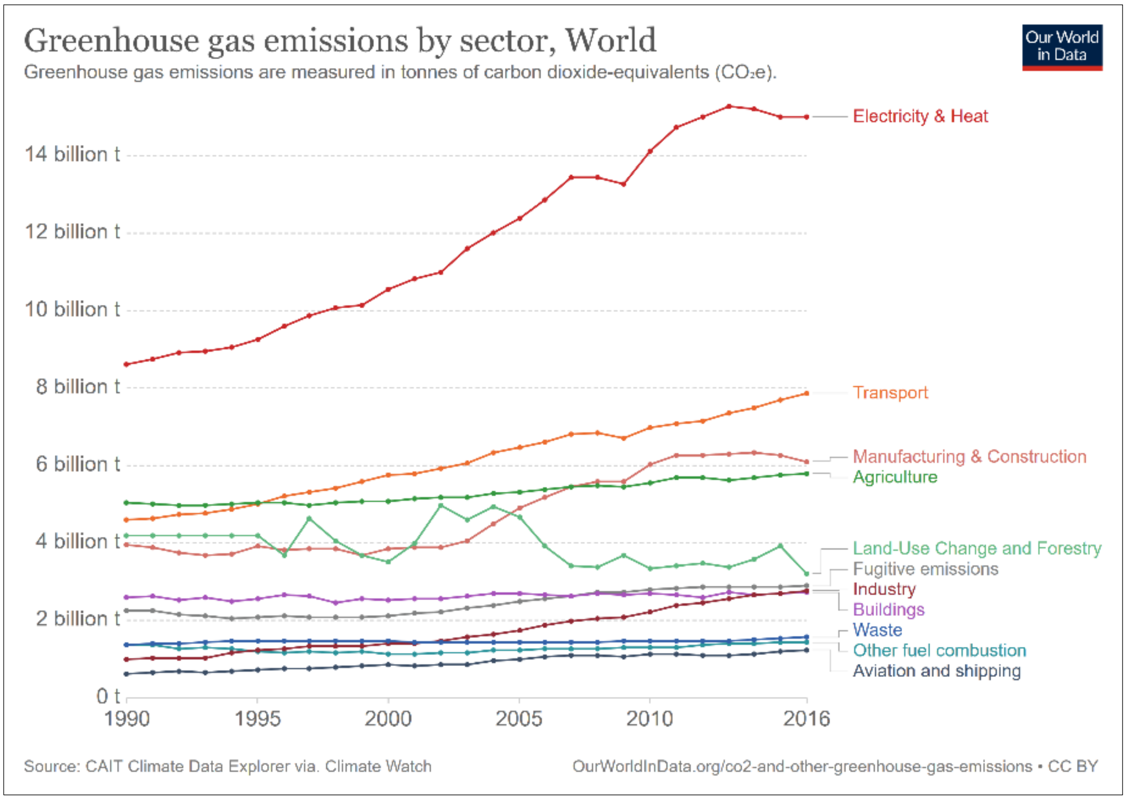


Figure 1.17 - GHG emissions in tonnes CO_2e by economic sector (Ritchie & Roser, 2020e)

Non-CO_2 gases can be converted into their carbon dioxide-equivalents (written as CO_2e) by multiplying their masses (e.g., kilograms of methane emitted) by their global warming potentials. Differences in GWP explain why methane and nitrous oxide have such relevant shares when compared to carbon dioxide despite being emitted in much smaller quantities.

Global emissions by economic sector in tonnes of carbon dioxide-equivalents (CO_2e) are shown in Figure 1.17 (Ritchie & Roser, 2020). Emissions by sector have different trends: some are stable or have slow growth; there are two reductions; but transport is still clearly increasing. The data refer to 2016. Since then, global emissions have not decreased, and even the fall due to the COVID19 pandemic is being reversed by the economic recovery.

Figure 1.18 from Ritchie & Roser (2020) shows long-term variations of global carbon dioxide in the atmosphere, in parts per million (ppm). The value for 2018 on the left diagram is approximately 409 ppm. As the diagram on the right shows, both this value and the amazing growth in emissions since industrialization have no historic precedent in more than 800 000 years.

The evidence just described raises immediate questions: is the planet able to accommodate the massive changes that have been described? Have humans already transgressed limits endangering life on Earth and their own future as a species?

Rockström et al. (2009) and Steffen et al. (2015) attempt to answer these questions by proposing *planetary boundaries* (PB), linked to a set of biophysical processes that regulate the stability of the Earth system and are being modified by human actions. The authors stress that: "human enterprise has grown so dramatically since the mid-20th century that the relatively stable, 11,700-year-long Holocene epoch, the only state of the planet that we know for certain can support contemporary human societies, is now being destabilized" (Rockström et al., 2009). And, that it is highly probable that the current trajectory will lead to a very different state of the Earth system, much less favourable to the development of human societies.

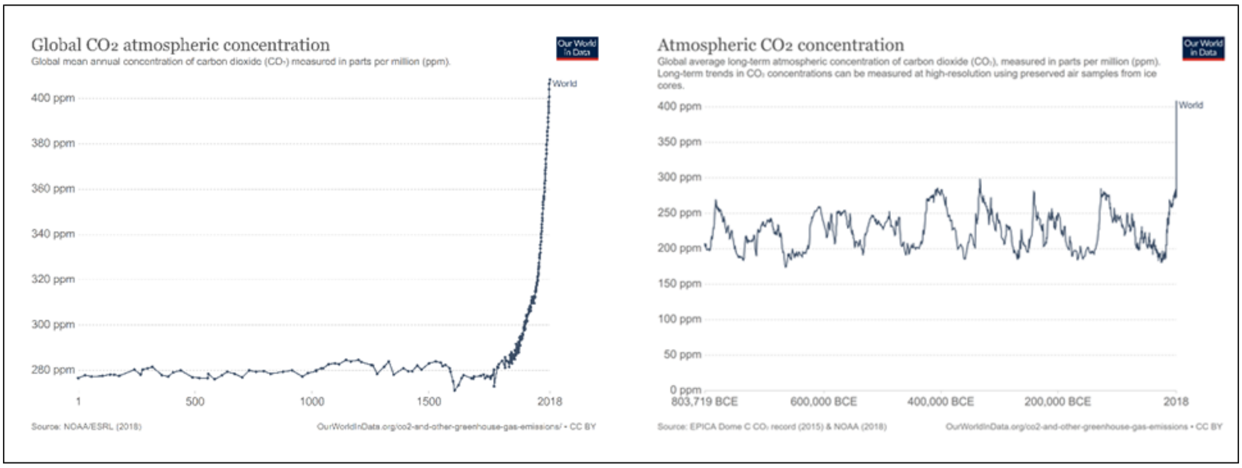


Figure 1.18 - Long-term concentration of atmospheric CO_2 (Ritchie & Roser, 2020f).

The planetary boundaries framework defines a "safe operating space" for human societies to develop and prosper, setting quantifiable limits that should be respected to reduce the risk that anthropogenic activities drive the Earth-system to a much less hospitable state. Steffen et al. (2015) define *nine* planetary boundaries associated with nine Earth-system processes: Climate change; Biosphere integrity; Stratospheric ozone depletion; Ocean Acidification; Biogeochemical flows (Phosphor and Nitrogen cycles); Land-system Change; Freshwater use; Atmospheric aerosol loading; Novel entities. Each process is monitored by one or more control variables, with defined boundaries.

For instance, the control variables of Climate change are the concentration of atmospheric CO_2 (boundary = 350 ppm) and the radiative forcing due to greenhouse gases at the top of the atmosphere (boundary = 1 W/m^2).

The PB framework defines three levels for each process: *safe* (below boundary); *increasing risk* (zone of uncertainty), and *high risk* (beyond zone of uncertainty). Figure 1.19 illustrates the status of the control variables for seven of the nine planetary boundaries, with Biosphere integrity and the Biogeochemical flows *already in the high-risk zone*, with only Freshwater use, Ocean acidification, and Stratospheric ozone depletion still below their boundary. In several boundaries, the definition of control variables and boundary values is preliminary or not yet possible (Steffen et al., 2015). The Novel entities boundary refers to the introduction of new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects - like, for instance, microplastics and chlorofluorocarbons.

Steffen et al. (2015) assert that Climate change and Biosphere integrity are highly integrated and connected to all the other planetary boundaries and occupy a higher hierarchical level in the framework. They operate at the level of the whole Earth system and have coevolved since life exists on Earth. On their own, *large changes* in the climate or in biosphere integrity would likely *push the Earth system out of the Holocene state*.

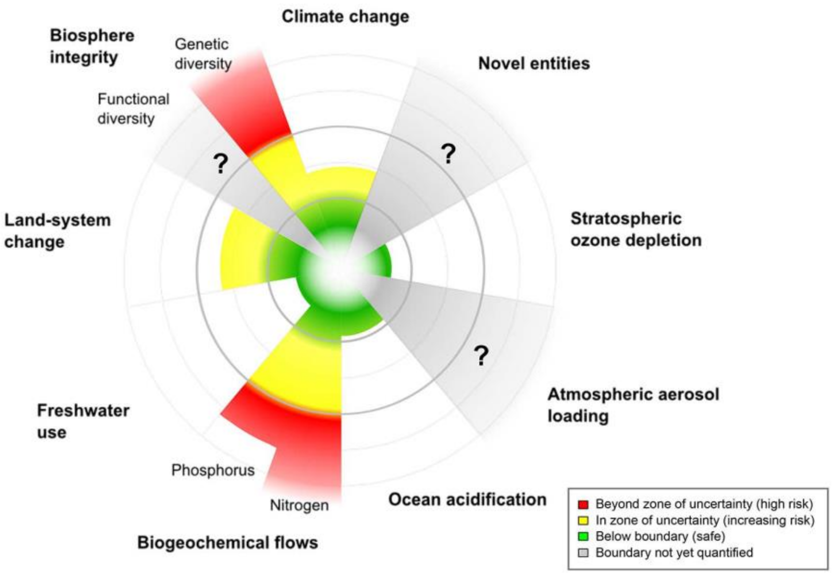


Figure 1.19 - Planetary boundaries and status (Steffen et al., 2015)

Biosphere integrity is the subject of a global assessment report by the IPBES, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019).

For political and cultural reasons, the IPBES defines “nature” as embodying “different concepts for different people”, including biodiversity and ecosystems - which will be adopted here as its meaning. The report emphasises the critical role of nature in providing food and feed, energy, medicines and genetic resources, and a variety of materials fundamental for people’s physical well-being and for maintaining culture. And that through its ecological and evolutionary processes, nature sustains the quality of the air, fresh water and soils on which humanity depends, distributes fresh water, regulates the climate, provides pollination and pest control, and reduces the impact of natural hazards.

About the present, two key messages are highlighted: (1) Nature and its vital contributions to people, which together embody biodiversity and ecosystem functions and services, are deteriorating worldwide; (2) Nature is being changed by direct and indirect drivers, which have accelerated in the past 50 years.

Figure 1.20 from IPBES (2019) summarizes the worrying trends of the first key message. From the 27 indicators of the state of biodiversity and ecosystem functions and services only three show positive trends – all three related with the use of resources for economic purposes. The 18 (anthropocentric) “contributions of nature to people” in the first column of the diagram are all negatively affected.

The direct and indirect drivers that are changing nature are illustrated in the diagram of Figure 1.21, which also highlights quantitative declines in the natural environment. The direct drivers: land-use and sea-use change; direct exploitation of organisms; climate change; pollution; and invasive alien species, are due to *societal causes* (indirect drivers), which are demographic (e.g., human population dynamics), sociocultural (e.g., consumption patterns), economic (e.g., trade), technological, or are related to institutions, governance, conflicts, and epidemics.

Land-use and sea-use change and direct exploitation account for more than 50% of the global impact on land, in fresh water and in the sea, although each driver is dominant in certain contexts.

In 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report on the impacts of global warming of 1.5°C and of 2°C above pre-industrial levels (IPCC, 2018), following the main goal of the Paris Agreement: “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” (UN, 2015).

The report concluded that until 2017 human activities had caused approximately 1.0°C of global warming since the 1850-1900 reference period, with a likely range of 0.8°C to 1.2°C. (These figures refer to GMST, the global mean surface temperature, an estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures over ice-free ocean regions.) It also concluded that greater warming was being experienced in “many land regions and seasons, including two to three times higher in the Arctic”. Also, that the intensity and frequency of *weather and climate extremes* increased even with increases of 0.5°C above the temperature of the reference period.

Figure 1.21 – Biodiversity and ecosystem indicators (IPBES, 2019)

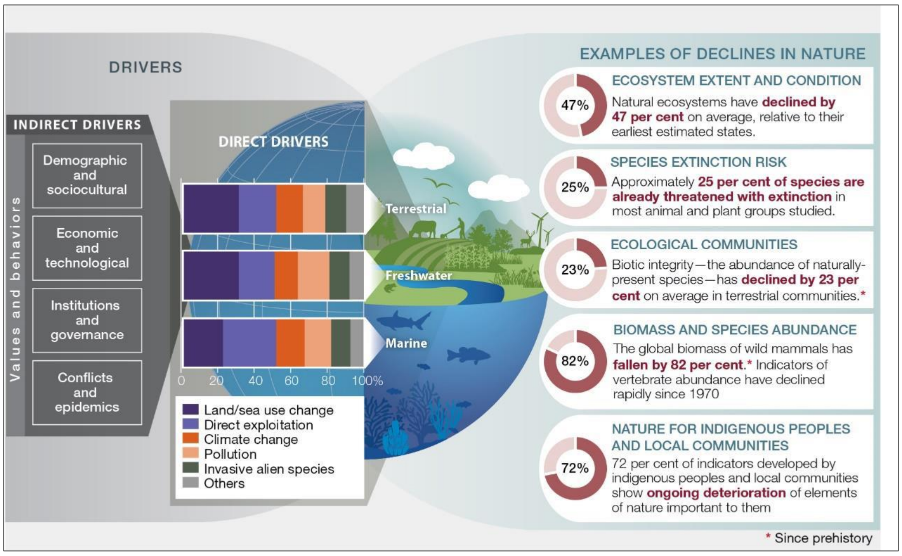


Figure 1.21 – Indirect and direct drivers of nature change (IPBES, 2019)

The negative impacts of 1.5°C global warming would be disastrous: 1) extreme temperatures, heavy precipitation, floods, with increased frequency and intensity; 2) sea level rise with the associated risks for coastal areas; 3) species loss and extinction, forest fires, spread of invasive species, progressive thawing of the permafrost; 4) impacts on a broad range of species due to increases in ocean temperature and acidification, reduced productivity of fisheries and aquaculture; 5) increased risks to the health, livelihoods, food security, water supply, human security, and economic growth.

In a careful wording aimed at promoting the “efforts to limit the temperature increase to 1.5°C” the IPCC continuously stresses that the risks of future global warming at 1.5°C are *much less* than the risks of global warming at 2°C. However, most of the negative impacts of global warming are already being felt *right now*. And that despite recent commitments of the European Union, the United States, and China, global anthropogenic GHG emissions have yet to peak and start their vertiginous descent until climate neutrality by 2050 or 2060 so that the global temperature “anomaly” does not exceed the 1.5°C target.

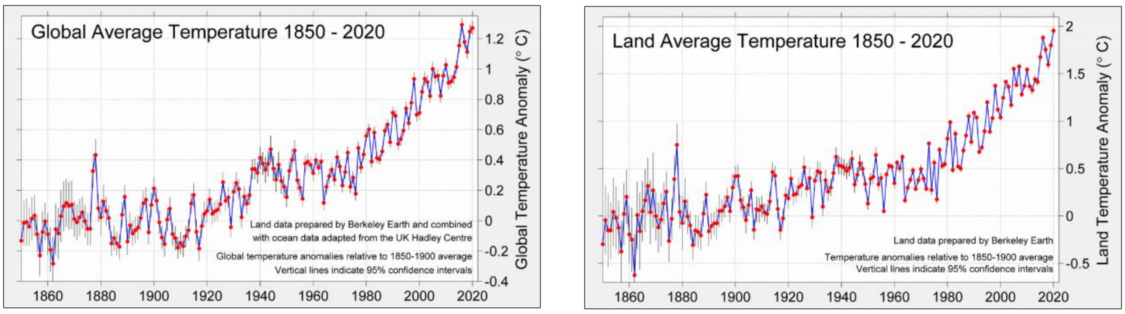


Figure 1.22 - Global average temperatures (Berkeley Earth, 2021a)

In his 2019 book “The Uninhabitable Earth”, written for general audiences, David Wallace-Wells (2019) presents an impressive collection of peer-reviewed literature and opinions by reputed experts about present day and future negative impacts of global warming.

His chapters have almost biblical names: hunger, drowning, wildfire, natural disasters, freshwater drain, unbreathable air, plagues of warming, economic collapse, climate conflicts, and systemic effects, e.g., climate migrations and heat-induced violence and mental diseases. It is tempting to call the author an alarmist, which he intends to be. But most of the cases he presents are now the daily subject of TV and the newspapers…

Figure 1.22 illustrates how global average temperature rose since 1850 (Berkeley Earth, 2021). The graph on the left represents the global mean surface temperature (GMST), which includes the temperature of the ocean. The graph on the right represents the mean temperature on land alone. In the last six years the mean temperature on land has consistently varied between 1.5°C and 2.0°C. Figure 1.23 also by Berkeley Earth (2021) illustrates how the temperature anomaly above the reference 1850-1900 average was distributed over the Earth surface in 2020. With many areas of the globe over

2°C and the anomaly in the Arctic going up to 6°C or 7°C, no wonder that wildfires are now so commonplace all over the world.

A final example of how climate change is endangering human life in some places on Earth is

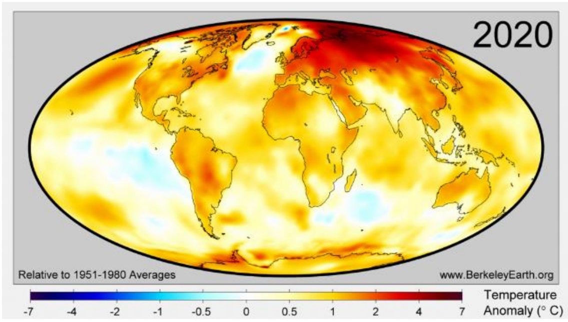


Figure 1.23 - Temperature anomaly in 2020 (Berkeley Earth, 2021b)

apparent from the global distribution of *wet bulb temperatures* (TW). A wet bulb measurement of surface temperature is performed by wrapping the bulb of a conventional thermometer in a wet cloth and shaking the set in the air so that heat energy is lost by the bulb through evaporation. The physical process is like what humans do when they sweat to reduce body temperature.

As explained by Raymond et al. (2020) a normal internal body temperature of 36.8° +/- 0.5°C requires skin temperatures of around 35°C to ensure outward heat flow. If air temperature (*dry bulb*) rises above 35°C metabolic body heat is lost by sweating. However, if *wet bulb* air temperatures exceed 35°C the cooling mechanism fails. Since this limit only applies to ideal conditions (perfectly healthy humans, in total inactivity, fully shaded, naked, and supplied with unlimited drinking water) severe morbidity and mortality will start at much lower wet bulb temperature values. For instance, in the deadly 2003 European and 2010 Russian heat waves *wet bulb* temperatures values did not exceed 28°C.

Figure 1.24 by Raymond et al. (2020) shows the observed daily maximum values of wet bulb temperatures, from 1979 to 2017. The colour-coded intervals represent the 99.9th percentile of the values for HadISD meteorological stations with at least 50% data availability in the period. The survey reveals many occurrences of wet bulb temperatures (TW) exceeding 31° and 33°C and two stations reporting multiple daily maximum TW values exceeding 35°C, for brief periods.

But the dangerous interval of 27°C to 29°C can be seen in many places of the globe, with occurrences in the hundreds of thousands in the period. The authors also highlight statistically significant correlations between the number of occurrences over a defined TW threshold and the progress of time within the 1979-2017 interval, meaning the situation has got worse with time.

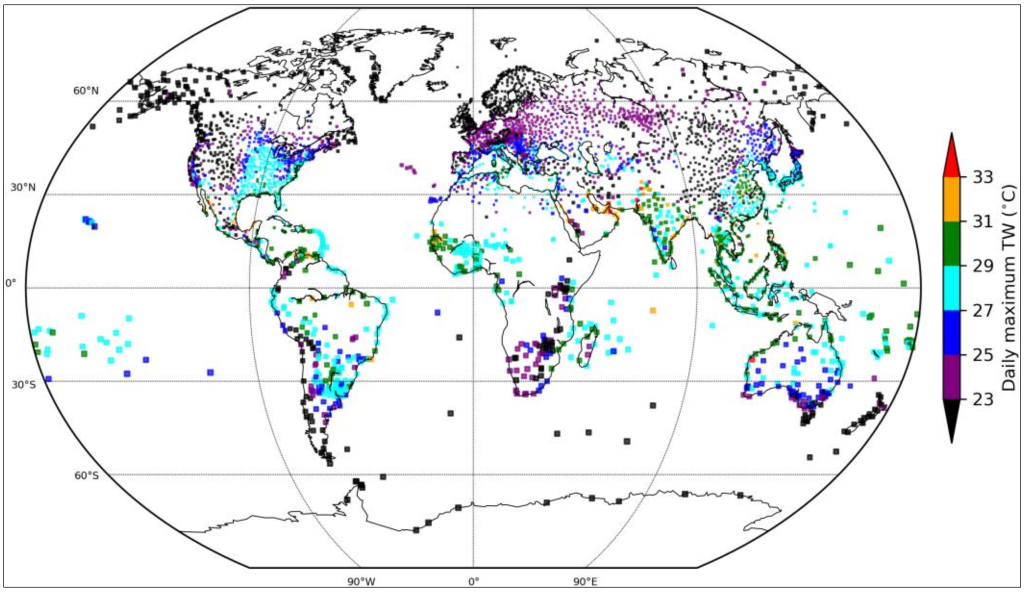


Figure 1.24 - Global wet bulb temperature distribution 1979-2017 (Raymond et al., 2020)

1.4. The Future of Energy Use

At the end of this chapter several questions arise: was the exponentially growing energy capture by humans inevitable? Given the devastating impacts on the planet can energy growth continue? What can be the future of energy use?

Alfred Lotka (Lotka, 1922) argues that evolution will favour those species having superior energy capturing capabilities since available energy is the fundamental object of dispute in the struggle for life. If there are sources supplying energy exceeding what is used by an entire system of living organisms, opportunities exist for able species to divert that energy for their own preservation, use it to increase their population and total mass, and increase to their advantage the rate at which they capture and use energy. For Lotka, energy capture meant establishing an energy flux through the living organism: energy processed, by unit of time, which has the dimensions of power. A competent species can divert excess energy to enter its own energy flux and increase that energy flux if excess matter is present, increasing the total mass. If matter is limited but excess energy is still available, the species may increase the energy flux by increasing the rate at which energy is handled. Humans have been, of course, a superior species at capturing energy. For instance, by setting a farming plot a community can divert excess solar and chemical energies to their own energy flux, then increasing it by farming more land to support a larger population. If a physical limit is attained (e.g., no more fertile land) farmers may still increase the energy flux by growing two crops in a year or use other ways to increase productivity.

Thus, evolution, by naturally selecting species most competent in capturing energy: "tends to make the energy flux to the system a maximum so far as compatible with the constraints to which the system is subject" (Lotka, 1922).

Lotka's maximum energy principle could explain how the human quest for energy, with its ever-increasing energy capture per capita per unit of time - i.e., the energy flux - determined the preponderance of our species: by maximizing useful power the predator *Homo sapiens* was able to become the *top predator* on the planet.

Leslie White (White, 1943) offers another perspective, based on the evolution of human culture. For White, human culture is an organization of material objects, bodily acts, ideas, and sentiments, which he considers *a form or organization of energy* ultimately derived from the Sun.

Stating that the purpose of culture is to satisfy human needs, White carefully sorts out factors affecting cultural situations to arrive at those he considers more relevant: the ones derived from the material, mechanical means by which humans exploit the resources of nature. He proposes three: the energy captured or harnessed per capita per unit of time (E); the efficiency at which human energy is expended (F), which depends on the technology; and the useful products (P) resulting from the expenditure of energy at a given efficiency.

A simple equation would relate the three factors: E*F = P.

Since culture serves human needs, P denotes the total amount of useful goods or services produced in any given cultural situation, therefore P also represents the degree or status of cultural development. The efficiency of energy use F, or the energy captured E, may each remain constant in cultural situations leading White to formulate two laws of cultural evolution: 1) other things being equal the degree of cultural development varies directly with the amount of *energy captured* per capita per unit of time and put to work; 2) other things being equal the degree of cultural development varies directly with the *efficiency* of the technological means with which the captured energy is put to work.

The laws merge into one: "We have, in the above generalizations the law of cultural evolution: culture develops when the amount of energy harnessed by man per capita per year is increased; or as the efficiency of the technological means of putting this energy to work is increased; or, as both factors are simultaneously increased" (White, 1944).

For White, culture not biology powers the evolution of humankind: "In human species the struggle for survival assumes the cultural form. The human struggle for existence expresses itself in a never-ending attempt to make culture a more effective instrument with which to provide security of life and survival of the species" (White, 1943). Therefore, culture could become more powerful by harnessing and putting to work more energy per capita per unit of time - an equivalent to Lotka's energy flux.

White goes further by arguing that unless humankind can capture additional quantities of energy by exploring new sources, cultural development will come to an end. And since fossil fuels would inevitably be depleted, he points to atomic and solar energies as the energies of the future. (Both were, technologically, a mere promise in 1943.)

White was also overly optimistic regarding energy: “The key to the future, in any event, lies in the energy situation. If we can continue to harness as much energy per capita per year in the future as we are doing now, there is little doubt that our old social system will give way to a new one, a new era of civilization” (White, 1943).

Both Lotka and White stress the importance of energy in the progress of humankind and offer plausible explanations for the exponentially increasing use of energy - although they did not anticipate its planetary consequences. Lotka’s maximum energy principle may explain how Homo sapiens has been favoured by evolution since his beginnings, an unconscious biological process. White’s approach, however, may be more relevant for present times since any human biological evolution (longevity, prosthetics, genetic improvement, etc.) will eventually result from accumulated knowledge: an outcome of culture.

Regarding future times, energy capture per capita *must certainly increase* for those countries where it is still low or very low since for them energy is a determinant factor in economic development, which implies economic growth.

In a comprehensive study of the energy requirements of what they define as decent living standards (DLS), Kikstra et al. (2021) start by estimating how much 193 countries in the world are deprived of these standards - their DLS gaps. Their definitions of DLS encompass a set of *material satisfiers* grouped in five categories: nutrition (sufficient calories, clean cook stoves, refrigerators); shelter (sufficient space, durable construction, clothing, and heating and cooling equipment); health (clean water, sanitation, hot water, general health care); mobility (rail and road infrastructure, vehicles, and energy for vehicles); and socialization (education, communication services, and access to information).

Their conclusions are interesting and upsetting. In all world regions, including North America and Western Europe, parts of the population lack one or more components of decent living. In Sub-Saharan Africa and South Asia, unsurprisingly, the gaps are deep: large shares or whole populations are deprived.

Comparing average DLS gaps with poverty standards (including the $5.5 per day poverty line of middle-income countries) all the surveyed countries show more population living with DLS gaps than living below the poverty line, meaning that DLS would provide a better characterization of poverty (or lack of it) than the usual monetary poverty lines.

Another important conclusion is that the current energy requirements for DLS are lower than the current average energy per capita per year in all world regions (data from 2015) meaning that while many people lack decent living energy there remains *energy for affluence* appropriated by wealthy segments of the population.

The authors also project the total energy required to achieve DLS in 2040 and conclude that, assuming a ‘middle of the road’ energetic scenario, it will amount to 23% to 28% of the world’s total energy demand by 2040. So, still plenty of remaining energy for affluence.

However, they are very assertive about the challenges of implementing DLS, namely regarding energy growth: countries currently suffering wide gaps in decent living standards (like Sub-Saharan Africa and some Asian countries) will require energy and economic growth rates much higher than the world average and their own growth projections considering population increase. Thus, implementing decent living standards will require *energy redistribution policies* or the promotion of unprecedented economic growth. The authors believe that the share of global energy demand taken by DLS in 2040 (or even in 2050) is compatible with the goals of climate neutrality, although they don’t handle decarbonization in their study.

Our dominant economic system, with its variants, is heir to the industrial capitalism of the 19th and 20th centuries. It is now apparent that two outcomes of the accelerated development enabled by capitalism – extraction of natural resources and generation of waste – are now reaching their safe limits, as discussed in the previous section. Another safe limit already passed is, of course, climate change, which is also related with the extraction of fossil energy resources.

The rates at which natural resources are extracted and their evolution in the last decades are for the United Nations distressing indicators of continued environmental degradation, as discussed in their last Sustained Development Goals Report (UN, 2019b). The global material footprint (total amount of raw materials extracted to meet final consumption demands) has grown 113% since 1990 reaching 92 billion metric tonnes in 2017: a growth rate outpacing both population growth and GDP growth, meaning that a badly needed decoupling of economic growth from resource extraction has not yet been reached. Material footprints per capita have equally grown at “alarming rates”, as the report puts it, rising globally from 8.8 tons in 2000 to 12.2 tons in 2017. High income countries had the smallest increase, but their levels were already much larger than the global average: 25.6 tons per capita in 2000 rising to 26.3 tons per capita in 2017. These material footprints hide a reality that can become apparent in their domestic material consumption, which measures the total amount of materials directly used by the economy to meet the demands for goods and services from within and outside a country. According to the report: “The material footprint of high-income countries is greater than their domestic material consumption, indicating that consumption in those countries relies on materials from other countries through international supply chains. On a per-capita basis, high-income countries rely on 9.8 metric tons of primary materials extracted elsewhere in the world” (UN, 2019b).

Waste that cannot be suitably integrated in natural or technical recycling processes will end up as pollution. Pollution, in its many forms, is now a very serious problem for humanity and the biosphere but greenhouse gases (GHG), which are direct or indirect waste products from most human activities, are causing a climate crisis of unprecedented dimensions.

Energy production is currently responsible for 73.2% of global GHG emissions, according to Ritchie & Roser (2020) with data from 2016. Energy use in industry (24.2%), transport (16.2%), and buildings (17.5%) are the main contributors. It is therefore quite clear that decoupling emissions from energy is an essential step to allow both energy and economic development to continue their growth trajectory so that decent living standards can be enjoyed by everyone.

Contrary to what happens with material footprint, there is evidence that a *decoupling between energy and emissions* is already happening, at least regarding electricity. As mentioned in Section

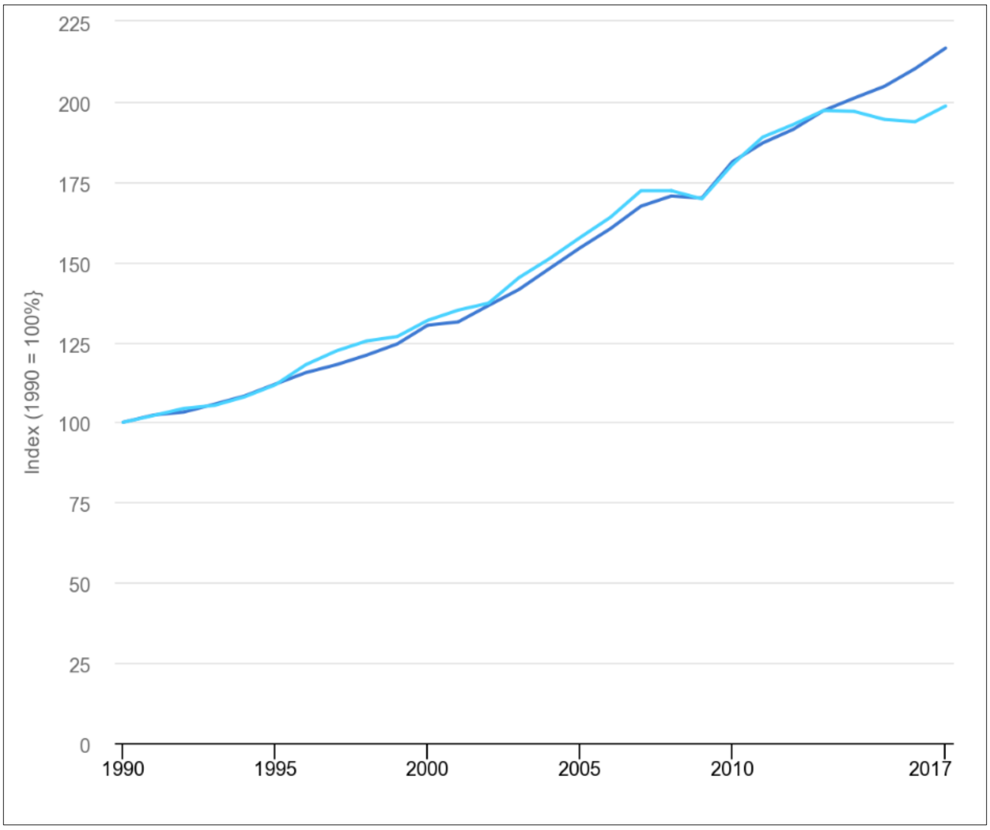


Figure 1.25 – Decoupling electricity (dark blue) from emissions (light blue) (IEA, 2019).

1.2.11 electricity is only about 21% of total final energy demand but its share is expected to become largely dominant in the next decades, so any observed decoupling is highly relevant.

The subject is discussed in a short publication by the IEA, the International Energy Agency (IEA, 2019). The authors observe that electricity is responsible for about 40% of the energy-related CO_2 emissions and that from 1990 to 2013 the carbon intensity of electricity at global level (measured in gCO2/kWh) had been tracking the increase in electricity demand, as shown in Figure 1.25 where the light blue line represents GHG emissions and the dark blue line electricity demand.

The tracking happened because of two opposing trends: western advanced economies were

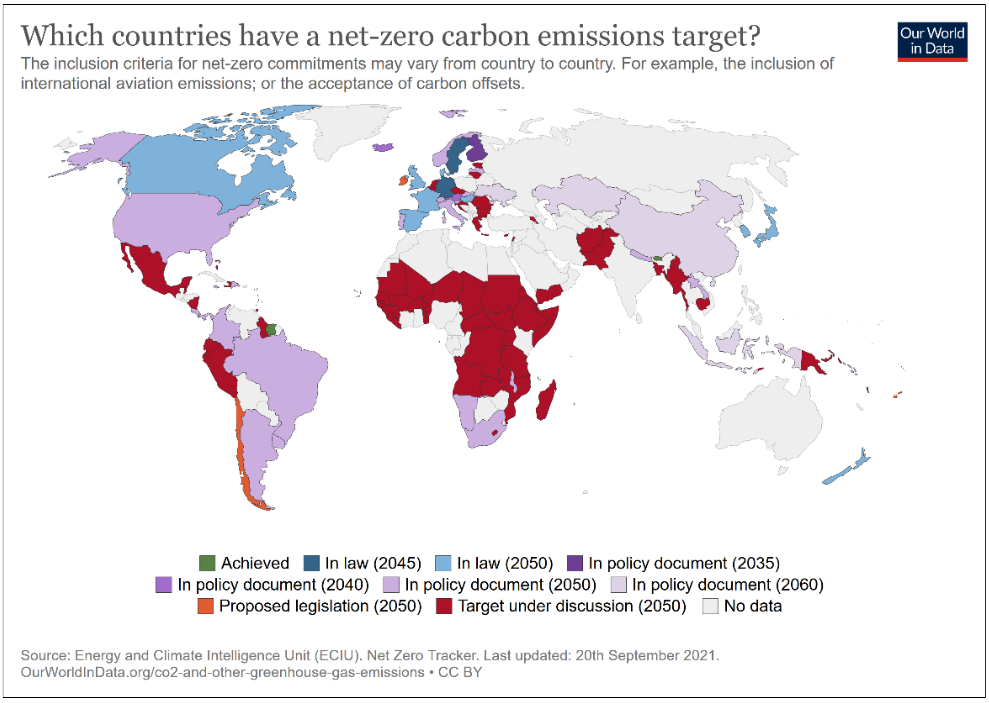


Figure 1.26 - Countries with net-zero emissions target (ECIU, 2021)

reducing the carbon intensity of their electricity production by increasing efficiency, switching away from fossil fuels, and increasing the share of renewable energies, while the emergent economies of South and East Asia, namely India and China, were increasingly generating electricity from coal. From 2013 to 2017, however, the global carbon intensity has become approximately constant while electricity demand has continued to grow. According to the IEA the reason for the decoupling was the adoption by China and India of the three reduction strategies: increased efficiency, less fossil fuels, and more renewable energies

Complete decarbonization of energy production is still a remote and difficult goal but as shown in Figure 1.26 a substantial number of countries (including China, currently the biggest GHG emitter) are planning to achieve climate neutrality by the middle of the century (ECIU, 2021).

What is then the future of energy use? The answer depends, of course, on the political will by all nations to address the climate and ecological crises. But also, on the political motivation to address the *profound inequality* separating *energy-rich and energy-poor* populations.

Even with these political unknowns, it seems that there is reason for some optimism: humanity now possesses knowledge and technology to generate energy with virtually no negative impacts on the environment.

However, whether the new energy technologies can fulfil their role – deliver plentiful, emission free, ecologically-acceptable energy – will depend on how the issues of their material and land requirements are handled.

Building the new energy infrastructure will involve potentially enormous amounts of material resources and comparatively large areas on land and sea. Both requirements must be met *while* the ecological problems created by the *extraction-waste* production paradigm are solved or mitigated. Otherwise, the new energy technologies may be helping to solve the climate crisis while worsening the ecological crisis.

McDonough & Braungart (2002) discuss the predominant *extractive culture* in contemporary industrial processes calling it the *cradle-to-grave* production paradigm: a *linear sequence* where natural resources are extracted, transformed into products, sold, and eventually discarded in some kind of 'grave', for instance an incinerator or a landfill, while generating harmful emissions and effluents along the whole process.

The authors argue that the paradigm has been addressed since the 1990's by strategies that don't solve its inherent problems, which stem from product design. This is the case of *eco-efficiency*, which advocates reduction, reuse, and recycling – the three R's - and material and energy efficiency. Reducing toxic waste, raw materials, or the product itself, only slows down depletion. Reduction strategies, like incinerating waste or diluting it in the environment may end up generating new toxic pollution. Reuse strategies also have poor results. Sewage sludge, for example, is recycled into animal food and fertilizer but the current sewage treatment plants do not handle new chemicals (like antibiotics and hormones) that end up in urban sewage. Recycling, the authors claim, is mostly *downcycling*: transforming recovered materials into products of lower quality, with lost value. True recycling, which they call *upcycling*, implies recovering materials without loss in their original value, which is currently very difficult due to design practices that do not support disassembly. For instance, steel recovered from scrapped automobile bodies is mixed with paint, copper and other materials leading to recycled steel with inferior quality.

McDonough & Braungart (2002) propose replacing *cradle-to-grave* with *cradle-to-cradle*, offering implementation strategies and case studies. Their framework for the new product and system design principles relies upon the concepts of biological and technical *metabolism*. A *biological metabolism* integrates the cycles of the biosphere, which operate through a system of nutrients and processes in which there is no waste because waste is transformed into food in a cyclical, cradle-to-cradle process that has nourished the planet for millions of years. A *technical metabolism* is formed by technical processes and systems where nutrients are the materials that can be *cycled back* into the technical processes from which they came. When designing products both metabolisms must be identified *and kept isolated*. A product made of organic materials may be designed to be safely returned to the environment at end of life, re-entering the biological cycle and becoming food for soil microorganisms. Or products may be designed to remain in technical cycles, their components recovered as technical nutrients at end of life and incorporated into the same or other products without losing value. Hybrid products may cycle in the two metabolisms: a shoe, for instance, may be designed so that the uppers are kept in a technical metabolism and the fully biodegradable rubber soles re-enter the biological metabolism.

The cradle-to-cradle paradigm may be incorporated into what is known as the *circular economy* (CE). The Platform for Accelerating the Circular Economy (PACE), a public-private collaboration of more than 50 leaders from international organizations, academia, and businesses recently published two reports about the circular economy, highlighting its status and prospects. The Circularity Gap Report 2019 (Circle Economy, 2019) starts by recalling the appalling conclusion of their first 2018 report: the global economy *is only 9% circular*. Data from 2015 show that the total volume of extracted resources in that year amounted to 84.4 billion tonnes while only 8.4 billion tonnes were cycled resources.

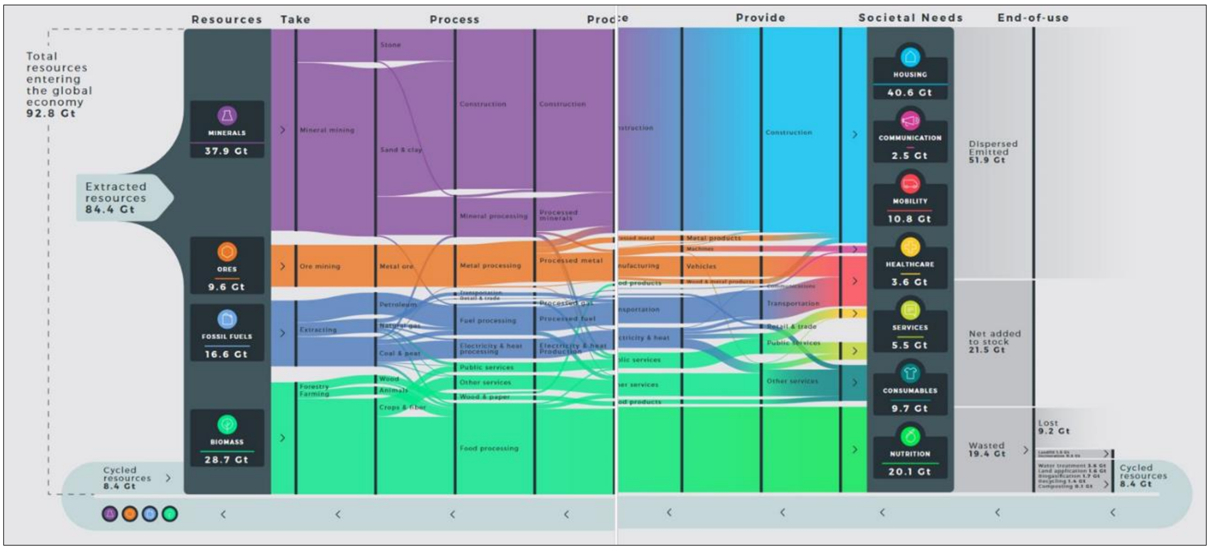


Figure 1.27 - Mass component of the MVC nexus (Circle Economy, 2019)

The report introduces the mass-value-carbon nexus (MVC), which describes and interrelates yearly flows of materials, value added, and carbon emissions (CO_2e emissions). The flows are associated with seven societal "needs and wants" – *housing and infrastructure*, *nutrition*, *mobility*, *consumables*, *services*, *healthcare*, and *communication* – providing opportunities to propose strategies to handle the pressing issues of excessive material footprint and emissions, while improving value creation.

Figure 1.27, a composite image taken from Circle Economy (2019) shows the complex material flows of the global economy starting from great classes of resources (minerals, ores, fossil fuels, and biomass) and ending in products and services that satisfy the seven societal needs. Colour coding facilitates the identification of inputs and outputs. The end-of-use values are remarkable: in one year, from the 92.8 Gt (billion tonnes) of input materials, 21.5 Gt were *net* additions to the stock of durable goods and 19.4 Gt were wastes - from which 8.4 Gt were cycled back, while 51.9 Gt *remained unaccounted for* and were assumed to be emissions and other matter dispersed into the environment.

Note that GHG emissions (the Carbon flow) are accounted separately but most of the 16.6 Gt in fossil fuels also contribute to the unaccounted 51.9 Gt dispersed and emitted.

The 21.5 Gt net addition to the economic material stock equals a 36 Gt flow into the stock of *Products That Last* (capital equipment, buildings, infrastructure) minus a 14.5 Gt flow out of stock and into waste. Current material stocks are estimated at 890 Gt, almost ten times the annual throughput.

The gross value added (GVA) accrued yearly by the global economy - its "financial footprint" – constitutes the Value flow and is also displayed in Circle Economy (2019) with shares of value added by production stage and by end products and services. From a global GVA of 58.2 trillion Euros in 2016, the *take* step (resource extraction) corresponded to €1.6 Tn, a small share, while the *process*, *produce* and *provide* steps corresponded to 7.1 Tn, 9.9 and 39.6 trillion Euros, respectively. The *provide* step, including the transport and distribution of products and the delivery of services, corresponds to the highest share (68%) of the GVA.

The report classifies manufactured products in *Products That Flow* (comprising consumables, lasting no longer than one year) and *Products That Last* (capital goods forming the economic stock). Manufactured products of both types contributed €20.5Tn while *services* contributed €37.7 Tn, *about 65% of the total GVA*. The report also estimates the global economic stock as €136 Tn, from which €8.7 Tn were depreciated at the end of the year, with a small fraction (€0.4Tn) becoming available as residual value from *Products That Flow*.

Greenhouse gas emissions per year - the Carbon component of the MVC nexus - represent the carbon footprint of the global economy. Figure 1.28 from Circle Economy (2019) shows the GHG emissions for 2017 (excluding emissions from land use change) measured in gigatonnes of CO_2e. The contributions are differentiated by step, including now an emissions-generating consumption and waste phase.

The graph assigns emissions to production steps and societal needs. The *take*, *process* and *produce* steps are responsible for most of the emissions: 31.2 Gt out of 50.9 Gt of carbon dioxide equivalent, a 62% share. The *provide* stage has the smallest contribution: 6.4 Gt CO_2e. Regarding societal needs, *mobility* is responsible for the largest share, 12.7 Gt CO_2e, a consequence of its reliance on fossil fuels. The carbon footprint of *nutrition*, 6.5 GtCO_2e looks relatively low because emissions due to land use change are not accounted for.

Comparing the shares of material resources, value added, and GHG emissions assigned to each societal need enable the authors of Circle Economy (2019) to define "profiles" grouping needs with similar characteristics.

Three profiles were identified. Profile 1 includes *housing*, *mobility*, and *consumables*, which together are responsible for 66% of the total material footprint, 64% of the carbon footprint, and 48% of the financial value footprint. Profile 2 includes only *nutrition*, with 21.7% of the total material footprint, 12% of the carbon footprint, and only 3% of the financial value footprint value. Profile 3 includes *services*, *health*, and *communication*, responsible for 13% of the total material footprint, 23% of the carbon footprint, and 63% of the financial value footprint value - its largest share. The shares

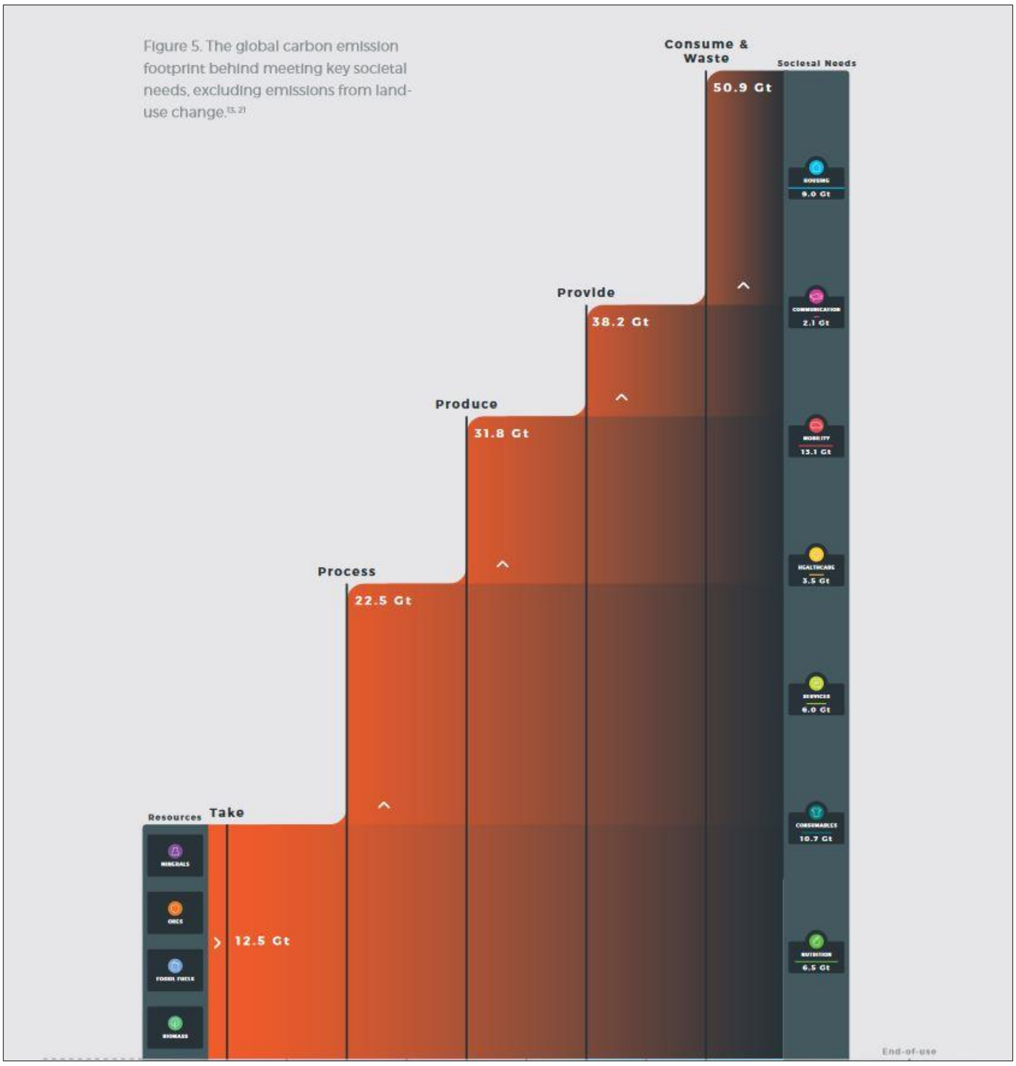


Figure 1.28 - Carbon component of the MVC nexus (Circle Economy, 2019)

were calculated for the dissertation from values in Circle Economy (2019), noting that the MVC footprints correspond to different years.

The three distinct profiles support different strategies to reduce *circularity gaps* proposed by the authors. Two general objectives are pursued: 1) minimize resource extraction from the lithosphere and ensure biomass production and extraction is regenerative; 2) minimize dispersion and loss of materials, ensuring technical materials have high recovery opportunities without degradation and quality loss, with emission to airs and dispersion to water and land prevented.

Reducing circularity gaps involves key elements giving direction to the transformative process: 1) *design* for the future; 2) *track and optimise resource usage* using digital technology; 3) *sustain and preserve* what is already present; 4) *maximize product lifetime*; 5) *rethink the business model* to create value from the interaction of products and services - *the product as a service*; 6) *use waste streams as resources*; 7) *prioritize regenerative resources* that are renewable, reusable, and non-toxic, used as materials and energy.

A final remark about the Circle Economy (2019) report. The authors argue that advances in circularity are essential to achieve the 1.5^{o} warming of the Paris Agreement. They base their conclusion on the expectation that the world will not be able to reach the goal by reducing emissions alone. And cite independent research asserting that materials recirculation and improvements in materials and energy efficiency may lead to 56% reduction in the GHG emissions in the industries of steel, plastics, aluminium, and cement.

CHAPTER 2

Solar Photovoltaic Power as a Sustainable Technology

2.1. Sustainable Development

The concern with the *sustainable use* of natural resources emerged in the mid-17th and early 18th centuries in England, France, and the German states, and had its roots in forestry when huge timber requirements for shipbuilding and other uses were leading to widespread deforestation, as described in Caradonna (2014) and Smil (2017). But the concept of sustainability as an environmental and economic ideal only gained prominence in the 1970s and 1980s with a series of international initiatives promoted by the United Nations (Caradonna, 2014; Purvis et al., 2018; Sachs, 2015). They followed a history of two centuries that saw the birth of an 'economy of nature' discipline in the 18th century - later to be established as the science of *ecology* - and a long, continuous intellectual debate between those proposing a harmonious coexistence of humankind with all the other natural organisms and those asserting humankind's dominion over nature and the right to use earth's resources to human advantage, as described in full detail by Worster (1994).

Not surprisingly, all discussions, interventions, and later political movements regarding the relation between humankind and nature happened while industrial capitalism was changing large areas of the planet beyond recognition, with increasingly concerning consequences as discussed in Chapter 1.

The UN took a fundamental step to coordinate international environmental efforts with the UN Conference on the Human Environment held in Stockholm, in 1972. From the conference came the 'Stockholm Declaration' (formally the Declaration on the Human Environment) and the creation of UNEP, the United Nations Environment Program. The declaration (UN, 1972) states that "man is both creature and moulder of his environment" acquiring the "power to transform his environment in countless ways and on an unprecedented scale" with the result that "we see around us growing evidence of man-made harm in many regions of the earth". It emphasises that "in the developing countries most of the environmental problems are caused by under-development" while insisting that those countries "must direct their efforts to development, bearing in mind their priorities and the need to safeguard and improve the environment." Although lacking an explicit mention, the Stockholm Declaration sets the tone for *sustainable development*: an endeavour to reconcile development, required to improve the wealth and welfare of the poorest populations, with the protection of the natural environment on which the economy depends. Besides these three *pillars* (economic development, people, and nature) an intergenerational imperative is already stated: natural resources "must be safeguarded for the benefit of present and future generations" (UN, 1972).

Another key initiative was the creation by the UN of the World Commission on Environment and Development (WCED), in 1983, which was chaired by Gro Harlem Brundtland. The commission delivered its final report in 1987, entitled *Our Common Future* (WCED, 1987). The document sounds a strong alert about the expanding environmental crisis: "Scientists bring to our attention urgent but complex problems bearing on our very survival: a warming globe, threats to the Earth's ozone layer, deserts consuming agricultural land", (…) "environmental trends that threaten to radically alter the planet, that threaten the lives of many species upon it, including the human species". It also acknowledges that "it is impossible to separate economic development issues from environment issues; many forms of development erode the environmental resources upon which they must be based, and environmental degradation can undermine economic development".

Poverty, for instance, is seen as a "major cause and effect of global environmental problems" being therefore "futile to attempt to deal with environmental problems without a broader perspective that encompasses the factors underlying world poverty and international inequality".

The now famous definition of sustainable development (SD) is introduced: SD must "ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs". While supporting economic growth, *Our Common Future* gives a much higher emphasis to the environment and the biosphere than the Stockholm Declaration, namely by stressing that the impacts of ecological stress are affecting the economic prospects of Humanity. As Gro Harlem Brundtland states in her foreword: "… the 'environment' is where we all live; and 'development' is what we all do in attempting to improve our lot within that abode. The two are inseparable" (WCED, 1987).

The Rio Earth Summit in 1992 was a huge and well publicized conference attended by UN member States and thousands of NGOs. The 'Rio Declaration' restated the main definition of sustainable development in *Our Common Future* and contained principles that were meant to guide policy toward the environment and development (Caradonna, 2014). Its 'Agenda 21' offered a detailed framework for implementing sustainable development organized by chapters, programme areas, objectives, and activities (UN, 1992).

According to Sachs (2015) over time the definition of sustainable development evolved to focus on a more practical, *holistic* approach linking economic development, social inclusion, and environmental sustainability, than on intergenerational needs - the three components of sustainable development should be integrated as *interdependent* and *mutually reinforcing* pillars.

An example of this approach was the Millennium Project, headed by economist Jeffrey Sachs, an outcome of the United Nations Millennium Declaration approved by the General Assembly in 2000 (UN, 2000). The declaration called for all countries to commit to great *global goals*: universal human rights, peace and security, economic development, environmental sustainability, and the drastic reduction in extreme poverty (Sachs, 2015; UN, 2000; Caradonna, 2014). The targets of the declaration to be achieved by 2015 were later expressed in the Millennium Development Goals (UNDP, 2005). The Millennium Development Goals (MDGs) are a set of eight well defined goals, each of them with assigned targets, seventeen in total. Many of the targets are quantified: for instance, *Goal 4 - Reduce Child Mortality* is assigned *Target 5 – Reduce by two thirds, between 1990 and 2015, the under-five mortality rate*. Figure 2.1 shows the icons representing the MDGs.

Figure 2.1 – The eight Millennium Development Goals.

2.1.1. Sustainable Development Goals

The Rio+20 conference of 2012 was the 20-year reunion of the Rio Earth Summit. The conference was marked by lamentation about failed efforts to implement the kind of environmentally sustainable global order envisioned in 1992 but renewed the commitment to the three pillars of sustainable development (Caradonna, 2014; Sachs, 2015; UN, 2012). Its final declaration, *The Future We Want* (UN, 2012) defines what should be the Sustainable Development Goals (SDGs): a new, enlarged set of goals incorporating "in a balanced way all three dimensions of sustainable development and their interlinkages" (UN, 2012). The elaboration of the SDGs was assigned again to Jeffrey Sachs and performed by the Sustainable Development Solutions Network (SDSN) – a UN sponsored structure involving universities, governments, businesses, and nongovernmental organizations (NGOs).

The *2030 Agenda for Sustainable Development* (henceforth 2030 Agenda), including the SDGs and their constituent *targets*, was approved by the UN General Assembly on 25 September 2015, with the participation of 190 countries (UN, 2015). A further General Assembly on 6 July 2017 approved *indicators* to assess the progress of the targets towards completion (UN 2017).

In the 2030 Agenda there are seventeen sustainable development goals (SDGs), each one with assigned targets, most of them quantified. There are also indicators, although limited in number. Most targets must be achieved by 2030, although some have 2020 as the fulfilment date or simply no deadlines. Figure 2.2 shows the icons of the seventeen SDGs, with a short label for each goal.

Their complete description is much more detailed: for instance, *Goal 15 Life on Land* is expressed fully as “Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss”.

Goals 1 to 16 have 150 targets in total, with 43 labelled with letters (as in 15.a, 15.b, etc.) meaning they are *means of implementation targets* to support the achievement of the remaining 107, which Castor et al. (2020) designate as *outcome targets*. Goal 17 is fully dedicated to means of implementation, although its 19 targets use numeric labelling (17.1, 17.2, etc.). *Goal 13 Climate Action* is limited: it acknowledges that most measures regarding the climate crisis are under the responsibility of the UN Framework Convention on Climate Change (UNFCCC).

Figure 2.2 - The seventeen Sustainable Development Goals.

In total and after several changes to the indicators (UN, 2021), the 2030 Agenda currently features 17 goals, 169 targets and 247 indicators - although some indicators repeat in several targets bringing the number of unique indicators to 231.

Goal 7 Affordable and Clean Energy expressed fully as “Ensure access to affordable, reliable, sustainable and modern energy for all” exemplifies the SDGs structure. The goal has three outcome targets - described in Table 2.1 together with their indicators - and two means of implementation targets that focus on enhancing international cooperation and promoting investment in modern energy technologies (7.a) and on expanding infrastructure and upgrading technology for supplying energy services (7.b), both with single indicators (UN, 2021).

The targets incorporated in the SDGs can be grouped according to the three pillars. An interesting model highlighting the hierarchy of the economic, social and environmental components of the SDGs is the ´wedding cake' representation of Folke et al. (2016) shown in Figure 2.3.

Table 2.1 - Targets and indicators of *SDG 7 Affordable and Clean Energy*.

Targets	Indicators
By 2030, ensure universal access to affordable, reliable and modern energy services	Proportion of population with access to electricity
	Proportion of population with primary reliance on clean fuels and technology
By 2030, increase substantially the share of renewable energy in the global energy mix	Renewable energy share in the total final energy consumption
By 2030, double the global rate of improvement in energy efficiency	Energy intensity measured in terms of primary energy and GDP

Figure 2.3 - The 'wedding cake' model of the Sustainable Development Goals (Folke et al., 2016).

Progress towards the SDGs is assessed mostly by the United Nations and by teams at the SDSN, through reports at global, regional, national, and subnational levels (UN, 2019, Sachs et al., 2016, Sachs et al. 2021). The last global report by the United Nations (UN, 2019) was mentioned in Chapter 1 about material footprints – a subject of Goal 12 Ensure sustainable consumption and production patterns. The UN also promotes reports on specific goals: for instance, Goal 7 is the subject of a policy brief entitled "Accelerating SDG7 achievement in the time of COVID-19" (UN, 2020). Other independent organizations like the SDG-Tracker website also measure SDG progress using the official indicators of the 2030 Agenda (Ritchie et al. 2018). The SDG-Tracker is unable to show results for many official SDG indicators since there is no data for them or data is available only for selected countries.

The lack of data for many of the official 231 indicators is an issue recognized by the UN since the inception of the 2030 Agenda. According to Sachs et al. (2016), 40% of the official indicators had agreed statistical methodologies and global data regularly available, 21% had clear statistical methodologies but little or no data available, and the remaining 39% had no agreed standards, methods, or data, or were still not addressed. This limitation is clear in the last global report by the UN (2019) referred above: the assessment of the SDGs is performed considering the world divided into seven large world regions.

The indicators issue led teams at the SDSN to rely on unofficial, reliable indicators with sufficient, regularly available data to assess SDG progress. The more comprehensive assessments are performed by Jeffrey Sachs and co-authors, which since 2016 have been evaluating progress towards the SDGs (Sachs et al., 2016; Sachs et al., 2021). Their reports include an SDG Index - developed by the authors and determined for most of the UN countries - which ranks countries according to their SDG achievement on a 0 to 100 scale. The reports also include country-level Dashboards, detailing the country's achievements on each of the 17 goals, assessed by the indicators used for the SDG Index. The dashboards use colour-coded marks, meaning that the SDG was achieved (green); challenges remain (yellow); there are significant challenges (orange); and that there are major challenges (red). The methodologies to construct the index and the dashboards from official and unofficial indicators are fully detailed in Sachs et al. (2016) and Sachs et al. (2021).

The SDG reports, supporting information, and the dashboards are available for download or online access at the Sustainable Development Report website (https://dashboards.sdgindex.org). Their results, namely the rankings of SDG Index, have been the subject of strong controversy as discussed in the next section.

Figure 2.4 shows the online version of the dashboard for Portugal (Sachs et al., 2021), reflecting mostly pre-COVID information. The evaluation resulted from the values of 121 indicators, common to all OCDE countries, with three of them having no data available. The dashboard overview shows the Portuguese SDG Index *rank* (27th position in 165 countries) and *score* (78.6 in 100). These values can be contrasted with those of the leaders: Finland and Sweden, scoring respectively 85.90 and 85.61.

Note that the icons of each SDG take the colour of the worst indicator used in assessing goal achievement – something the authors classify as giving 'tough marks' to alert for challenges. Portugal has many yellow icons, but a detailed analysis reveals that most of the indicators behind are green. The red icons, though, hide several major challenges, namely in diet and fertilizer use (SDG 2), CO_2

emissions (SDG 13), fishing practices and ocean pollution (SDG 14), and protection of freshwater key biodiversity areas (SDG 15).

Figure 2.4 - SDG dashboard for Portugal (Sachs et al., 2021).

The dashboard also shows the Portuguese score of the Spillover Index, an indicator included in the SDG reports since 2017. International spillovers are impacts caused in countries by actions of other countries, like imports that threaten biodiversity in the countries of origin or exports of weapons fuelling local wars. The spillover score is calculated from indicators grouped in Environment and Social impacts embodied into trade (8 indicators, including exports of hazardous pesticides; CO_2, SO_2 and nitrogen emissions in imports; marine and terrestrial and freshwater biodiversity threats in imports; and fatal work accidents embodied in imports); Economy and Finance (4 indicators, including official development assistance, corporate tax haven and financial secrecy scores, and shifted profits of multinationals); and Security (one indicator, for export of major conventional weapons).

The Spillover Index score is determined by methods like those used for the SDG Index (Sachs et al., 2021) but the scale is inverted: the nearer to 100 the less spillover. Figure 2.5 from Sachs et al.

(2021) shows the Portuguese spillover score (69.92) compared with those of the seven world regions considered in the report. Portugal ranks only 134 on 165 in the Spillover Index.

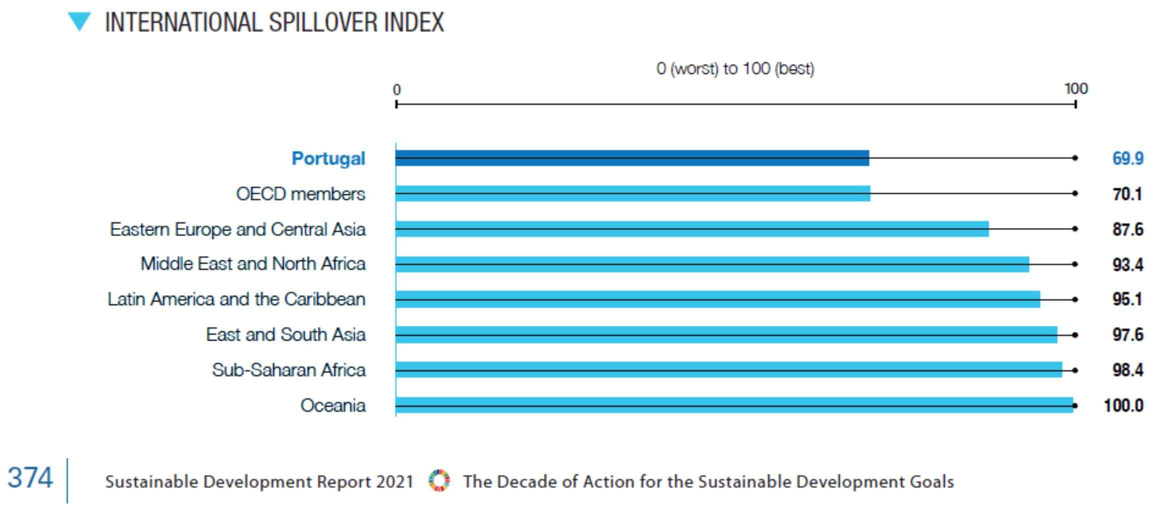


Figure 2.5 - Portuguese score in the Spillover Index, compared (Sachs et al., 2021).

Unsurprisingly, the Spillover Index score of the more developed countries *is the worst* of all regions due to the impacts embodied in their imports from less developed countries. A major work analysing how rich countries affect poor countries through international trade is presented in Lenzen et al. (2012).

2.1.2. Criticism

The 2030 Agenda has been evaluated negatively on various aspects, with the criticism focusing mostly on the official indicators and on the unofficial but influential SDG Index (Elder & Olsen, 2019; Hickel, 2020; Wackernagel et al., 2015; Zeng et al.,2020).

Elder & Olsen (2019) argue that the environmental targets in the 2030 Agenda were spread across most of the goals, effectively creating an integrated approach against what they call an outdated division of the agenda in pillars (goals 1-5 being social, 8-10 being economic, and 11-15 being environmental), but that the *interlinkages among goals are not clear* in the adopted structure. Their analysis finds 73 targets directly related with the environment, over half of them (53%) under goals 1 to 15. (Targets under goals 16 and 17 apply in principle to all goals.) The official indicators are in their opinion a weak point of the agenda since many of them reduce the scope of the environmental contents of the targets or eliminate completely their environmental content, and do not reflect the integrated approach in formulating goals and targets.

The official indicators are also criticized in Zeng et al. (2020) leaving them to assert that the SDGs "do not avoid environmental destruction".

From the official 247 SDGs indicators the authors selected 101 that were environment-related although of these only 75 had sufficient data for analysis. The performance of 120 countries about these 75 environmental indicators was then compared with the same countries' performance against a set of independent indicators assessing the status of the biosphere: marine wilderness, marine threats, freshwater threats, terrestrial wilderness change, intact forests, terrestrial threats, precipitation anomalies, Living Planet Index, and Human Footprint. The result was a *discrepancy* between the assessment by the SDGs indicators and by the independent indicators: only 7% of all correlations between both sets were significantly positive, with 14% being significantly negative, and a majority (78%) being non-significant.

A similar comparison was made between the SDGs indicators and a set of socio-economic indicators: Life Expectancy Index, Poverty Index, Education Index, Income Index, Socio-Demographic Index, and Human Development Index. In this case, however, about 41% of all correlations between the SDGs indicators and external socio-economic indicators are significantly positive, while only 7% are significantly negative and 51% are non-significant.

The authors conclude that many SDG indicators do not adequately reflect changes in external indicators of successful biodiversity conservation and recommend a reformulation of the indicators or a greater focus on data collection, quantification, and possible combination of the existing ones.

Hickel (2020) and Wackernagel et al., (2017) focus their criticism on the SDG Index presented by Sachs et al. (2016).

Hickel (2020) argues that by giving the top ranks to Sweden, Denmark, Finland, Germany (and many other rich Western nations) the SDG Index presents them *as if they were real leaders* in achieving sustainable development. But he points out, Sweden has a very high material footprint and Finland a very high carbon footprint, with both countries being far from leaders in environmental sustainability. The territorial metrics used in the SDGs are also criticized since they do not account for impacts related with international trade, as discussed in Lenzen et al. (2012). So, rich countries have good evaluations in air pollution because *they have offshored* most of their polluting industries. In conclusion, the environmental goals, and targets of the 2030 Agenda are poorly represented and the SGD Index ranks are misleading.

Wackernagel et al. (2017) present a detailed evaluation of the SDG Index by arguing first that the equal weighting given to the goals in the index is correct and that the choices to quantify performance of the SDGs seem reasonable - although Goal 11 and Goal 12 should have a higher focus on resource security in the index. Exemplifying: in the SDG Index, indicators that decrease the people's resource dependence (e.g., activities increasing zero carbon energy, crops, and water availability) contribute only to 13.6% of the weight while indicators that increase resource dependence (e.g., building infrastructures and factories) make up 67% of the weight; while the remaining 18.8% do not affect resources (e.g., securing equal rights for women). Other choices of indicators, they claim, could reduce the weight of the resource-demanding indicators making countries with good environmental practices score higher in the index.

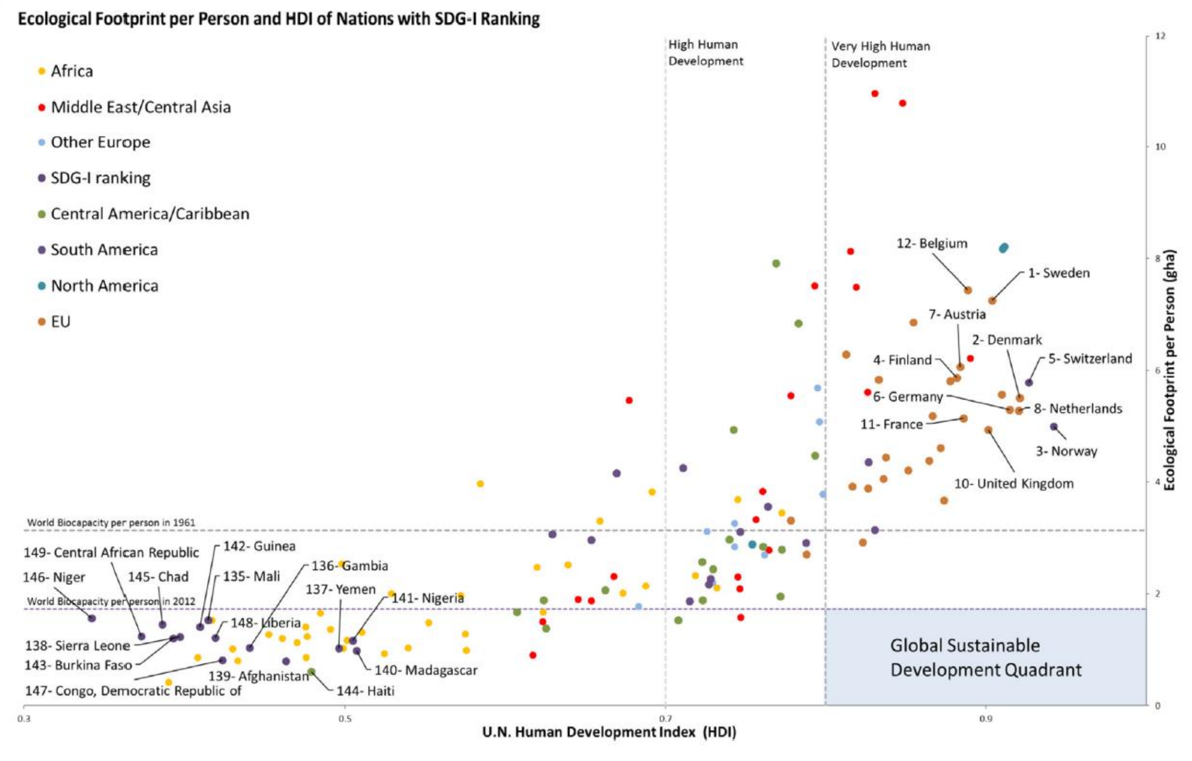


FIGURE 1 | Ecological Footprint per person and HDI by country indicate how close each country is to basic global sustainable development criteria (high human development, within resource requirements that are globally replicable). Each number indicates the country's ranking on the sustainable development goal (SDG) index (only top and bottom 10 are marked here).

Figure 2.6 – Ecological Footprint, HDI, and SDG Index (Wackernagel et al., 2017).

The authors also quantify the consistency of the countries' rankings on the SDG Index against their sustainability by a combination of the Human Development Index – HDI (Ness et al. 2007) and the Ecological Footprint (Wackernagel & Rees, 2002; Ness et al., 2007), as illustrated in Figure 2.6. The bottom-right rectangle (Global Sustainable Development Quadrant) corresponds to a HDI value higher than 0.8 (Very High Human Development) and a Global Ecological Footprint per capita lower than 1.7 global hectares. (A Global Ecological Footprint per capita not exceeding 1.7 hectares ensures that the carrying capacity of the planet is not exceeded.) The definition of the bottom-right quadrant as the locus of sustainable development is related with a *strong sustainability* perspective (Wackernagel & Rees, 2002; Dietz & Neumayer, 2007).

It is apparent that none of the 10 best performing countries on the SDG Index is inside the SD quadrant. Also, the authors argue, there must be a correlation between the *high-ranks* of countries and their *unsustainable* values of global resource consumption – their very high ecological footprints. To prove the assertion, they start by assuming that having high ranks on the SDG Index is completely uncorrelated with having high values of global ecological footprints and proceed by calculating the probability that 19 of 20 countries with ecological footprints higher than 5 global hectares per capita are all randomly assigned to the 'very high human development' band of the graph. Calculation shows that the likelihood of this event happening by chance is vanishingly small (Wackernagel et al., 2017). So, there must be a correlation between high achievement on the SDG Index with unsustainably high resource consumption levels.

Hickel (2020) also argues that the high index rankings obtained by countries with very high resource consumption levels was evidence that the SDG Index was legitimizing the transformation of natural capital into artificial capital – a tenet of *weak sustainability* – with the associated resource depletion and environmental impacts.

To conclude, it is fair to say that the information currently available in the sustainable development reports website (Sachs et al., 2021) provides sufficient detail to correctly evaluate the performance of each country against the Sustainable Development Goals. Also, the UN has recently made freely available their SDGS indicator database - with country-level information – enabling complementary analyses of SDG performance (https://unstats.un.org/sdgs/UNSDG).

2.1.3. SDG interlinkages – synergies and trade-offs

The 2030 Agenda states clearly that the SDGs are *integrated and indivisible* and that their interlinkages and integration are of "crucial importance" to the realization of the resolution's purpose. However, the interlinkages are not specified, and the 2030 Agenda also does not contain a methodology to define them, leaving the matter to the implementation process (UN, 2015).

These omissions led to the investigation of methods to address the interlinkages and determine the instances where they reinforce, or they counteract others. For instance, increasing the supply of renewable energy (Target 7.3) by *installing PV power plants over arable land in a low-income country* will likely counteract the production of food needed to eradicate hunger (Target 1.1).

Nilsson et al. (2016) propose a framework to express the interlinkages of sustainable development goals and targets. It is based on a discrete, seven-point scale ranging from -3 to +3, with negative values expressing *trade-off*, positive values *reinforcement,* or *synergy*, and zero expressing the absence of interaction between goals or targets. Figure 2.7 from Nilsson et al. (2016) explains their scale, exemplified with goals and targets from the 2030 Agenda. The authors suggest that SD initiatives (like strategies, programs, or projects) begin with an intended goal (e.g., 100% access to electricity) and then check all positive and negative interactions with the other SDGs, retaining the synergies and minimizing the trade-offs.

Additionally, they recommend checking: 1) if the interactions induced by the initiative are *irreversible*; 2) if they are *bidirectional*, either by mutually reinforcing or counteracting each other; 3) what is the *size of the impact* since e.g., weak negative interactions could be acceptable; 4) what is the *uncertainty* associated to the interaction, e.g., if it will mostly likely happen or it is just a remote possibility.

Nilsson et al (2016) stress that any implementation of the SDGs that considers their interactions must acknowledge *context*: differences in geography, governance, and technology do not allow application of generalized knowledge. So, the authors propose building an evidence-based knowledge base "to characterize goal interactions in specific local, national or regional contexts".

GOALS SCORING

The influence of one Sustainable Development Goal or target on another can be summarized with this simple scale.

Interaction	Name	Explanation	Example
+3	Indivisible	Inextricably linked to the achievement of another goal.	Ending all forms of discrimination against women and girls is indivisible from ensuring women's full and effective participation and equal opportunities for leadership.
+2	Reinforcing	Aids the achievement of another goal.	Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.
+1	Enabling	Creates conditions that further another goal.	Providing electricity access in rural homes enables education, because it makes it possible to do homework at night with electric lighting.
0	Consistent	No significant positive or negative interactions.	Ensuring education for all does not interact significantly with infrastructure development or conservation of ocean ecosystems.
–1	Constraining	Limits options on another goal.	Improved water efficiency can constrain agricultural irrigation. Reducing climate change can constrain the options for energy access.
–2	Counteracting	Clashes with another goal.	Boosting consumption for growth can counteract waste reduction and climate mitigation.
–3	Cancelling	Makes it impossible to reach another goal.	Fully ensuring public transparency and democratic accountability cannot be combined with national-security goals. Full protection of natural reserves excludes public access for recreation.

Figure 2.7 – Scoring in SDG interlinkages (Nilsson et al., 2016).

Other works have explored the synergies and trade-offs of the SDG in various areas, with some using the framework proposed by Nilsson et al (2016).

The interlinkages involving *energy* and *energy projects* are addressed in Bisaga et al. (2021), Brunet et al. (2020), Castor et al. (2020a), Fuso Nerini et al. (2017a), Leite de Almeida et al. (2020), and McCollum et al. (2018). The focus on energy is not surprising since energy pervades human activity as discussed in Chapter 1 and it appears (as confirmed by these works) *as a key factor* in the implementation of most of the contents of the 2030 Agenda. Two of the works, Bisaga et al. (2021)

and Brunet et al. (2020) specifically address the sustainable development implications of implementing *solar PV power*.

Fuso Nerini et al. (2017a) perform a systematic mapping of the synergies and tradeoffs between energy and the other SDGs with two objectives: 1) to identify which targets require actions regarding *energy systems*, defined broadly and including energy from fossil fuels; 2) to identify *published evidence* of synergies and trade-offs between the targets of SDG 7 and all the targets in the goals. The first objective was achieved through expert elicitation while the second involved searching for published studies in academic and peer-reviewed grey literature (e.g., UN reports), with all results being thoroughly discussed by all authors until a consensus was reached.

For the first objective Fuso Nerini et al. (2017a) found 113 targets, 67% from the full 169 in the 2030 Agenda, that required action regarding energy systems. For the second objective, the authors found 143 targets (85%) for which there was published evidence of synergies and trade-offs with the pursuit of SDG 7, with the number of synergies (146) being much larger than the number of trade-offs (65).

In their detailed results, the authors present, target by target the published evidence and a summary of the identified synergies and trade-offs. But the interactions are not assigned *scores*, like proposed by Nilsson et al. (2016).

McCollum et al. (2018) go further in the study of the energy interlinkages of the SDGs with a work based on the framework of Nilsson et al. (2016) and supported by a large-scale assessment of energy related literature. The energy-related actions considered in the interlinkages are those resulting from the SDG 7 targets (Table 2.1), which the authors summarize as being about: *renewables*, *efficiency*, and *energy for the poor*. The literature assessment was the result of two steps: 1) expert identification of relevant keywords from multiple academic sources and grey literature; 2) structure keyword queries in the Scopus database. The systematic queries yielded more than eight hundred results, which through a phased review process yielded 53 'definitely relevant' publications. McCollum et al. (2018) present their results in table form as shown in Figure 2.8, a fragment of the full table of results. Each row corresponds to a goal and its constituent targets impacted by SDG 7, for which the authors present from left to right: the literature asserting the evidence of interlinkages; a summary of the findings; the score (sometimes expressed only as a range); the robustness of the evidence base; the degree of agreement on the evidence base; and the confidence level on the scores assigned. McCollum et al. (2018) remark that the number of synergies outweigh the number of trade-offs both in number and magnitude, confirming the findings of Fuso Nerini et al. (2017a).

They also acknowledge limitations stemming from a lack of more interdisciplinary work that might enrich the evidence base, from the use of academic literature, and from the dependence of the interlinkages on context.

Regarding policymaking they stress that the traditional *silo approach* common in many countries is no longer suitable to achieve systemic change. And that policymakers "must do more than simply acknowledge the mere existence of SDG interactions; they also need to mobilize additional resources and implement new laws and planning and evaluation methodologies" (McCollum et al., 2018).

Castor et al. (2020a) and Leite de Almeida et al. (2020) both address the application of SDG interlinkages to *energy projects*.

Castor et al. (2020) remark that while there are several frameworks and analytical tools to assess the sustainability of a project from the perspective of one or more of the three pillars, including the widely used Environmental Impact Assessment (EIA), Lifecycle Assessment (LCA) and Multicriteria Decision Analysis (MCDA) as addressed in Ness et al. (2007), no method exists to assess energy projects considering all aspects of sustainability included in the 2030 Agenda, namely the interlinkages between SDGs.

Table 2. *Continued.*

12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Natural Resource Protection (12.2/12.3/12.4/12.5)	Ali et al. (2017); Banerjee et al. (2012); Bhattacharyya et al. (2016); Cameron et al. (2016); Carmona et al. (2017); Gutowski et al. (2017); Ham and Lee (2017); Riahi et al. (2012); Schandl et al. (2016); Schwanitz et al. (2014)	Renewable energy and energy efficiency slow the depletion of several types of natural resources, namely coal, oil, natural gas, and uranium. Advanced technologies and infrastructure will, however, still require vast amounts of minerals, including both common commodities and critial rare earth elements. Supplies of these minerals face long-term limitations, and it will take time before recycling activities can contribute at a massive scale. Increasing recycling rates offers a means to improve the energy efficiency of materials production and use and consequently to reduce the impacts of mining and extraction, raw goods conversion, and waste incineration and landfilling. Waste-to-energy technologies can generate useful energy (electricity, heating/cooling) from disposables that are not suitable for recycling. The phasing-out of fossil fuel subsidies encourages less wasteful energy	[+2]	robust	high	***very high***
	Sustainable Practices and Lifestyles (12.6/12.7/12.8)	CDP (2015); European Climate Foundation (2014); Khan et al. (2015); New Climate Economy (2015); Stefan and Paul (2008)	Sustainable practices adopted by public and private bodies in their operations (e.g., for goods procurement, supply chain management, and accounting) create an enabling environment in which renewable energy and energy efficiency	[+1]	robust	high	***high***
13 CLIMATE ACTION	Climate Strategies and Education (13.2/13.3)	IPCC (2011); Jennings (2009); Schreurs (2008)	Better integrating climate change measures into national planning and improving education, awareness, and capacity on climate issues will go a long way in furthering international targets for renewables and energy efficiency.	[+2]	robust	high	***high***
	Global Warming (*)	Anenberg et al. (2013); Cherian (2015); Gambhir et al. (2017); Kriegler et al. (2013); Kriegler et al. (2014); PBL (2012); Riahi et al. (2015); Riahi et al. (2017); Rogelj et al. (2013); Tavoni et al. (2013); van Vuuren et al. (2015)	Meeting the renewable energy and energy efficiency targets of SDG7 is a necessary, but not entirely sufficient, condition for long-term temperature stabilization below 2 °C. For the latter to be achieved with high probability, an up-scaling of efforts beyond 2030 will be needed. Providing universal access to modern energy services by 2030 is fully consistent with the Paris Agreement, as reaching this target will have only a minor effect on global carbon emissions. *[*Note: The 2030 Agenda text describing SDG13 does not specifically mention a long-term temperature goal, but it does refer to the UNFCCC process, and the*	[0,+2]	robust	high	***very high***
14 LIFE BELOW WATER	Marine Protection (14.1/14.2/14.4/14.5)	Inger et al. (2009); WBGU (2013)	Depending on the local context and prevailing regulations, ocean-based energy installations could either induce spatial competition with other marine activities, such as tourism, shipping, resources exploitation, and marine and coastal habitats and protected areas, or provide further grounds for protecting those	[-1,+1]	limited	high	***medium***
	Ocean Acidification (14.3)	Caldeira and Wicket (2003); Feely et al. (2009); Gruber (2011); Le Quére et al. (2009); The Royal Society (2005); WBGU (2013)	Deployment of renewable energy and improvements in energy efficiency globally can reduce carbon dioxide emissions, and this, in turn, will slow rates of ocean acidification.	[+2]	robust	high	***high***
	Marine Economies (14.7)	Buck and Krause (2012); Michler-Cieluch et al. (2009); WBGU (2013)	Ocean-based energy from renewable sources (e.g., offshore wind farms, wave and tidal power) are potentially significant energy resource bases for island countries and countries situated along coastlines. Multi-use platforms combining renewable energy generation, aqua-culture, transport services and leisure	[+1]	limited	high	***low***

Figure 2.8 - Framework to assess SDG energy interlinkages: extract (McCollum et al., 2018).

To overcome this research gap, a method is proposed - the Sustainable Development Goals Impact Assessment Framework for Energy Projects (SDGs-IAE). The method relies on the framework by Fuso Nerini et al. (2017a), enriching its database with new evidence of relationships between energy systems and the SDGs and of synergies and trade-offs between the goals and targets.

Its main tool is a questionnaire (a decision tree with yes/no questions) to be used by project stakeholders. Implemented in Excel, it guides the users in identifying SDG synergies and trade-offs in energy projects. The results are summarized graphically in a map signalling the presence of synergies and trade-offs. To test the SDGs-IAE the authors selected two energy projects: the *Hinkley Point C* nuclear power station in the UK and the *Grand Ethiopian Renaissance Dam*. To fill the questionnaire the authors relied on published literature and reports from local governments, news outlets, and project developers. The results for both projects show synergies but also a considerable number of trade-offs, as discussed in Castor et al. (2020a).

The work by Leite de Almeida et al. (2020) is a follow-up to Castor et al. (2020a). Referring to the findings by Fuso Nerini et al. (2017a) the authors point out that the achievement of 113 targets involves *actions* regarding energy systems, motivating researchers and decision makers to *design policies* and *support actions* prompting the energy sector towards the SDGs.

The SDGs-IAE framework by Castor et al. (2020a), they argue, stopped at the identification of SDG interlinkages in energy projects without defining *actions* that project developers and stakeholders can use proactively when implementing their projects. Leite de Almeida et al. (2020) propose *an extension*, the Sustainable Development Goals Impact Assessment Framework for Energy Projects and Actions (SDG-IAEA), based on the Excel tool of Castor et al. (2020), but including now a 'sizable compilation' of actions allowing practitioners to enhance the synergies and mitigate the trade-offs identified in their energy projects.

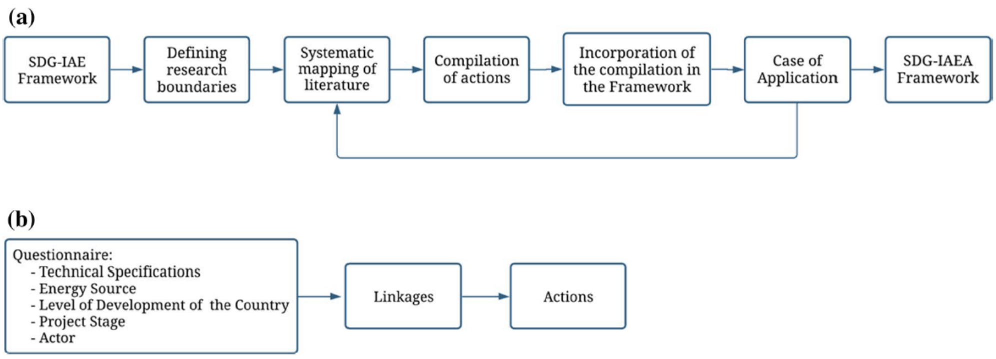


Fig. 1 SDG-IAEA Framework. **a** Workflow used to develop this study and achieve the SDG-IAEA. **b** Structure of the SDG-IAEA Framework: questionnaire regarding the technical specifications of the project, the energy source, the level of development of the country, the project stage and the actor; identification of the linkages, synergies and trade-offs, with the SDG targets based on the information of the questionnaire; selection of actions to present to the user based on the linkages, project stage and actor

Figure 2.9 - Development workflow for the SDG-IAEA framework (Leite de Almeida et al.,2020).

The projects are characterized in the new framework by primary energy source, technical specifications, implementation stage, level of development of the country, and implementation actors. Figure 2.9 from Leite de Almeida et al. (2020) illustrates the workflow used to develop and improve the framework (a) and the structure of the framework (b). There are seven energy sources considered by the authors: hydropower, wind power, solar power, biomass/biofuels, waste to energy, nuclear, and fossil fuels. Two actors perform the actions: Policymaker and Project Developer. And projects have three stages: Planning, Building, and Operations. A total of 283 actions resulted from the workflow in

Figure 2.9. To identify actions for the linkages of the seven energy technologies with the SDGs, and their synergies and trade-offs as characterized by McCollum et al. (2018), the authors *performed Google searches* covering academic and grey literature. The searches tried to answer the questions: how can the project actors enhance the synergies? How can they mitigate the trade-offs? Examples of actions identified, applicable to several energy technologies: address energy poverty, avoid threats to cultural and natural heritage, promote decentralized energy solutions, increase grid connections, provide digital payment methods, increase stakeholder engagement (Leite de Almeida et al., 2020). The proof of concept for the new framework was project VARGA, under progress in a wastewater treatment plant in Denmark and involving biogas and fertilizer production from sludge and organic waste.

Bisaga et al. (2020) investigate the linkages between *off-grid solar PV energy* in Rwanda and the SDGs. Electricity reached only 55% of Rwandan households in 2020 with 40% connected to the national grid, mainly in urban and peri-urban areas, and 15% served via off-grid systems, mostly in rural areas. Due to barriers to grid expansion, off-grid Solar Home Systems (SHSs) and other distributed solutions

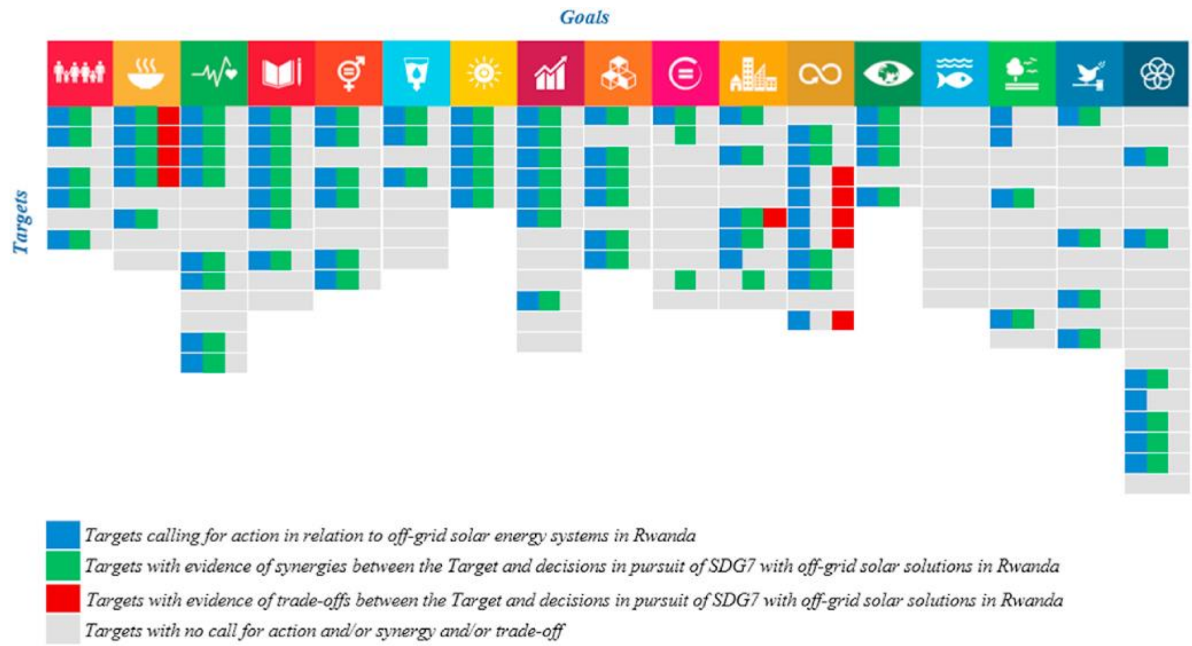


Figure 2.10 - Synergies and trade-offs for off-grid solar PV in Rwanda (Bisaga et al., 2020).

for electricity supply are actively promoted by the government to serve households without electricity access. The authors analyze the linkages, synergies, and trade-offs of Solar Home Systems with the SDGs aiming, in their words “to identify existing evidence and opportunity gaps for mainstreaming off-grid solar energy to achieve a just low carbon transition and support the delivery of sustainable development in Rwanda”. The study focusses on SHSs and not on mini grids since the number of connections to the former (about 390,000) is vastly larger than connections to the latter (about 4 000).

The authors use the framework of Fuso Nerini et al. (2017a) to address linkages, synergies, and trade-offs, remarking that their goal was not to undertake a systematic review of the evidence relevant to each target but rather to identify where synergies and trade-offs exist.

The search for evidence included academic literature but also policy documents, non-peer reviewed grey literature, and experiential work. Since, the authors argue, they needed to incorporate the *latest developments* from the field to complement the *limited* peer-reviewed publication universe. Their results are illustrated in Figure 2.10, from Bisaga et al. (2020).

The graph shows all SDGs with their full constituent targets represented as vertical bars. There are three parallel bars under each goal, marked in *blue*, *green*, and *red* if *linkages*, *synergies*, and *trade-offs* were identified by the authors, respectively. As illustrated by the figure, there are trade-offs in SDG 2 (*Zero Hunger*), SDG 11 (*Sustainable Cities and Communities*), and SDG 12 (*Responsible Consumption and Production*), while the authors report 80 cases of synergy linkages. The trade-offs with SDG 2 are all due to the competition between land for the installation of the off-grid systems and land for agriculture. The trade-off with Target 11.6 is due to the likely contribution to urban waste by dismantled systems. The trade-offs in Goal 12 are mainly related with the environmentally sound management of substances and materials used in the systems; reduction of waste at their end of life, preferably with recycling; and sustainable and fair procurement practices.

There is also a trade-off with Target 12.c, which calls for the elimination of fossil-fuel subsidies thus promoting the use of sustainable energy. However, in less developed countries eliminating fossil-fuels subsidies can at the same time *harm the poorest people*, which may not be able to pay for modern, sustainable energy.

Brunet et al. (2020) address the sustainability impacts of a 20 MWp grid-connected solar PV plant in Madagascar, the largest in the country and the most powerful in the Indian Ocean, which started operating in 2018. Their approach is different from Bisaga et al. (2020) since they focus on a specific solar PV plant and adopt a bottom-up, qualitative organizational research approach, designed as a *case study* (Symon & Cassel, 2012). The case study relied on several methods: semi-structured interviews, focus groups, and observations. The authors also relied on detailed information about the plant (the project developer was part of the involved stakeholders) and about the country.

The authors adopted a Sustainable Development Impact Assessment framework (Ness et al., 2007) identifying positive and negative impacts of the solar power plant grouped under impact areas: Energy, Environment, Water and food, Women, Social, Governance and territory, and Economy. The areas are then associated with the SDGs, as illustrated in Figure 2.11.

Brunet at al. (2020) specify the positive and negative impacts, summarized at local, regional, national, and international levels. Within each level, as applicable, the results are summarized by impact area (Economy, Environment, etc.).

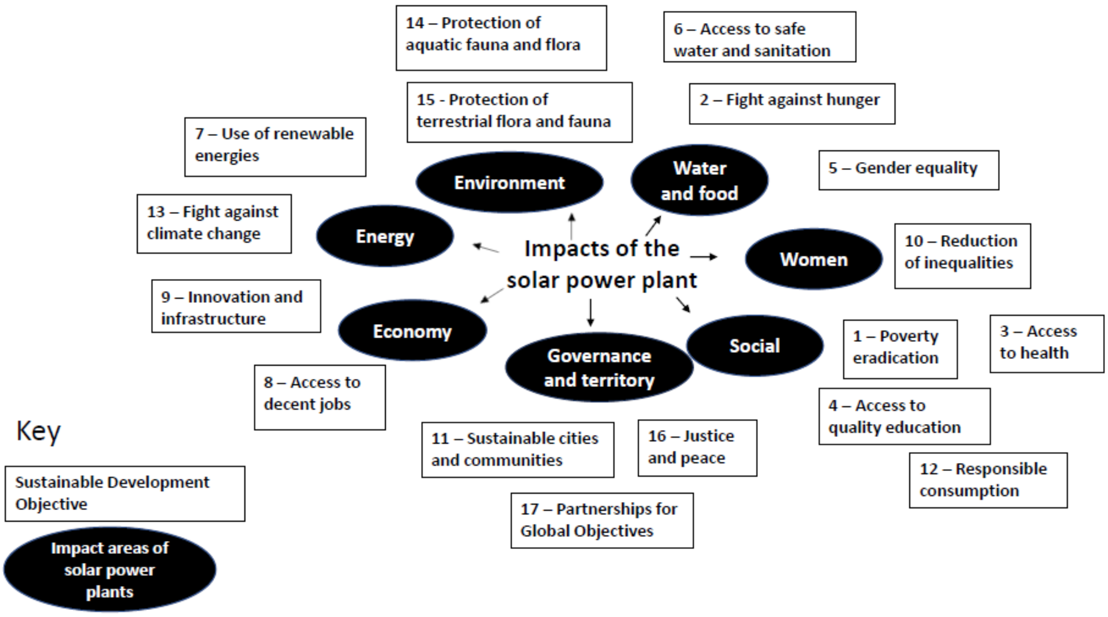


Figure 2.11 - Sustainable Development Impact Assessment framework (Brunet et al., 2020).

Their outcome is an interesting, quite detailed picture of the impacts arising when a modern, utility-scale PV power plant is implemented, with some specific to the country where the plant is located but many others applicable worldwide.

In their study, Brunet at al. (2020) also associate in general terms the impacts with the SDGs. Table 2.2 adapted from Brunet et al. (2020) shows, at local level, how the major impacts identified by the authors contribute to the SDGs and the reasons for non-contribution. The negative impact on SDG 6 (*Clean Water and Sanitation*) is assessed at regional level and is not in Table 2.2: there is a concern that the availability of extra energy due to the PV plant might support further growth of existing polluter industries (textiles, tobacco, food).

Table 2.2 - Contributions to the SDG by the PV power plant. Data from Brunet et al. (2020).

Solar power plant supporting or contributing	Solar power plant not supporting or not contributing	Reason for impairment or non-contribution
SDG 16—Peace, justice and strong institutions (fees paid to the commune)	SDG 15—to be confirmed	Impact of night light on biodiversity
SDG 15—Life on land (trees preserved)	SDG 10—Reducing inequalities	Inequalities between households with electricity and those without
SDG 11—Sustainable cities and communities	SDG 8—Decent work and economic growth	No impact on income generating activities

SDG 8—Decent work and economic growth (job creation)	SDG 7—Affordable and clean energy	Not available for local residents
SDG 9—Industry, innovation and infrastructure	SDG 6—Clean water and sanitation (Impact to be confirmed)	
SDG 7—Clean and affordable energy	SDG 5—Gender equality	Women's well-being affected or not supported
SDG 3—Good health and well-being for people (night light and security)	SDGs 1/2/3—no poverty, zero hunger, good health and well-being for people	Fertile area could be used for cultivation, roads in poor condition, limited employment

2.2. Is Solar Photovoltaic Power Sustainable?

This section is a contribution to the assessment of the synergies and trade-offs between solar PV power and the sustainable development goals. It considers the sustainability implications of *solar PV* power *systems and projects* and the interlinkages between the goals and targets caused or mediated by solar PV power.

The text follows closely the work of Fuso Nerini et al. (2017a), which focus on energy systems, in general, and the work of Castor et al. (2020a) which extend the methodology of Fuso Nerini et al. (2017a) to *energy projects* and, as discussed before, builds a decision support system to assess SDG interlinkages. The reason to opt for these works, besides their relevance, was the open access to their detailed results as *supplementary information* to their articles: Fuso Nerini et al. (2017b) and Castor et al. (2020b).

This section of the thesis is neither a systematic literature review nor an assessment tool, like some of those described in the previous section. It takes the conclusions of the two works mentioned above and *instantiates and extends them to solar PV power systems and projects*.

Its outcome is a goal by goal *summary* that helps to check whether a solar PV system or project is sustainable by identifying its synergies and trade-offs with the SDGs. While always using the results of Fuso Nerini et al. (2017b) and Castor et al. (2020b) it presents and discusses additional and updated peer-reviewed and grey literature. And discusses the situation in Portugal whenever there is information available.

The section is organized by the sustainable development goals, from SDG 1 to SDG 15. Goals 16 and 17 were left out, although relevant for a wider assessment of energy projects as done in Castor et al. (2020). For each SDG there are summaries of the conclusions by Fuso Nerini et al. (2017b) and by Castor et al. (2020b), with variable depth depending on the subject. In some cases, only one of the works is mentioned if the other does not bring additional information. The summaries are followed by comments and literature analysis on solar PV, and on solar PV *in Portugal*.

The targets in each SDG are specified in *abbreviated* form: full descriptions (which are sometimes quite long) can be found in UN (2015). The deadlines are omitted in the abbreviated descriptions. The text will mention conclusions by Fuso Nerini et al. (2017b) and Castor et al. (2020b) using verbs and verbal phrases like: “report”, “see”, “remark that”, “point out”, etc. This means in all cases that the authors *report evidence in the literature* that some interlinkage or impact exists.

Goal 1. End poverty in all its forms everywhere

Castor et al. (2020b) report synergies between energy access and Targets 1.1 (*Eradicate extreme poverty for all people everywhere*), 1.2 (*Reduce by half the proportion of people living in poverty in all its dimensions*), and 1.4 (*Ensure that all men and women have equal rights to economic resources and access to basic services*).

Fuso Nerini et al. (2017b) also report a synergy between energy access and Target 1.3 (*Implement social protection systems and measures for all*), which may include promoting energy access with social tariffs and protecting people against disconnection of basic services.

Electricity from solar PV allows further synergies with poverty reduction, especially when deployed in decentralized form. Zhang et al. (2020) report the results of a government sponsored large-scale initiative in China to install PV power plants in 211 pilot counties, with a total capacity of about 15 GW. The subsidized plants are managed by the villagers, which sell electricity to grid companies with part of the proceeds going directly to poor families.

Off-grid solar PV is also being used to address *energy poverty*, when households are unable to pay their energy bills or reduce energy spending to the detriment of health or spend a high proportion of their income on energy. Judson et al. (2019) and Lee & Shepley (2019) report results of government sponsored initiatives to address energy poverty by delivering off-grid PV systems to low-income tenants respectively in Australia and Korea with mixed, limited results.

Portugal has defined a long-term strategy to fight energy poverty, from 2021 to 2050, which Silva et al. (2021) analyse. Measures already implemented for low-income families include protection against disconnection, a social tariff for electricity, and a €1,300 ‘efficiency voucher’. The voucher can be used to implement energy efficiency measures, including solar PV implementation but only by low-income *house owners*. Future measures include the promotion of *energy communities* exploiting solar PV power, which may be more effective in alleviating energy poverty.

Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture

Fuso Nerini et al. (2017b) find evidence that energy systems support Targets 2.1 (*End hunger and ensure access by all people to safe, nutritious and sufficient food*), 2.3 (*Double the agricultural* *productivity and incomes of small-scale food producers*) and 2.a (*Increase investment in agriculture: infrastructure, research, extension services, technology, and gene banks*)

Castor et al. (2020b) report synergies and trade-offs between energy projects and Targets 2.1, 2.2 (*End all forms of malnutrition*), 2.3 and 2.4 (*Ensure sustainable food production systems and implement resilient agricultural practices*). They see trade-offs with 2.1, 2.2, and 2.3 if the energy is used for *irrigation*: drawing excessive water for farming may deprive other farms of water leading to malnutrition and hunger. Trade-offs are also noted with 2.1 and 2.2 if energy systems are located on land suitable for agriculture, particularly in the case of low power density technologies. There will be synergies (or trade-offs) with 2.4 if energy systems are prepared (or not) to resist to extreme weather events, droughts, and temperature rises.

Solar PV shares all the synergies and trade-offs reported, with added concerns about trade-offs caused by the occupation of land suitable for agriculture since it is a low power density technology. Nevertheless, in least developed and developing countries solar PV may be crucial to ensure food security. Efficiency for Access Coalition (2021) stresses the importance of solar powered *refrigerators*, like the one developed by Cold Hubs (2021), in the fight against food waste. The World Food Program (2021) stresses that solar powered irrigation has a key role in food production in developing countries. And, of course, if solar PV replaces fossil-fuel based energy in these applications there is a synergy with SDG 13: reduction of GHG emissions.

In Portugal, solar PV is already used to power agricultural greenhouses (Renováveis Magazine, 2015). It is also being promoted for farm irrigation (Agroportal, 2020).

Goal 3. Ensure healthy lives and promote well-being for all at all ages

Castor et al. (2020b) report synergies between energy projects and Targets 3.1 (*Reduce maternal mortality*) 3.2 (*Reduce new-born and child mortality*) 3.3 (*End disease epidemics*) 3.4 (*Reduce mortality from non-communicable diseases*) 3.7 (*Access to sexual and reproductive healthcare*), and 3.8 (*Universal healthcare and vaccine access*). The synergies are related with providing electricity to *medical centres*, which improves health, for instance via lighting and thermal control, access to clean water, and improved storage of medical supplies. Renewable energy systems, which are non-polluting in their operation phase, also support Target 3.9 (*Reduce disease and death from hazardous chemicals and pollution*).

Solar PV systems have a key role in achieving these targets in developing countries as highlighted by UN-chronicle (2019). The *Solar for Health* initiative of UNDP, the United Nations Development Programme, had installed by 2018, solar PV systems in 652 health facilities in sub-Saharan Africa with a 7.7 MW total capacity (UNDP, 2018).

Solar PV systems have negligible health and safety impacts in their installation, operation, and end-of-life phases as discussed by NC Clean Energy (2017). However, manufacturing PV components, namely PV panels, may generate pollution and GHG emissions due to fossil-fuel use, as discussed in the following sections of this document. Thus, there is a trade-off between PV systems and Target 3.9, namely in manufacturing countries relying on fossil fuel for manufacturing.

In Portugal, hospitals and medical centres have reliable and ample energy access. However, installing rooftop solar PV systems (with storage batteries in the larger units) would lead to reduced energy bills and, possibly, to the autonomous provision of electricity in emergency situations.

Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

Castor et al. (2020b) report synergies between energy access and all the outcome targets in this goal: 4.1 (*Complete primary and secondary education for all girls and boys*), 4.2 (*Access to childhood care and pre-primary education*), 4.3 (*Access of all women and men to technical, vocational and tertiary education*), 4.4 *Increase the number of youths and adults with technical and vocational skills*), 4.5 (*Eliminate gender disparities in education, ensure access to education for the vulnerable*), 4.6 (*Ensure all youths achieve literacy and numeracy*), and 4.7 (*Ensure education for sustainable development*).

Achieving Goal 4 looks like a daunting task. UNESCO (2017) reports a first evaluation of Target 4.1, fully stated as "By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes", and concludes that globally 617 million children and adolescents are *not achieving minimum proficiency standards* in reading and mathematics, corresponding to 56% of the world school-age population in primary education (6-11 years old) and low secondary education (12-14 years old). Sub-Saharan Africa has the worst record (reading 88%, mathematics 84%) followed by Central and Southern Asia (reading 84%, mathematics 76%). Northern America and Europe together have the "best" record: 14% of children and adolescents are not achieving minimum proficiency standards in reading and mathematics. Girls fare a little worse than boys in primary education but clearly less bad in low secondary education. Not surprisingly, low-income, and low-middle income countries have much worse results.

Sovacool & Ryan (2015) perform a global, in-depth survey of the improvements and difficulties linked to the *electrification* of primary and secondary schools, which broadly justifies the synergies reported by Castor et al. (2020) and helps to explain the crisis described by UNESCO (2017).

A starting point is the extremely low levels of school electrification in the poor regions of the globe: 80% of children in Sub-Saharan Africa attend primary schools without electricity; more than a quarter of village schools in India lack electricity access; and fewer than half of the schools in Peru are electrified. In total, about 200 million children attend schools not connected to electricity of any kind. And this despite important progress in traditional grid expansion from 1990 to the 2010s. The absence of electricity in schools is detrimental to education, the authors point out: early morning and late-night instruction becomes almost impossible; computers and television cannot be used; recruiting of teachers becomes difficult since they tend to refuse working in schools without basic services, which also includes, e.g., access to drinkable water. For example, in one African country, before electrification the toilets were seldom cleaned due to lack of electrified water pumping. This led to diseases like typhoid and cholera originating huge absenteeism levels. Conversely, schools with electricity enjoy benefits that include lighting and extended studying hours; access to information and communication technologies; enhanced staff retention and teacher training; better school performance through attendance, completion rates, test scores; and co-benefits like improved sanitation and health, gender empowerment, and community resilience. Electrification may also lead to less rural-urban migration, convincing youths to remain in their communities.

Sovacool & Ryan (2015) remark that school electrification also brings challenges: high initial costs and difficulty in financing; technical problems, vandalism, and theft; lack of household access to basic services; *class and urban bias* regarding the needs of rural schools; negative impacts on learning and increased energy consumption; and *non-energy* barriers like corruption and classroom overcrowding.

One example is that while schools may gain electricity *households* will rarely gain electricity access at the same time. Thus, students will lack night-time hours for their homework, and they also have house chores to do. One study reported by the authors even claims that household electrification has a greater impact on education than school electrification. Another study shows that the benefits of rural solar electrification may be captured primarily by the rural middle class, enhancing existing income inequalities. Finally, non-energy barriers may compromise the quality of education, like having 50 to 90 pupils per class in Chad and the Central African Republic and high absenteeism and deliberate reduction of class time by teachers in several Indian states.

In Portugal, all schools have electricity access but rooftop solar PV in school buildings would bring benefits: savings in energy bills could be used for educational purposes and schools would contribute to reduce the GHG emissions of the Portuguese electrical grid, a synergy with SDG 13.

Goal 5. Achieve gender equality and empower all women and girls

Castor et al. (2020b) report synergies and trade-offs between access to energy and Targets 5.1 (*End discrimination against all women and girls*), 5.2 (*Eliminate violence against women and girls in the public and private spheres*), 5.4 (*Recognize and value unpaid care and domestic work*), 5.5 (*Ensure *women's participation and equal opportunities for leadership in all spheres of life*), and 5.6 (*Ensure universal access to sexual and reproductive health and rights*).

There are synergies between access to electricity and Targets 5.2 and 5.4 since it may avoid water collection and fuel collection – recurrent, unpaid work performed by women in low-income countries, which leaves them vulnerable to violence. The same synergies will exist if energy projects provide alternatives to traditional biomass use. Electricity access reinforces 5.6 since it supports health infrastructure in general (SDG 3). There are trade-offs with 5.2 created by *energy projects* (e.g., large hydroelectric dams) that lead to dislocation of people or bring in large workforces, which may cause social disruption and violence against women. If hiring practices are fair and equal with regards to gender, there are possible synergies between the energy project and Target 5.1 and 5.5.

The International Renewable Energy Agency (IRENA) released in 2019 the results of a survey about women's participation in the renewable energy sector (IRENA, 2019). The survey, performed on-line in the last quarter of 2018, had more than 1,500 respondents (69% women), from which 1,155 were individuals and 285 answered on behalf of organizations. World coverage was global, with participants from 144 countries. The survey revealed that *women represent 32% of the fulltime employees* of responding organisations, substantially higher than the 22% average for the global oil and gas industry, although the average hides disparities: 28% of women had STEM jobs (science, technology, engineering, and mathematics), 35% had technical non-STEM jobs, and 45% had administrative jobs.

IRENA (2019) groups the results in two broad classes: *modern energy context* (renewables displacing or complementing conventional modern energy, e.g., in urban areas) and *access context* (renewables in areas presently without access to modern energy services, e.g., unelectrified rural areas). Among many others results, the survey characterizes *barriers to entry* and *barriers to retention and career advancement* ('glass ceilings'), the subject of Targets 5.1 and 5.5. In the modern energy context, the former includes perception of gender roles, cultural and social norms, and prevailing hiring practices; while the latter comprise cultural and social norms (again), lack of flexibility in the workplace (e.g., because of childcare), and lack of mentorship opportunities. In the access context, 66% of women report barriers to entry and progression despite the key role of women in promoting new energy forms in low-income countries. Barriers include cultural and social norms (the most common), lack of gender-sensitive policies, lack of training opportunities, and inequity in asset ownership (with limited financing for female entrepreneurship).

Interestingly, among renewable energies *solar power* was the technology considered most relevant to their work by 82% of the individual respondents and by 82% of the organizations.

As a *modular* technology, decentralized solar PV presents fewer technical difficulties than other renewable energies and can thus lower barriers to entry by women and men with basic training, especially in access contexts. IRENA (2019) presents several initiatives promoting women's entrepreneurship involving solar power. ENERGIA (www.energia.org), an international network of people and organizations promoting equitable access and control over sustainable energy services, including women-led micro and small businesses, offers numerous examples in Africa and Asia.

In Portugal, no statistics could be found about the proportion of women holding jobs and positions in the renewable energy sector. But absent barriers to entry and glass ceilings, solar PV is another sector that can provide equitable work opportunities for women at all levels, including company management, system design, project management, commissioning, and operation and maintenance, whether in urban or rural areas.

Goal 6. Ensure availability and sustainable management of water and sanitation for all

Fuso Nerini et al. (2017b) report synergies and trade-offs of energy systems with Targets 6.1 (*Universal access to drinking water*), 6.4 (*Higher water-use efficiency, sustainable withdrawals, less people suffering from water scarcity*), and 6.6 (*Protect and restore water-related ecosystems*).

While electricity is fundamental to achieve all these targets through power and control, some renewable energy technologies lead to trade-offs with 6.4, namely if they rely on water for cooling heat-based electricity generators, like bioenergy or concentrated solar power (CSP). Large-scale hydroelectricity with reservoirs spreading over large areas have strong impacts on water-related ecosystems: a trade-off with 6.6.

The growth of small and medium-scale hydroelectricity as *energy storage* systems (Spector, 2020) for *variable* renewable energy sources, like wind turbines and solar PV plants, points to indirect trade-offs with 6.6 from technologies that do not require water while operating (wind turbines) or require insignificant amounts of water for surface cleaning as in the case of solar PV (Wilson et al., 2012).

Castor et al. (2020b) report synergies and trade-offs between access to electricity and Targets 6.1, 6.2 (*Access to sanitation and hygiene for all*), 6.3 (*Improve water quality by reducing pollution, eliminate release of hazardous substances, reduce untreated wastewater, increase water recycling and reuse*), 6.4, 6.5 (*Implement integrated water resources management including transboundary cooperation*), and 6.6.

Electricity access supports provision of drinking water, through treatment, conveyance, or desalination hence creating a synergy with 6.1. Electricity can also be used for sanitation and hygiene, a synergy with 6.2. These, in turn, also have a positive impact on water quality by reducing pollution: a synergy with 6.3. The trade-offs pointed out by Castor et al. (2020b) refer to negative impacts of energy systems on water withdrawals, which may affect 6.1, 6.2, and 6.4, and water-related ecosystems, affecting 6.6. Depending on whether energy projects adopt (or not) *integrated water* *resources management* there may be synergies (or trade-offs) with 6.5, for instance if a hydroelectric dam has transboundary impacts.

Solar PV has several important roles in supporting SDG 6, mostly leading to synergies. Wang et al. (2019) remark that lack of energy access and scarcity of clean water are key challenges for sustainable development, leading them to design a system that integrates in *one device* an energy-providing standard PV panel *and* a membrane distillation system, on the non-illuminated back of the panel. The system can produce distilled, clean water from seawater at a rate of more than 1.64 kg of water per square meter of panel per hour. The innovative solution recycles the heat generated by the solar energy that is *not* converted to electricity (about 80% of the total incident radiation) to energize the distillation process. The device by Wang et al. (2019) focuses on desalination of seawater with concurrent electricity generation but solar PV powered distillation can be used for other purposes relevant to the targets of SD6: potable water production from quality-reduced water, wastewater volume reduction, metal extraction and recycling, and sterilization.

Other uses of solar PV contributing to SDG 6 are those involving electricity in non-grid connected areas. An important area is solar PV power sanitation. A solar toilet for human waste management has been deployed as a pilot in low-income areas of Asia: The *Seva* solar PV toilet, whose development is supported by the Bill & Melinda Foundation. The energy supplied by the solar panels enables the production of solid matter suitable for fertilizer and sanitized water (about 15 litres in five hours) that can be used in the toilet or for other water needs (Wendt, 2020).

An example of a combination of solar PV and water for which there are neither synergies nor trade-offs is floating PV power, also called *floatovoltaics* (Kougias, 2016). Installing PV systems over dam reservoirs or irrigation channels - which are already artificialized water bodies - avoids conflict between the use of land for PV and for other purposes. There are also advantages for electricity generation: installing PV systems over water helps keeping panel temperatures lower and more stable, improving energy yields.

In Portugal there are trade-offs between energy systems and Targets 6.3 and 6.6 due to discharges of hot water from thermal-powered electricity plants. And, with target 6.5 since several hydroelectrical dams are fed by border-crossing rivers.

Solar PV power plants in Portugal do not significantly impact water provision and water quality though their operation: annual water requirements for panel cleaning are very low. However, clearing forests to install large PV stations has possible negative impacts on geohydrological resources (Turney & Fthenakis, 2011). Portugal has a large floating PV power plant being constructed over the Alqueva dam (EDP, 2021).

Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all

Fuso Nerini et al. (2017b) report synergies and trade-offs between energy systems and Targets 7.1 (*universal access to affordable, reliable and modern energy services*) and 7.2 (*increase substantially the share of renewable energy in the global energy mix*). Castor et al. (2020b) also report synergies and trade-offs with 7.1 and 7.2, extended to 7.3 (*double the global rate of improvement in energy efficiency*).

Regarding 7.1 there will be trade-offs with energy projects that *do not expand* energy services. For instance, if a utility-scale, grid-connected PV power plant is implemented on a region lacking electricity and locals are not provided with electricity 7.1 will be negatively affected (Brunet et al., 2020). Also, if off-grid energy systems are implemented without energy storage, access to electricity will not be reliable, a trade-off with 7.1. (Without storage solar PV will only provide power for 4 to 6 hours per day.) Renewable energy systems will support 7.2 if they increase the share of renewable energies in the global energy mix.

Energy efficiency and the rate at which it increases over time (Target 7.3.) depend on several factors besides energy technology, like building standards, appliances, and consumer behaviour, but improvements in *conversion efficiency* also play an important role. Variable renewable energy technologies, like wind power and solar PV have currently a much lower conversion efficiency than best-of-breed fossil-fuel based generators, like the combined cycle gas turbine generators featuring over 60% (GE, 2018). For example, the best efficiencies of commercial solar PV are now about 22%, meaning that from the standard 1,000 W/m^2 irradiance of the sun only 220 W/m^2 are converted to electricity. However, natural flows like wind and solar radiation are free of charge and their availability largely supplants all present and future human needs. So, in *absolute terms* the efficiency at which they are converted is irrelevant. But solar PV also has a low *capacity factor* (which is given by full operation time over total time, e.g., average number of sunny hours over 24 hours) compared to traditional plants: hydro, fuel-based or nuclear power. Therefore, to obtain *energy outputs* like those of traditional power stations solar PV plants must occupy large extents of land, making solar PV a low *power density* technology. Increasing conversion efficiency is thus important to increase power density even if in absolute terms it remains lower than the efficiencies of fuel-fossil power stations.

Nerini et al. (2016) study the options to achieve Target 7.1 in countries with low rates of electricity access using a cost-based model having as metrics the Levelized Cost of Electricity (LCOE) and the total cost per household connected, between 2015 and 2030. Their purpose is to provide decision support on cost-optimal choices for electrification. Four key parameters are defined for the calculations: target level and quality of energy access; population density; local grid connection characteristics; and local energy resources and technology costs.

There are five target levels depending on electricity requirements: 1 - task lighting and phone charging or radio; 2 - general lighting, ventilation, television, computing, and printing; 3 – as level 2 plus small electric appliances; 4 - as level 3 plus medium or continuous appliances, e.g., water heating and microwaves; 5 - heavy or continuous electrical appliances, including air conditioning. Population density varies from 50 to 650 households/km^2. Distance to the closest grid connection varies from 5 to 50 km. The technologies studied are wind power, mini hydro, solar PV, biogas generators, and diesel generators, used in three electricity access types: *grid connection*, *mini grids*, and *stand-alone systems* (like those installed on roof-tops).

Among their results Nerini et al. (2016) present values for the LCOE of grid, mini grid, and stand-alone access types as the population density varies. They show that for level 1 *stand-alone* beats all the alternatives, and that for level 2 and up to 150 households, *stand-alone and mini grids* cost less than grid access. The situation changes rapidly as population density increases, with grid connection becoming preferable. On the other hand, grid access costs depend strongly on the distance to the closest connection point. Interestingly, considering average prices for Africa in 2015, *PV stand-alone* systems are in all cases a little costlier than *diesel generators* - for all target levels and low or high population densities - while *solar PV mini grids* are always a little cheaper than the diesel generators. The model is tested on two African countries (Nigeria and Ethiopia) showing that the cost-optimal approach involves implementing the three access types depending on the existing grid infrastructure and on the distribution of population density - a strategy recommended by the authors for countries with limited electrification budgets.

Portugal is considered by the Sustainable Development Report (2021) as having achieved SDG 7: the only green semaphore in its country profile. The *share of renewable energy in the primary energy mix* is reported as 23.17% in 2019, much higher than the world average of about 11% (OWD, 2021). However, the report has no indicators for energy efficiency (Target 7.3). And although all Portuguese enjoy access to electricity this does not mean that some get *all the energy they need* - an energy poverty problem, already mentioned in SDG 1.

Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

Fuso Nerini et al. (2017b) find synergies and trade-offs between energy systems and Targets 8.1 (*Sustain per capita economic growth in the least developed countries*), 8.2 (*Achieve higher productivity through diversification, technological upgrading and innovation*), 8.3 (*Promote policies that support* *productive activities, decent job creation, entrepreneurship, creativity and innovation*), 8.4 (*Improve global resource efficiency in consumption and production, endeavour to decouple economic growth from environmental degradation*), 8.5 (*Achieve full and productive employment and decent work for all women and men)*, 8.6 (*Reduce the proportion of youth not in employment, education or training*), and 8.9 (*Promote sustainable tourism that creates jobs and promotes local culture and products*).

Castor et al. (2020b) report synergies and trade-off between energy projects and Targets 8.1, 8.2, 8.4, 8.5, 8.6, 8.8 (*Protect labour rights and safe and secure working environments for all workers)*, and 8.10 (*Strengthen domestic financial institutions to expand access to financial services for all*).

Synergies between solar PV and Targets 8.1, 8.2, and 8.3 are common to modern energy projects, which may promote economic growth, enable technological upgrading and innovation, create jobs, and promote entrepreneurship. This is valid for countries at all stages of development, for different reasons, including the least developed countries. Solar PV also supports 8.4 since it generates low carbon energy with minimum environmental impact if its implementation is well managed. Synergies with 8.5 and 8.6 depend on policies promoting renewable energies as employment generators. Large PV power plants create *permanent employment* that has *little impact* in the regions where the solar plants are implanted: maintenance, like cleaning panels or mowing grasses, creates very few work posts. Decentralized PV, on the contrary, may lead to the creation of a network of small and medium companies working at regional level. Solar PV may support 8.9 by providing clean energy for sustainable tourism if its environmental impact is minimized and cultural heritage sought by tourists is not affected due to visual impact.

Like 8.5 and 8.6, support to 8.8 by solar PV will depend on policies and regulation: the work environment in solar PV implementation is like the work environment of other electrical energy projects, and not particularly dangerous (NC-Clean, 2017). Implementation of decentralized solar PV in less developed countries requires expanded access to financial services, a synergy with 8.10.

Trade-offs between solar PV systems and projects and 8.5 and 8.6 could happen if projects provide only temporary jobs - which is unlikely since the solar PV sector requires specialization. Trade-offs with 8.8 could happen if solar PV created obsolescence in other energy sectors, leading to job losses. Again, this is unlikely because although solar PV slows down the growth of non-renewable power the process is incremental leaving time for adaptation. For instance, oil and gas companies are already investing in renewable energy despite continuing to promote oil and gas. In summary, trade-offs with 8.5, 8.6, and 8.8 will be small or negligible.

Trade-offs with 8.9, though, will probably happen since utility-scale PV power plants can have strong visual impacts and, due to high occupation areas in the countryside may lead to the destruction of natural and cultural heritage, namely if their implementation is poorly planned and licensed carelessly. This will negatively affect sustainable tourism (Target 8.9) besides creating trade-offs with other SDGs.

The number and distribution of jobs in renewable energy can be appraised through the annual reports on jobs released by IRENA, since 2012. The last report by IRENA (2021) shows that the renewable energy sector (which includes *solar PV*, *bioenergy*, *hydropower*, *wind energy*, *solar heating/cooling*, and *others* like geothermal, CSP, and municipal waste) was responsible for 20 million jobs in 2020, with the main shares going to solar PV (4 million), bioenergy (3.52 million), hydropower (2.18 million), and wind energy (1.25 million). According to the report, solar PV has been consistently growing in number of jobs since 2012, becoming in 2016 the first employer in renewable energy, a position it maintained until now. Projecting the future under a 1.5° compatible global roadmap IRENA expects that the *energy sector* will be responsible for 122 million jobs in 2050, with 42 million in the *renewable energy sector*. Like today, solar PV will have the largest share (19.9 million) followed by bioenergy (13.7 million), wind (5.5 million) and hydropower (3.7 million).

The impacts of electricity from renewable sources in Portugal are addressed in a joint study by the Portuguese association for renewable energy (APREN) and Deloitte, a consultancy (Deloitte & APREN, 2019). The study encompasses impacts on the electricity market, GDP, employment, fiscal income, and CO_2 emissions avoidance, between 2014 and 2018 with projections until 2030. The contribution for GDP from the renewable energy sector in 2018 is reported as €3,306 million, 1.6% of the Portuguese GDP for the year. From this value, 55% is estimated to be *direct* gross value added (GVA).

In 2018, the biggest contribution for GDP came from wind power (58%) followed by hydropower (24%). Solar PV contributed only 14% but despite the relatively low value the *share per megawatt* of installed capacity was the highest: 661,000 €/MW versus 360,000 €/MW from wind energy. The reason (not mentioned in the report) may be the strong growth in capacity-adding solar PV *projects* from 2014 to 2018 compared with the stagnation in wind power. For 2030, the authors estimate a contribution of 4.6% to GDP from electricity from renewable sources. The share of solar PV in all electricity generation in Portugal in 2030 will be 59%, the highest: a capacity of 6.5 GW, with 276 MW from decentralized PV. Wind power will be second, with a 30% share.

The contribution of electricity from renewable sources (RE) to job creation is also addressed by Deloitte & APREN (2019). The sector was responsible for an estimated 46,790 jobs in 2018, with a (non-specified) very large majority corresponding to *indirect* employment. This is consistent with the low permanent work posts required by solar PV and wind power. For 2020, the contribution of solar PV to jobs in RE electricity is estimated as 30% (16,795 work posts) against 40% from wind power. In 2030, solar PV will be responsible for more than 100,000 jobs (64%) with the share of wind energy decreasing to 23%.

Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

Fuso Nerini et al. (2017b) report synergies between Targets 9.1 (*Develop infrastructure support economic development and well-being*), 9.2 (*Promote inclusive and sustainable industrialization*), 9.3 (*Increase access of small-scale enterprises to affordable credit*), 9.4 (*Upgrade infrastructure and retrofit industries to make them sustainable*), 9.5 (*Enhance scientific research, upgrade the technological capabilities of industrial sectors*), and 9.b (*Support domestic technology development, research and innovation in developing countries*) with the achievement of SDG 7, *Energy for all*.

Thus, for the authors, it is developments in infrastructure, access to finance, sustainable industry, and scientific and technology capacity that enable access to energy for all: reinforcement runs from these targets to energy systems, not in the opposite direction. In the case of Target 9.c there is a synergy between *renewable energy* systems and access to ICT (information and Communication Technologies).

Castor et al. (2020b) find synergies between energy projects providing *centralized* access to electricity from *renewable sources* and Targets 9.1, 9.2, and 9.4 since these projects can be considered *sustainable and quality energy infrastructure*, which supports development. Projects that expand energy from renewable sources to industry have a synergy with 9.2, while projects achieving higher conversion efficiency will also promote higher resource efficiency therefore supporting 9.4.

Like Fuso Nerini et al. (2017b), the authors remark that lack of infrastructure e.g., for transmitting and distributing electricity has trade-offs with energy access (Target 7.1) and with Target 9.1 itself. Planning centralized energy systems for all possible weather conditions has synergies with 9.1, otherwise there will be a trade-off with the target.

Solar PV has two types of roles regarding infrastructure. It can support centralized provision of electricity through utility-scale power plants (using the existing infrastructure) and provide energy access where the electrical infrastructure does not yet exist, for instance forming cores for future integration as discussed previously about SDG 7. Where an electrical infrastructure already exists *decentralized* solar PV (e.g., rooftop systems) will use it, confirming the enabling effect of infrastructure on new energy systems. Commercial and industrial buildings, carparks, and enterprises with adjacent land are implementing roof-top and grounded PV systems for self-consumption, contributing to GHG emission reductions and lower electricity bills. Highways, hydropower dams and irrigation channels are also examples of infrastructures having non-functional areas that can be used to site solar PV systems. For instance, the French government recently announced (PV magazine, 2021) the urgent promotion of solar PV projects on large rooftops, including warehouses, hangars, and covered carparks (that become *carports*). The projects will also be promoted in public lands, including land along highways.

Solar PV in Portugal also shows the two roles referred above: contribute to centralized electricity through utility-scale PV plants and use existing infrastructure for decentralized PV. Commercial, industrial, and agricultural companies are installing decentralized solar PV on their buildings and adjacent land. The website of ENGIE Hemera, a developer of solar PV working exclusively for the enterprise market illustrates PV systems built at the Portuguese facilities of several well-known companies (https://engie-hemera.com/projectos/).

Goal 10. Reduce inequality within and among countries

Castor et al. (2020b) find synergies between energy projects and Targets 10.1 (*Achieve and sustain income growth of the bottom 40 per cent of the population),* 10.2 (*Empower and promote the social, economic and political inclusion of all*), 10.3 (*Ensure equal opportunity and reduce inequalities of outcome*), and 10.7 (*Facilitate orderly, safe, regular and responsible migration and mobility of people*).

The positive impact occurs through *access to modern energy services*, which promotes income growth (10.1); empowerment and inclusion of all (10.2) through the reduction of poverty (SDG 1 synergies); improvement of food security (SDG 2 synergies); and expansion of health services and education (SDG 3 and SDG 4 synergies). The authors also report synergies with 10.1, 10.2, and 10.3 via *fair and equal hiring practices*, which support the employment of everyone, including those in the bottom 40% of the population (10.1), social, economic, and political inclusion of all (10.2), and ensuring equal opportunities and eliminating discrimination (10.3).

Regarding *jobs made obsolete* due to energy projects, there will be a synergy with 10.1 if the project provides a replacement or alternative for these lost jobs. Otherwise, there is a trade-off with the target. Castor et al. (2020b) also point out that *relocation of communities* that might be needed for the project should involve the community in the decision-making process, a synergy with 10.7, which concerns migration. Conversely, relocation without consultation of the affected population causes a trade-off with the target.

Fuso Nerini et al. (2017b) find synergies with 10.1 through energy access and remark that renewable energy projects can create new jobs and new income opportunities, also supporting 10.1.

Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable

Fuso Nerini et al. (2017b) report synergies and trade-offs between energy systems and Targets 11.1 (*Access for all to adequate, safe, and affordable housing*), 11.2 (*Access to safe, affordable, accessible, and sustainable transport systems for all*), 11.3 (*Enhance inclusive and sustainable urbanization, enhance participatory, integrated, and sustainable human settlement planning and management*), 11.4 (*Protect and safeguard the world's cultural and natural heritage*), 11.5 (*Reduce deaths, number of people affected, and economic losses caused by disasters*), 11.6 (*Reduce the adverse per capita environmental impact of cities*), and 11.7 (*Universal access to safe, inclusive, and accessible, green and public spaces*).

Target 11.1 is supported by access to energy, a basic service. However, there might be trade-offs with other SDGs if *there is not enough available renewable* energy by 2030, the target deadline. Target 11.2 is supported by renewable energy systems, a synergy. Target 11.3 calls for greater participation in urban planning, which includes decision making on energy systems. Thus, achieving 11.3 *supports* SDG 7, and not the opposite.

Target 11.4 may have trade-offs with energy systems and projects through extraction and siting of energy facilities, negatively impacting natural and cultural heritage. This also happens with low power density renewable energies (solar PV, wind power). However, carefully implemented renewable energy systems can have synergies with the target, e.g., solar PV systems with *natural co-benefits* or harmoniously *integrated in the landscape* (Scognamiglio, 2016). Energy systems have synergies with 11.5, for instance through solar lanterns and emergency stand-alone PV power.

Supplying clean, renewable energy to cities and settlements supports 11.6 but *providing modern energy access as fast as possible* can lead to trade-offs with the target if implemented with polluting systems. There is evidence of trade-offs between green spaces and land for energy and other infrastructure, but well-planned renewable energy applications could be harmonized with such spaces.

Castor et al. (2020b) report synergies and trade-offs between energy projects and 11.1, 11.2, 11.3, 11.4, 11.5, 11.6, and 11.7.

Regarding 11.1 energy can be considered a basic service thus expanding energy access is a synergy with access to basic services. The authors note, however, that energy projects in areas desirable for housing and other infrastructure can compete with safe and affordable housing, a trade-off. And that the trade-off is generally stronger for projects with low energy densities, like most renewables.

In developing countries, if *the energy is provided at a higher cost than non-sustainable alternatives* there is a trade-off with access to affordable basic services for all. Regarding 11.2 energy from renewable sources can help build sustainable and accessible public transport systems, a synergy. Lighting in public spaces, including roads and transit stations, has synergies with improved safety in transit systems, also required by Target 11.2. Regarding 11.3 energy projects in areas desirable for housing and other infrastructure can compete with safe and affordable housing, a trade-off with sustainable urbanization. Regarding 11.4 if energy projects harm or destroy protected natural species, introduce non-native, invasive species into ecosystems, and affect areas of historical or cultural importance they conflict with the protection of world's natural heritage, a trade-off with the target.

However, if an energy project minimizes or eliminates the use of traditional biomass it may have synergies with 11.4 since it can reduce stress on local ecosystems and protect local natural heritage. Relocating populations and bringing in large workforces without proper management can be considered a disruption of cultural heritage, a trade off with 11.4. Regarding 11.5, the authors consider that continued energy access from resilient energy systems during extreme weather or disaster scenarios could reduce the number of deaths and people negatively affected, a synergy with the target, while reduced availability of energy in those cases may have negative consequences for the economy and people in vulnerable situations.

Regarding 11.6 there are synergies between energy from renewable sources used in urban settings and the reduction of environmental impacts of cities, while energy from non-renewable, air-polluting sources conflicts with the target. Target 11.7 has potential trade-offs from land use competition between public green spaces and energy projects, especially in urban or quickly developing areas. Trade-offs are generally stronger for technologies with low energy densities. Harmonization is possible, though, as mentioned about Target 11.1.

Solar PV energy can contribute to the targets of SDG 11 via *decentralized* systems in cities and settlements, sharing most of the characteristics discussed about SDG 9. In urban spaces, stand-alone PV systems will use, essentially, rooftops and façades in all kinds of buildings, and areas that can be covered by solar panels without altering its main function, like carparks.

Administrative, commercial, service, and condominium buildings, along with stadiums, convention halls, hangars, carparks, and schools possess horizontal and/or vertical surfaces where PV panels can be installed to generate electricity for self-consumption. Isolated villas in cities or urban peripheries also have usable surfaces, namely rooftops, garages, or shading areas for cars that can be transformed into carports for electric vehicles.

Solar PV can be applied to existing buildings, but it can be part of the design from the start, as it happens with BIPV - building-integrated photovoltaics (Heinstein et al., 2013). Fitting solar PV to existing rooftops, namely in classical or historical buildings can be challenging but is becoming possible with *solar tiles* that look like conventional tiles (Bellini, 2021). Some replacements, though, can destroy historical heritage like it will happen in Goa, India, with the local government intending to replace the traditional rounded colonial tiles by different tiles or metal sheets with PV panels (Lal, 2019).

Stand-alone PV systems must be installed in places not normally accessible, like rooftops and elevated surfaces. Installing a PV in a backyard would require fencing to avoid danger of electrical shock.

The numbers for decentralized PV in Portugal are unknown or simply not divulged by the authorities - considering that the installation of any system over 350 W (about two standard PV modules) must be communicated to DGEG, the general directorate for energy and geology. The

National Plan for Energy and Climate (PNEC, 2019) estimates 500 MW of decentralized solar PV for 2020 but this value includes systems outside cities, e.g., in industrial parks and farms.

Solar PV potential in building façades and carparks in Portugal has been studied by Portuguese researchers (Brito et al., 2017; Figueiredo et al., 2017).

The reality of *decentralized PV* in Portugal does not seem to follow its potential. In an opinion article about decentralized PV, Serôdio (2020) stresses the importance of going from 500 MW in 2020 to 2 GW in 2030 as officially planned (PNEC, 2019) while pointing out barriers to the development of distributed generation of electricity. The author complains, for instance, of lack of clarity in the concepts of *self-consumption*, *collective self-consumption*, and *energy community*. And that it is not acceptable that producers in these classes, while legally allowed, cannot sell their excess energy because of limitations in the electrical grid – an obstacle increasing costs and deterring further investment. Barriers are also noted in the unreasonably complicated licensing and in the bureaucratic delays due to lack of human resources at DGEG. The author argues that 30% of the electricity needs of Portuguese companies could be covered by self-consumption, leading to savings of 5% to 10% in their electricity bills.

Goal 12. Ensure sustainable consumption and production patterns

Castor et al. (2020b) see synergies and trade-off between energy projects and Targets 12.1 (*Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns*), 12.2 (*Achieve the sustainable management and efficient use of natural resources*), 12.3 (*Halve per capita global food waste and reduce food losses*), 12.4 (*Achieve the environmentally sound management of chemicals and wastes*), 12.5 (*Reduce waste generation through prevention, reduction, recycling and reuse*), and 12.8 (*Information and awareness for sustainable development and lifestyles in harmony with nature*).

The 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns (10YFP) mentioned in 12.1 was established at the "Rio+20" Conference of the UN in 2012 and currently include six programmes (UNEP, 2021): *Sustainable Public Procurement*, *Consumer Information for SCP*, *Sustainable Tourism*, *Sustainable Lifestyles and Education*, *Sustainable Buildings and Construction*, and *Sustainable Food Systems*.

Castor et al. (2020b) remark that renewable energy and efficient energy systems have synergies with the target, cautioning that increasing energy access has a possible trade-off with implementing SCP programs since it *tends to increase consumption and waste*. Regarding 12.2, they stress that many forms of energy have trade-offs with this target although renewable energy (RE) can contribute to sustainable management of natural resources since they depend on natural renewable flows and stocks.

The authors do not mention, though, that *renewable* energies require *non-renewable* natural resources for its construction (like metals and minerals) raising present and future sustainability issues as discussed below.

Regarding 12.3, they note that increasing energy access supports economic growth (SDG 8), which tends to increase consumption and waste, including food waste. Thus, increasing energy access has a possible trade-off with decreasing food waste. However, increasing energy access can also decrease food waste by allowing *better food conservation* measures during food harvesting, transportation, and retail. Besides, energy access in homes can decrease food waste by allowing individuals to refrigerate their food. Increasing energy access has thus a possible synergy with decreasing food waste. Regarding 12.4, they remark that *most* renewable energy technologies do not produce atmospheric pollution during operation and do not continuously produce a waste that must be landfilled, a synergy with SDG 12, contrary to energies involving incineration (e.g., coal-burning power plants and waste-to-energy power plants) or generating hazardous residues that must be stored and controlled (nuclear power plants). Biomass and biofuel power (which use renewable energy sources) have possible trade-offs with reducing the releases of chemicals and waste because energy is typically produced via incineration and the by-products of incineration are often landfilled, which can cause soil and water pollution. There may also be air pollution if the treatment of flue gas is not adequate. End of Life (EOL) management plans are seen as a key factor to manage the trade-offs. Regarding, 12.5, renewable energies may produce negligible waste during operation, a synergy with this target. However, as mentioned about 12.4 biomass and biofuel energy generates waste, a trade-off with *reducing waste* as required by Target 12.5.

Castor et al. (2020b) remark that waste-to-energy can also be seen as a form of *reuse*, a synergy with Target 12.5.

The existence of End of Life (EOL) management plans is seen as a key factor to manage the trade-offs, like in the case of SDG 12.4. The authors do not mention, though, that the strong growth in renewable energies required to mitigate the climate crisis, will generate complex EOL waste management issues as discussed below. Regarding 12.8, Castor et al. (2020b) mention that energy project that involve education initiatives about sustainable development have synergies with this target.

Fuso Nerini et al. (2017b) report synergies and trade-offs with 12.1, 12.2, 12.4, and 12.5, with less detail than Castor et al. (2020b) but not contradicting their findings. But they also see synergies and trade-offs of energy systems with 12.6 (*Encourage companies to adopt sustainable practices*), 12.7

(*Promote public procurement practices that are sustainable*), and 12.8 (*Ensure people have information and awareness for sustainable development and lifestyles in harmony with nature)*.

Regarding 12.6, the authors note that the target requires efficient use of energy and other energy-related sustainable practices in business, however that there are synergies and trade-offs associated with energy efficiency and renewable energy integration, which can affect countrywide energy demand and supply. Regarding 12.7, they report evidence that sustainable public procurement may result in more sustainable energy systems, thus contributing to SDG7.

Solar PV prompts concerns about sustainable consumption and production patterns, together with other RE technologies like wind power, power storage batteries, and fuel cells. They originate in the *huge* amounts of metals and minerals needed to build in the next decades a new carbon-free electrical and fuel supply infrastructure. And the systems relying on them, like battery and fuel-cell electric vehicles, and heat pumps (Sovacool et al., 2020; Månberger & Stenqvist, 2018).

Sovacool et al. (2020) highlight the development opportunities created by the demand of raw materials needed for climate change mitigation while stressing the *legacy* of environmental degradation, adverse impacts to public health, marginalized communities and workers, and biodiversity damage in many parts of the world. The future will be even more challenging. Citing projections by Månberger & Stenqvist (2018) - which estimate that demand for critical materials between 2015 and 2060 will increase 87,000% for EV batteries, 1,000% for wind power, and 3,000% for solar PV - the authors remark that the largest shares of critical metals and elements, like cobalt, copper, dysprosium, gallium, indium, lithium, neodymium, nickel, platinum, selenium, silver, and tellurium, are located at a few countries, creating tensions about resource security and risks of trade wars.

The article recommends policies to support sustainable consumption and production of these critical materials, which include diversifying mining enterprises for local ownership and livelihood dividends; implement resource traceability; explore new resource streams; and include minerals into global climate change and energy planning. The first policy would support artisanal and small-scale mining (ASM), which although not immune from poor governance or environmental harm, could provide livelihood potential for many million people worldwide. The second would make companies ensure that raw materials supply chains are not sourced from mines involving illegal labour and/or child labour. Some successful cases are mentioned although the authors also caution that traceability can be limited. The third policy would lead to exploitation of the ocean for raw materials through *deep-sea mining* and desalination to extract chemical elements. The fourth policy would require countries to include raw materials in their Nationally Determined Contributions (NDC) together with the current commitments about GHG reductions.

Sovacool et al. (2020) acknowledge that sustainably exploiting the badly needed materials is difficult since “mineral and metal supplies are geological determined, yet socially mediated”. And remark that “there is an ethical conundrum to addressing climate change only by aggravating other social and ecological problems related to unsustainable mineral and metal supply chains”.

The demand of materials for wind and solar PV power in the transition to a decarbonised energy system is addressed by Carrara et al. (2020) in a technical report published by the Joint Research Centre of the European Union. Regarding solar PV power, the authors calculate the material intensity in kilograms per megawatt of installed capacity of the four mature PV technologies: crystalline silicon (c-Si), cadmium telluride (CdTe), copper indium gallium di-selenide (CIGS), and amorphous silicon (a-Si). The materials required fall in two categories: *general materials* common to all PV technologies and *specific materials*, used in the energy generating cells. Examples of general materials are *concrete* and *steel* for support structures; *plastic* for environmental protection of the modules; *glass* for substrates and module encapsulation; *aluminium* for module frames, racks, and supports; and *copper* for wiring, cabling, and earthing, DC-AC inverters, transformers, and connection of PV cell ribbons. Specific materials differ according to technology. For instance, crystalline Silicon, which captures 95% of the market (ISE, 2021), requires *silicon* and *silver*. Crystalline ‘solar grade’ silicon is the photosensitive element from which PC cells are made. Silver is used in soldering pastes.

The models of Carrara et al. (2020) for materials demand consider three scenarios for the increase in PV capacity until 2050: low demand (LDS), medium demand (MDS), and high demand (HDS). And two geographies: the EU and the whole world. In the EU model LDS and MDS reach similar capacity in 2030 but diverge afterwards. The HDS for Europe considers almost complete decarbonisation by 2050 and greater decarbonisation by 2030 and is aligned with the 55% objective laid out in the European Green Deal. In 2050, PV capacity would reach over 2,500 GW, equal to 2.5 terawatt (TW).

The global model forecasts similar values in 2030, like in the EU model, but in HDS installed capacity diverges strongly in 2020 to reach in 2050 almost 13,000 GW (13 TW). In LDS and MDS capacity reaches only about 2 TW and 4 TW, respectively.

The results for the EU in all PV technologies in the HDS scenario show that *Germanium* (Ge) and *Tellurium* (Te) will be needed in 2050 in quantities that *exceed 20%* of their current global annual availability. The 20% limit was established as a security threshold: Ge will not go over 80% of the current annual availability although Te will exceed 160%. However, the authors remark that the 20% security threshold does not account for the demand of the materials for other purposes than solar PV: silicon, for example, is the dominant material in silicon *chip manufacturing*. Besides Ge and Te, they also caution that demand for gallium, indium, selenium, silicon, and glass could pose threats to the global supply chain. Regarding general materials, *except for glass* there is no cause for concern since all the amounts required in the HDS in Europe are between less than 0.5% and less than 5% of global annual availability.

The results for the whole world show bottlenecks like those forecast for the EU. In conclusion, although no major supply issues are foreseen, in MDS and HDS, the medium and high demand scenarios, there *will be a significant pressure on several materials*, namely germanium, tellurium, indium, selenium, and silicon.

Note that the installed capacity in the high demand scenario of Carrara et al. (2020) is already an amazingly high value: 13 TW. But, as discussed in the Introduction, Bogdanov et al. (2021) find 60 TW for solar PV capacity in 2050, roughly five times more! It looks like the odds of providing clean and cheap electricity for global needs in 2050, as Bogdanov et al. (2021) suggest, will strongly depend on finding enough raw materials for the energy transition.

The contribution of renewable energy systems to Target 12.2 raises the issue of their *material efficiency*, especially when compared to non-renewable technologies: is a solar PV plant more *materially efficient* than a coal power plant?

The material efficiency of a product is expressed by the mass of materials per functional unit delivered: for a power generation device it can be measured, for instance, in kilograms per kilowatt-hour (kg/kWh). The research on material efficiency is scarce and no publication could be found specifically for solar PV, although one study was found for three CSP (Concentrated Solar Power) configurations (Samus et al., 2013). There is, however, research on material efficiency of wind power systems (Wisen et al., 2013) and batteries (Mostert et al., 2018), with the first article comparing the material efficiencies of wind turbines and traditional energy systems.

Wiesen et al. (2013) study two offshore wind farms in the German North Sea, analysing its material efficiency through their material inputs per service unit (MIPS) values. Simply put, MIPS is given by the summation of all materials and associated impacts needed for a specific device divided by the total amount of service it provides (one megawatt-hour of electricity, for instance). Material inputs can be *abiotic* (concrete, steel, etc.), *biotic* (wood, fibres, etc), *water* (surface, ground, deep ground), *air* (e.g., chemically changed particles), and correspond to *soil movements* (in construction or in agriculture). The calculations can be kept separate for the material classes or aggregated to yield a *material footprint*.

The results by Wiesen et al. (2013) show differences between the two wind farms regarding the three material classes considered in their study: abiotic materials, water, and air. For instance, one of the turbines had 162 kg/MWh of in *abiotic* material efficiency while the other had 103 kg/MWh.

Very interesting results, however, appear when the material efficiency of wind turbines is compared with the *material efficiency* of the European *electrical power mix* and with the material efficiency of a hard-coal power plant. For one of the wind farms (WFAV), abiotic, water, and air efficiencies were, respectively: 162; 948; and 9 kg/MWh, while the corresponding efficiencies for the European electrical grid were: 1,580; 63,530; and 420 kg/MWh. And for the hard coal power plant, they were: 892; 6,434; and 751 kg/MWh. So, the wind turbines were much more materially efficient.

The results estimated by Samus et al. (2013) for CSP systems show that for *parabolic through* configurations (which physically resemble PV configurations) the abiotic, water and air efficiencies in were, respectively: 208; 6,462; and 13 kg/MWh. Note that regarding water use the CSP system and the coal power plant have similar results. But this is because CSP is *also a thermal generating technology* and requires water for cooling purposes. Therefore, it seems fair to conclude that solar PV power is much more materially efficient that fossil fuel generators.

Although the idea is not developed by Wiesen et al. (2013), their results suggest the calculation of *material footprints* for technologies *that replace* grid electricity, like wind power and solar PV. Then, if the material efficiency of the electric grid is known (i.e., its material footprint) both values could be used to compute *savings in natural resources* resulting from the replacement, similarly to what is done with GHG emissions.

Target 12.5 calls for the reduction of waste generation raising the issue of what to do with the solar panels and other materials discarded by PV plant owners and roof-top PV owners. A report by IRENA (2016) presented the first global projections for future PV waste volumes to 2050. In their calculations, the authors assumed approximately linear growth for the projected *global cumulative PV capacity* from 222 GW in 2015, 511 GW in 2020, to about 4.5 TW in 2050. Two *waste models* were considered: a *regular-loss* scenario and a refined *early-loss* scenario.

The projections showed *staggering amounts* of accumulated waste: in the regular-loss scenario PV waste (mostly panels) could rise to 60 million tonnes in 2050, with 1.7 million tonnes already in 2030. In the early-loss scenario waste would rise to 8 million tonnes in 2030 and would total 78 million tonnes in 2050. To put the numbers in perspective: in 2050, depending on the scenarios accumulated waste would be 55% to 60% of the *total mass* of the panels *in operation* at the time.

The projections by IRENA (2106) can already be considered underestimates: by the end of 2020 global capacity had reached 708 GW instead of the projected 511 GW stated in the report. And according to the high demand scenario (HDS) used by Carrara et al. (2020) global capacity in 2050 will be 13 terawatts, not the 4.5 terawatts projected by IRENA (2106). Not to mention that Bogdanov et al. (2021), as noted above, forecast 70 TW for 2050.

With such huge amounts of waste looming PV, panel recycling and reuse are urgent, fundamental policies. In the EU the waste of electric and electronic equipment is regulated by the WEEE Directive, which in its last revision in 2012 (2012/19/EU) included, for the first time, rules for end-of-life management of PV panels. At the core of the directive lies the *extended-producer-responsibility principle* (ERP) which requires 'producers' seeking to place products on the EU market to be legally responsible for their end-of-life management, no matter where their manufacturing sites are located. ‘Producers’ include a range of parties involved in bringing a product to market, not just the original equipment manufacturer, and include sellers established inside or outside the EU, selling directly or indirectly, selling online, etc. ‘Producers’ are subject to requirements and have responsibilities. For example, they are financially responsible for the cost of collection and recycling of products sold to private households, and for financing public collection points and treatment facilities. They have reporting duties about the products they put on the market, and labelling responsibilities about product disposal and recycling. They must also inform buyers about disposal rules and collection facilities (IRENA, 2016).

PV Cycle (www.pv-cycle.org) is a non-profit association of ‘producers’ of PV panels, which participate voluntarily, providing WEEE compliance and recycling services to its members. PV Cycle is said to aggregate 70% of the ‘producers’ operating in Europe. The association develops recycling processes, having claimed in 2016 it had achieved a record 96% recycle rate for silicon-based PV modules (Kenning, 2016). More recently, it announced the collection in 2019 of more than 280,000 PV modules in France and French overseas territories, 95% of which to be recycled at the new *Triade* recycling factory in southern France (Spaes, 2020).

EU countries are required to create national regulatory frameworks based on the WEED Directive. In Portugal, this happened in 2014 with the publication of a government decree: *Decreto-Lei nº 67/2014, de 7 de Maio*.

The quantity of PV panels at end-of-life in Portugal is not known but a magazine article by staff at DGEG provides some potentially useful information. Gil & Isidro (2019) use data held by DGEG about the number of panels (i.e., modules) in solar PV plants in Portuguese territory, from 2005 to 2018, and estimate their total mass as 26,000 tonnes. Regarding plants *not known* to DGEG but that inject power into the grid, their estimate is 10,000 tonnes. Thus, solar PV plants in operation in Portugal may contain 36,000 tonnes of PV panels that sooner or later will become waste. While acknowledging the importance of PV recycling, Gil & Isidro (2019) do not attempt to estimate the current and future amounts of waste from the data they present.

Goal 13. Take urgent action to combat climate change and its impacts

Regarding SDG 13, the 2030 Agenda acknowledges that UNFCCC, the United Nations Framework Convention on Climate Change, is the main forum where the actions to combat climate change are decided.

The targets of SDG 13 are not comprehensive enough to address the complex relationship between energy systems and climate change. Still, Castor et al. (2020b) see synergies and trade-offs between energy projects and Targets 13.1 (*Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries*), 13.2 (*Integrate climate change measures into national policies, strategies and planning*), and 13.3 (*Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning*).

Synergies with 13.1 result from energy projects that acknowledge possible impacts from climate-related hazards and natural disasters and have adequate plans to build resilient and adaptive systems. Trade-offs will result if these practices are not followed. Also, energy projects that require water extraction have possible trade-offs with 13.1 since they may reduce resilience. Regarding 13.2 energy projects that release carbon dioxide to the atmosphere (bioenergy, for instance) but have carbon capture and storage (CCS) capabilities will have synergies with the target, trade-offs otherwise. Energy projects implementing renewable energy and more efficient technologies will also have synergies with 13.2, trade-offs otherwise. The authors also mention nuclear power as supporting the target since despite being non-renewable it is a low carbon technology. Finally, Target 13.3 will have synergies with energy projects if they involve education or enhance awareness of climate change mitigation and related issues, trade-offs otherwise.

Solar PV power has profound impacts, positive and negative, on the battle against climate change. These will be addressed in Section 2.5 of this thesis.

Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Fuso Nerini et al. (2017b) report synergies and trade-offs between energy systems and Target 14.3 (*Minimize and address the impacts of ocean acidification*) through the contribution of energy technologies to acidification, with only low-carbon technologies having synergies with 14.3.

Castor et al (2020b) report synergies and trade-offs between energy projects and Targets 14.1 (*Prevent and reduce marine pollution of all kinds*), 14.2 (*Sustainably manage and protect marine and coastal ecosystems*), 14.3, and 14.5 (*Conserve at least 10 per cent of coastal and marine areas*).

Regarding 14.1 the authors see trade-offs with 14.1 in energy projects that require disturbance of marine ecosystems; discharge untreated or higher temperature process water to the ocean; or use fertilizers that contaminate surface or ground water running-off to the ocean (like biomass or biofuel projects). Regarding 14.2 they see trade-offs with projects that cause pollution (mentioned about 14.1) and projects causing ocean acidification since both classes may harm marine and coastal ecosystems. There may also be trade-offs with systems that extract ocean water, which may harm ecosystems. However, some non-polluting energy systems located in marine or coastal areas may create habitats for ecosystems (e.g., offshore wind turbines). Regarding 14.3 they note that energy projects emitting carbon dioxide to the atmosphere will cause ocean acidification, including renewable energy using incineration. However, there will be synergies with the target with low carbon technologies or those that include CCS. Regarding 14.5 they note that projects physically located in coastal areas may trade-off against conserving 10% of marine and coastal areas.

Solar PV systems may disturb coastal areas through micro-habitat changes if improperly planned, a trade-off with 14.2. A greater concern is caused by the combination of solar PV and *desalination systems*. Desalination is used to obtain potable water or to recover valuable chemical elements from sea water. If the hypersaline waste (called "brine") is then discharged into the ocean it will generate pollution and harm marine ecosystems, trade-offs with 14.1, 14.2 and 12.5.

Jones et al. (2019) present and discuss the status of desalination at global level and, although acknowledging that unconventional water resources are key to support SDG 6 achievement, they remark that the existing 16,000 operational desalination plants produce 95.37 million m^3/day of desalinated water while *generating brine* at an estimated rate of 142 million m^3/day. Sea water desalination accounts for 61% of desalinated water but other sources, like *brackish* (or over salted) water and river water are also used. Brine production in Saudi Arabia, UAE, Kuwait, and Qatar accounts for 55% of the estimated world total.

Desalination plants located near the shoreline often discharge untreated brine directly into the ocean or seas. And since almost 50% of the brine is produced within 1 km of the coastline (with almost 80% produced within 10 km) ocean disposal is assumed to be the *dominant brine disposal* method worldwide. The impacts on marine ecosystems are not only due to the high concentration of salt: the waste may also contain chemicals used in the desalination process. The authors caution that improvements in brine management strategies are required to limit the negative environmental impacts and reduce the economic cost of disposal, thereby stimulating further developments in desalination facilities to safeguard water supplies.

Another serious concern comes from *deep-sea mining*, mentioned by Sovacool et al. (2020) about SDG 12. In a short document the International Union for Conservation of Nature (IUCN, 2018) presents the status of deep-sea mining and discusses the issues raised by the exploitation of the seabed. The growing interest in the mineral deposits of the deep sea is due to rising demand for metals like copper, nickel, aluminium, manganese, zinc, lithium, and cobalt to be used in smart phones and new energy technologies (wind power, solar panels, batteries). So far, the focus has been on *exploring* the seabed, for which the International Seabed Authority (ISA), which regulates activities in areas beyond national jurisdiction, has already issued about *thirty contracts*. The area marked for *exploitation*, which will likely begin in the next few years, amounts to 1.5 million square kilometres, roughly the size of Mongolia. Deep-sea mining will affect marine ecosystems severely: 1) the seafloor will be scrapped and disturbed with possible extinction of many endemic species, some still unknown; 2) sucking materials from the seafloor through pipes and returning the water to the seabed will create sediment plumes that may kill many sea creatures and create turbid waters affecting many others; 3) there may be pollution from the equipment used for mining, including fossil fuel emissions from the specialized ships.

The IUCN recommends baseline studies and high-quality environmental impact assessments, together with mitigation through improved mining techniques, enhanced regulation, and circular economy practices to reduce the need for virgin materials. It remains to be seen, however, whether the seafloor is going to be the next frontier of environmental destruction.

Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

Fuso Nerini et al. (2017b) report synergies and trade-off between energy systems and Targets 15.1 (*Ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems*), 15.2 (*Promote sustainable management of forests, halt deforestation, restore degraded forests and increase afforestation and reforestation*), 15.3 (*Combat desertification, restore degraded land and soil*), 15.4 (*Ensure the conservation of mountain ecosystems*), 15.9 (*Integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts*), and 15.a (*Mobilize and increase financial resources to conserve and sustainably use biodiversity and ecosystems*).

Regarding 15.1, 15.2, and 15.4 the authors acknowledge possible trade-offs with energy systems through negative impacts on ecosystems, forests, and mountain habitats. Regarding 15.3 they see opportunities in siting bioenergy and solar PV plants on *degraded lands*, in synergy with the target. Regarding 15.9 they remark that integrating ecosystems and biodiversity in national planning may affect how energy systems develop, a trade-off with Target 7.1. Regarding 15.a the authors note synergies with investments in energy systems in developing countries that might reduce the use of traditional biomass for energy. However, areas set aside for conservation may prevent access to traditional biomass resources resulting in trade-offs with SDG 7.

Castor et al. (2020b) see synergies and trade-offs between energy projects and Targets 15.1, 15.2, 15.3, 15.4, 15.5 (*Reduce the degradation of natural habitats, halt the loss of biodiversity, protect and prevent the extinction of threatened species*), 15.6 (*Promote fair and equitable sharing of the benefits from the utilization of genetic resources*), 15.8 (*Prevent the introduction and reduce the impact of invasive alien species on land and water ecosystems*), and 15.9.

Regarding 15.1 the authors note trade-offs of energy projects with the target caused by disturbance of ecosystems, pollution of ground or surface water, and introduction of non-native invasive species. A synergy may exist if sustainable forest management practices are used as a part of the energy project since they may contribute to healthy ecosystems. And, if the energy project helps moving away from traditional biomass, reducing stress on local ecosystems.

Regarding 15.2 deforestation for the purpose of an energy project conflicts with this target. The same will happen if sustainable forest management practices are not used. If energy projects help moving away from traditional biomass there will be a synergy with the target. Regarding 15.3 the authors acknowledge trade-offs with the target if energy projects require ecosystem disruption, leading to land-degradation impacts. Solar or biomass projects can utilize degraded land and can potentially aid habitat restoration. And moving away from traditional biomass through energy projects may reduce stress on local ecosystems and reduce land degradation.

Regarding 15.4 energy projects may conflict with the target, if improperly planned. Projects help moving away from traditional biomass and have a synergy with the target. Regarding 15.5 there will be trade-offs if energy projects do not include alternatives or methods for protecting threatened species, synergies otherwise. The introduction of a non-native invasive species into an ecosystem for the project could have negative consequences. However, the introduction of non-native species with a carefully considered species management plan could be considered a synergy with the target if it helps prevent degradation of habitats and preserve biodiversity. Again, energy projects help moving away from traditional biomass have a synergy with this target.

Regarding 15.6 development of bioenergy crops could promote sharing of benefits from the utilization of genetic resources. Regarding 15.8 the introduction of non-native and/or potentially invasive species into an area for a biomass or biofuel project generally has negative ecosystem impacts, some of which may not be fully known or studied at the beginning of the project.

Regarding 15.9 the authors remark that energy projects can integrate and account for ecosystem and biodiversity values, thus constituting a synergy with this target. However, like Fuso Nerini et al. (2018) they remark that accounting for ecosystem and biodiversity values may result in some trade-offs for the projects.

Some of the conclusions by Fuso Nerini et al. (2017b) and Castor et al. (2020b) deserve further discussion. Details about the synergies and trade-offs of solar PV systems and the targets of SDG 15 will be presented and discussed in Sections 3.3 and 3.4. The latter includes original research on present and future land occupation by PV power plants with implications for SDG 15.

2.3. Environmental Impacts of Photovoltaic Power Plants

In the previous section solar PV systems were characterized by their synergies and trade-offs with the sustainable development goals, in themselves a vast set of social, economic, and environmental requirements. However, as remarked at the beginning of Section 2.2 and confirmed by its content there are many opportunities for solar PV to conflict with the SDGs. This section addresses the environmental impacts of solar PV, namely caused by utility-scale power plants, which are ground-mounted and occupy large areas of land formerly covered by natural vegetation or used for agriculture and forestry.

Solar PV plants have positive and negative environmental impacts. The main positive impact is the potentially high or very high reduction in GHG emissions when power plants burning fossil fuel are replaced by PV power plants. The extent of the benefits, however, depends on specific factors and must be assessed case by case, the subject of the research presented in Section 2.5.

Negative environmental impacts occur in several dimensions as discussed in Aman et al. (2015), Botelho et al. (2017), Chiabrando et al. (2009), Delfanti et al. (2016), Gasparatos et al. (2017), Hernandez et al. (2014b), Hernandez et al. (2014b), Mauro and Lughi (2017), Moore & Hackett (2016), Sachelli et al. (2016), Scognamiglio (2016), and Turney and Fthenakis (2011).

The impacts are summarized by the items listed below with the description including related literature. Some of the publications present negative impacts while also suggesting measures to mitigate them and manage the associated trade-offs.

1. Solar PV power plants require large areas of land as discussed in Aman et al. (2015), Calvert (2018), Denholm & Margolis (2008), Hernandez et al. (2014a), Mauro and Lughi (2017), Ong et al. (2013), and WWF (2012).
2. They may replace cultivable land and displace food crops as reported by Botelho et al. (2017) and Sachelli et al. (2016).
3. Solar PV plants may lead to landscape and biome fragmentation with negative impacts on the local ecosystems and biodiversity as discussed in Hernandez et al. (2014b) and Turney & Fthenakis (2011).
4. They may lead to landscape changes with strong visual impact and deteriorate cultural and aesthetical values as discussed in Scognamiglio (2016), which also suggests mitigation measures through careful PV landscape integration.
5. Land covering by solar plants disturbs local fauna and flora and aquatic ecosystems as addressed in Hernandez et al. (2014b), and Turney & Fthenakis (2011). The latter also discuss the impacts of deforestation due to the installation of solar plants.
6. Large PV plants affect local climate causing thermal pollution as discussed in Botelho et al. (2017) and Barrow-Gilford et al. (2016).
7. Harmful products like herbicides and PV panel cleaning chemicals may run-off to the environment, as remarked by Hernandez et al. (2014b).

8. Solar light reflected off the panels may cause unpleasant glare affecting households, road travellers, and airports as reported by Botelho et al. (2017) and assessed by Chiabrando et al., (2009).
9. Solar PV panels and other system components are responsible for the emission of greenhouse

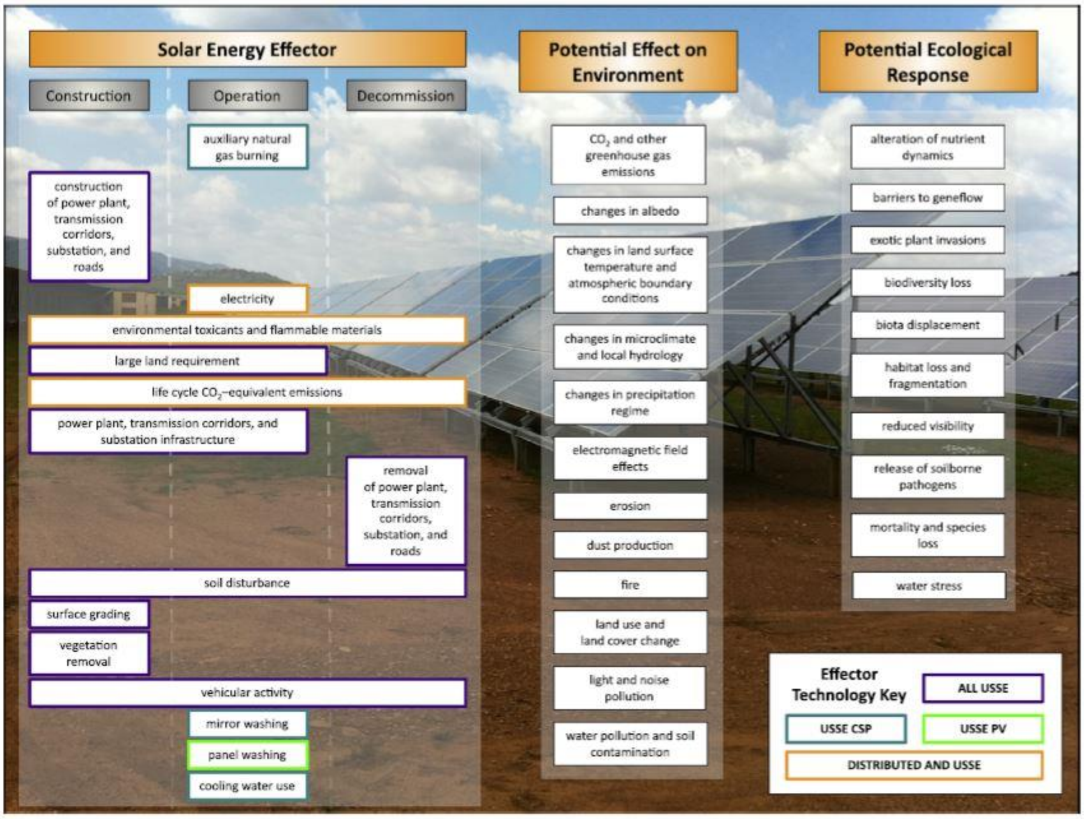


Figure 2.12 - Environmental impacts of utility-scale solar energy (Hernandez et al., 2014b).

gases and other pollutants in their manufacturing phase as discussed in Amman et al. (2014), De Wild-Scholten et al. (2014), Nugent & Sovacool (2013), Sinha et al. (2014), and Turney & Fthenakis (2011). The subject is further discussed in Section 2.5, where are also surveyed additional publications.

The rest of this section contains short reviews of the articles more relevant to understand the impacts, social reactions, and mitigation measures.

Hernandez et al. (2014b) present a comprehensive survey of known negative environmental impacts of utility-scale solar energy – defined as PV or CSP power plants with peak power capacity over 1 MW – noting positive aspects too, like reduction of greenhouse gases, stabilization of degraded land, increased energy independence, job opportunities, acceleration of rural electrification, and improved quality of life in developing countries. The impacts are presented as originating at all phases of the systems' lifetimes (25 to 40 years). Potential impacts are classified as those affecting the environment in general and those affecting wildlife through its ecological responses. Figure 2.12 from Hernandez et al. (2014b) summarizes the environmental impacts of utility-scale solar energy, with environmental effects and ecological responses detailed in their article. The authors also discuss opportunities for *co-benefits* in the implementation of solar power plants: 1) utilization of degraded lands, like brownfields and landfills; 2) co-location of solar panels with agriculture, now called *agrivoltaics*; 3) hybrid systems - PV plants and wind power; 4) *floatovoltaics* - PV plants placed over lakes, dam reservoirs, irrigation ponds, and canals; 5) PV panels in architecture and design - systems in rooftops and façades, electricity-producing noise barriers alongside roads. The authors argue that utilization of degraded land is an opportunity *to recover the area from its degraded state* while building the solar system. This is a recurrent topic also in other publications: degraded land is a way to spare land dedicated to other uses, like agriculture from being occupied by solar plants.

Turney and Fthenakis (2011) address the impacts of the construction and operation phases of large-scale (utility-scale) solar plants by identifying and appraising 32 environmental impacts from which they find 22 as being beneficial when compared with the traditional power generation technologies in the United States. Impacts are grouped in four categories: human health and well-being, wildlife and habitat, land use and geohydrological resources, and climate change from solar energy either global or near the power plant. Each impact (CO^2 emissions, for instance) is evaluated by the effects relative to traditional energy technologies, e.g., CO^2 reduction; by being beneficial or detrimental; and by its priority: CO^2, for instance, is a high-level impact meaning that it requires mitigative action that is both costly and must be fully completed. Despite the mostly qualitative overall evaluation all impacts are discussed in considerable detail in the article. A section concerning the environmental impact of land use change is particularly relevant for the research presented in Section 2.5 and will be discussed there.

Amman et al. (2014) focus on the two main solar energy technologies – PV power and CSP - offering a comprehensive survey of their life-cycle environmental and economic metrics, including carbon footprint in gCO_2-eq/kWh, energy payback time (EPT), and levelized costs of electricity (LCOE). Two conclusions from this article should be highlighted: 1) carbon footprint of solar PV is the highest among low carbon-emitting energy technologies – solar, hydro, nuclear, and wind - due to the massive amounts of energy required to manufacture the PV cells and panels; 2) the authors asserts that the increasingly large amounts of PV panels reaching the end of their lifecycles are already being recycled.

Chiabrando et al. (2009) discuss the impacts of PV plants on the territory and the landscape during the operation phase of PV power systems: land use, reduction of potentially cultivable land, countryside fragmentation, vegetation degradation, visual aspect on the landscape, microclimate change, glare; an also the construction phase impacts. However, a large part of their work is dedicated to the *assessment of glare*. Glare is defined as "the temporary loss of vision or reduction in the ability to see the details of the human eye as a result of a (real or imaginary) surface whose luminance at a given point in the direction of the observation exceeds the luminance that can be perceived by the human eye" (Chiabrando et al., 2009). Glare can lead to hazards at roads and airports and it is very disagreeable to humans and animals. The authors show how the risk of glare can be evaluated using GIS by building an elevation model of the terrain overlayed with the reflecting panels and possible receptors, like houses and roads. A chart of the Sun for the latitude of the location will help determine the range of solar altitudes and azimuths leading to perception of glare by the receptors and the corresponding times of the day when this can happen. A case study involving a PV system built on the south side of a 20^o slope shows that part of the receptors in their houses could indeed be subjected to glare for a short interval after sun rise, only during two days of the year.

Nugent & Sovacool (2013) present a critical *meta-survey* of LCA studies from solar PV and wind

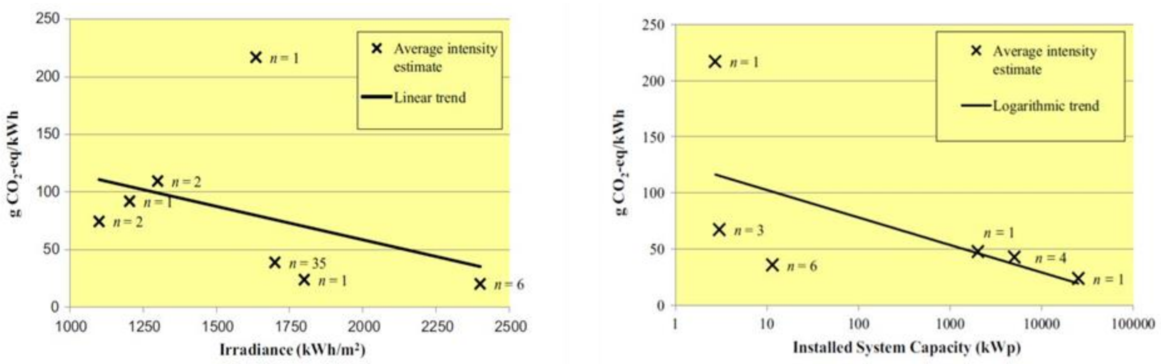


Figure 2.13 - Carbon footprint vs. irradiance and capacity (Nugent & Sovacool, 2013).

energy. From all studies found in their literature survey only 153 studies were selected deemed to be relevant, recent, rigorous, original, and complete. Regarding solar PV energy a short-list of 23 studies and associated 57 estimates were analysed statistically to determine a range of greenhouse gas emissions measured in gCO_2-eq/kWh (grams of CO_2 equivalent emissions per kWh of delivered energy). The analysis yielded values from 1 to 218, with a mean value of 49.9 gCO_2-eq/kWh adding the average emissions associated with each part of the lifecycle.

There are at least three important conclusions from the meta survey by Nugent & Sovacool (2013):

1. Cultivation and fabrication of the panels is by far the most carbon-intensive lifecycle phase with 33.67 gCO_2e/kWh, followed by construction with 8.98 gCO_2e/kWh), operation with 6.15 gCO_2e/kWh, and decommissioning with -1.56 gCO_2e/kWh. All figures are mean values with the negative sign in the last parcel meaning a reduction due to recycling.
2. The carbon footprint decreases linearly with irradiance in kWh/m_2, as shown in Figure 2.13 (left).
3. The carbon footprint decreases logarithmically with the size of the solar PV plant in kW (kilowatt of peak capacity), as shown in Figure 2.13 (right).

The second conclusion presents no surprises since the higher the irradiance the higher energy is collected during the PV system operational lifetime and thus total carbon emissions are divided by more delivered energy. The third conclusion was unexpected for the authors since solar PV is a modular technology and thus not sensitive to the scale effect, at least in principle.

De Wild-Scholten et al. (2014) present a 2011 world average estimation of the carbon footprint of solar PV using technology shares as weighting factors – with monocrystalline and multi-crystalline silicon technologies being the largest majority (87.9%). The world average carbon footprint (1,798 kg CO_2e/kWp) was then used to estimate regional PV carbon footprints for world countries at NUTS I level, with footprints calculated at NUTS II level for some regions of Europe. The countrywide and regional calculations use national reported values of installed capacities in 2013 and their yearly solar irradiation values determined by the PV-GIS solar energy database (PVGIS, 2020). The average PV carbon footprint for continental Portugal - the only Portuguese region included - was 43 gCO_2e/kWh. The installed capacity was 281 MW in 2013. The 43 gCO_2e/kWh contrasts with the 629 gCO_2e/kWh for the carbon footprint *or carbon intensity* of the Portuguese electrical grid in 2011. A similar but much more detailed analysis for continental Portugal is presented in Section 2.5.

Sinha et al. (2014) present a full lifecycle assessment (LCA) for an existing combined roof-top and ground-mounted 1.3 MW solar PV plant located in Kitakyushu-shi in Japan. The plant used cadmium telluride (CdTe) photovoltaic panels; a technology known by its low carbon footprint as demonstrated in Section 2.15. The LCA study covers 16 environmental impacts classified as relevant to *ecosystems*, *human health*, and *natural resources*. All indicators with one exception show the considerably lower impacts of the CdTe technology when compared to the corresponding impacts of the electricity generation mix in Japan. The exception was the “Mineral, fossil & renewable resource depletion” indicator: PV technologies require considerable quantities of mined materials and energy (still coming largely from fossil fuels) to manufacture photovoltaic panels as discussed in Section 2.2 about SDG 12.

Hernandez et al. (2014a) address the land occupation of solar power plants (PV and CSP) by studying 200 utility-scale solar energy installations in California using all the data available, including permitting processes. First, the authors discuss the main metrics used to access the land use of solar plants: 1) land use efficiency (LUE) expressed in W/m_2, a *capacity-based* indicator with the numerator expressing the nominal, peak power capacity of the PV panels; 2) LUE expressed in m_2/kWh, a *generation-based* indicator with the denominator expressing energy obtained from a square meter of PV panel. They also distinguish between the land surface occupied by the PV panels themselves and the total land area of the PV installation, which is significantly higher since the panels must be spaced to avoid shading and require pathways for maintenance and additional space for the so-called BOS (*Balance of System*) components, like inverters batteries, and transformers, which connect the generating elements to the electrical grid. (Note: land use efficiency is also designated as *land use intensity* by some authors.)

For PV power plants their statistical analysis shows an average value of 35 W/m^2 for the capacity-based LUE of 183 photovoltaic plants, with a variation of ± 4.8 within a 95% confidence interval, which the authors argue is much more accurate than estimates found in other studies on PV systems land use. (Note: 35 W/m^2 corresponds to approximately 2.86 hectare/MW of installed capacity.)

Regarding impacts of land-use change due to large-scale solar PV facilities Hernandez et al. (2015) discuss the U.S. case. They estimate that attaining the U.S. decarbonization goals, a -80% reduction of 1990 emissions by 2050 - would require 71,428 km^2 of land, assuming a 500 GW photovoltaic capacity replacing fossil-fuel generation, a land-use efficiency equal to 35W/m^2, and a 20% capacity factor for PV energy. The authors then analyse the *land cover* classes currently affected by the existing PV installations in California finding that some land covers are preferred over others. As shown in Figure 2.14 developers prefer "shrubland/scrubland" and "cultivated crops" land to site their PV power plants, signalling a potential increase of land-related impacts with the projected increase in overall PV capacity.

Table 1. USSE installations and land cover type

	Nameplate capacity, MWdc				Area, km^2			
Land cover type	PV	%	CSP	%	PV	%	CSP	%
Barren land (rock/sand/clay)	2,102	12	**1,000**	**48**	77	11	**34**	**45**
Cultivated crops	3,823	22	280	14	110	15	8	11
Developed (all)	2,039	12	50	2	70	10	1	1
Developed, high intensity	50	0	0	0	1	0	0	0
Developed, medium intensity	624	4	0	0	17	2	0	0
Developed, low intensity	160	1	0	0	9	1	0	0
Developed, open space	1,205	7	50	2	43	6	1	1
Emergent herbaceous wetlands	60	0	0	0	1	0	0	0
Grass/herbaceous	1,483	9	0	0	72	10	0	0
Pasture/hay	1,397	8	0	0	37	5	0	0
Shrubland/scrubland	**6,251**	**36**	744	36	**343**	**48**	32	43

The nameplate capacity [in megawatts (MWdc)], footprint (in square kilometers), and number of photovoltaic (PV) and concentrating solar power (CSP) USSE installations (>20 MW) in California (in planning, under construction, operating) by land cover type. Bold data represent the greatest value among all land cover types.

Figure 2.14 - Land preferred by PV developers in California (Hernandez et al., 2014a).

The authors also briefly present a decision support system to assess the land use suitability of solar energy with *technical* factors, like slope and power lines proximity, and *environmental criteria*, like locating plants on natural reserves and on habitats for endangered and threatened species or in their proximity. The decision tool, the Carnegie Energy and Environmental Compatibility model is applied to 161 utility-scale installations in California (planned, under construction, or operating) assigning them a compatibility level (compatible, incompatible, or potentially compatible). The results for PV energy showed 14.1%, 15.8% and 70.1% of power plants respectively as compatible, incompatible, and potentially compatible. For CSP energy the results were: 11.1%, 44.4% and 44.4%.

Several conclusions from Hernandez et al. (2015) are worthy of note: 1) siting solar power plants near natural reserves or habitats for endangered and threatened species can negatively impact the protected wildlife; 2) solar power plants, even in countries like the U.S. that have large areas of desert and bare land, tend to be located on *all kinds* of land cover, including agricultural land, dispersing the impacts through the territory; 3) solar PV plants may be installed in areas with slopes up to 45%, a criterion that expands areas for PV installations, namely in countries with many hilly, south-facing land plots, like Portugal. Installing PV plants over sloped terrain has, however consequences. As noted by Turney and Fthenakis (2011) about Spain this may lead to soil erosion connected to the disappearance or disturbance of the plant cover.

2.3.1. Social impacts and public opposition

The social implications and related conflicts due to the explosive growth of solar PV, especially in the last few years are now apparent in the general press as reported by Balaskovitz (2017), Bellini (2018a), Bellini (2018b), Bellini (2019a), Bellini (2019b), and Spiegel (2017).

For instance, Spiegel (2017) reports the social and political discussion around the conversion of agricultural land to land for solar plants in Connecticut, United States. Bellini (2019b) reports on the proliferation of large-scale PV plants in central Italy (tens to hundreds of MW, occupying thousands of hectares) and on the active opposition of "Italia Nostra", an environmental group claiming against the uncontrolled spread of PV plants on the regional territory "whose proliferation, due to the simplified authorization regime is generating important and widespread impacts on the landscape, which have attracted strong attention from local communities". At the same time, "Italia Solare", a solar energy industry association supports the development of large-scale projects arguing that "the majority of the country's commercial and industrial buildings are not suitable for solar and if Italy wants to hit ambitious renewable energy targets, rooftop PV may not be enough". They also claim that 53 GW of large-scale PV capacity by 2030 will occupy only 0.64% of Italy's agricultural land. These contradicting views about the trade-off between land for energy and land for agriculture (and other uses) will be further discussed in Section 2.4. Portugal is not immune to the social implications of large scale implementation of PV plants and the contradicting views on the subject, as discussed in Section 2.6.

2.3.2. Impact mitigation and co-benefits

The mitigation of the environmental impacts of solar power is addressed by several of the publications reviewed. One possible mitigation approach is the one proposed by Stoms et al. (2013): install solar energy power plants on sites that are the most ecologically degraded, i.e., with low conservation value.

The authors perform a GIS-based multicriteria assessment of a study area - the part of the American Semi-Desert and Desert Province that belongs to California - using a location-dependent metric they call Compatibility Index, where high compatibility is assigned to sites with low conservation value - what the authors call “no-regrets” areas. The study concludes that the areas with high Compatibility Index (over 0.7 in a 0 to 1 scale) are more than one order of magnitude higher than the area required to attain the 8.7 GW photovoltaic capacity target of the state of California by 2040. The authors use a decision tree with two quantitative top-level nodes expressing In-site degradation and Off-site impacts, which are averaged together to yield a value for the Compatibility Index. Off-site impacts measure the degradation of the places crossed by the grid-connecting power lines.

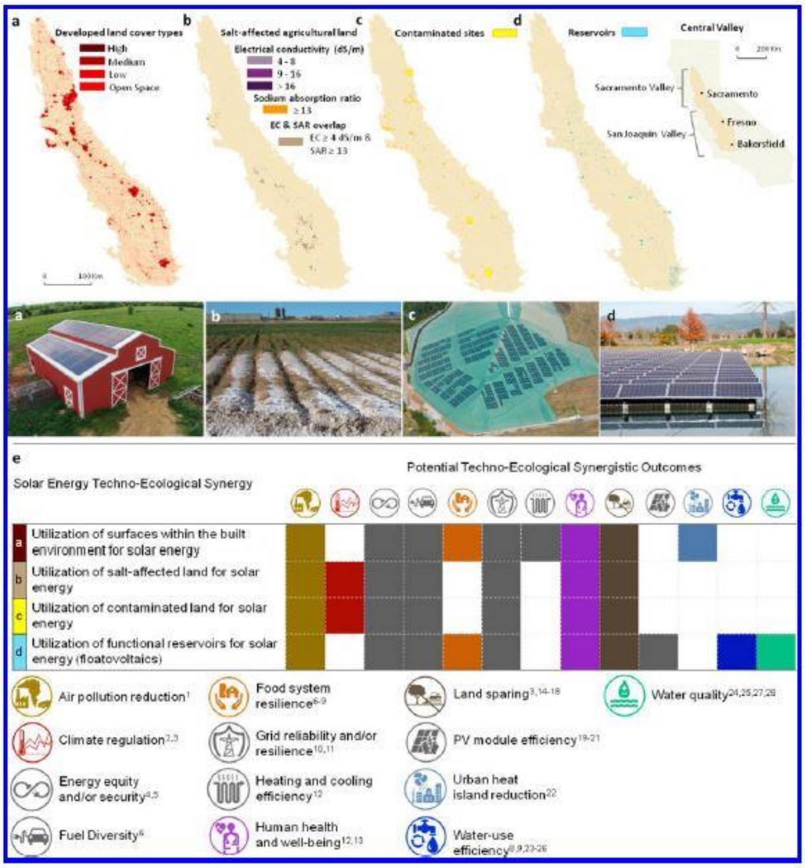


Figure 2.15 – Land types and potential techno-ecological outcomes (Hoffacker et al., 2017).

The assessment of In-site degradation involves several decision steps. First, their method starts by deciding about the recoverability of the soil (either from fire or from farming degradation), selecting the worst situation. A measure of soil recoverability is then compared with the results of permanently removing the vegetation cover (which PV plants usually cause), and again the worst situation is chosen, leading to a measure of Impacted Native Cover. This is checked against Fragmentation (a measure of habitat fragmentation) and the worst case is finally assigned to In-site degradation.

The authors explain their criteria to derive the various indicators leading to the index. For the fragmentation indicator, for instance, they use a weighted assessment of linear features in the geography: freeways and ramps, highways, major roads, local roads, other roads, pedestrian ways, railroads, power transmission lines, canals/aqueducts. It should be noted that the "no-regrets" areas are degraded natural lands, not brownfields or contaminated lands.

Mitigation of impacts through co-benefits can be achieved by siting solar plants over land already used for other purposes or using the land occupied for additional uses other than producing energy, as reported in Day (2018), Hoffacker et al., (2017), Mesa (2014), and Parker & Green (2014).

Hoffacker et al. (2017) present an evaluation of the land-sparing potential of solar energy developed on four non-conventional landcover types: built environment, salt-affected land, contaminated land, and water reservoirs. These are all located in the Great Central Valley of California, in their words "a globally significant agricultural region where land for food production, urban development, and conservation collide". The authors estimate the solar energy potential of the four land cover types using several metrics while discussing the qualifying assumptions and exclusions used in their GIS-based assessment. An example of exclusion from the study is prime salt-affected cropland that should be recovered for agriculture and not for energy generation. The utilization of degraded land for solar PV assumes in all cases that the land is recovered from its degraded state as part of the solar energy project. Figure 2.15 taken from Hoffacker et al. (2017) shows the overall maps of the four land cover types and their potential techno-ecological outcomes, as envisaged by the authors.

Parker & Green (2014) present the recommendations of the National Solar Centre created by BRE, a consultancy. Their report discusses opportunities to enhance wildlife habitats and generate co-benefits through grazing spaces for sheep within the fenced area of a PV plant. Their focus is on preserving or enhancing biodiversity in PV stations through natural and artificial features, including hedgerows, field margins, wild-flower meadows, pasture, pollen and nectar strips, wild bird seed mixes, woodland habitats, ponds, and water courses where possible, and artificial structures for wildlife use. Day (2018) presents the potential of combining beehives with solar PV systems for honey production and professional pollination services in many regions of the United States. And Meza (2014) describes a large scale, "ecological flagship" 25 MW PV project completed in Southern France by juwi (a German solar engineering company) supporting local wine growers, beekeepers, and sheep farmers.

Agrivoltaics is a fast developing field associating solar energy production and agriculture and an example of co-benefits between PV plants and agriculture, instead of a conflict between the two land uses.

Weselek et al. (2019) review the status and future trends of agrivoltaics (APV) remarking that the expansion of renewable energy requires large areas of land while at the same time food security is threatened by the impacts of climate change and a growing world population the two factors leading to increasing competition for limited land resources. APV systems combine solar panels placed over agricultural fields at a height of 4 to 5 meters, allowing farming machinery to work the plots. The authors review the current commercial and experimental APV facilities all over the world (not more than a dozen at the time) pointing out to the strong and weak points of the technology. A first, well established conclusion is that APV systems increase the productivity of the land through energy and crop production, although agricultural yields suffer a decline, which is acceptable by the farmers in the most successful experiences. The limitations in yield can be mitigated through technical means, namely by introducing sun tracking to orient the panels and increase the spacing between panel rows. Sun tracking can be adaptive: in one facility the PV panels orient themselves for maximum energy yield in the hours around mid-day (while shielding the crops from excessive sunlight in dry, hot days) and rotate to positions maximizing crop irradiation in the early morning and late afternoon.

Weselek et al. (2019) stress that APV can address land-use competition issues in the densely populated countries of central Europe and help to solve the "land for food or bioenergy" dilemma. And note important synergies of agrivoltaics in semi-arid or arid countries where crop cultivation often suffers from high solar radiation and water losses. APV has been demonstrated to increase water use efficiency underneath the panels and benefit crops by reducing excessive solar radiation. An additional synergy is that APV can support rural electrification enabling efficient irrigation and the use of electrical machinery, reducing fossil fuel emissions.

Interestingly, the authors comment on the perceived obstacles to APV development, namely in Germany where the uncontrolled expansion of ground mounted PV systems "has led to a diminishing acceptance within the population followed by legal restrictions concerning the construction of PV facilities". And remark that "although there is a clear call within society for the development of renewable energies, there is often a lack of social acceptance at local level, particularly when a loss of visual landscape quality, damage to cultural landscapes or consequences for the environment are feared".

2.4. Land Occupation by Solar Photovoltaic Plants

There is little comprehensive, detailed information about Portuguese PV power plants, especially concerning their land use intensity. The regulator authorities do not provide public access to project licensing files and the environmental impact assessments (which are public-domain information) are mandatory only for plants of 50 MW or higher capacity, still a small minority.

The research presented in this section had two objectives. The first was to calculate values for the capacity-based land use intensity (LUI) of utility-scale PV power plants in continental Portugal, i.e., those having one MW or higher installed capacity. The second was to estimate *future* land occupation by PV plants in continental Portugal considering future PV capacity additions as planned by the government (APA, 2019) and the likely improvements in PV panel efficiency.

A novel method, in which land occupation reflects, simultaneously, the evolution of PV capacity and PV panel efficiency, was developed for this purpose.

2.4.1. Data sources and methods

As discussed in Section 2.3 about Hernandez et al. (2014a) the *land-use intensity* (LUI) or land-use efficiency of a PV power plant is the ratio of the total land area it occupies to its installed power or energy delivered yearly to the grid, being commonly stated in hectare per megawatt of installed power (capacity-based LUI) or hectare per megawatt-hour of yearly delivered energy (generation-based LUI). The former may also be expressed as a "power density", in W_{DC}/m^2 or MW_{DC}/ha where the under scripted DC refers to a power in *direct current*, the electrical output of the solar panels before being converted to alternating current (AC) to be delivered to the grid.

Determining the capacity based LUI of PV plants in continental Portugal required knowing their total land areas, installed capacities, and ground mounting types (since the LUI depends on whether the panels are fixed or tracking the daily movement of the Sun). The information was obtained from two credible Portuguese sources, with the area measurements performed through satellite imagery. The first source was the "e2p" database of operating PV plants maintained by INEGI, a research institute, and APREN, an association of renewable energy suppliers (INEGI & APREN, 2019). It contains locations, installed capacities in MW_{DC}, administrative data (plant name, owner, developer, dates), and

Figure 2.16 – Measuring the "Ferreira do Alentejo" PV power plant (Távora et al., 2020).

in some cases technology details. The second source was the online GIS map and database maintained by DGEG (2020a). The database contains licensing information (plant name, owner, status, relevant dates) of *planned* and *operating* solar plants and in many cases station perimeters, although they rarely match the actual perimeters seen on satellite imagery. The sources also do not agree on the PV stations in operation in continental Portugal: "e2p" records 104 operating plants while DGEG's database records only 89 - while reporting a total of 221 stations, either planned or operating. Filtering "e2p" for 1 MW or higher capacity led to the selection of 78 plants, to which was added one station identified only in DGEG´s map.

By grouping contiguous stations when they corresponded to different phases of the same project, a set of 64 station perimeters was obtained, which were then inspected and measured using Google Earth Pro™, including its image timeline and Street View, where available. To confirm findings, all the information that could be found on the Internet about the PV stations (like press releases or project references in company sites) were also used. Regarding total land occupation the protection fences of the PV plants were identified, and their inner areas measured using the tools included in Google Earth Pro™. Areas occupied by grid connection infrastructure, like substations or power lines were left out.

Figure 2.16 illustrates the area measurement process. From perimeter area measurements and maximum DC power for each plant, their LUI was calculated. The values originated a global LUI distribution and separate distributions according to mounting type. Individual LUI values, $A_P(i)$, were calculated from $P_M(i)$ values taken from the "e2p" database and area measurements. Dividing the areas by installed capacities yielded $A_P(i)$ in hectare per MW_{DC}. Distributions for 46 fixed-arrays, 10 single-axis tracking, and 8 dual-axis tracking stations were obtained and will be discussed below.

2.4.2. Land-use intensity of PV power plants in continental Portugal

The distributions for LUI results, segregated by the mounting type of the sampled PV stations, are summarized in the box plots diagrams of Figure 2.17. All values shown are in hectare per megawatt of installed power (MW_{DC}).

The distribution for all stations (N=64) is not represented but can be summarized by 3.336, 2.989, 2.224, and 4.247, respectively its mean, median, Q1, and Q3 values.

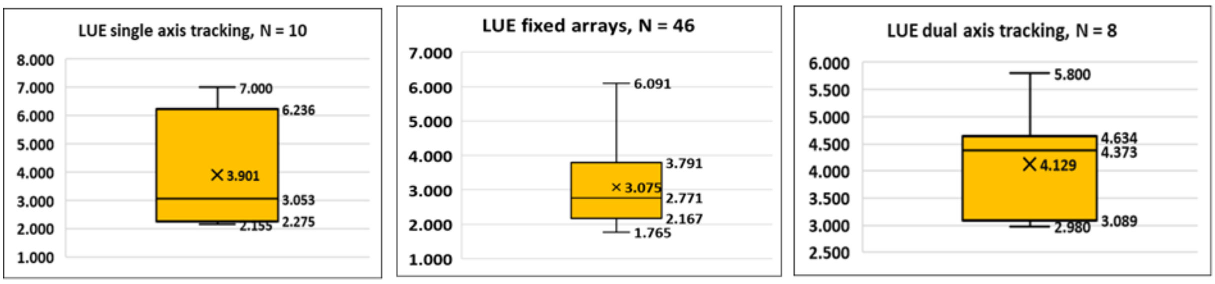


Figure 2.17 - LUI distributions for PV plants in continental Portugal (Távora et al., 2020).

2.4.3. A model for calculating future occupation areas

Future land occupation by PV stations can be derived by simultaneously integrating total installed power P_M and average land use intensity A_P, both dependent on time (Equation 1). Modelling time-dependency linearly yields Equation 2 where K_1 is the growth rate of P_M and M_a is a factor that relates the land use intensity A_P with K_2, the growth rate of the average PV panel efficiency (Equation 2). E_{f*}

represents E_f (the panel efficiency, usually defined as a percentage) in MW/hectare. With A_P measured in hectare/MW, the factor M_a becomes a unit less constant (Equation 3).

It should be noted that M_a represents an *area multiplier* yielding the total area of a PV station from the total area of its panels. An average value for M_a must be estimated, as described below.

$$A_T(t) = \iint dP_M dA_P \qquad (1)$$

$$A_T(t) = K_1\, M_a \int_{t_0}^{t} \frac{1}{E_f}\, dt = K_1\, M_a \int_{t_0}^{t} \left(\frac{1}{E_f(t_0)+K_2 t}\right) dt \qquad (2)$$

$$A_p = \frac{M_a}{E_f} \qquad (3)$$

Note also that the integral in Equation 2 lacks a term for the initial occupation, $A_T(t_0)$, the area at time t_0. Whether or not this area should be included depends on the time horizon of the projections. For time horizons of 30 or more years the land occupied by existing stations will be all taken by new stations or by other uses: the initial area should therefore be discarded. For time horizons shorter than 30 years (the usual lifetime of PV stations) the initial area should be partly included, depending on the age of the existing PV plants at time t_0.

Equation 2 can be used with piecewise linear approximations of $P_M(t)$ and $E_f(t)$: the time integral is then expressed as a sum, e.g., with intervals from 2020 to 2030, from 2030 to 2040, etc.

2.4.4. Estimating the value of Ma

The area multiplier M_a can be calculated from Equation 3 by estimating a value for E_{f*}. As this is the average PV panel efficiency (in MW/hectare) of all the stations used to calculate the LUI, one possible approach is to assume for each station a panel efficiency *consistent with the year it started operation*. We therefore selected fixed-arrays stations for which the operation starting year was known (43, in total) and assumed that they were equipped with mono-Si or poly-Si panels having the compound efficiency reported in ISE (2020). (The value for 2019 was extrapolated.) The results are shown in Table 2.3. Computing a weighted-average value for E_f (with the number of stations as weights), converting to obtain E_{f*} in MW/ha, and multiplying E_{f*} by the average A_P for fixed-arrays stations (Cf. Section 2.4.2) yields the estimate for M_a. Table 2.4 illustrates the calculation.

Table 2.3 – Estimated PV efficiencies for PV plants in continental Portugal

Year	No. PV stations	E_f (%)	E_f (weighted average, %)
2008	1	14.4	
2009	2	14.5	
2010	3	14.8	
2011	1	14.9	
2012	3	15.0	
2013	4	15.3	
2014	15	15.6	
2015	5	15.8	
2016	1	16.3	
2017	3	16.8	
2018	4	17.3	
2019	1	18.5	
			15.7

Table 2.4 - Calculating the value of Ma

A_p (ha/MW)	E_{f*} (MW/ha)	M_a
3.075	1.57	4.83

2.4.5. Future occupation area

PV land occupation in 2050 in continental Portugal was estimated using Equation 2 with two power demand scenarios for utility-scale or "centralized" solar energy, defined in the Portuguese official roadmap to carbon neutrality (APA, 2019).

P_M values at the end of each decade until 2050 were calculated using the average PV output for continental Portugal found in Huld (2014). Fixed-arrays PV stations were assumed to be dominant. PV capacity in 2020 was set equal to 0.9 GW (DGEG, 2019a). Average panel efficiency for this simulation was assumed to increase linearly from 20% in 2020 to 24%, 28%, and 32% at the end of each decade until 2050.

Table 2.5 shows the two PV electricity scenarios, with the demand values in GWh at the end of each decade (APA, 2019) and the corresponding installed capacities required by the PV output defined in Huld (2014).

Table 2.5 - Demand scenarios in the Portuguese roadmap to carbon neutrality (APA, 2019).

Scenarios	Years	Demand [TWh]	P_M [GW_{DC}]
“Peloton” (PL)	2030	12.8	8.2
	2040	21.4	13.7
	2050	25.8	16.5
“Yellow Jersey” (YJ)	2030	9	5.8
	2040	17.7	11.3
	2050	24.7	15.8

Table 2.6 presents K_1 and K_2 - linear growth rates of installed power and efficiency, respectively - calculated for each decade in the two scenarios. Together with M_a they form the set of parameters required by Equation 2. The table also shows the partial and total results of the simulation: land areas occupied by PV plants at the end of each decade, and in the year 2050.

Table 2.6 - Growth parameters and land occupation results for the two demand scenarios.

Years	K_1 [MW_{DC}/year]	K_2 [MW/ha/year]	A_T [hectare]
2020-’30	730	0.04	16 071
2030-’40	550	0.04	10 238
2040-’50	280	0.04	4 516
Total PL			30 825
2020-’30	490	0.04	10 988
2030-’40	550	0.04	10 429
2040-’50	450	0.04	7 393
Total YJ			28 810

2.4.6. Related work

The land use intensity of PV power plants has been addressed before: for the United States by Hernandez et al. (2014a) and Ong et al. (2013); and for Canada by Calvert (2018) and Denholm & Margolis (2008).

Hernandez et al. (2014a), already introduced in Section 2.3 calculated the capacity-based LUI in W/m^2 of 183 utility-scale solar plants in California, comprising PV and CSP plants with capacities ranging from 20 to 200 MW. Their information sources were public-domain and official documents, only. The calculation used the reported nominal capacities of each plant and the total area occupied by each facility, whether in operation or not. PV power plants (n= 171) had an average LUI of 35 W/m^2, which reported inversely corresponds to 2.86 ha/MW.

Ong et al (2013) determined the LUI of 192 utility-scale PV plants (i.e., with 1 MW_{DC} or higher capacity) located in the United States in 2012, having used multiple data sources including satellite imagery. The power plants were either completed, under construction, or simply planned. The plants were classified according to their ground mounting type (*fixed-tilt*, *1-axis tracking*, and *2-axis tracking*) and their results include capacity-based and generation-based LUI values, separately for "small" (< 20 MW_{DC}) and "large" (> 20 MW_{DC}) power plants. The authors present their results in acres/MW_{AC}. Considering only capacity-based LUI results, converting acres to hectares, and derating DC to AC using the 0.85 factor suggested by the authors, their values in ha/MW_{DC} range from 2.61 to 2.58; 2.99 to 2.86; and 3.13 to 2.79, for fixed-tilt, 1-axis tracking, and 2-axis tracking, respectively. The higher values on the ranges – meaning more land is occupied by power unit – belong to the PV plants with less than 20 MW_{DC} capacity. Importantly, Ong et al. (2013) differentiate between *direct land area* and *total land area* when calculating the LUI. Total land area means all the land enclosed by the facility as in Hernandez et al. (2014a). Only the total-area LUI values by Ong et al. (2013) were reported, for comparison purposes.

Calvert (2018) determined the LUI of 95 photovoltaic plants under various stages of construction at the Canadian province of Ontario, finding values for capacity based LUI ranging from 2.31 to 15.40 ha/MW_{DC}, with 5.11 ha/MW_{DC} as average value. Calvert (2018) argues that future improvements in the efficiency of PV panels and their *packing* inside the plant enclosures will lead to lower land use intensities.

Martin-Chívelet (2016) presents a formal, consistent approach to the land use intensity of photovoltaic plants by relating the total PV *panel area* to the area they occupy on the ground when spaced to prevent inter-shading. Summing the total area *projected by the panels on the ground* with the total *inter-panel area* yields what the author calls the *generator area*. This generator depends on the design of the PV station, being a function of the *tilt* or *slope* angle of the panels relative to the ground plane and of the height and azimuth (orientation) of the Sun, particularly when the shade projected by the panels is maximum. Thus, depending on station design the panels could be spaced, for instance, so that from 9:00 am until 3:00 pm on 21 or 22 December, when winter solstice occurs, the inter-shading between panels is minimized or absent.

Martin-Chívelet (2016) defines *packing factor* (PF) as the ratio between the total (unprojected) panel area and the generator area, as defined above. And *ground to station ratio* (GSR) (or ground to "suitable land" ratio) as the quotient between the generator area and the total station area. GSR values depend on multiple factors, like terrain shapes and slopes or the presence of rocks or protected trees and must be determined experimentally for each PV plant or a set of PV plants.

The land occupied by PV power plants in hypothetical or future scenarios where solar energy becomes predominant is addressed by Calvert (2018), Denholm & Margolis (2008), and WWF (2012).

Denholm e Margolis (2008) consider what-if scenarios where all the electricity consumed in the U.S. in 2006 is provided by PV solar energy and calculate, state-by-state, what they call *solar footprints*. One of them, the *existing demand* footprint is obtained dividing the yearly electricity consumption per capita by the *PV energy density* in kWh/m^2 that could be obtained per year from a unit area of land. The PV energy density varies with the insolation of each state, of course. Their results for this solar footprint ranged from 50 m2 to 450 m2 per capita, depending on the state.

In one of their simulations, Denholm e Margolis (2008) calculate the hypothetical land occupation by PV plants at state and national level considering a mix of PV sources with 13.5% average efficiency. The mix would have 25% of rooftop systems, 40% of ground-mounted stations, and 35% of solar-tracking ground-mounted stations. Land use intensity be 50 to 70 W/m^2, a figure obtained by the authors from industry partners. The results of the simulation show that PV power plants would occupy at national level an area of about *0.6% of the whole US area*. In their article, the authors also compare, state-by-state, the per capita *existing-demand* solar footprints with per capita areas for other land uses, like agriculture, forestry, industry, airports, golf courses, etc.

The Photovoltaic Solar Atlas of the World Wildlife Fund (WWF, 2012) promotes the adoption of PV solar energy in developing countries, with worked examples for Indonesia, Madagascar, the Madhya Pradesh state of India, Morocco, South Africa, and Turkey. For each of the countries and the Indian state the authors estimate land areas required for 100% of PV electric energy in 2050, concluding that they are in all cases less than 1% of the national land areas. And much smaller than the areas of their protected natural zones leading the WWF to assert the compatibility between renewable energies and environmental protection. The simulations take the worldwide forecast consumption of electricity in 2050 (35,400 terawatt-hour per year) and divide it by the forecast population (9,191 million people) obtaining an average per capita consumption of 3,850 kWh per year. This value is multiplied by the demographic projection for the inhabitants of each region in 2050. The calculation assumes a 15% PV panel efficiency - a conservative estimate - and a LUI obtained by multiplying the panel area by 1.2. WWF (2012) projects future PV land occupation but their calculation yields values *for* 2050. It does not account for the *build-up* in occupied areas that will occur from now *until* 2050.

Calvert (2018) estimates the land occupation by PV plants in Ontario in case they provided all *present-day* electricity demand *plus* the requirements of a fleet of electric vehicles (EV); and how the occupation would impact agriculture by changing land use to energy production. The author considers two capacity scenarios: 21.16 GW and 25.82 GW (excluding or including the EV fleet); several PV technologies with different efficiencies; and values for a “packing factor” taken from an empirical analysis of the PV plants in Ontario. For crystalline silicon panels with 25% efficiency and an average packing factor of 0.22 the share of agricultural area occupied by PV plants would range from 1.5% to 3.3%. This range would go down to 0.8% to 1.8% for the maximum packing factor found in the empirical analysis: 0.41.

Note that the packing factor of Calvert (2108) is different from PF, the packing factor defined by Martin-Chívelet (2016). For Calvert (2018) the packing factor is simply the ratio between total PV panel area and total PV plant area. This makes it correspond to the *reciprocal* of the area multiplier M_a defined in this thesis. Converting the 0.22 and 0.41 empirical values of Calvert (2018) yields M_a values of 4.5 and 2.4, respectively.

Concerning land use intensity, the research presented in this thesis is close to the works of Ong et al. (2013), Hernandez et al. (2014a) and Calvert (2018) although bringing new, empirical results for a European country.

The future occupation of land by PV plants is addressed by Calvert (2018), Denholm & Margolis, and WWF (2012), as discussed before. However, the research presented in Section 2.4.3 to Section 2.4.5 is arguably more effective at modelling future PV land occupation. For instance, Calvert (2018) stresses that future PV occupation will depend on the improvement in panel efficiencies but provides only static equations to calculate future LUI and total areas. But PV power plants have lifetimes of 30 years and any future land occupation within this time interval will have contributions from power plants with *different* conversion efficiencies. This dynamic is captured by the integral equations of Section 2.4.3, which express a piece-wise linear model for PV land occupation based on the concurrent time dependence of both installed capacity and panel efficiency.

2.4.7. Discussion

The average LUI for *all* utility-scale PV power plants in continental Portugal reported in Section 2.4.2 (3.336 ha/MW_{DC}) is higher than the corresponding value by Hernandez at al. (2014a) for PV plants in California (2.857 ha/MW_{DC}). A comparison between the average LUI of fixed-arrays, single-axis, and dual-axis tracking PV plants in continental Portugal, respectively 3.075, 3.901, and 4.129 ha/MW_{DC} with the corresponding values found by Ong et al. (2013) for power plants of less than 20 MW in California (2.61, 2.86, and 3.13 ha/MW_{DC}) indicates again higher values for Portugal, although there is consistency for the LUI according with mounting types. The values are not comparable, though, since solar irradiation is different in both regions.

Regarding future land occupation by solar PV, the areas reported in Section 2.4.5 for 2050 are *quite large*. Considering for instance 30,000 hectares and comparing with the areas given by Caetano et al. (2018) solar PV occupation would correspond to about 80% of the area currently taken by roads and railroads. And to 26 % of the *urban growth* in the twenty years between 1995 and 2015. However, when compared with land uses, an area of 30,000 hectares is comparatively small: 1.3% and 0.9% of the areas occupied by agriculture and forestry, respectively. An area of 30,000 hectares is only 0.3% of the area of continental Portugal.

These figures show that the main issue regarding future PV land occupation in continental Portugal lies not in its *total area* but *where and how* the area will be distributed. The installation of power plants occurs in areas with access roads, near high voltage lines, where there is land to buy or lease for long periods, where there is good irradiation, and where adapting the field will costs less (flat agricultural land). The *distribution* of solar PV occupation at high penetration rates will not be uniform. This leaves plenty of opportunity for land-use conflicts and deep landscape alterations, especially in the countryside.

It should be noted that the cumulative installed capacity in 2050 *may be higher* than the value planned by APA (2019) since Portugal is very rich in solar resources and may become an important exporter of solar electricity. Also, the planned capacity in *decentralized* solar PV in 2050 - with about the same value as centralized solar PV (APA, 2019) - may not materialize for several reasons. This could lead to an increase in centralized solar PV with the corresponding increase in non-urban occupation. Future capacity additions to produce green hydrogen could likewise increase PV land occupation beyond the current estimates. On the other hand, unexpected breakthroughs in the efficiency of PV technologies could reduce land occupation in the future.

2.4.8. Further research

Estimating M_a only from presumed panel efficiencies like was done in Section 2.4.4 is a limitation of the research on future land occupation. A more accurate value for M_a must be found by measuring areas *inside* each fenced enclosure of the PV plants. The measures can then be used to calculate distributions for GSR (the ground to station ratio) and PF (the packing factor, equal to panel area over generator area) as described in Section 2.4.6 about Martin-Chívelet (2016).

Multiplying GSR by PF for each station yields a value for the fraction of the total station area represented by the total area of the PV panels. The reciprocal of this value is the area multiplier, M_a.

At the time of writing these measurements were already performed for 41 fixed-arrays PV stations in continental Portugal but only a very preliminary result can be given: the measurements must be repeated, performed on stations of the other mounting types, and subjected to measurement error analysis. The result point to an average value of M_a clearly lower than the estimation of Section 2.4.4 (M_a = 4.83). A likely average value for the measured area multiplier will be (M_a = 4.0) with considerable variation between a minimum of about 2.4 and a maximum of 7.6. The new value will lead to reductions in future PV occupation areas. The new calculation will be part of future research together with a sensitivity analysis considering variations in the parameters of the integral model of Section 2.4.3.

The values for the area multiplier M_a are ultimately the result of options taken by PV plant promoters, which will tend to use land as efficiently as possible. However, note that the area multiplier may also be seen as a *design parameter*. For instance, due to future environmental restrictions on land occupation by solar PV there may be regulation imposing that only a fraction of the total station area can be covered with panels. (Similar restrictions occur, for other reasons, in the construction of residential buildings.) The fractional area allowed – although it may refer to the area projected on the ground by the panels - can be related with M_a and the equations of Section 2.4.3 used to *plan solar PV occupation* on a regional or national basis.

The work described in Section 2.4 was the subject of a paper and poster presentation at the EU PVSEC 2020, 37th European Photovoltaic Solar Energy Conference and Exhibition (Távora et al., 2020). Both documents are reprinted in Appendix A1.

2.5. Solar Photovoltaic Emissions and Returns on Energy and Carbon

The research presented in this section examines the benefits of solar PV energy in the mitigation of global warming, which may be achieved by replacing electricity derived from high emission sources like fossil fuels by solar PV power plants. The work involves the determination of *emission metrics* for solar PV systems including, when applicable both the contribution of primary, technology related emissions and secondary, environment related emissions. It also involves the determination of *energy metrics* proving that solar PV systems, while involving in their creation an expenditure of energy will give back energy in much higher quantity than was needed to create them.

While energy metrics are not dependent on the type of PV system (rooftop, building integrated, or ground mounted) emission metrics also depend, in the case of ground-mounted systems *on the land* affected by its installation. The research focuses on ground-mounted systems installed over fields with vegetation, whether wild or cultivated for agriculture or forestry. These fields occur mostly in rural land but can also be found in green spaces in urban areas, like parks and gardens.

Emissions from PV systems can be divided in *primary* and *secondary*. Primary emissions are linked to the GHG released during the lifecycle of a PV system. As already mentioned in Section 2.3 those emissions will occur mostly during the manufacturing of main components of the system: PV panels, mounting hardware, cabling, and the DC-AC inverters. Secondary emissions are GHG emissions from land use change, including emissions from the vegetation cut down, from soil degradation, and from emissions *that would be avoided* if the land maintained its vegetation and acted as a carbon sink.

Both energy and emissions metrics depend on the solar irradiation of the place. The energy expended and the emissions released to manufacture the PV systems will be divided by the total energy they will produce during their lifetimes. A place with high yearly irradiation will lead to "better" energy and emission metrics.

The research opted for a geographical approach covering the continental part of Portugal. Therefore, the metrics vary with geographical coordinates leading to 'metric maps' of continental Portugal.

When looking to the secondary emissions, the approach was to exclude parts of the territory: *settled* areas (urban or semi-urban zones, infrastructure) and inland water bodies, wetlands, and the coastal sea. The focus was on wild or natural areas, agricultural land, and forested land. The purpose was to include only zones where the plant cover might be affected by the installation of power PV plants and reflect the impact in the emissions metrics.

The analysis was centered on three PV technologies marketed by best-of-breed manufacturers: *crystalline silicon* (monocrystalline silicon, also designated by mono-Si or m-Si), *cadmium selenide* (CdTe), and *copper indium selenide* (CIS).

The spatial-referenced metrics calculated were the *Carbon Footprint* (also called Carbon Intensity); the *Energy Payback Time - EPBT*; the *Carbon Payback* Time (also called *Emissions Payback Time)*; the *Energy Return on (Energy) Invested - EROI*; and the *Net to Gross Energy Ratio - NTG*.

The metrics are then used to illustrate the *return on the energy* invested in manufacturing and operating a PV power plants and, importantly, the *return on carbon emissions*, which must be compensated by the *savings in carbon emissions* offered by the PV plant during its lifetime.

2.5.1. Data sources and methods

The metrics were calculated from core data found in LCA studies, largely in Leccisi et al. (2016) combined with geographical land use information; PV technology data; and geographical solar irradiation and PV performance data. The process followed the LCA and LCIA (Lifecycle Impact Assessment) methodologies presented by Frischknecht et al. (2016).

The *system boundary* was defined around the *product stage* of PV systems (raw material and energy supply), which includes the manufacture of PV panels, mounting system, cabling, and inverters. No energy storage devices e.g., batteries were considered. The system boundary is the same used by Leccisi et al. (2016) and De Wild-Scholten (2013) enabling the use of their data.

The *functional unit* is the alternating current (AC) electrical output supplied by the inverters to the electrical grid or to intermediate transformers, which were considered as being *outside* the system boundary.

The study considers only *fixed-arrays* PV systems with the PV panels oriented towards South (*zero azimuth*) at an *optimum slope* angle. (The optimum slope was determined by the solar PV geographic information system mentioned below.)

The three PV technologies - mono-crystalline silicon (m-Si), Cadmium Telluride (CdTe), and Copper Indium Selenide (CIS) - were represented by recent, high-performance products by their main manufacturers. The calculations used technical characteristics from the product datasheets and included *rated power*, *panel size*, *panel efficiency*, and *degradation rate*. The latter was unavailable in the CIS datasheet and was taken from De Wild-Scholten (2013). A 30-year lifetime was assumed for all PV system components. (This involved a simplification; inverters are usually replaced after 15 years.)

For the geographical approach the work used the TerrSet Version 18.31 geographic information system (GIS) and the *on-line non-interactive* service of the PVGIS European geographic photovoltaic system (PVGIS, 2020), together with worksheets and external software programs developed in the Python programming language by the author.

The average yearly *solar irradiation* (in kWh/m^2.year^{-1}) was read from PVGIS using its PVGIS-SARAH solar radiation database. The irradiation was sampled at 3,751 geographical locations in a regular grid covering continental Portugal with a resolution of about 5.5 km.

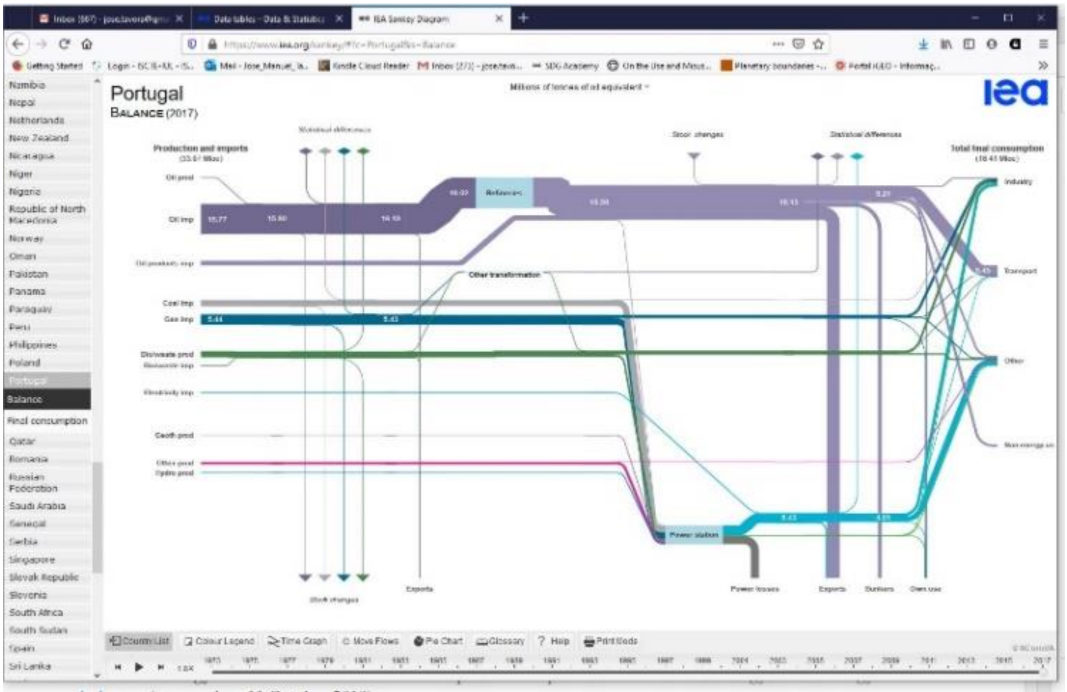


Figure 2.18 - Sankey diagram of the Portuguese energy balance for 2017 (IEA, 2020).

The *performance factor* of the PV systems – defined as the quotient between its actual electrical output per unit area per year and the average yearly irradiation falling on the unit area of the panels times their efficiency - was *not* considered fixed, e.g., equal to 80% for ground-mounted systems. Instead, several types of solar energy *losses* were introduced in the calculations: 1) *panel losses*, read from PVGIS due to panel inclination, irradiation spectrum (CIS data unavailable), and temperature and low irradiation; 2) average lifetime *degradation loss*es, calculated from datasheet values; 3) other *system losses* (panel mismatch, cabling, inverters) were included as a 4% *constant*.

The efficiency of the electricity grid η_G (or its inverse, the Primary Energy Factor - PEF) is the ratio between the *electrical output* delivered to final users by the power stations of a country or region and the *primary energy* needed to deliver that output (e.g., in the form of fossil fuels). With electricity generation depending on fossil fuels η_G can be low (e.g., η_G = 0.3 equivalent to PEF = 3.33). However, Portugal has a relatively high share of renewable energies in electricity generation, and therefore it became necessary to determine a value for η_G consistent with that reality.

As no publications could be found with a Portuguese value for η_G the work resorted to the energy balances reported yearly by the IEA (International Energy Association) in the form of Sankey diagrams (IEA, 2020). By inspecting the input and output values of the *power station* node in the diagrams, stated in *oil-equivalent energy units* from 2013 to the last reported year, 2017 and averaging the values, the Portuguese grid efficiency was found to be η_G = 0.52 (PEF = 1.92). Imports of electricity were also considered but due to their small share the current European standard PEF = 2.5 was used instead (COGEN, 2018). Figure 2.18 shows the Sankey diagram of the Portuguese energy balance for 2017. Table A3.2 in Appendix A3 illustrates the calculation of the efficiency of the Portuguese electrical grid.

2.5.2. Energy Payback Time

The Energy Payback Time - EPBT can be calculated using Equation 4, below.

$$EPBT = \frac{E_{mat}+E_{manuf}}{\frac{E_{agen}}{\eta_G}} \quad (4)$$

The EPBT is the number of years a PV system takes to generate the same amount of energy that was used to create and operate the system, with both amounts expressed as *primary energy*. Using the defined system boundary only the energies associated with materials and manufacturing are included in the numerator, respectively E_{mat} and E_{manuf}. In the denominator E_{agen} is the *yearly* average energy delivered by the system during its lifetime and η_G the energy efficiency of the grid, as discussed. Primary energies are usually measured in megajoule. For the calculations, the values in the numerator were obtained for each technology from Leccisi et al. (2016) in joule per kilowatt of PV panel power, being then calculated per meter squared (m^2) using panel size information.

2.5.3. EROI and NTG

The Energy Return On (Energy) Invested – EROI is the ratio between the amount of energy *returned to society* as a useful energy carrier (e.g., electricity) by a chain of processes exploiting a primary energy source (e.g., the sun) to the total energy *invested* in finding, extracting, processing, and delivering that energy (Raugei et al., 2016).

For PV systems and expressing both numerator and denominator as primary energy it can be calculated from Equation 5,

$$EROI_{PE-eq} = \frac{OUT_{PE-eq}}{INV} \quad (5)$$

where $OUT_{PE\text{-}eq}$ is the (primary) energy returned to society from exploiting solar energy and INV is the energy *diverted from other social uses and invested* in implementing the PV system. When expressed in primary energy INV is equivalent to (E_{mat} + E_{manuf}) and since E_{gen} is equal to E_{agen} multiplied by the lifetime LT, the EROI and the EPBT indicators for the same PV system are related by Equation 6.

$$EROI_{PE-eq} = \frac{\frac{E_{agen}}{\eta_G} * LT}{(E_{mat} + E_{manuf})} = \frac{LT}{EPBT} \quad (6)$$

Since the *net energy* returned to society in the EROI definition is equal to ($OUT_{PE\text{-}eq}$ – INV) a Net to Gross Energy Ratio – NTG can also be defined by Equation 7.

$$NTG = \frac{OUT_{PE-eq} - INV}{OUT_{PE-eq}} = \frac{EROI_{PE-eq} - 1}{EROI_{PE-eq}} \quad (7)$$

When the values of energy returned to society are near the values of energy invested (which were diverted from other societal uses) NTG approaches zero, meaning there are no gains to society from the energy transformation process. Thus, EROI must be much higher than unity to ensure that an energy technology returns to society a high net share of the *gross primary energy* that is being exploiting.

2.5.4. Carbon Footprint

The Carbon Footprint - CFT of a PV system, also called Carbon Intensity (per unit of electric output) or GHG Emissions Rate, can be calculated from Equation 8.

$$CFT = \frac{CC_{mat} + CC_{manuf}}{E_{gen}} \quad (8)$$

In the equation, CC_{mat}, and CC_{manuf} represent the *climate change impacts* of the activities to obtain the materials and manufacture the system components, measured for instance in kilograms of CO_2e per unit of peak power delivered by the system (kg CO_2e/kW_p). As in previous equations, E_{gen} is the energy delivered during the system lifetime measured e.g., in kWh.

The values in the numerator are obtained from Leccisi et al. (2016) per kilowatt of panel peak power for each technology, which were then converted to m^2 using panel size information. The quantities of the several emitted greenhouse gases can be expressed by their carbon dioxide equivalent (CO_2e).

The Carbon Footprint represents the quantity of greenhouse gases emitted by a PV system or product per unit of delivered *electric energy* - the functional unit of any electric power producing system. For PV systems, it is usually expressed in gCO_2e/kWh (grams of carbon dioxide equivalent greenhouse gas per kilowatt-hour).

The carbon footprint indicator measures the quantity of greenhouse gases - integrated over a 100-year period and expressed in CO_2 equivalent (CO_2e) units - that are released by the system per unit of delivered electrical energy.

2.5.5. Carbon Payback Time

The Carbon Payback Time – CPT, also called Emissions Payback Time, is the number of years a PV system takes *to save or avoid* the same quantity of emissions that was involved in the creation and operation of the system. The metric is analogous to the Energy Payback Time but in this case the *return to society* takes the form of avoided or saved emissions. Saving or avoiding GHG emissions mean replacing energy systems that pollute *more or much more* than the PV system replacing them.

The Carbon Payback Time can be calculated from Equation 9,

$$CPT = \frac{CC_{mat}+CC_{manuf}}{\frac{CC_{avoided\,LT}}{LT}} \qquad (9)$$

where the numerator represents the climate change impacts as in Equation 8 and in the denominator $CC_{avoidedLT}$ represents the emissions avoided or saved during the system lifetime.

The carbon intensity of the Portuguese electricity grid in gCO_2e/kWh reported by DGEG (2020) was used to calculate values of the Carbon Payback Time for continental Portugal. The calculations were done for primary emissions and for primary *and* secondary emissions, as explained in Sections 2.5.7 and 2.5.9.

2.5.6. Including time in GHG emissions

The timing of GHG emissions from an energy system influences its global warming effect as discussed by CARBON TRUST (2008), Levasseur et al. (2010), and Kendall (2012). Compared with an emission occurring at t_0 an emission happening t years in the future will stay in the atmosphere t years less at the end of a *time horizon* considered for analysis.

The method of Time Adjusted Warming Potentials (TAWP) developed by Kendall (2012) offers a practical way to include emissions timing in global warming calculations by defining coefficients - the TAWP - that adjust all later emissions so that they can be compared at time t_0. The method is based on Equation 10, where AT is the analytical time horizon and RF_i and RF_{CO2} are, respectively the *radiative forcing* factors (Forster et al., 2007) for greenhouse gas i and CO2, the reference gas. The values given by Equation 10 can be approximated by polynomial regressions or calculated from a worksheet supplied by Kendall (2012).

The work described in this section used several values for the time horizon and both the worksheet and polynomial tools by Kendall (2012). The results were also compared with those given the PAS 2050 standard described in CARBON TRUST (2008). The greenhouse gas included in the calculations was CO_2 only, since the conversion to CO_2e had been previously performed by the LCA studies providing data for the research.

$$TAWP\ (t) = \frac{\int_0^{AT-t} RF_i(t)dt}{\int_0^{AT} RF_{CO2}(t)dt} \qquad (10)$$

2.5.7. Results for the energy and primary emission metrics

The results for the emission and energy metrics presented in Sections 2.5.2 to 2.5.5 were obtained through a combination of: 1) *constant* values derived from technical characteristics of the PV technologies and assumptions about the PV systems, including energy and emissions; 2) *location-dependent* values expressed in quantitative maps of continental Portugal.

Table 2.7 shows the values for each PV technology. The product references correspond to PV modules, the energy generating elements in the PV systems. But the values for emissions and energy include the contributions of the other components (mounting hardware, inverters, etc.). Three values in the table are presented as *factors* associated with energy losses and used to reduce the system output from its energy input. *Efficiency* and *Degradation* of output depend on the technical characteristics of the panels. *System losses* are linked mostly to the cables and inverters and were estimated and set to the same value in all technologies (4%). All energy and emissions data were read from Leccisi et al. (2016).

The value for the degradation of the CIS panel was read from De Wild-Scholten (2013) since it was not specified by the manufacturer. The maps of the location-dependent values are shown in Figures A3.1 to A3.6 in Appendix A3. The yearly irradiation map of Figure A3.8 in Appendix A3 is the primary energy input for the calculations. The map with values in $kWh/m^2.year^{-1}$ was built by querying the PVGIS system by means of an external program. The maps of the total panel-related losses, shown in Figure A3.9 in Appendix A3 were also built using values also read from PVGIS, in the same querying operation as for the irradiation map. The thin stripes seen in the figures are most likely PVGIS errors, to be reported to their responsible staff. To build the final maps for the energy and emissions metrics all factors mentioned before were transformed into maps, which were then combined the irradiation and error maps in the TerrSet Geographic Information System (GIS) using map algebra.

Table 2.7 – Technology data and parameters (mono-Si, CdTe, CIS).

Technology	Country of origin	Manufacturer	Reference	Peak capacity @ STC (Wp)	Panel area (m2)	Power density (W/m2)	Efficiency (%)	Efficiency factor	Area per kWp (m2)	Degradation lifetime avg. (%)	Degradation factor	Emissions (kg CO2e/kWp)	Emissions (kg CO2e/m2)	Energy mat. fab. (MJ/kWp)	Energy mat. fab. (MJ/m2)	Other losses factor
Mono-Si	China	Jinko Solar	Cheetah HC60M Mono PERC 60 half-cell JKM345M-60H	345	1.6874	204.4604	20.45	0.2045	4.96	9.89	0.9011	1980	398.96	26500	5339.68	0.96
CdTe	USA	First Solar	Series 6 FS-6450	450	2.4751	181.8117	18.18	0.1818	5.50	8.2	0.9180	650	118.18	10500	1909.02	0.96
CIS	Japan	Solar Frontier	SFK185-S (CIS utility)	144	1.2281	117.2553	11.73	0.1173	8.53	0.3	0.997	1050	123.12	17600	2063.69	0.96

The maps for EPBT, Carbon Footprint, CPT, EROI, and NTG for the three technologies are shown in Figures A3.2 to A3.6 in Appendix A3. Figure A3.1 also in Appendix A3 illustrates the *energy yield* for each technology – their average energy output in $kWh/m^2.year^{-1}$.

Table 2.8 presents the minimum, mean, and maximum values of the distributions read from their histograms. All metrics except the Carbon Payback Time have values comparable to those found by De Wild-Sholten (2013) and Leccisi et al. (2016), despite some differences. (The Carbon Payback Time is not calculated by these authors.)

The average EPBT found by Leccisi et al. (2016) for the 1,700 kWh/m2 standard irradiation of Southern is 1.6, 0.6, and 1.1 years, respectively for the mono-Si, CdTe, and CIS technologies. These values are clearly better than those in Table 2.8 - even with most of continental Portugal having irradiations higher than 1700 kWh/m2. The reason lies in the value of the grid efficiency used by Leccisi et al. (2016), η_G =30, which is much lower than the value found for the Portuguese grid (η_G = 0.52). A lower grid efficiency “improves” the energy metrics.

Regarding the average Carbon Footprint (which is independent of grid efficiency) Leccisi et al. (2016) find 48, 15, and 26 gCO2e/kWh, respectively for mono-Si, CdTe, and CIS. These values are a little higher than those in Table 2.8, which is consistent with higher irradiation values.

The results by De Wild-Scholten (2013), which use $\eta_G = 0.315$ show the same pattern: better values for EPBT and worse for the Carbon Footprint. For EPBT, the author reports 2.34, 0.68, and 1.02 years; for Carbon Footprint, 81.2, 15.8, 27.6 gCO_2e/kWh.

Table 2.8 – Results for the energy and emission metrics

Metric/Indicator	Crystaline Silicon (mono-Si)			Cadmium Telluride (CdTe)			Copper Indium Selenide (CIS)		
	Min	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max
EPBT - Energy Payback Time (years)	2.16	**2.45**	3.15	0.84	**0.94**	1.23	1.34	**1.52**	1.95
Carbon Footprint (gCO2e/kWh)	37.0	**42.1**	54.2	11.9	**13.5**	17.5	18.4	**20.9**	26.7
PBTE - Emissions Payback Time (years)	9.90	**11.28**	14.52	2.94	**3.34**	4.3	3.07	**3.48**	4.48
EROI - Energy Return On (Energy) Invested	9.90	**12.27**	13.92	24.50	**31.86**	35.87	15.32	**19.78**	22.36
NTG - Net to Gross Energy Ratio	0.892	**0.918**	0.928	0.959	**0.968**	0.972	0.936	**0.949**	0.955
System yield - yearly average over lifetime (kWh/m2.y-1)	245	**316**	360	230	**294**	331	154	**197**	223

The EROI and the NTG metrics are related with the EPBT so the comments about the former metrics are like those about the EPBT.

The values found for the Carbon Payback Time (called Emissions Payback Time in Table 2.8) are a matter of concern: in the case of mono-Si (the predominant technology) the Carbon Payback Time ranges from 10 to over 14 years. This means that *for one third to almost half of their lifetimes*, monocrystalline PV systems installed now *do not avoid or save* GHG emissions. This is the result of two factors: 1) Grid emissions will the progressively reduced as determined by Portugal's roadmap to carbon neutrality in 2050 (APA, 2019); 2) Grid emissions should be discounted over time, as explained in Section 2.5.6. Table A3.3 in Appendix A3 illustrates the progression of grid emissions from their current value to virtually zero in 2050, assuming a linear decrease rate due to the roadmap to carbon neutrality and the adjustment of their global warming effects by the TAWP coefficients (Kendall, 2012).

The values for the Carbon Payback Time become even more concerning when secondary emissions are accounted for, as discussed in the next section.

2.5.8. Secondary emissions due to land-use change

According to Turney & Fthenakis (2011) the secondary emissions due to land use change after installation of a PV plant have three components: 1) emissions due to former vegetation being cut down; 2) emissions from the uncovered soil; 3) emissions due to the absence of the *carbon sink effect* after vegetation is cut down.

For continental Portugal there is sufficient information to calculate the first component but very little information to calculate the third component. No information was found to calculate the second component: emissions over time from the uncovered soil. However, the second component may probably be ignored because the current practice of installing PV power systems minimizes soil removal and the spontaneous growth of vegetation after the panels are installed will likely avoid significant emissions from the soil.

A simplified calculation for the first component is now presented. The method resorts to COS2018, the most recent land cover/land use map of continental Portugal (DGT, 2019) and to Costa-Pereira et al. (2019), responsible for the last official report on national GHG emissions.

The first step was to extract from the database underlying COS2018 only the land classes relevant for the research: areas of continental covered with wild vegetation or used for agriculture and forestry. The result were 32 land classes, including shrublands, grasslands, croplands, orchards, forests, and agroforest lands, etc. as shown in Table A3.1 in Appendix A3.

The second step was to assign to the classes the 19 classes of vegetation for which Costa-Pereira et al. (2019) supply *carbon stock* information. The assignment requires some reasonable guessing since there are more land classes than biomes for which Costa-Pereira et al. (2019) specify carbon stocks, according to their reporting requirements.

From carbon stock data for above ground biomass (AGB), below ground biomass (BGB), and vegetation litter, all expressed in Mg/ha (megagrams or metric tons per hectare) it is possible to calculate the quantity of carbon dioxide emitted in case all the vegetable matter was converted to CO^2. This is performed by multiplying the carbon content by 44/12 or 3.667, the fraction relating the atomic masses of the CO_2 molecule and the carbon atom. The assignment of the reporting classes to the selected COS2018 classes, and their carbon and CO_2 contents are also shown in Table A3.1.

The data in Table A3.1 can be used to build 32 maps of the carbon or CO_2 contents of each land use class. The maps can then be used to determine the CO_2 emissions that will result from completely clearing the vegetation to install a PV plant, providing a value for the first component referred above. A combined map of the CO2 content in all the 32 classes is shown in Figure A3.7 in Appendix A3.

The assumption that all plant matter removed will immediately or very soon be transformed into atmospheric CO_2 corresponds to the simplified Level 3 approach of the IPCC concerning land use conversion, as defined in Penman et al. (2003). This may not be the case: wood carbon can stay for centuries stored in furniture, for instance.

At the time of writing the only publication allowing some limited evaluation of the third component - the missing carbon sink effect - is Pereira et al. (2007), which provides measured results of carbon dioxide balances for a few ecosystems in continental Portugal.

A worked example of the effect of secondary emissions on the Carbon Payback Time is detailed in a conference paper by Távora et al. (2021), reprinted in Appendix A2. The example concerns the effects of completely clearing part of a forest of managed eucalyptus to install a solar PV station. It includes the calculation of the emissions caused by the removal of trees and the emissions due to the lost carbon sink effect.

2.5.9. Related work

A literature review about the research described in this section yielded many journal articles and reports coming from the application of the methods of LCA (Life Cycle Assessment/Analysis) to solar PV technologies and systems. This section lists those references grouped by their main subjects and reviews the publications deemed more relevant for the thesis.

Bhandari et al. (2015), Kommalapati et al. (2016), Hsu et al. (2012), Peng & Yang (2013), and Nugent & Sovacool (2014) present LCA reviews and surveys on the emission and energy metrics of PV technologies and systems. In these reviews and surveys the authors collect hundreds of LCA studies on PV technologies and systems and perform statistical analyses on samples of the publications (e.g., dozens of references) selected by criteria including for instance relevance, originality, and publication date. The results of interest are usually carbon and energy metrics (carbon footprint, EPBT, EROI). Some surveys like those by Hsu et al. (2012) and Bhandari et al. (2015) *harmonize* the results to reduce the wide variations in the values reported. Harmonization is performed by setting *standard* average parameters to be used in the re-calculations, e.g., module efficiency by PV technology; average irradiation (1700 $kWh/m_2.year^{-1}$ is commonly used for Southern Europe); and system lifetime (like 25 or 30 years). Other surveys compare the emissions of solar PV power and concentrating solar power (CSP) as in Kommalapati et al. (2016).

Peng & Yang (2013) perform an extensive, mostly descriptive review of PV technologies and LCA studies and report their results on emission and energy metrics.

Nugent & Sovacool (2014) focus on samples of LCA studies regarding PV energy and wind power (on-shore and off-shore) selected by strict, well defined exclusion rules. Their study, already commented in Section 2.3, provides statistical results for the Carbon Footprint of solar PV and wind power systems all lifetime stages, including operation and end-of-life, and discuss the attributes leading to low emissions in both technologies. For solar PV, for instance increased capacity, lifetime, and use of thin-film technologies; for wind power, for instance turbine power capacity, lifespan, and off-shore installation. The article includes an interesting table comparing GHG emission rates of 23 electricity generator technologies, including solar, wind, hydroelectricity, biomass, nuclear, and fossil-fuel.

De Wild-Scholten et al. (2013), Leccisi et al. (2016), and Yue et al. (2014) present LCA studies containing values for energy and GHG emissions *per unit of PV capacity*, which were used in the research described in Sections 2.5.1 to 2.5.7. De Wild-Scholten (2013) and Leccisi et al. (2016) use life cycle inventory data from the Ecoinvent Database (versions 2.2 and 3.1, respectively) and information collected from manufacturers. Yue et al. (2014), which compare LCA results of PV panels manufactured in Europe with those made in China use the Chinese Life Cycle Database (CLCD) version 0.8. The LCA studies by De Wild-Scholten (2013) and Leccisi et al. (2016) both address the commercially available technologies used in Sections 2.5.1 to 2.5.7: mono-crystaline silicon (mono-Si); cadmium telluride (CdTe), and copper indium selenide (CIS). The system boundaries for analysis are also the same: inclusion of materials and energy for the fabrication of the components of a PV system, comprising energy and emissions; and exclusion of energy and emissions arising during the installation, operation, and end-of-life (EOL) stages.

Leccisi et al. (2016) were the preferred data source since they report more recent, specific results for the countries where the targeted technologies are manufactured (or predominantly manufactured): China for mono-Si, USA for CdTe, and Japan for CIS. Note that the exclusion of the installation, operation and EOL stages is the preferred approach in global studies since PV installation, operation and EOL depend on many local factors. The EOL phase is also difficult to characterize despite the many projects and studies about the end-of-life of PV systems. The net balance in emissions and energy from dismantling, discarding, recycling, or upcycling all the components of PV systems is not yet well defined. Nugent and Sovacool (2014) report that from of all the lifecycle stages, the manufacturing phase is responsible for 71% of emissions. Hou et al. (2015), analyzing the full lifecycle of PV systems in China, report that about 85% of the energy and emissions are linked to the manufacturing stage.

Constantino et al. (2018) calculate GHG emissions and energy metrics for a set of ten PV stations under operation in Brazil (1.1 MW total capacity) using secondary *averaged* data from *several* LCA studies and primary data measured at the stations: their yearly electric generation output. The metrics computed by the authors include the EPBT, the Carbon Footprint, and the Emissions Payback Time (Carbon Payback Time). Their results are interesting and revealing, namely concerning the Carbon Payback Time. Due to the energy mix of electricity generation in Brazil (with a large share of hydroelectricity and biomass) grid emissions are relatively low: 81.7 gCO_2e/kWh in 2016, with 63.9 gCO_2e/kWh planned for 2020. This causes large values of the Emissions Payback Time, which are almost equal to the planned 25-year lifetimes of most PV stations, and *greater than the lifetime* of one station. The authors conclude, correctly, that importing PV technology manufactured in regions where fossil fuels are still dominant to regions of low-emission electrical grids may transform clean energy sources into *net polluters*. Another interesting aspect pointed out (but not developed) by Constantino et al. (2018) is that, while PV systems release most of their emissions in the *manufacturing and installation periods* (which are near in time and of short duration compared to system lifetimes) the electrical grid emits greenhouse gases at a *constant* rate year upon year.

Anctil & Fthenakis (2012), De Marco et al. (2014), Fthenakis & Kim (2009), and Turney & Fthenakis (2011) study the impact of land use and land use change due to solar PV in the GHG emissions associated with the technology.

Ground-mounted PV power plants are responsible for primary and secondary emissions. Primary emissions are linked to the manufacturing, installation, operation, and EOL lifecycle stages of each PV plant component, and are addressed in the LCA studies presented in former paragraphs. Secondary emissions are those linked to land-use changes that PV technology induces, e.g., due to mining and construction of factories for PV components, and those linked to the *transformation and occupation* of land by the PV plant. The emissions in the first category are also designated as resulting from *indirect* land use changes (iLUC).

Fthenakis & Kim (2009) estimate land area indirectly transformed due the production of PV plant components as 15 m^2/GWh for PV panels (mono-Si) and as 7.5 m^2/GWh for the BOS components, considering a 1800 kWh/m^2yr^{-1} insolation and a 30-year lifetime. They compare these values with about 400 m^2/GWh for the land directly transformed by the PV plant itself, concluding that the former can be ignored.

Murphy et al. (2015) estimate what they call the “off-site” (or indirect) land-use intensity of PV plants concluding that it is less than 1% of the “on-site” (or direct) land-use intensity and can be therefore discarded in the calculations. Both studies compare indirect or off-site land *areas*, not land *emissions* but their rationale is applicable to emissions.

Turney & Fthenakis (2011) present examples of the lifetime GHG emissions of PV power plants *that include* the secondary emissions caused by siting solar energy facilities over specific biomes - forests, grasslands, farmlands, desert shrublands and true deserts – assuming total clearing of the plant cover. The lifecycle savings in CO^2 emissions achieved by PV power plants are also calculated assuming an electricity mix with 69% of fossil fuels (U.S data, 2010).

Addressing specifically the impacts of PV stations on GHG emissions, Turney & Fthenakis (2011) argue that the land transformed and occupied by the power stations becomes a source of *secondary emissions* from the initial clearing of the vegetation; from the soil becoming unprotected; and from the loss of the carbon sink represented by the vegetation removed. When comparing the GHG emissions avoided by replacing fossil-fuel based energy with solar energy, the authors argue, the *secondary* emissions from land-use change should be added to the *primary* emissions from the technology itself. Their view is illustrated by an example where a PV station is installed over a forested area in the US with complete removal of the trees, including their roots. (Forests in the US are assumed to hold 100 to 500 Mg/hectare of carbon, including soil carbon.) Their results, which include assumptions about the utilization of part of the cut trees for furniture or other carbon-sequestering uses, yield the following values for secondary emissions in their worst-case scenario: 36 gCO_2/kWh due to initial vegetation removal; 2 gCO_2/kWh due to soil emissions during the 10 years following deforestation; and 9 CO_2e/kWh due to the loss of the forest's natural carbon sequestration. These emissions are added to primary emissions from up to 40 CO_2e/kWh showing that secondary emissions, often ignored, are relevant in total emission calculations. The lost carbon-sink emissions (9 CO_2e/kWh) represent an *opportunity cost* in carbon units: while the soil is covered by solar panels there will be no natural carbon capture by the trees that were cut down to install the PV plant.

The research in this Dissertation is close to Anctil & Fthenakis (2012), Constantino et al. (2018), De Wild-Scholten et al. (2014), Turney & Fthenakis (2011), and Louwen et al. (2017) but differentiates from these works by featuring a detailed geospatial approach that includes the carbon content of nineteen plant biomes and considers the effect of time on GHG emissions.

Anctil & Fthenakis (2012) and Turney & Fthenakis (2011) study secondary emissions from cut down forests in the US. De Wild-Scholten et al. (2014) and Louwen et al. (2017) present PV metrics for Europe and the world, respectively, but do not include secondary emissions nor the effect of time on emissions in their works. Louwen et al. (2017) report regions in Europe with emissions payback times over 10 years, namely in France, Sweden, and Norway. Constantino et al. (2018) calculate carbon payback times for PV plants in Brazil showing how a low carbon intensity electrical grid may lead to carbon payback times near or over PV plant lifetimes also pointing out that emissions from PV systems are expressed mostly before operation while grid emissions are spread continuously over PV plant lifetimes but do not develop the subject.

2.5.10. Discussion

This research clearly demonstrates that primary emissions alone are responsible for large values of carbon payback times for the dominant PV technology – crystalline silicon. This happens in a country with one of the best solar resources in Europe but with a national electricity grid with just an intermediate level of carbon intensity. The reason is the introduction in our analysis of an inescapable reality: roadmaps to carbon neutrality will steeply reduce the carbon intensity of the grid in the next decades leaving PV power plants installed *now* (on in the next few years) with reduced emissions saving capabilities. Another reason is at play, stressed for example by Constantino et al. (2018): importing PV products with high carbon footprints and implementing them in countries with low grid carbon intensities (Brazil or France, for instance) will weaken or even cancel out the emissions avoided or saved by PV power plants.

Secondary emissions have been largely neglected in the appraisal of emissions avoidance by PV systems, except for Anctil & Fthenakis (2012), De Marco et al. (2014), and Turney & Fthenakis (2011). The worked example presented in Távora et al. (2021) demonstrates, however, that if forested land is cleared for PV power plants the contribution of secondary emissions can be determinant. In fact, as PV technology reduces its inherent carbon footprint (e.g., through "solar for solar" approaches) secondary emissions and other impacts in ecosystem services will come to the foreground. It is possible that in the next few years, for some technologies and implementation regions GHG emissions avoidance by PV power plants will cease to be a relevant justification to change land use. Solar PV projects will instead be evaluated by their ability to not degrade ecosystems or by the introduction of ecosystem services that improve overall benefits - including climate positive outcomes as it may happen with agrivoltaics.

A main recommendation from this research is that national regulators enforce checks on the carbon footprint credentials of PV technologies as it already happens in France (République Française, 2020). Secondary emissions from PV implementation should also be included in environmental impact assessments, together with primary emissions.

2.5.11. Further research

This research resorted to simplifications, which nevertheless do not affect its general conclusions: the vegetation is fully cut down in the whole fenced area of the PV power station; initial vegetation clearing results in products with a very short lifecycle compared to the lifetime of the system; soil carbon remains undisturbed by vegetation removal; and PV recycling does not contribute to negative emissions. The assumptions are all plausible but should be adapted depending on each implementation case.

Much work remains to be done, however. A first line of research would be measuring the carbon capture balance for the main ecosystems in Portugal, extending the work by Pereira et al. (2007). A second line would be devising an appraisal method for the environmental impact of ground-mounted PV plants that considers both carbon balance and ecosystem services removals or additions. This would mean converting carbon emissions and ecosystem services in a common measurement unit: a currency.

2.6. Opportunities and Issues of Solar PV Power in Portugal

Portugal is highly dependent on other countries for the energy it needs. Each year, more than *two thirds* of all the primary energy processed in the country and delivered to final users comes from abroad. The energy may come, for instance, in the form of oil products for transport vehicles or as natural gas to be burned in power plants to produce electricity.

Yet, the country is rich in *domestic*, *renewable* energy resources: sun, wind, sea waves, and even biomass, which can be captured to generate electricity and heat. An energy transition (which is already in progress) is thus required to increase energy self-sufficiency, decrease the GHG emissions linked to the imported energy forms (mostly natural gas oil and oil, since coal has been phased out) and increase energy efficiency.

2.6.1. Energy in Portugal - a snapshot

The sources, transformations, and uses of energy in Portugal in 2019 - the last year for which there are consolidated results - are illustrated in Figure 2.19, a Sankey diagram of the energy balance for the year by the IEA (2021). Similar results, although with numerical differences can be found in the detailed government data published by ADENE (2021). Both entities state the results in 'tonnes of oil equivalent' (*toe*), which measures the energy produced by burning 1,000 kgs of crude oil. Converting to a usual energy measurement unit: one toe is equivalent to 11.63 MWh (11,630 kWh).

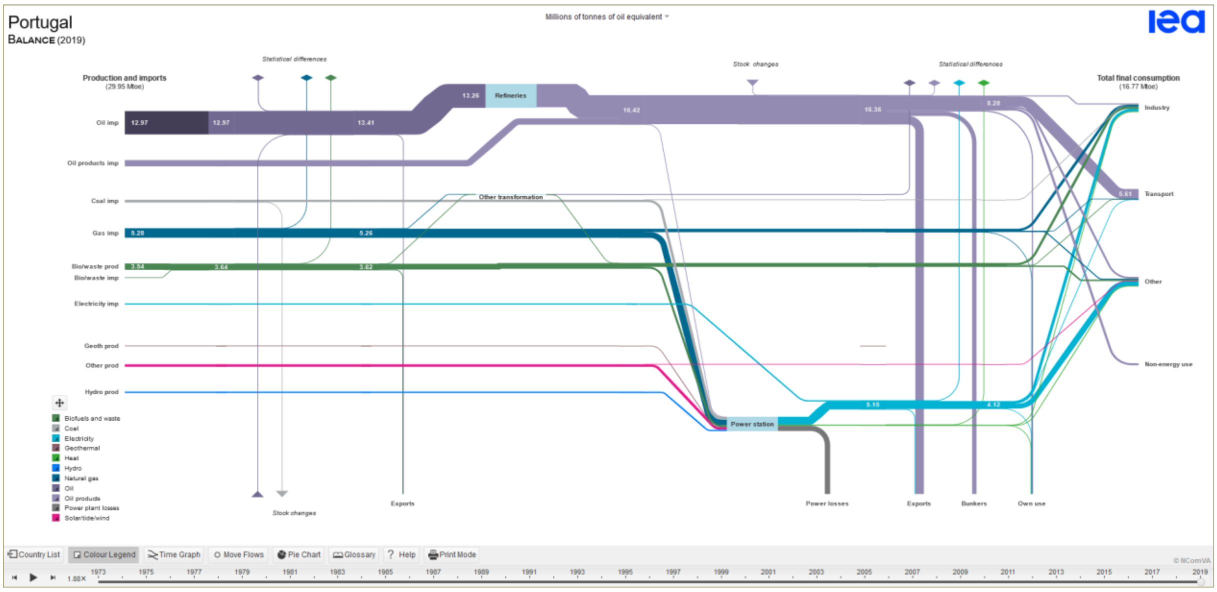


Figure 2.19 – Energy balance of Portugal, 2020, Sankey diagram (IEA, 2021).

The diagram presents on the left the inputs of energy coming from abroad (imports) and the energy produced domestically. The violet flows represent imports of crude oil and oil products (e.g., gasoline) and the dark blue flow represents natural gas imports. In 2019 there were still imports of coal, albeit small. And small imports of electricity although electricity is also exported. The green, red, and light blue lines correspond to domestic production: biomass, wind and solar, and hydropower, respectively. There is also a grey line for geothermal energy production in the Azores. And part of biomass is also imported (thin green line).

Inside the diagram there are two transformation nodes: *refineries* and *power plants*. Looking at the flow of oil, it is apparent that part of the refined products is exported, and another goes to the *international* aviation and shipping *bunkers*. The latter are stocks of fuel to be used by airplanes and ships travelling in and out of Portugal. But the largest share goes directly to the *transport* output in the final consumption. The power plants receive imported and domestic energy in all forms (including inputs that do not require transformation since they are already in electricity form, like solar PV and wind power). Note that natural gas (dark blue flow) ends mostly as fuel for power plants although a significant part ends up in the 'industry' output in final consumption. Electricity, the light blue flow coming out of the 'power plants' node is partly exported, partly used by the power plants themselves, ending up in the industry and the 'other' outputs. The contribution for 'transport' was insignificant in 2019 although it will likely rise fast in the future with the increased use of electric vehicles. In 2019, final consumption of energy was still dominated by oil products (about 5.6 Mtoe) compared to electricity (about 3.9 Mtoe). In 2019 electricity was produced mainly from fossil fuels as can be seen in the pie diagram linked to the *power station node*, shown in Figure 2.20. Coal was terminated this year, but it was likely replaced by an increase in the importation of natural gas.

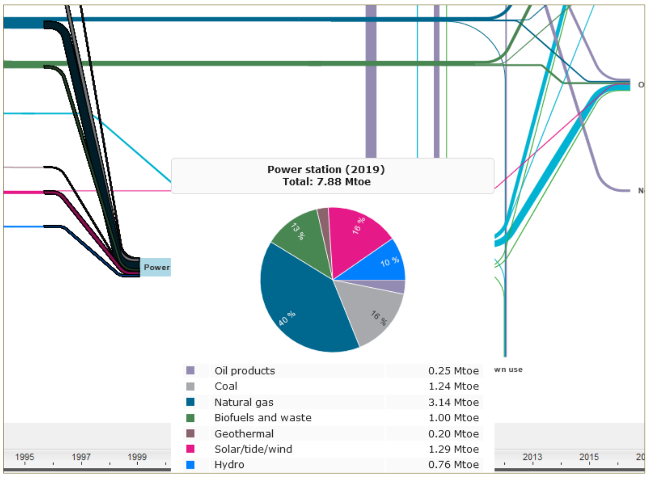


Figure 2.20 - Energy mix of electricity in Portugal, 2020 (IEA, 2021).

The figures for energy dependence and other indicators can be calculated from the energy balance information by ADENE (2021). A key figure to start with is the *import balance*, the difference between imports and exports. In 2019, energy imports amounted to 24.268 Mtoe while exports amounted to 5.816 Mtoe, making the import balance equal to 18.452 Mtoe. Gross *domestic production* of energy amounted to 6.487 Mtoe (from which, by the way 2.019 Mtoe were electricity from solar PV, wind power, hydro power, and geothermal power).

Adding the import balance and the domestic production of energy gives a figure for all the energy available to be transformed and transferred to final users during the year but part of this energy is stocked in the shipping and aviation bunkers or simply as stock for future use. *Stock changes* in 2019 amounted to 0.059 Mtoe, the balance between an increase in the stock of coal and a decrease in the stock of oil. Increases in the international aviation and shipping bunkers were 1.458 Mtoe and 0.951 Mtoe, respectively. Adding import balance and domestic production and subtracting the three positive stock values yields: 18.452 + 6.487 – 0.059 -1.458 – 0.951 = 22.471 Mtoe. This figure is the total *primary energy consumption*, which after being deducted of energy losses in the transformation process and parcels for own use, results in 16.649 Mtoe of *total final consumption* (TFC) - energy delivered to end users in industry, transports, services, households, etc.

A first indicator can be given by dividing domestic energy production and primary energy consumption: 6.487/22.471 = 28.9%. So, less than 30% of the energy in Portugal comes from internal resources.

The *energy dependence* indicator is calculated officially by dividing the energy import balance by the primary energy consumption *plus* the international bunkers. Thus, 18.452/ (22.471 + 1.458 + 0.951) = 74.2%. As discussed in ADENE (2021) this is the real energy dependence figure although EU rules for wind and hydro power normalize the indicator to a slightly smaller value: 74%.

The energy dependence has decreased since 2009 although not monotonically. Some values in the series read in from ADENE (2021): (2009, 81.2%), (2014, 70.5%), and (2017, 77.7%). The low value in 2014 was perhaps due to the economic recession. The high value in 2017 was most likely due to the severe drought, which reduced hydropower resources increasing electricity imports.

Focussing now on electricity DGEG (2021a) reports the installed capacity (or installed power) of all Portuguese power stations in 2020, with a total of 22,459 GW. From these 14,609 GW are from power stations using renewable energy sources (including biomass, biofuel, and renewable waste) while the remaining 7,655 GW belong to power stations burning fossil fuels.

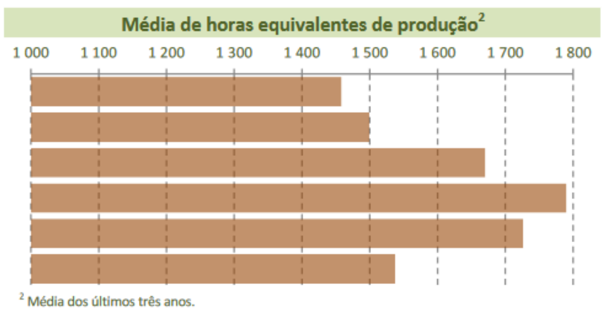
The installed power for each electric generation technology is shown in Table 2.9 together with the electricity produced during 2020 in GWh, read from DGEG (2021b). Note that the biomass, natural gas, and coal power plants were aggregated since their contributions could not be distinguished in the electricity production data of DGEG (2021b). The third column in Table 2.9 presents the share of each technology in the total installed capacity.

Table 2.9 - Capacity factors of energy sources in Portugal, 2020.

<table>
<tr><td>Generation technology</td><td>Installed power [MW]</td><td>Electricity production [GWh]</td><td>Share of installed power [%]</td><td>Capacity factor [%]</td></tr>
<tr><td>Hydroelectricity</td><td>7,129</td><td>13,633</td><td>31.7</td><td>22</td></tr>
<tr><td>Solar PV</td><td>1,076</td><td>1,691</td><td>4.8</td><td>18</td></tr>
<tr><td>Wind energy</td><td>5,502</td><td>12,299</td><td>24.5</td><td>26</td></tr>
<tr><td>Biomass</td><td>868</td><td rowspan="2">25,214</td><td rowspan="2">38.8</td><td rowspan="2">38</td></tr>
<tr><td>Nat. gas and coal</td><td>7,655</td></tr>
<tr><td>Geothermal</td><td>34</td><td>217</td><td>0.2</td><td>73</td></tr>
<tr><td>TOTAL</td><td>22,459</td><td>53,054</td><td>100</td><td>27</td></tr>
</table>

It is interesting to compute the *capacity factor* of each power generation technology, shown in the fourth column of Table 2.9, from their capacity and production values. The capacity factor (CF) is the *fraction of the total time in one year for which a power station needed to work at full capacity to produce the energy it delivered in that year*. For instance, a wind turbine may work every day in one year but only some hours each day at full power. Summing all the electricity the turbine provided in one year, expressed in megawatt-hour, and dividing the value by its capacity in megawatts times the number of hours in one year (365*24= 8,760) yields the capacity factor. Taking wind energy from the table: 5,502*8760 = 48,197,520 MWh would be produced if the wind turbines worked at their full or installed capacity. As they produced only 12,299,000 MWh, their capacity factor is 12,299,000/ 48,197,520 = 26%.

The same concept can also be expressed by other metrics like the *equivalent production hours*, *full-load hours*, and *maximum availability factor*. For wind power and solar PV, which have low capacity factors due to their variable energy flows, equivalent production hours (EPH) are a common metric. Figure 2.21, extracted from DGEG (2021c) presents regional 3-year averages and yearly equivalent production hours of solar PV. Alentejo and Algarve are the regions where solar energy collection is higher, therefore having the highest EPH values. Converting to CF the values would be 20.8% and 20.4%, respectively.



	Horas Equivalentes de Produção				
	2016	2017	2018	2019	2020
Norte	1 616	1 592	1 358	1 467	1 551
Centro	1 639	1 664	1 436	1 488	1 574
Lisboa	1 780	1 822	1 632	1 690	1 691
Alentejo	1 946	1 976	1 756	1 826	1 789
Algarve	1 804	1 777	1 687	1 772	1 722
R.A. Madeira	1 612	1 611	1 560	1 650	1 401

Figure 2.21 – Solar PV equivalent production hours in Portugal (DGEG, 2021c).

Power generating technologies depending on stocks of fuel (like coal or natural gas) or on constant energy flows (like nuclear or geothermal power) can have much higher capacity factor values (over 90%) than the majority of those displayed in Table 2.9. Geothermal generation in the Azores is an example with a 73% capacity factor. However, the Portuguese electric power system relies mainly on *variable renewable energies* and its managers will *dispatch* (i.e., connect to the grid) fossil-fuel power plants only when renewable power is not available or is not sufficient to satisfy electricity demand. Solar PV plants and wind parks have priority since, absent energy storage, they can only supply power when they get it from the natural flows. Gas-fired power plants – currently the only ones using fossil fuel in continental Portugal - will supply electricity just to compensate for sudden variations in supply or demand. And coal power plants, even before their recent termination, were already being used sparingly. This explains the relatively low 36% CF value for *thermal generation* (biomass, natural gas, and coal).

2.6.2. A future of renewable energy

Following the Paris Agreement of 2015 Portugal committed to achieve neutrality of its GHG emissions until 2050. The announcement was made in COP 22, the Conference of Parties of the UN Framework Convention on Climate Change held in Marrakech, December 2016. By the end of 2018 the Portuguese government presented for public consultation its strategy to achieve the goal in a summary document entitled "Roteiro para a Neutralidade Carbónica 2050" (RNC2050, 2018), the Portuguese roadmap to carbon neutrality by 2050, hereafter RNC2050. Separate documents regarding agriculture, forests and land use, and energy and industry were also presented.

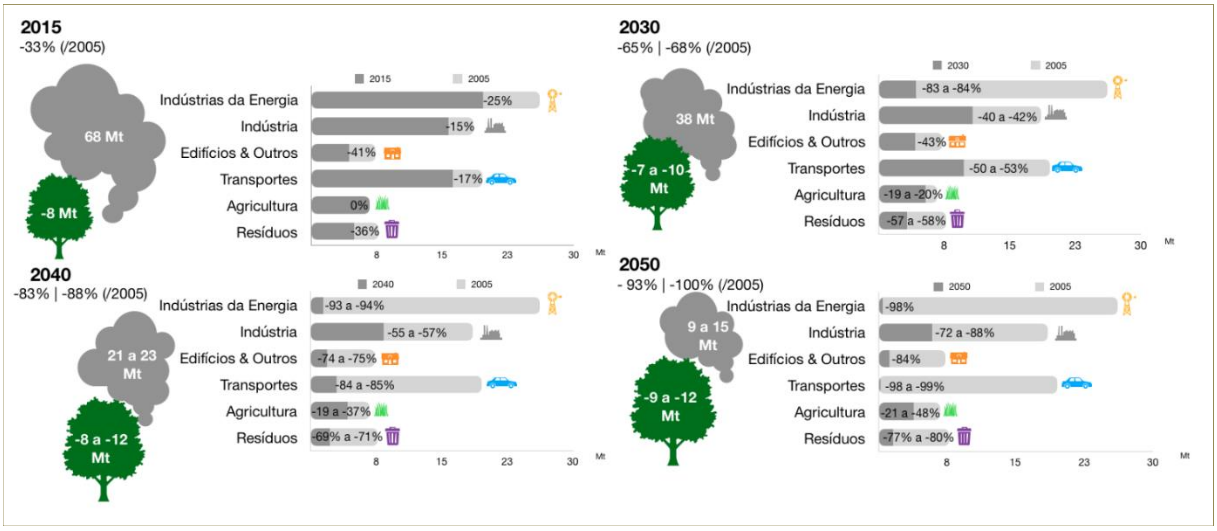


Figure 2.22 – Portuguese emission sources and sinks, 2015 to 2050 (RNC2050, 2018).

Overall, the strategy called for the rapid abatement of emissions through a strong increase in the use of domestic renewable energies and a dominant role for electricity in final energy consumption in all sectors. Forests would also have a key role in providing the emissions sink needed to achieve GHG emissions ("carbon") neutrality by 2050. Imports of natural gas for hard to decarbonize industrial sectors would continue until 2050, together with oil and oil products, most of it for export purposes.

The RNC considers three macroeconomic scenarios: "off-track", "peloton" (PL), and "yellow jersey" (YJ), with carbon neutrality achieved only under the last two scenarios. The socio-economic *narratives* underlying the scenarios are discussed in RNC2050 (2018). Concerning solar photovoltaic power, YJ assumed a larger role for decentralized solar and self-consumption linked to a more regionally-spread economy compared to PL.

The essential role of Portuguese forests as a carbon sink to balance domestic GHG emissions in all the other sectors is illustrated in Figure 2.22 from RNC2050 (2018), which shows the planned GHG abatements and carbon sink removals by the end of the three decades to 2050. Emissions are expressed in Mt (millions of metric tons) of CO_2e gases.

The RNC2050 technical annex regarding energy and industry (APA, 2019) provides information that can be used to perform a simple assessment of the *future* of energy in Portugal by 2050 with its *present*, discussed in Section 2.6.1. The departure point is the Sankey diagram of Figure 2.23, from APA (2019), depicting 2050 energy figures and flows in the YJ scenario. The Sankey diagram is simplified, as noted by APA (2019), but the information is enough to provide meaningful comparisons with 2020. Note that the energy figures are now in petajoules, PJ, which will be converted to Mtoe (1 petajoule = 0.0239 Mtoe).

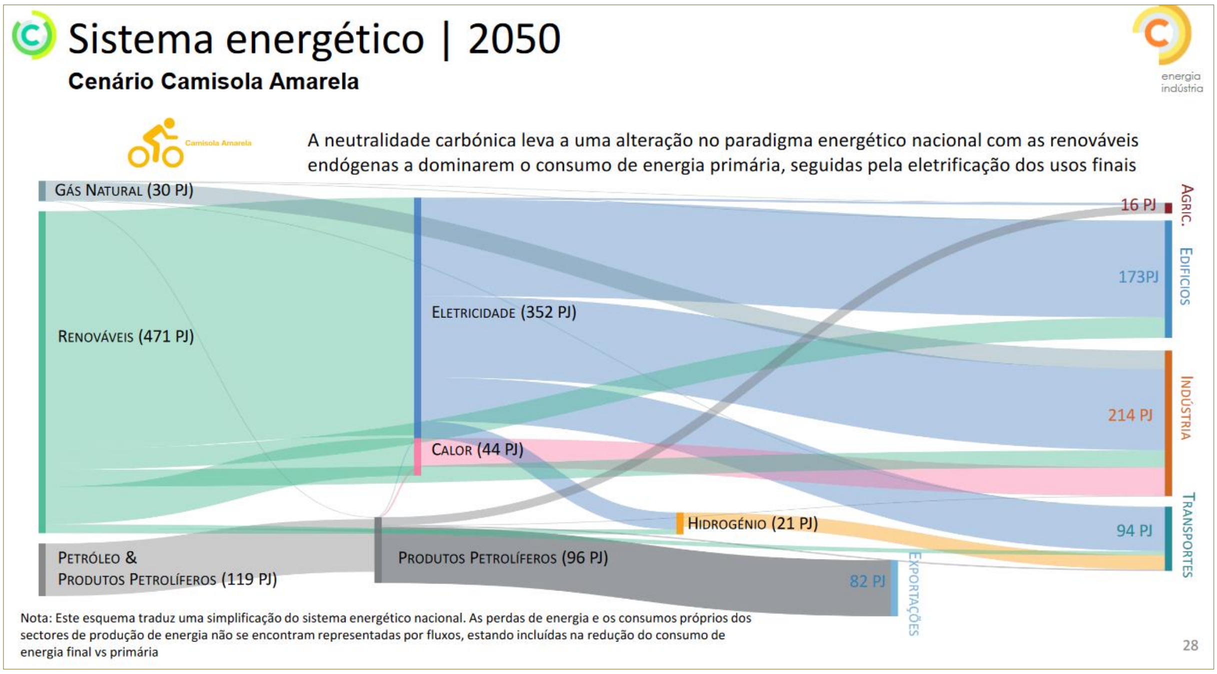


Figure 2.23 - Energy balance of Portugal, 2050, Sankey diagram (RNC2050, 2018).

The energy import balance is equal to 1.4337 Mtoe, summing the imports of natural gas and oil and its products and subtracting the exports of oil products. Domestic energy production, "Renováveis" in the diagram, is now equal to 11.2569 Mtoe. Primary energy consumption, the sum of these two parcels, equals 12.6906 Mtoe.

Energy dependence is now equal to import balance divided by primary energy consumption (ignoring the international bunkers since they are unknown). The result is 12.7%, much lower than the 74.2% figure for 2020.

In 2050 electricity becomes largely dominant in final consumption. The figure cannot be calculated from the diagram but APA (2019) estimates that the share of electricity in total final consumption will be over 66% compared with 26% in 2015.

The diagram also shows a 21 PJ flow of energy linked to hydrogen to supply fuel cell electric vehicles (FCEV). The energy to produce it will be mostly electricity, as can be seen from the diagram, which implies the deployment of hydrogen production by *electrolysis* to be powered by wind energy and/or solar PV. According to the RNC2050, this is projected to happen only after 2030. It remains to be seen whether the investments will wait until the end of the decade.

Finally, in the YJ scenario there will be a strong reduction in primary energy consumption, which also occurs in PL: from 22.471 Mtoe in 2020 to 9.7804 Mtoe in 2050, a decrease of 43.5%. As in YJ both population and GDP are expected to increase (RNC2050, 2018) there will be corresponding reductions in *energy consumption per capita* and in *energy intensity*, the amount of energy per monetary unit of production. Energy intensity is expected to become less than 40 toe/M€ in 2050 compared to about 80 toe/M€ in 2020.

An important result of RNC2050 is that electricity generation and supply will be virtually free of GHG emissions by 2050, in both the PL and YJ scenarios. In 2050, according to APA (2019) electricity will be 100% derived from renewable sources and the electrical grid will have a net carbon footprint of less than 1.7 gCO_2e/kWh.

The projections of RNC2050 were performed using the energy modelling tool (TIMES_PT) whose workings were briefly described by RNC2050 (2018) and in more detail by Fortes et al. (2019).

RNC2050 includes projections for 2030 and 2040 which will not be presented here since they have been superseded by the approval in 2020 of the National Energy and Climate Plan for the decade 2021 to 2030 (PNEC, 2019) following a call by the European Union on all member states. The plan (hereafter PNEC) and RNC2050 have common goals and targets but differ in some of their assumptions and modelling technology tools (which is now the government-developed JANUS system), as detailed in DGEG (2019).

There are two scenarios in PNEC, called "WEM" (With Existing Measures) and "WAM" (With Additional Measures). As the former is a *business as usual* scenario only WAM will be hereby considered. The plan includes forecasts for all the energy technologies (including some not addressed by RNC2050) but only its projections for solar electricity technologies will be hereby discussed.

In PNEC solar electricity is generated by *solar PV plants*, *concentrated solar PV plants* (CPV), *solar PV plants with energy storage*, *concentrated solar power* (CSP) *with energy storage*, and *small-scale solar PV* systems (for self-consumption and energy trade). Note that CSP (with or without energy storage) is a solar *thermal* electricity-generating technology, not a photovoltaic technology. RNC2050 mentions the same solar power technologies but its results specify only *Centralized PV* and *Decentralized PV*. PNEC provides much more detail.

The projections of PNEC and RNC2050 regarding solar power are presented in the tables of Figure 2.24 and Figure 2.25, respectively. The tables show the planned *cumulative* installed power (in MW) by the end of the year on the columns and the *yearly* electricity production (in GWh) provided by the installed capacity. The production figures in the PNEC table were converted from petajoules (PJ) to gigawatt-hour (1 PJ = 277.78 GWh) to match the units used by RNC2050. A third section in both tables, calculated for the thesis, shows the equivalent production hours of the power systems, as discussed in Section 2.6.1.

	Capacity [MW]					Prodution [GWh]				Equivalent production hours		
power plants	**2020**	**2025**	**2030**	**2035**	**2040**	**2020**	**2025**	**2030**	**2035**	**2025**	**2030**	**2035**
Solar PV	1 084	3 479	6 030	4 560	3 110	2 028	6 528	11 306	8 528	1 876	1 875	1 870
Solar PV storage		252	510	3 273	6 035		389	778	5 028	1 543	1 525	1 536
Concentrated Solar PV	25	155	500	500	500	28	306	944	944	1 971	1 889	1 889
Concentrated solar thermal (CSP)		113	300	650	1 000		222	583	1 222	1 967	1 944	1 880
Small units	**2020**	**2025**	**2030**	**2035**	**2040**	**2020**	**2025**	**2030**	**2035**	**2025**	**2030**	**2035**
via solar PV	553	1385	1800	2 400	3000	778	1 944	2 556	3 389	1 404	1 420	1 412
Self consumption units	**2020**	**2025**	**2030**	**2035**	**2040**	**2020**	**2025**	**2030**	**2035**	**2025**	**2030**	**2035**
Solar PV for H2				250	500				417			1 667
Solar PV at buildings	285	822	1 078	1 112	1 157	528	1 500	1 972	2 028	1 825	1 830	1 824

Figure 2.24 - Solar PV projections in PNEC. Data from DGEG (2019).

A first comment on the projections is that the figures for the *total* installed capacity in 2030 and 2040 are different in PNEC and RNC2050, for both YJ and PL scenarios. PNEC projects higher solar power in 2030 (10,212 megawatts versus 7,600 in YJ and 9,600 in PL). In 2040, the situation reverts: 15,302 megawatts vs. 16,090 and 18,500 in YJ and PL).

But despite the apparent “slow down” compared to RNC2050, the details of PNEC are relevant for the discussion about the land-use impact of solar power. In 2030, for instance, from the total 10,212 megawatts only 1,078 will be surely over buildings or infrastructure. The “small units” could be mostly ground mounted systems over farmland or wildland, for instance. Taking out the contribution of *solar PV at buildings* yields 9,134 megawatts for the likely capacity of *ground-mounted* solar power in 2030. This is higher than the centralized PV projection of RNC2050 in 2030: 5,000 megawatts in YJ and 7,300 megawatts in PL. In 2040 there would be 14,145 megawatts of possibly ground-mounted solar power plants compared to 9,300 MW of centralized PV in YJ and 13,600 in PL.

Of course, it can be said that the figures for decentralized PV in RNC2050 were *hiding* a large capacity of ground-mounted solar power systems. And that PNEC has limited the total installed capacity in 2040. In any case, the possibility that ground-mounted capacity may reach 10,212 MW in 2030 and 14,145 MW in 2040 mostly likely turns the projections of land occupation by Távora et al.

(2020), discussed in Section 2.4, into *underestimates*, since they were based on the centralized PV figure provided by APA (2019).

Finally, two comments about the equivalent production hours (EPH) calculated for the PNEC projections. The first is that the technologies with energy storage, like PV with storage and, *most likely*, CSP and the small units, are presented with lower EPH values, which is due to losses in transferring energy to and from the batteries or storage devices. CSP systems, for instance, would have much higher EHP values than solar PV if they did not have energy storage (Bib).

	Capacity [MW]			Production [TWh]				Equivalent production hours		
Yellow Jersey	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**		**2030**	**2040**	**2050**
Centralized solar PV	5 000	9 300	13 000	9	17.7	24.7		1 800	1 903	1 900
Decentralized solar PV	2600	7 600	13 000	3.8	13.3	22.3		1 462	1 750	1 715
Peloton	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**		**2030**	**2040**	**2050**
Centralized solar PV	7 300	11 300	13 600	12	21.4	25.8		1 644	1 894	1 897
Decentralized solar PV	2 300	7 200	12 000	3.8	12	20		1 652	1 667	1 667

Figure 2.25 - Solar PV projections in RNC20250. Data from APA (2019).

Small units, even resorting to less productive technology than large PV power stations would also have higher equivalent hours if they did not have storage. A second comment is that solar PV without storage is set with quite high EPH values, higher than the highest values in Figure 2.21, approaching the limits imposed by the natural irradiation levels on horizontal surfaces. This could result, for instance, of considering a large share of sun-tracking PV systems and/or bifacial solar panels which have increased solar collection capabilities compared with fixed, single face PV panels.

2.6.3. Sunny places and siting decisions

The Global Solar Atlas study of ESMAP (2020), mentioned in the Introduction, includes a ranking of 210 countries according to their 'practical' solar PV potential expressed by the country average *energy provided per day* by a PV system of one kilowatt of peak/maximum power, measured in $kWh/kW_p/d$. The countries of Europe do not generally fare well in the global ranking except for the countries of Southern Europe. Cyprus ranks 51 with 4.698 kWh/kW_p, Malta 68 with 4.562 kWh/kW_p, Spain 83 with 4.413 kWh/kW_p, Portugal 100 with 4.316 kWh/kW_p, and Italy ranks 140 with 3.993 kWh/kW_p.

All other European countries have much lower ranks: France is number 180 while Germany ranks 197, for instance. But as the authors of ESMAP (2020) remark this does not avoid that Germany and France and other northern European countries have important solar PV installed capacities, they simply are not as productive.

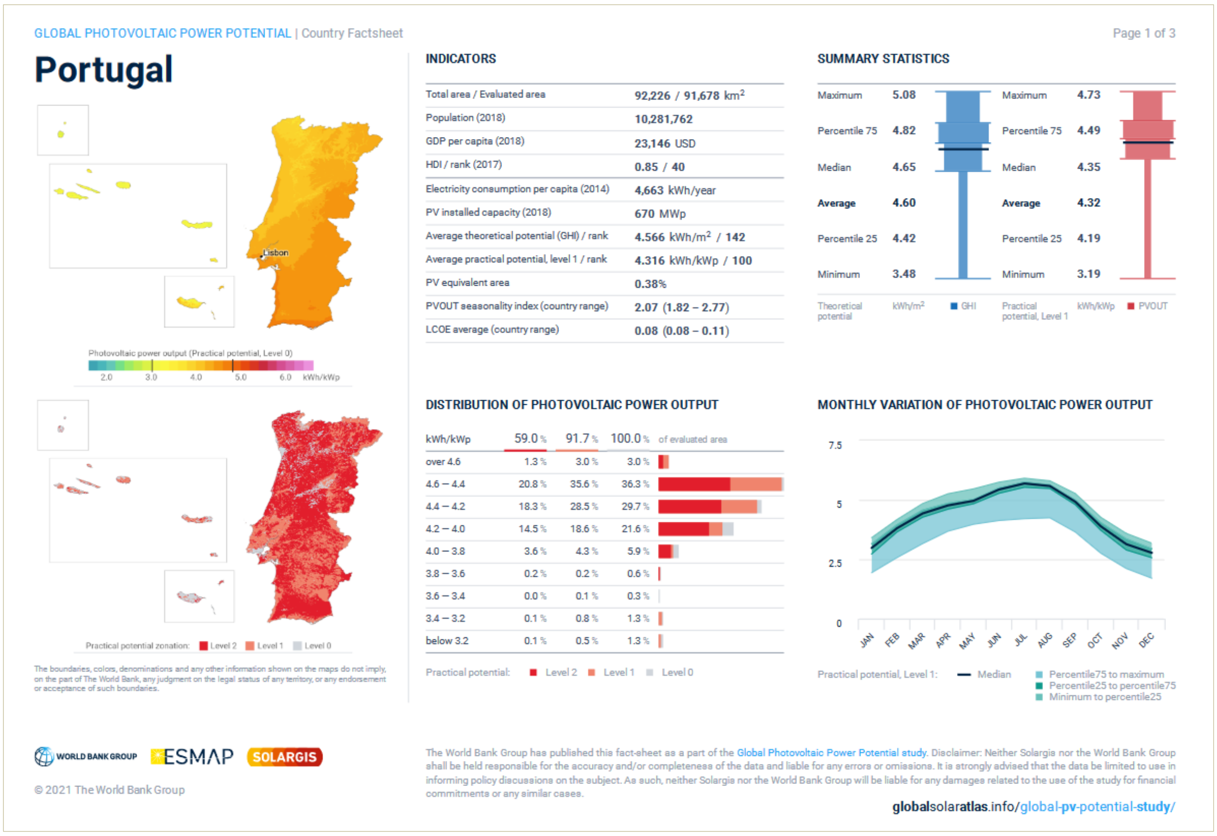


Figure 2.26 - Portugal in the Global Solar Atlas (ESMAP, 2021).

ESMAP (2020) provides factsheets with data and results for each country, which can be downloaded from (https://globalsolaratlas.info/global-pv-potential-study). The first page of the fact sheet for Portugal is shown in Figure 2.26.

There are two maps on the left of the figure. The top map illustrates the average *theoretical PV potential*, which authors equate with the Ground Horizontal Irradiation (GHI) - the solar energy captured by a horizontal surface of unit area at ground level, measured in kWh/m2. The GHI, the authors argue, has a strong correlation with the maximum energy that can be collected by the panels of a PV system over a period, when suitably oriented. The bottom map below illustrates the average *practical PV potential* over the Portuguese territories - which the authors calculate by *simulating a real PV power plant* using mono-crystalline silicon panels, optimally tilted and oriented to collect maximum energy over one year, as detailed in ESMAP (2020). Note that the result is given in *kWh per* kW_p, making it independent of the actual *efficiency* of the PV panels. For instance, if a commercial PV module is 20%

efficient, meaning that it delivers energy at 200 watts per m^2, the system would need 5 m^2 of panels to attain 1 kW_p.

Box plots of GHI and practical PV potential are presented on the top right corner of the figure. The area of the "boxes" in the diagrams is proportional to the geographical area within the ranges of PV potential. Looking at the diagrams it is immediately apparent that a large majority of Portugal has PV potential within a relatively narrow range of *high* daily energy values. This had already been remarked in Távora et al. (2021) for continental Portugal although with a different measure.

The calculation of the practical PV potential for a region or country by ESMAP (2020) follows a *zoning* criterion with three levels, successively excluding areas inconvenient for PV power plants or that might cause environmental problems or land use conflicts. The authors consider the whole territory as *level 0*, for which they determine the theoretical PV potential (GHI). Next, they obtain *level 1* by excluding areas of highly sloped or irregular terrain, or remotely located and/or very sparsely populated. But from level 1 are also excluded natural *protected areas* and *thick forests*, which the authors define as forested land with more than 50% tree coverage, as well as *dense urban areas*. Finally, they establish *level 2* by excluding cropland, defined as *rainfed* or *irrigated and post-flooding*. (Post-flooding is used in rice cultivation, for instance.)

Note that PV plants can be installed in highly sloped terrains at a higher cost and off-grid PV systems may be essential to provide power to remotely populated areas. But the focus is on utility-scale PV power plants.

The three levels marked are displayed in grey, rose, and red colour in the maps of practical PV potential of the Portuguese territories. The distribution of their areas by range of PV daily output can be seen on the diagram beside the map.

The authors of ESMAP (2020) determine the practical PV potential of a country or region using the *full level 1 area*, arguing that although usually competing with agriculture solar PV power can be made compatible with cropland use (through agrivoltaics) or may use abandoned land, even if temporarily. But they advise against using forested land, which would be counterproductive since forests are carbon sinks that help to reduce emissions like solar PV.

Using the tools developed for this thesis yields a similar value for the average practical PV potential of the Portuguese territories. As shown in Table 2.7, there must be 4.96 m^2 of mono-Si panels to achieve 1 kW of maximum power. Therefore, multiplying the map in Figure A3.1 left by 4.96 gives the practical PV yield per kW_p. As the period in Figure A3.1, left, is one year rather than day, all values in the maps must be divided by 365. Averaging, results in 4.30 kWh/kW_p per day, a little lower than the 4.316 kWh/kW_p calculated by ESMAP (2020).

Note, however, that the calculation by ESMAP (2020) applies to the *whole* Portuguese territory, not just continental Portugal. Moreover, the authors of ESMAP (2020) consider only level 1 areas and their model for GHI and overall PV system losses differs from the model used by PVGIS.

The distribution by levels and PV output enables a simple calculation of the *difference* between the areas of level 1 and level 2, performed in Table 2.10.

Table 2.10 - Area differences between levels 1 and 2. Data from ESMAP (2020).

kWh/kW$_p$/d	59.0 % [2]	91.7% [1]	Difference [%]	Area [km^2]
over 4.6	1.3	3.0	1.7	1 558.5
4.6 – 4.4	20.8	35.6	14.8	13 568.3
4.4 – 4.2	18.3	28.5	10.2	9 351.2
4.2 - 4.0	14.5	18.6	4.1	3 758.8
4.0 – 3.8	3.6	4.3	0.7	641.7
3.8 – 3.6	0.2	0.2	0.0	0.0
3.6 – 3.4	0.0	0.1	0.1	91.7
3.4 – 3.2	0.1	0.8	0.7	641.7
below 3.2	0.1	0.5	0.4	366.7
TOTAL				29 979

It is apparent from the table that even if PV power plants were *not* implemented over cropland, i.e., on level 2 areas, there would still be plenty of land for solar PV power. This is still the case for the best places, from 4.0 to maximum, where the difference adds up to 28,237 square kilometres. This is still much larger than the 300 square kilometres of future PV land occupation estimated in Távora et al. (2020).

But of course, utility-scale solar PV *will* compete for cropland (which is in general flat and sunny) located near the main branches of the electrical grid, present or future. And there may be strong economic incentives for the landlords to surrender their land to solar PV developers. For instance, Sachelli et al. (2016) show that in Italy the economic returns provided by solar PV investments are much higher than the returns provided by agriculture, in most cropland classes.

Forested land is also not immune to the advances of solar PV. As remarked by Pereira (2016) among European countries Portugal has one of the highest proportions of land occupied by planted forests (35.4% in 2010), which are by far privately owned (86%). And while there are large successful forestry companies (exploiting mostly eucalyptus and cork trees) there are many small landowners facing such meagre returns on their property that their lands are left uncared for, at the mercy of wildfires.

No wonder that small and medium private forest owners are tempted by solar PV developers into selling or leasing their properties for energy farms. As pointed out by ESMAP (2020) this leads to counterproductive results regarding climate change. For instance, as shown in Távora et al. (2021) the lifecycle net emissions avoided by PV plants that replace eucalyptus forests can be very small.

It is interesting to compare the distribution of the three levels in Portugal with those of Spain and Italy, shown in Figure 2.27. It is immediately apparent that while the reduction in level 1 area compared to the whole territory (level 0) is higher in Italy and Spain (70.8% and 85.7%, respectively, against 91.7 in Portugal) their level 2 areas are much smaller: 21.7% and 41.0%, respectively, against 59% in Portugal.

The share of Portugal is also higher than the corresponding level 2 shares of Cyprus and Malta. Thus, the likelihood of competition for prime locations occupied by agriculture and forestry will be higher in Portugal than in its European solar partners with good PV potential. A less strict regulation in Portugal than in its neighbours can also lead to an increase in foreign investment on solar PV in Portugal, with the energy exported to other countries where demand for 'clean' energy is higher.

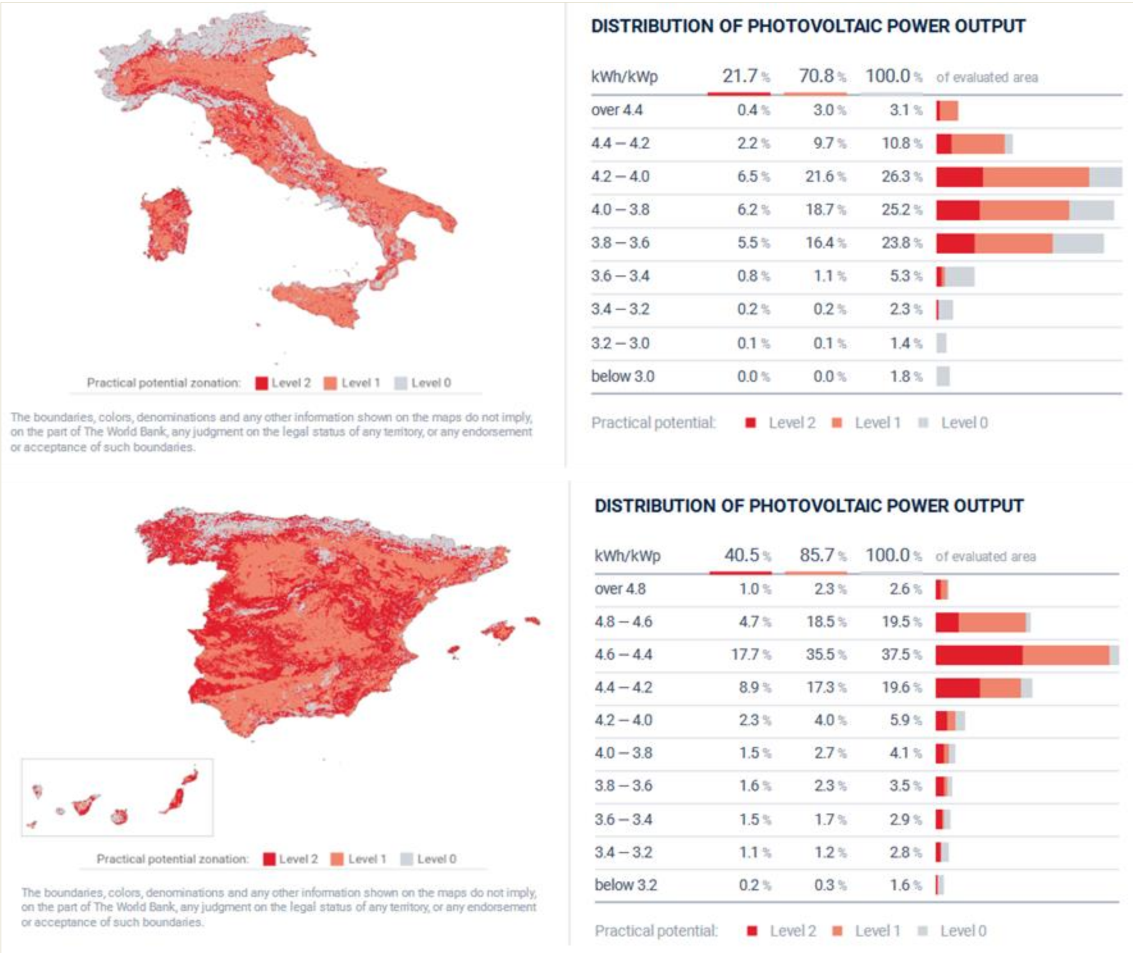


Figure 2.27 – Italy in Spain in the Global Solar Atlas (ESMAP, 2021).

2.6.4. Public concerns and vested interests

Public opinion in Portugal became aware of the likely impacts of solar energy when in 2008 a large PV power plant started operating near the village of Amareleja in the municipality of Moura, Alentejo. The 45.8 MW capacity plant was for some time the largest in the world (Vidal, 2008) although by today's standards can only be considered medium-sized. It occupies, nevertheless, 277 hectares and is located so near the 2,500 people village that it looks like a very large industrial extension of the houses.

The social and economic impacts of the Amareleja plant were studied by Junqueira et al. (2016) through a case study approach that privileged document analysis and interviews with stakeholders. The Amareleja plant was driven by a local development initiative that included, among others, a factory of PV modules. The factory project was abandoned in its early years due mainly to the flood of cheaper modules made in China.

The abrupt landscape changes caused by the plant led to the main objections from the population. It was considered too big, ugly, a “tin-foil olive groove”. But overall, the feelings were mixed: the village became a spot for “technology tourism” and people assigned little importance to the land where the plant was located - except for the occupation of an old airfield used for communal activities about which they were not previously consulted. The plant was also open for grazing by local sheep flocks, which was seen as positive. However, by 2013 the civil parish president of Amareleja was declaring that, of course, he preferred “the cork trees to the panels” and that “even the undergrowth is more beautiful than the panels”.

Much more plants and bigger in size would later be implemented in Portugal, raising the concerns and opposition of citizens, journalists, environmental organizations, and affected businesses.

Lusa (2013), a news agency, reports that a group of citizens opposed the construction of the APRA PV plants in Loulé, Algarve. They complained about the “demolishing visual impact” it would cause and their unpleasant glare. Moreover, they were being built over a sensitive area with communal importance. A formal complaint was even sent to EU authorities. The plants (APRA-A and APRA-B, side by side) were built, nevertheless, starting operation in 2014. They occupy an area of 26 hectares and have a combined capacity of 10 MW. The plot on which they were built was formerly a very green pastureland but the land below the panels is now totally bare, as the author of the thesis confirmed by satellite imagery.

Revez (2017) reports on the concerns about the impacts on *Via Algarviana* (a nature track running across the whole of inner Algarve) by the very large Solara4 PV power plant in Alcoutim. The concerns were raised by Almargem, an environmental organization, and by the local nature tourism companies. “Tourists come here to see the flower fields, not to walk between solar panels”, complained the owner of a local business. Almargem demanded that the developers of Solara4 (which were investing 200 million Euros) paid for an alternative section of the *Via Algarviana* far from the plant, an investment of just 20,000 Euros that they were not willing to support. Solara4, currently the largest PV plant in Portugal, has an installed capacity of 219 MW and a total area of 320 hectares, and started operating in September 2021. No information could be found about how the conflict was solved.

Zero (2017), an environmental NGO, alerts that the Alcaboucia and Vale da Cota solar plants in Alentejo, under evaluation at the time, showed environmental benefits that were lower than the estimated environmental costs. Developing the plants would affect the National Ecological Reserve (REN) and eliminate 135 hectares of cork and oak agroforestry land.

Interestingly, the NGO estimates the *secondary emissions* of the PV plants due to the removal of the trees and permanent elimination of their carbon sink effect. Balancing the secondary emissions against the emissions avoided by the PV plant *if it replaced* a combined-cycle natural gas power plant, Zero (2017) concluded that over a 20-year horizon the net result would be consistently negative - about 250 tonnes of carbon dioxide per year. The organization supplies the core data they used in the estimate. Replicating their calculations, their conclusions seem generally correct although Zero (2017) omits the primary emissions of the PV panels and considers a lifetime of only 20 years. Also, their assumption about emissions avoidance is not correct: the PV plants avoid the emissions of the electrical grid, not the emissions of a hypothetical combined-cycle gas power plant. In Távora et al (2021) the calculations use a much complete model, which also includes the effect of time on the emissions. Anyway, the concern of Zero (2017) with the secondary emissions and their support for the calculation of full carbon balances for solar plants are important steps to promote public awareness about this issue.

Zero (2017) also proposes government policies regarding solar PV plants: 1) Exclude large PV plants from classified areas (Protected Areas, Natura 2000, RAMSAR Sites, and Biosphere Reserve) unless sited in highly degraded zones; 2) Exclude Large PV plants from forest and agricultural lands whenever the environmental costs are higher than the environmental benefits, for instance if the carbon balance is negative or there is a significant destruction of protected natural values; 3) Give financial incentives to PV power plants over degraded land near urban centres (e.g., mines and abandoned quarries, industrial zones, plots with contaminated soil); 4) Support the self-consumption of renewable energies, namely by housing condominiums and other communities.

Vicente (2019) reports on a large PV plant planned for a natural area in Cernache, near Coimbra. The development would occupy 70 to 100 hectares. "Cidadãos por Coimbra'', a local political organization, expressed their concern about the destructive effects of the power plant and declared their surprise about the inaction of the larger political forces in the region. The plant would have an installed capacity under 50 MW so the project could pass without an EIA. It would affect an area with high biodiversity fauna and flora, nature tracks, and protected fauna and flora as reported by local biologists.

Satellite images from April 2021 examined by the author of this thesis show a vast area from where trees have been removed, roughly corresponding to the shape of the PV plant shown in Vicente (2019). It seems that the developer company, called 'Vertente Planetária', has managed to raze the natural area to install the PV plant. There are several villages around the site of the plant, whose people will likely suffer the impacts of living close to an industrial-scale solar plant.

Silveira (2020) starts by noting that the development of two solar PV stations planned for Torrebela - a large manor near the village of Alcoentre (Azambuja, Lisbon) - had been suspended by the Portuguese government following the slaughter of more than 500 wild animals living on a hunting reserve inside the manor. (The suspension was meanwhile revoked, and the PV plant will proceed.) But Silveira (2020) continues by asserting that the suspension did not clear the impacts already felt in the agriculture and forestry sectors, as well as on biodiversity, caused by the installation of large solar PV parks. And that apart from the "removal" of the wild animals, implementing the power stations at Torrebela, with a total area of 775 hectares, would imply cutting down most of the eucalyptus trees inside the property.

She then interviews the general manager of Celpa - an association of forestry companies that includes the large wood pulp producers. The manager expresses strong concerns with the widespread conversion of forest lands into solar PV plants. He believes that forests, including production forests, are places of high biodiversity and that the conversion leads to a "gigantic sterile areas, in terms of life". He then proposes that forest lands lost to solar PV can be replaced by equivalent areas, i.e., new authorized forestry developments.

Silveira (2020) also interviews the president of Zero, the above-mentioned environmental NGO. Zero's president warns that solar PV plants are being allowed on the National Ecological Reserve (REN). And that although solar PV can be made compatible with ecologically sensitive areas like those in the REN this should only be acceptable for medium sized areas (up to 300 hectares). He also remarks that the landscape is becoming more and more artificial due to solar energy and that PV plants destroy ecosystem services, including the provisioning of wood and carbon dioxide capture. Agriculture is also being affected, he says, with PV solar plants implemented over fertile land of the National Agriculture Reserve (RAN), which could lead to food security problems in the future.

Dias (2021) reports on the anticipated impacts of several large-scale PV projects in Alentejo , which he says are clearly acknowledged in their EIA reports. And compares the sprawl of solar farms to the previous explosion of intensively-cultivated olive groves and almond orchards. He presents a disturbing case where over 100,000 olive trees, planted just five years ago, were removed to place the PV panels of the 48.5 MW Ínsua power plant in the Galinhas manor, near Serpa.

Despite the concerns and opposition, solar PV investments continue to grow unabated, meaning that there must be incentives that lead interested parties to support the solar energy 'wave'. To the author it seems plausible that four parties have vested interests in solar energy developments in Portugal.

Two of them have already been mentioned: solar PV *developers* (and their financial backers) and *landowners* leasing or selling their lands. The former are motivated by the excellent solar resource and a friendly business environment regarding solar power. The latter are captivated by the high leasing prices paid by developers, when compared to the returns of agriculture and forestry.

The other two are the local municipalities and the central government. Regarding the first, it seems from the news and reports that many mayors want to have solar PV over their lands, despite some internal opposition. They have a good financial incentive to do so: the municipal surcharge ("derrama"), which can go up to 5% of the income of the energy companies located in their territories. Apren & Deloitte (2019) estimate that between 2014 and 2018 municipalities collected 12 million euros in "derrama" from renewable energy companies.

The government also has a strong financial incentive: the solar energy *auctions*, in which Portugal was a pioneer. The two auctions in 2019 and 2020 showed that the international investors are willing to sell the solar energy they produce in Portugal for net prices that are very well below the LCOE of solar energy, for extended periods (Willuhn, 2019; Bellini, 2020). As reported by Brito (2020), the government acknowledges that the record low bids are due to the *scarcity* of grid injection points and the fact that the successful bidders receive a *perpetual* connection to the electric grid, an asset they can explore and sell in the future at a profit.

The energy auctions (while interesting for a debt burdened country and possibly bringing benefits to consumers, as the government claims) may lead central authorities to overlook, within reasonable bounds, the environmental problems created by solar PV power: the winners must find lands where to install their solar plants and the sooner they start producing energy the sooner they start compensating the Portuguese state.

2.6.5. Avoiding the environmental impacts of solar PV

Sousa et al. (2021) present an on-going survey of Environmental Impact Assessment (EIA) practice in Portugal to identify if and how Ecosystem Services are reflected in EIA procedures. Recalling international standards, they define EIA as "the process of identifying, predicting, assessing and mitigating potential impacts before making decisions".

The main failure of EIAs in Portugal, the authors argue, is in assessing the impacts on the natural components (water, soil, atmosphere, weather, minerals, landscape, plants, and animals). The assessment is always present, they say, but always performed in a "differentiated way, separating all groups, ignoring all the connections that exist between the biotic and abiotic factors".

Sousa et al. (2021) stress that this practice must be corrected since EIAs should contribute to a healthy environment and to sustainable development. And, to comply with the European legislation and corresponding Portuguese law (Decree-Law no. 152-B/2017), which emphasize the importance of contemplating in the evaluation and decision making about projects the *sustainability of resource usage*, the *protection of biodiversity* and the *mitigation of climate change*. For the authors, the ecosystem services (ES) from Portuguese forests (namely oak forests) should be carefully assessed due to their environmental importance.

The survey of 339 studies collected in 2018 by Sousa et al. (2021) reveals that the concern with ES is poor. The authors report that over half of the EIA documents have *implicit* references to ecosystem services with only 1% mentioning ES explicitly. The studies mention the importance of the study area as feeding, breeding, nursing spots for numerous species but less frequently the services of air purification, soil retention, water-cycle, temperature regulation, and soil improvement. They note more references connecting production services (wood, food) to some affected ecosystems. But references to cultural services are infrequent, and usually related to a scientific value, landscape, tourism, or education. From their results the authors conclude that “ecosystem services are rarely considered in environmental impact studies in Portugal”.

A systematic review of the Environmental Impact Assessment practice *regarding solar PV plants* is out of the scope of this work. However, analysing a sample of EIA documents for sizeable PV plants confirms the findings by Sousa et al. (2021) about the general lack of an integrated approach (PROMAN, 2017; Matos-Fonseca, 2015, Matos-Fonseca, 2020; Recurso, 2018).

In the sample, which includes large, government approved solar plants in several stages of completion, the project is always justified *ex-ante* by the EIA consultants, only in general terms: international and national commitments to reduce GHG emissions and to increase the share of electricity from renewable sources. The rich solar resource in Portugal and in the region reinforces the justification, together with the expected growth of solar PV energy in Portugal. Negative impacts always exist but are always considered acceptable against the overall benefits, evaluated only in general terms, as mentioned. The mitigation measures proposed are poor: one project even states that planting grass below the panels aims to reduce dust that might soil the PV panels.

The technology is never evaluated regarding its own GHG emissions (primary emissions). In some documents there is a simple calculation of the emissions avoided by the PV plant if it replaced electricity from a coal power plant or from a natural gas power plant. No comparison with the carbon footprint of the grid is attempted (although it would certainly show benefits). Primary emissions from PV technology are always omitted. Secondary emissions are always never considered, including in a project that led to the complete removal of a large area of trees in the Torrebela manor (Matos-Fonseca, 2020).

A notable exception is Recurso (2018), which addresses secondary emissions. The EIA consultants calculate the *carbon balance* (secondary emissions) of the area affected by the PV plant using the 2015 release of COS, the Portuguese map of soil occupation mentioned before, and three literature sources providing values for the net absorption of carbon dioxide by the plant biomes inside the project area. They find a significant value of carbon dioxide absorbed by the vegetation to be removed. However, they do not compare the losses in the carbon sink with the benefits brought by the PV plant in avoiding emissions.

The impacts of solar PV power have led other countries to take measures to limit the damages of the unregulated growth of solar energy (Bellini, 2020a; Bellini, 2020b; Bellini 2020c; République Française, 2020; Matalucci, 2021).

Bellini (2020b) reports that the government of Taiwan has severely restricted the installation of PV plants over agricultural land, which led to an important slow-down in the PV capacity additions planned for 2020. One of the regulatory measures was to forbid local authorities from approving PV projects of more than 2 hectares, which must be approved by the central Council of Agriculture. More restrictions were later reinforced, as reported by Bellini (2020c): solar PV plants cannot be installed over the ecologically sensitive areas (bird habitats) where salt is explored. The competition for land between solar PV and other land uses arises from the geography of Taiwan: two thirds of its territory is covered by mountains.

South Korea was also forced to introduce restrictions on solar PV power. Bellini (2019) reports that projects up to 1 MW capacity (which do not require licensing) proliferated in the country causing widespread deforestation. According to the government there were 18,000 unlicensed solar projects. The developers are accused by the opposition party of having cut down 2 million trees nationwide, leading the government to announce restrictions on small-scale arrays to reduce their environmental impact.

As mentioned before in the thesis, another area where some governments are acting is on the evaluation of the carbon footprint of large solar PV plants *before* large projects are approved in PV auctions (République Française, 2020). The example is now being followed by South Korea, as reported by Bellini (2020b). The carbon footprint of PV panels (which are associated with most of the GHG emissions) will be evaluated according to lifecycle assessments of their environmental impacts. The rules apply to national and foreign PV manufacturers.

One of the reasons pointed out by solar PV enthusiasts for the carbon footprint rules is that the two countries currently enforcing them have both nuclear power stations, a low carbon technology, and are trying to protect their nuclear industry. This may be so, but it is arguable that having a low-carbon electric grid is also a way *to set high standards* regarding carbon footprints. Manufacturers *can* cope with the high standards and provide low-carbon PV technology. Chinese manufacturers, for instance, continue to supply silicon modules for large PV power plants in France under the tight government rules.

Governments may take other measures, if environmental impact assessments are poor or biased towards solar PV developers, which pay for the services of EIA consultants. Italy, which has a past of environmental degradation due to solar PV as discussed by Delfanti et al. (2016), has recently announced the creation of a state-controlled technical commission to assess the environmental impacts of solar plants over 10 MW capacity, as reported by Matalucci (2021).

The new regulation is also accompanied by less restrictions to the existing simplified licensing procedure. As the Italian government is projecting large increases in PV capacity for the next few years - there were requests for more than 150 GW in the first half of 2021 - it seems reasonable they want to keep the solar 'wave' under control.

Conclusions

The previous chapters of this thesis developed two main subjects. The first was the endless growth of energy captured by humans throughout history, and its increasingly negative consequences since fossil fuels became the main source of energy in human societies. The second was how a relatively new technology, solar PV power, can be an effective driver of sustainable development, and if so in what conditions. Both subjects are linked by positive and negative effects. Plentiful energy in the future may bring much less inequality, also in the economic sense, if the means to generate energy services are distributed more fairly. And solar PV may also have damaging consequences.

This chapter will now present a set of conclusions that are drawn from what was written across the previous chapters. Each conclusion will occupy a paragraph and be succinct, by referencing the various sections where the matters are discussed. The chapter ends with a discussion of the limitations of the work described in Sections 2.4 and 2.5, followed by research ideas and developments to be pursued later.

The huge amount of energy consumed per capita in present times hides, of course, enormous disparities among world regions, as noted in Section 1.1. Inequalities in energy capture reflect inequalities in income and living standards, since culture in a broad sense can also be seen as an organization of energy, following White (1942) cited in Section 1.4. Trusting the global study by Kikstra et al (2021) there are reasons to believe that the energy required to provide *decent living standards* to the world population in 2040 or 2050 can be met with the current levels of *average* energy consumption – confirming the assertion by the authors that while many people lack energy for a decent living there remains *energy for affluence* appropriated by wealthy segments of the population. A rebalancing will be necessary, or the poorest countries will have to grow enormously, with irrecoverable damage to the biosphere. The figures and projections in IEA (2021a) and IEA (2021b) discussed in Section 1.1 offer some optimism: per capita consumption of energy has been decreasing in developed countries and will decrease further until 2050 due to renewable energy and increased energy efficiency. Future times will not bring generalized *energy starvation*, it seems.

Solar PV power is primed to become the key energy technology for achieving many Sustainable Development Goals (SDGs). ESMAP (2021) shows how the best solar PV potentials can be found in most of the less developed countries, all over the world. Bogdanov et al. (2021) find electricity as the *dominant energy* form within three decades, with solar PV as the *dominant technology* to generate it. The potential of solar PV as a sustainable technology is thoroughly discussed in Section 2.2. While responsible for potential trade-offs with important goals - including *SDG 2 End Hunger* due to the occupation of fertile land, *SDG 12 Responsible Consumption and Production* due to scarce raw materials, and *SDG 15 Life on Land* due to the disturbance of ecosystems and their services – solar PV power has many synergies with the SDGs, including some against which has trade-offs: for instance, solar PV power can be made compatible with agriculture.

The projected increase in solar PV installed capacity, which according to Bogdanov et al. (2021) may reach the astronomical value of 60 terawatt by 2050, raises the question whether these lofty goals can be achieved within the existing reserves of raw materials, and with the currently poor recycling rates. The conclusion is drawn from the discussion in Section 2.2, under *SDG 12 Responsible Consumption and Production*. And, from Section 1.4 in what concerns the concepts of linear versus circular economy, and the discussion about global recycling rates. Returning to the previous conclusion about the role of solar PV in sustainable development, it seems inevitable that: the material footprint of solar PV must be reduced; high levels of recycling must be ensured; technological changes will be needed to avoid bottlenecks in key materials, as discussed by studies cited in Section 2.3.

The environmental impacts of solar PV plants are manageable, but they require adequate policies by governments, namely in countries with high risks of conflict between the use of land for energy and for other essential uses. The environmental impacts of solar PV plants are discussed in detail in the literature review of Section 2.3, together with measures for impact mitigating and the practice of co-benefits, including the preservation of existing ecosystems and the introduction of new ecosystem services - like sheep grazing, beekeeping, and the combination of energy and agricultural production (agrivoltaics). Impacts on the natural and cultural heritage may also be addressed by careful integration of solar PV equipment in natural fields, leading to new *energy landscape*s that are visually acceptable, while being ecologically acceptable. These goals require well defined policies and rules, to be issued by governments and monitored in its application by state authorities. Several policies and rules are discussed in Sections 2.6.3, 2.6.4, and 2.6.5. As it is clear from 2.6.4, stakeholders like local populations, business owners, and environmental organizations should be actively involved in the siting decisions *while* they are being planned.

The future occupation of solar PV plants will be large but always a very small proportion of national territories and a small proportion of areas dedicated to other land uses. Land use conflicts arise because solar developers have *siting preferences* that may increase their profits and lower their costs: sunny, flat plots, near electric grid branches, roads, and towns, and with acceptable land lease prices. As discussed in Section 2.6.4 many landowners have financial incentives to lease their lands for energy even if that means destroying previous agricultural and forestry investments. Regions and councils could, however, plan for future PV occupation by establishing layout and occupation rules for PV power plants. They could, for instance, impose that the area covered by PV panels does not exceed a certain share of the total PV plant area. And take the initiative of *planning for future PV occupation*, at council or regional level, considering the classes of land where power plants might be installed. The dynamical model to estimate future PV occupation areas presented in Section 2.5 can be used for these planning purposes.

Forests and vegetation remove carbon dioxide from the atmosphere and are specified in the Portuguese Roadmap to Carbon Neutrality (RNC2050, 2018) as *the* carbon sink to compensate for GHG emissions still to be released until carbon neutrality is achieved – as illustrated in Section 2.6.2. Cutting down vegetation to install PV power plants should always involve overall carbon balance calculations and measures to offset the lost ecosystem services, including climate regulation. Environmental Impact Assessments for PV power plants should address these two components, or they will fail to comply with minimum standards of sustainability assessment, as discussed in Sections 2.6.4 and 2.6.5. Carbon balances should also include the primary emissions due to the technology. As noted in Section 2.5.8, *precise* information to perform carbon balances with primary and secondary emissions is scarce but that should be no excuse to ignore such an important environmental impact: reference information, which is widely available, is enough to arrive at meaningful estimates. Government directives requiring that solar PV developers divulge the carbon footprint of their products, like those in force in France and Taiwan mentioned in Section 2.6.5, would also be important: not only to arrive at more accurate values for carbon balances but also to encourage PV manufacturers to lower their carbon footprints and not be tempted to export their GHG pollution to countries with low standards. Section 2.5 presents accurate models that can be used to perform carbon balances in PV power plants.

The research presented in Sections 2.4 and 2.5 suffers from limitations, highlighted throughout both sections. Regarding land occupation by PV plants in continental Portugal (Section 2.4), research in progress using satellite imagery will determine for each station the total plant area, the area occupied by PV panels and the area between panels. Together with corrections to installed power values it will enable a more accurate determination of land use intensities, and a more accurate value for the area multiplier M_a. Regarding energy and emission metrics of PV technologies (Section 2.5) the limitations stem from the calculation of secondary emissions. The method must be tested with other forest biomes, and with non-forest biomes that may increase positive carbon balances in PV power plants: for instance, planted grass biomes inside their enclosures. Further tests may include the estimation of carbon balances for existing PV power plants, using data from environmental impact assessments.

Regarding ideas for further research there are two types to consider: new research that may be performed using the spatial-oriented tools developed for the thesis or the knowledge accumulated about PV power plants in Portugal; and new research *extending* the methods developed as part of the thesis. Descriptions, below, follow this order.

Characterizing the land occupation patterns of PV plants in Portugal. This work would determine what were the *former* land use classes of the plots occupied by power plants. It involves using the timeline tools of a satellite imaging system to identify when the land was changed. And establishing the former occupation by a land-use map released *before* the installation of the PV plant - there are soil occupation charts of continental Portugal going back to 1995. The occupation may involve several land uses classes (e.g., forest and shrubland).

Determining the LCOE value of solar PV for continental Portugal. The work would use the PV yield maps determined for the thesis and land price information to be collected from business associations. CAPEX information would be obtained through solar PV installers and PV module manufacturers. Criteria for assigning OPEX costs could be collected from Portuguese solar industry associations and/or from the available international studies.

Developing a cost-benefit analysis methodology for solar PV projects incorporating ecosystem services valuation. This new research subject, already mentioned in Section 2.5.11, would integrate the carbon return accounting method of Section 2.5 - which determines the net value, in CO_2 weight, of the climate-mitigation service of PV power stations - with other methods to calculate net values for added or eliminated ecosystem services. (These would include only ecosystem services for which there are academically-reviewed valuation methods.) The combined values would be converted to a common monetary unit and become part of a cost-benefit analysis tool for energy projects. The research would enrich existing CBA methodologies that include the social cost of carbon with ES valuation.

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A1 - Participation in the EU PVSEC 2020 conference

Távora, J., Cortinhal, M. J., & Meireles, M. (2020). LAND USE INTENSITY AND LAND OCCUPATION OF UTILITY-SCALE PHOTOVOLTAIC POWER PLANTS IN CONTINENTAL PORTUGAL. In *37th European Photovoltaic Solar Energy Conference (EUPVSEC)* (pp. 1975–1978). ISBN: 3-936338-73-6. http://dx.doi.org/10.4229/EUPVSEC20202020-6CV.2.41. http://hdl.handle.net/10071/23446

LAND USE INTENSITY AND LAND OCCUPATION OF UTILITY-SCALE PHOTOVOLTAIC POWER PLANTS IN CONTINENTAL PORTUGAL

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ABSTRACT: Details about Portuguese PV stations are scarce: no public access is provided to project files and environmental impact assessments (EIA) - public-domain information - are mandatory only for power plants of 50 MW or higher capacity, a small minority. In our research, we measured the land use intensity (LUI) of utility-scale PV power plants in continental Portugal and estimated their future land occupation from the capacity additions forecast by the government and from the expected future improvements in LUI due to the increase in PV panel efficiency. A novel method, with land occupation depending simultaneously on the evolution of capacity and panel efficiency, was developed for the purpose. We found 3.336 ha/MW for the average LUI of all stations in operation in continental Portugal, with the LUI varying with mounting type. For land occupation by PV plants in 2050 we found large areas albeit small when compared with other land cover types, e.g. 30 000 hectares would be 1.3% and 0.9% of the current areas dedicated to agriculture and forestry, respectively. However, with EIAs required only for large stations there will be opportunities for land-use conflicts and deep landscape alterations.
Keywords: Large Grid-connected PV Systems, Land use intensity, PV land occupation, Environmental Effect

1 INTRODUCTION

In the last twelve years, Portugal has seen significant developments regarding photovoltaic (PV) solar energy. In 2008, the 45.8 MW Amareleja solar plant started operation and was announced as the world's largest PV power plant [1]. In 2019, at the first auction of unsubsidized PV, a successful bidder committed to supply electricity at 14.8 € per MWh for fourteen years, a worldwide record [2].

Despite all the excitement and Portugal's admission to the "gigawatt club" there is little detailed information about Portuguese PV power plants: the project files cannot be accessed by the public and (public-domain) environmental impact assessments (EIA) are mandatory only for plants of 50 MW or higher capacity, currently a small minority.

The research presented in this paper had two objectives. The first was to calculate the capacity-based land use intensity (LUI) of utility-scale PV power plants in continental Portugal, i.e. those having one MW or higher installed capacity. The second was to estimate future land occupation by PV plants from the government's plans for PV capacity additions [3] and from the improvements in LUI due to the increases in PV panel efficiency.

A novel method, in which land occupation reflects, simultaneously, the evolution of PV capacity and PV panel efficiency, was developed for this purpose.

2 MATERIALS & METHODS

2.1 Land use intensity of PV stations

The land-use intensity of a PV station is the ratio of the total land area it occupies to its installed power or energy delivered yearly to the grid, being commonly stated in hectare per megawatt of installed power (capacity-based LUI) or hectare per megawatt-hour of delivered energy (generation-based LUI). The former may also be expressed as a "power density", in W_{DC}/m^2 or MW_{DC}/ha. To determine the capacity based LUI of PV plants in continental Portugal we needed their full land areas, installed capacities, and mounting types (since the LUI depends on whether the panels are fixed or tracking the daily movement of the Sun). We have used two credible Portuguese sources and performed area measurements using satellite imagery. The first source was the "e2p" database of operating PV plants maintained by INEGI, a research institute, and APREN, an association of renewable energy suppliers. It contains locations, installed capacities in MW_{DC}, administrative data (plant name, owner, developer, dates), and in some cases technology details [4]. The second source was the online GIS map and database by DGEG, a government agency [5]. It includes licensing data (plant name, owner, status, dates) of planned and operating solar plants and, in many cases, station perimeters that rarely match the actual ones seen on satellite imagery. The sources do not agree on the PV stations in operation in continental Portugal: "e2p" records 104 operating plants while DGEG's database records only 89 - while reporting a total of 221 stations, either planned or operating. Filtering "e2p" for one MW or higher capacity we selected 78 ground-mounted plants, to which we added one station identified only in DGEG´s map. Grouping contiguous stations when they were phases of the same project, we obtained a set of 64 station perimeters, which were inspected and measured using Google Earth Pro ™ (including its image timeline and Street View, where available). To confirm findings, we also resorted to all press releases or project references in company sites that could be found about the PV stations. Regarding land occupation our main criterion was to identify the protection fence of each station and measure its inner areas. Grid connection infrastructure (e.g. substations, power lines) was left out. Figure 1, below, illustrates the area measurement process. From perimeter area measurements and installed DC power we calculated the LUI for each station and obtained global and separate distributions according to mounting type. Individual LUI values, $A_P(i)$, were calculated from $P_M(i)$ values taken from the "e2p" database [4] and the area measurements. Dividing the areas by installed capacities yielded $A_P(i)$ in hectare per MW_{DC}. We obtained values for 46 fixed-arrays, 10 single-axis tracking, and 8 dual-axis tracking stations, to be presented in the Results section.

Figure 1: "Ferreira do Alentejo" PV station: installed capacity 12.7 MW_{DC}, total land area 56.5 hectare.

2.2 Future land occupation of PV stations

Future land occupation by PV stations can be derived by simultaneously integrating total installed power, P_M, and average land use intensity, A_P, both dependent on time (Equation 1). Modelling time-dependency linearly yields Equation 2, with K_1 as the growth rate of P_M and M_a relating A_P with K_2, the growth rate of the average PV panel efficiency (Equation 3).

E_{f^*} represents E_f (the panel efficiency, normally defined as a percentage) in MW/hectare. With A_P measured in hectare/MW, M_a becomes a unit less constant.

It should be noted that M_a is an "area multiplier", yielding the total area of a PV station from the total area of its panels. An average value for M_a must be estimated, as shown below.

$$A_T(t) = \iint dP_M dA_P \quad (1)$$

$$A_T(t) = K_1\, M_a \int_{t_0}^{t} \frac{1}{E_{f*}}\, dt = K_1\, M_a \int_{t_0}^{t} \left(\frac{1}{E_{f*}(t_0) + K_2(t - t_0)}\right) dt \quad (2)$$

$$A_p = \frac{M_a}{E_{f*}} \quad (3)$$

Note also that the integral in Equation 2 lacks a term for the initial occupation, $A_T(t_0)$, the area at time t_0. Whether or not this area should be included depends on the time horizon of the projections. For time horizons of 30 or more years the land occupied by existing stations will all be taken by new stations or other uses: the initial area should therefore be discarded. For time horizons shorter than 30 years (the usual lifetime of PV stations) the initial area should be partly included, depending on the age of the existing PV plants at time t_0.

2.2.1 Estimating M_a

The area multiplier M_a can be calculated from Equation 3 by estimating a value for E_{f^*}. As this is the average PV panel efficiency (in MW/hectare) of all the stations used to calculate the LUI, one possible approach is to assume for each station a panel efficiency consistent with the year it started operation. We therefore selected fixed-arrays stations for which the operation starting year was known (43, in total) and assumed that they were equipped with mono-Si or poly-Si panels having the compound efficiency reported in [6]. (The value for 2019 was extrapolated by us.) The results are shown in Table I, below. Computing a weighted-average value for E_f (with the number of stations as weights), converting to E_{f^*}, and then multiplying it by the average A_P for fixed-arrays stations (Cf. Results section) yields an estimate for M_a. Table II, below, illustrates the calculation.

Table I: Estimating the weighted-average PV panel efficiency (43 PV plants, fixed-arrays).

Year	No. PV stations	E_f(%)	E_f (weighted average, %)
2008	1	14.4	
2009	2	14.5	
2010	3	14.8	
2011	1	14.9	
2012	3	15.0	
2013	4	15.3	
2014	15	15.6	
2015	5	15.8	
2016	1	16.3	
2017	3	16.8	
2018	4	17.3	
2019	1	18.5	
			15.7

Table II: Calculating M_a, the area multiplier.

A_p (ha/MW)	E_{f^*} (MW/ha)	M_a
3.075	1.57	4.83

3 RESULTS

The distributions for LUI results, segregated by the mounting type of the sampled PV stations, are summarized in the box plots diagrams of Figures 2, 3 and 4, below. All values shown are in hectare per megawatt of installed power (MW_{DC}).

The distribution for all stations (N=64) is not represented but can be summarized by 3.336, 2.989, 2.224, and 4.247, respectively its mean, median, Q1, and Q3 values.

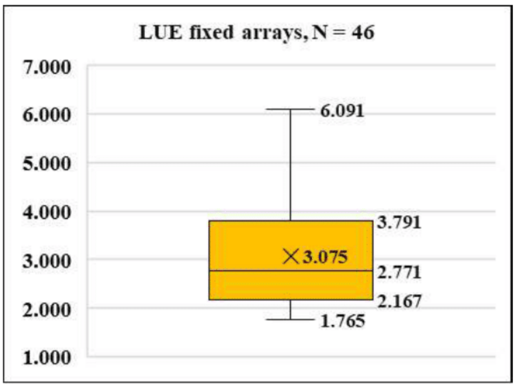

Figure 2: Distribution for fixed-arrays stations.

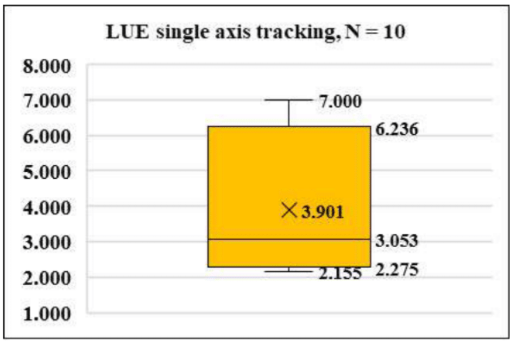

Figure 3: Distribution for single-axis tracking stations.

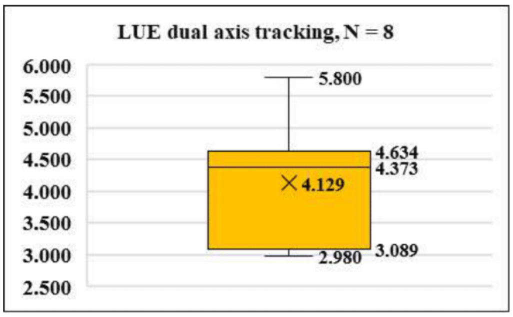

Figure 4: Distribution for dual-axis tracking PV stations.

PV land occupation in 2050 in continental Portugal was estimated using Equation 2 with two power demand scenarios for utility-scale or "centralized" solar energy, defined in the Portuguese official roadmap to carbon neutrality [3].

P_M values at the end of each decade until 2050 were calculated using the average PV output for continental Portugal found in [7]. Fixed-arrays PV stations were assumed to be dominant. PV capacity in 2020 was set equal to 0.9 GW [8]. Average panel efficiency for this simulation was assumed to increase linearly from 20% in 2020 to 24%, 28%, and 32% at the end of each decade until 2050.

Table III, below, shows the two PV electricity scenarios, with the demand values in GWh at the end of each decade [3] and the corresponding installed capacities required by the PV output defined in [7].

Table III: Demand scenarios of the Portuguese roadmap to carbon neutrality in 2050 [3].

Scenarios	**Years**	**Demand** (GWh)	P_M (GW_{DC})
"Peloton" **(PL)**	2030	12.8	8.2
	2040	21.4	13.7
	2050	25.8	16.5
"Yellow Jersey" **(YJ)**	2030	9	5.8
	2040	17.7	11.3
	2050	24.7	15.8

Table IV, below, shows K_1 and K_2 - linear growth rates of installed power and efficiency, respectively - calculated for each decade in the two scenarios. Together with M_a, they form the set of parameters required by Equation 2. The table also shows the partial and total results of the simulation: land areas occupied by PV plants at the end of each decade, and in the year 2050.

Table IV: Growth parameters and land occupation results for the two demand scenarios.

Years	K_1 (MW_{DC}/yr.)	K_2 (%/yr.)	A_T (hectare)
2020-'30	730	0.04	16 071
2030-'40	550	0.04	10 238
2040-'50	280	0.04	4 516
Total PL			30 825
2020-'30	490	0.04	10 988
2030-'40	550	0.04	10 429
2040-'50	450	0.04	7 393
Total YJ			28 810

4 CONCLUSIONS

Concerning land use intensity of PV solar plants, our work is close to [9][10][11] with new measured results for a European country.

Future PV land occupation is addressed in [11][12][13]. Our dynamic estimation model can be contrasted with the static approach of [11], relying instead on the simultaneous evolution of installed capacity and panel efficiency. In fact, since PV stations have lifetimes of 30 years any future land occupation will have contributions of stations with different panel efficiencies. This dynamic is captured in our integral expression, a piece-wise linear model based on the time dependence of both installed capacity and panel efficiency.

Estimating M_a only from presumed panel efficiencies is a limitation of our work. Our team is currently researching complementary methods to estimate M_a that are independent of actual panel efficiencies.

As stated in the Results section, we found an average value of 3.336 hectares per MW_{DC} for the LUI of all utility-scale PV power plants in continental Portugal. This is higher than the value reported in [9] for PV plants in California (2.857 ha/MW_{DC}), although our range of values is smaller. The LUI also varies with the mounting type, consistently with the country-wide USA figures reported in [10].

The areas estimated for PV land occupation in 2050 are large. For instance, 30 000 hectares would correspond to almost 80% of all the area currently taken by roads and railroads; and 26 % of the urban growth in the twenty years between 1995 and 2015. But when compared with the areas of other land uses, they are comparatively small: just 1.3% of agriculture and 0.9% of forestry. It would correspond to just 0.3% of the area of continental Portugal [14].

Future capacity additions to produce green hydrogen and to export electricity could increase PV land occupation beyond the estimates for the current scenarios. On the other hand, unexpected breakthroughs in PV efficiency would reduce the total area.

The figures above allow us to conclude that the main issue regarding future PV land occupation in continental Portugal lies not in its total area but where and how the area will be distributed. A main concern is that environmental impact assessments are currently required only for power stations of 50 MW or higher capacity. This leaves plenty of opportunity for land-use conflicts and deep landscape alterations, especially in the countryside.

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Land use intensity and land occupation of utility-scale PV plants in continental Portugal

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INTRODUCTION

Details about Portuguese PV stations are scarce: there's no public access to project files and environmental impact assessments (EIA) - public-domain information - are mandatory only for 50 MW or higher capacity power plants, currently a small minority.

OBJECTIVES

1. To measure the land use intensity (LUI) of utility-scale PV power plants in continental Portugal (one MW or higher installed capacity).
2. To estimate future land occupation by PV plants in continental Portugal from the capacity additions planned by the government **[1]** and future improvements in LUI with PV panel efficiency. A novel method with occupation depending both on the evolution of PV capacity and panel efficiency was developed for this purpose.

CONCLUSIONS

- The average LUI of all stations in continental Portugal was found to be 3.336 ha/MW, with the LUI varying with mounting type.
- Land occupation in 2050 will be large, although small in relative terms. A land occupation of 30,000 hectares would be: 1.3% of the total agricultural area; 0.9% of the forestry area; 26% of the urban growth in the twenty years between 1995 and 2015; and 0.3% of the area of continental Portugal **[2]**.
- Requiring EIAs only for large stations could thus lead to further land-use conflicts and deep landscape alterations.
- Regarding LUI, our work is close to **[3][6][10]** with new measured results for a European country. Future PV land occupation is addressed in **[3][4][11]**. Our dynamic model departs from the static approach found in **[3]**: our piece-wise linear model relies on simultaneous evolution of both installed capacity and panel efficiency. Ongoing research: estimating M_a independently of panel efficiency.

MATERIALS & METHODS

Future land occupation can be derived by simultaneously integrating total capacity P_M and average land use intensity A_P, both dependent on time (*Eq. 1*). Modelling time-dependency linearly yields *Eq. 2*, with K_1 as the growth rate of P_M. M_a relates A_P with K_2, the growth rate of the average PV panel efficiency E_{f*} in MW/hectare (*Eq. 3*). M_a gives the total area of a PV station from the area of its panels. An average value for M_a must be estimated, as shown below.

$$A_T(t) = \iint dP_M dA_P \qquad (1)$$

$$A_T(t) = K_1\, M_a \int_{t_0}^{t} \frac{1}{E_{f*}}\, dt = K_1\, M_a \int_{t_0}^{t} \left(\frac{1}{E_{f*}(t_0)+K_2(t-t_0)}\right) dt \qquad (2)$$

$$A_p = \frac{M_a}{E_{f*}} \qquad (3)$$

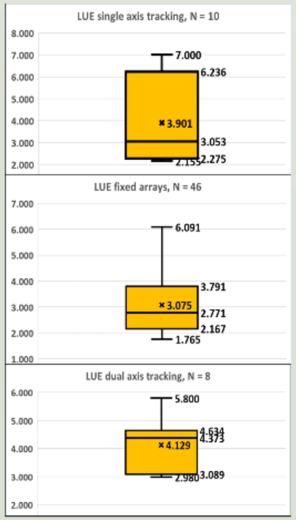
Year	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	E_f (weight. avg.)
No. stat.	1	2	3	1	3	4	15	5	1	3	4	1	
E_f (%)	14.4	14.5	14.8	14.9	15	15.3	15.6	15.8	16.3	16.8	17.3	18.5	15.7

A_P (ha/MW)	E_{f*} (MW/ha)	M_a
3.075	1.57	4.83

M_a was estimated from 43 fixed-arrays stations having, presumably, mono-Si and poly-Si panels with compound efficiency as reported in **[7]**. Multiplying, the weighted-average E_{f*} in MW/ha by their average A_p in ha/MW yields the unit-less M_a.

Individual capacity-based LUI values, $A_P(i)$, were calculated from $P_M(i)$ values from the "e2p" **[9]** database and area measurements using Google Earth™, as pictured above. Dividing the areas by installed capacities yielded $A_P(i)$ in hectare per MW_{DC}. We obtained values for 46 fixed-arrays, 10 single-axis tracking, and 8 dual-axis tracking stations. Subsequent phases of the same station were measured together.

RESULTS



Results for LUI by mounting type are shown on the box-plot diagrams. The results for all stations (N=64) were: 3.336 ha/MW, mean value, with Q1, median, and Q3 equal to 2.224, 2.989 and 4.247, respectively.

PV land occupation in 2050 in continental Portugal was estimated from *Eq. 2* with two power demand scenarios for PV utilities defined by the government **[1]**. P_M values at the end of the three decades to 2050 were calculated using the average PV output given in **[8]**. Fixed-arrays were assumed to be dominant, and PV capacity equal to 0.9 GW in 2020 **[5]**. Panel efficiency was assumed to go from 20% in 2020 to 24%, 28%, and 32% by the end of each decade.

Scenarios	Years	Demand (GWh)	P_M (GW)
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A2 - Participation in the EU PVSEC 2021 conference

Távora, J., Cortinhal, M. J., & Meireles, M. (2021). GREENHOUSE GAS EMISSIONS AVOIDANCE BY PHOTOVOLTAIC PLANTS ON THE ROAD TO CARBON NEUTRALITY. In *38th European Photovoltaic Solar Energy Conference (EUPVSEC)* (pp. 1975–1978). ISBN: 3-936338-78-7. https://www.eupvsec-proceedings.com/proceedings?advanced[title]=GREENHOUSE+GAS+EMISSIONS+AVOIDANCE+BY+PHOTOVOLTAIC+PLANTS+ON+THE+ROAD+TO+CARBON+NEUTRALITY&advanced[date]=&advanced[author]=&advanced[keyword]=&paper=50209

GREENHOUSE GAS EMISSIONS AVOIDANCE BY PHOTOVOLTAIC PLANTS ON THE ROAD TO CARBON NEUTRALITY

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ABSTRACT: Roadmaps to carbon neutrality challenge GHG emissions savings by solar PV energy: current systems are still largely produced using fossil fuels and PV plants occupy for decades land areas that might capture and store atmospheric carbon. We take primary emissions from three PV technologies and secondary emissions from vegetation clearing in PV power plant sites and compare them to lifecycle emissions savings from PV energy over continental Portugal assuming that the carbon intensity of the electrical grid is decreased linearly to near zero in thirty years. The balance is revealed by the emissions payback time (CPBT) metric. In our approach, time affects emissions over a PV plant's lifetime in three ways: overall decreasing grid carbon intensity, yearly avoided grid emissions, and yearly cancelled carbon capture due to land cover clearing - a forest of planted eucalyptus trees. Results for mono-Si reveal mean emissions payback times of 14 years for the lowest irradiation places, and 10.5 to 12.5 years for 93% of the territory. Secondary emissions increase the mean value to 19, with a maximum of 24 years. These figures strongly recommend that national regulators enforce checks on primary and secondary emissions by PV systems sited on forested land.
Keywords: CO2 footprint, Environmental effect, Sustainable, Carbon payback time, Secondary emissions.

1 INTRODUCTION

Massive deployment of solar photovoltaic energy is currently a main strategy to decarbonize electricity supply in roadmaps to carbon neutrality being deployed in many countries, including Portugal [2]. Solar PV plants contribute to reduce GHG emissions by replacing fossil fuel power generators. But their emissions avoidance role will be challenged by the steep decarbonizing process because PV modules are still largely produced using fossil fuels and PV power plants occupy for decades large areas of land that might capture and store atmospheric carbon.

Our research addresses the interplay among the declining carbon intensity of the electrical grid, the GHG emissions of the materials and manufacture of PV systems, and the emissions caused by cutting down vegetation when installing PV power plants, and how these factors modify emissions avoidance. We assess the balance between the emissions avoiding effects of PV power plants and their own primary and secondary emissions in continental Portugal. The GHG Emissions Payback Time also referred as Carbon Payback Time (CPBT) is used to appraise the result. Primary emissions will be CO_2 equivalent releases from materials and manufacture of PV components. And secondary emissions will be CO_2 releases from land transformation: cutting down the vegetation cover and cancelling its constant carbon-capture activity. Time is a key factor in our analysis: the emissions from the electrical grid will steadily decline due to the roadmap to carbon neutrality [2] but at the same their release occurs *continuously* and therefore their effect on the atmosphere declines as time passes. The same happens with the CO_2 not captured from the atmosphere due to vegetation clearing – equivalent to a CO_2 emission. On the contrary, the GHG emissions from PV materials and manufacture are conventionally released as an *impulse* just prior to the installation and are not affected by the passage of time. In our assessment, secondary emissions will be caused by cutting down planted eucalyptus forests, one of largest biomes in continental Portugal [9].

Our work is close to [1][4][6][10][14] but based on a detailed geospatial approach that includes nineteen plant biomes and considers the effect of time on emissions. [1] and [10] study secondary emissions from cut down forests in the US. [6] and [14] present PV metrics across Europe and the world, respectively, but do not include secondary emissions nor the evolution of emissions with time. [14] report regions in Europe with emissions payback times over 10 years, namely in France, Sweden, and Norway. [4] report carbon payback times for PV plants in Brazil showing how a low carbon intensity electrical grid may lead to carbon payback times near or over PV plant lifetimes. They have also point out that emissions from PV systems are expressed mostly before operation while grid emissions will be spread over PV plant lifetimes, although their work does not develop the subject.

2 MATERIALS & METHODS

To obtain primary GHG emissions we combined monocrystalline silicon (m-Si), cadmium telluride (CdTe), and copper indium selenide (CIS) product data from, respectively, Jinko™, First Solar ™, and Solar Frontier ™ with LCA results from [12] as displayed in Table I. The 'product stage' of PV components was chosen as system boundary, consistently with the sources. The 'functional unit' is the alternating current output of the inverters. Solar yields and losses for continental Portugal were obtained by several processes. For average yearly irradiation and inclination, spectrum, and temperature and low irradiation losses on south-oriented, optimally inclined panels we queried PVGIS ™ at 3751 locations, forming a 5.5 km resolution grid, through a custom developed program. Lifetime average degradation losses for PV modules were taken from product datasheets (Cf. Table I), except degradation for CIS, taken from [7]. System losses were fixed at 4%.

One-off CO_2 emissions from clearing eucalyptus forests were obtained from tree carbon content in [5] and maps in [9]. We assumed that trees cut down would be converted at once into CO2 emissions, a reasonable simplification since eucalyptus trees are used mostly for wood fuel and wood pulp. Measurements of yearly carbon capture by eucalyptus plantations were taken from [15]. Total PV plant areas were assumed to be four times PV panel areas - a conservative, revised figure by the authors, lower than the value estimated in [17]. We also assumed that the whole PV station area was initially covered by trees. Values for the current and planned future GHG grid emissions were taken from [2] and [8].

The timing of GHG emissions by a source influences its global warming effect [3][11][13]. Compared to an emission occurring at t_0 an emission happening t years in the future will stay in the atmosphere t years less at the end of an analytical time horizon. The method of Time Adjusted Warming Potentials (TAWP) [11] integrates emissions timing in global warming calculations through TAWP coefficients that adjust later emissions so that they can be compared at some initial time $\mathbf{t_0}$. Table 2, below, illustrates the method applied to electrical grid emissions in the next 30 years assuming the Portuguese roadmap to carbon neutrality [2], and to secondary emissions from cancelled carbon capture by a eucalyptus forest. The analytical time horizon was chosen to be 100 years – a conservative approach that enables comparing TAWP results with PAS 2050 results shown in the last column. The TAWP coefficients were calculated by a 3rd degree polynomial regression provided by [11] as supplementary information.

Emissions balancing are illustrated by the GHG Emissions Payback Time metric, also known as Carbon Payback Time (CPBT), calculated from Equation 1.

$$CPBT = \frac{CC_{mat} + CC_{manuf}}{\frac{CC_{avoided\ LT}}{LT}} \qquad (1)$$

CC_{mat} and CC_{manuf} are the climate change impacts of the materials and manufacturing of the PV system components, in gCO_2e. $CC_{avoided\ LT}$ represents emissions avoided during the PV plant's lifetime, LT, also in gCO_2e.

Table I: Technical and environmental characteristics of PV components.

Tech.	Origin	Capacity @STC [W_P]	Panel area [m^2]	Eff. [%]	LT average Degradation [%]	Emissions [$kgCO_2e/kW_p$]	Emissions [$kgCO_2e/m^2$]	Energy mat & fab. [MJ/kW_p]	Energy mat & fab [MJ/m^2]
m-Si	China	345	1.687	20.45	9.89	1980	398.96	26500	5339.7
CdTe	USA	450	2.475	18.18	8.20	650	118.18	10500	1909.0
CIS	Japan	144	1.228	11.73	0.30	1050	123.12	17600	2063.7

Table II: Calculations of the effect of time on emissions (T.A. = Time-adjusted).

Time [years]	TAWP AT = 100 years	Grid carbon intensity [gCO_2/kWh)]	Grid carbon int. (T.A.) [gCO_2/kWh]	Secondary emissions [$kgCO_2/m^2$]	Secondary emissions (T.A.) [$kgCO_2/m^2$]	PAS 2050 general case N= 30 years
0	1	254.0	254.0	35.23	35.23	
1	0.9918043	245.6	243.6	9.24	9.16	0.0330
2	0.9836389	237.2	233.3	9.24	9.09	0.0327
3	0.9755018	228.8	223.2	9.24	9.01	0.0323
(…)	(…)	(…)	(…)	(…)	(…)	(…)
28	0.7752386	18.5	14.4	9.24	7.16	0.0240
29	0.7671133	10.1	7.8	9.24	7.09	0.0237
30	0.7589607	1.7	1.3	9.24	7.01	0.0233
	TAWP avg. weighting factor	Lifetime average	Time-adjusted lifetime average	Lifetime total	Time-adjusted lifetime total	PAS 2050 weighting factor
	0.8794	123.6	113.3	312.4	277.9	0.8450

Table III: Mean and limit values for carbon payback time distributions.

Metric	m-Si			CdTe			CIS		
	Min.	**Mean**	Max.	Min.	**Mean**	Max	Min.	**Mean**	Max.
CPBT **Carbon Payback Time** [years]	9.8	**11.2**	14.4	3.1	**3.6**	4.6	4.9	**5.5**	7.1
CPBT **with secondary emissions** [years]	16.7	**19.3**	24.3	10.6	**12.2**	15.5	16.0	**18.3**	23.0

3 RESULTS

Table III presents the mean value and limits of CPBT distributions of the three PV technologies, for primary and total (primary and secondary) emissions. Regarding primary emissions, CdTe and CIS have much lower carbon payback times than monocrystalline silicon, as expected. However, when adding secondary emissions, their CPBTs increase dramatically due to the additional weight in the numerator of Equation 1. CdTe, for instance, features 118.2 $kgCO_2e/m^2$ of primary and 277.9 $kgCO_2e/m^2$ of secondary emissions, so the latter are 2.4 times higher than the former. Thin-film advantages over m-Si are thus strongly reduced as can be seen from Table III. Figure 1 shows the spatial distribution of CPBT for monocrystalline silicon over the eucalyptus biome, for primary emissions. Figure 2 shows a similar result for total emissions. Analysis of the histogram of primary emissions of monocrystalline silicon over continental Portugal reveals that 93% of the territory has carbon payback times of between 10.5 to 12.5 years.

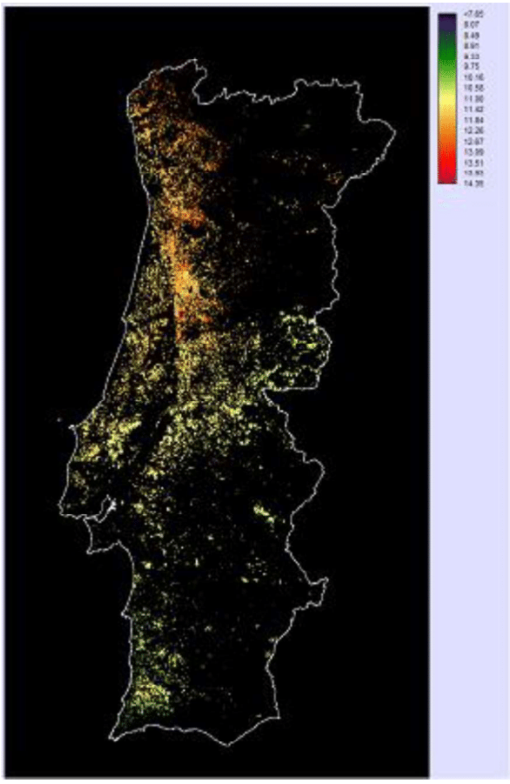

Figure 1: CPBT on eucalyptus areas – primary emissions

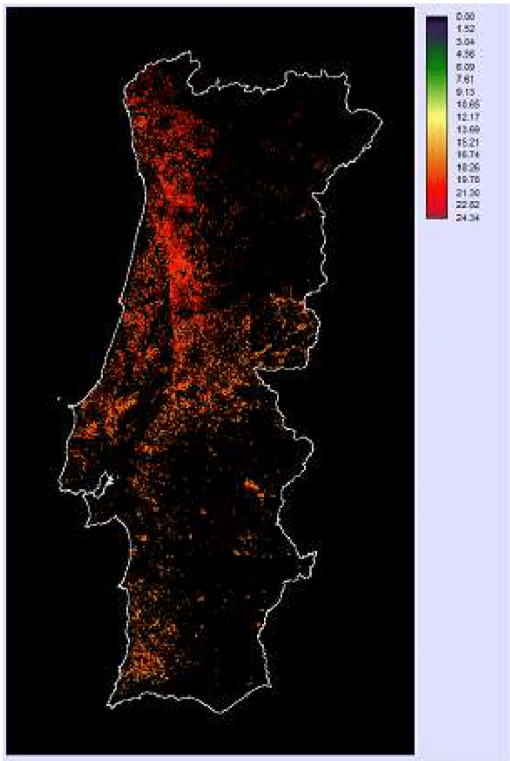

Figure 2: CPBT on eucalyptus areas – total emissions

4 CONCLUSIONS

Our results clearly demonstrate that primary emissions alone are responsible for large values of carbon payback times for the dominant PV technology – crystalline silicon. This happens in a country with one of the best solar resources in Europe but with a national electricity grid with just an intermediate level of carbon intensity. The reason is the introduction in our analysis of an inescapable reality: roadmaps to carbon neutrality will steeply reduce the carbon intensity of the grid in the next decades leaving PV power plants installed *now* (on in the next few years) with reduced emissions saving capabilities. Another reason is at play, stressed for instance in [4]: importing PV technology with high or moderate carbon footprint and implementing it in countries with a low grid carbon intensity (Brazil or France, for instance) will weaken or even cancel any emissions avoidance advantage.

Secondary emissions have been mostly neglected in the appraisal of emissions avoidance by PV systems, except for [1][10]. Our example shows, however, that in the case of forested land being cleared for PV power plants their contribution can be determinant. In fact, as PV technology reduces its inherent carbon footprint (e.g., through "solar for solar" approaches), secondary emissions and other impacts in ecosystem services will come to the foreground. We believe that soon, for some technologies and implementation regions GHG avoidance by PV power plants will cease to be a relevant justification to change land use: PV projects will instead be evaluated by their ability to not degrade ecosystems or by introducing new ecosystem services improving overall benefits - including climate positive outcomes as it may happen with agrivoltaics.

A main recommendation from our research is that national regulating authorities should enforce checks on carbon footprint credentials of PV technologies, as in already happens in one European country [16]. Secondary emissions from PV implementation should also in environmental impact assessments, together with primary emissions.

Our work resorts to simplifications, which do not affect its general conclusions: the vegetation to cleared occurs in the full area of the power station and is fully cut down; soil carbon remains undisturbed by vegetation removal; initial vegetation clearing results in products with a very short lifecycle compared to the lifetime of the plant; and PV recycling does contribute to negative emissions. The assumptions are all plausible, depending on each case. Much research work remains to be done, namely about carbon capture measurements for the main ecosystems in the country, considering local climate conditions [15].

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GHG emissions avoidance by photovoltaic plants on the road to carbon neutrality

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INTRODUCTION

Roadmaps to carbon neutrality challenge the GHG emissions saving capability of solar PV energy since current PV modules are still largely produced using fossil fuels and because PV power plants occupy for decades large areas of land that might capture and store atmospheric carbon.

OBJECTIVES

We assess the balance between the emissions avoiding effects of PV power plants and their primary and secondary GHG emissions in continental Portugal. Primary emissions are, in our case, CO2 equivalent releases from materials and manufacture of PV components. Secondary emissions are CO2 releases from land transformation: cutting down the plant cover and cancelling its permanent carbon-capture activity. Importantly, we consider the Portuguese roadmap to carbon-neutrality, a 'moving target' constantly reducing electrical grid emissions. Also, the effect of time on the avoided GHG grid emissions and on the cancelled carbon capture by the plant cover. In our assessment, secondary emissions result from clearing managed forests of eucalyptus, one of largest biomes in continental Portugal .

CONCLUSIONS

- Results for primary emissions reveal mono-Si carbon payback times over 14 years in the lowest irradiation places, with between 10.5 and 12.5 years for 93% of the territory.
- Clearing a forest of eucalyptus, a highly efficient net carbon absorber **[12]**, to install a PV power plant increases the mean carbon payback time by 8 years and makes it reach a maximum of 24 years.
- These results justify the urgent need to qualify the carbon footprint of PV technologies used in Portugal and to evaluate secondary emissions in environmental impact assessments of PV power plants in forested land.
- Our work is close to **[1][3][7][11]** with new contributions regarding the effect of time on GHG emissions over the lifetime of PV systems.

MATERIALS & METHODS

To obtain primary GHG emissions we combined m-Si, CdTe, and CIS product data from, respectively, Jinko™, First Solar ™, and Solar Frontier ™ with LCA results from **[10]** as in 1st table, below. Solar yields and losses for about 4000 locations were obtained by querying PVGIS™. System losses were fixed at 4%. One-off CO2 emissions from clearing eucalyptus forests were obtained from tree carbon content in **[4]** and maps in **[6]**. We assumed that trees cut down would be converted immediately into CO2 emissions. Measurements of carbon capture by eucalyptus plantations were taken from **[12]**. Total PV plant areas were assumed to be four times PV panel areas **[13]**. Values for the current and planned future GHG grid emissions were taken from **[5]** and **[2]**. For the effect of time we used the TAWP method **[9]**, comparing it to PAS 2050 **[8]** as shown in the 2nd table, below.

Tech.	Origin	Cap. @STC [Wp]	Panel area [m2]	Eff. [%]	Degrad. LT avg. [%]	Emissions [kgCO2e /kWp]	Emissions [kgCO2e /m2]	Energy mat. & fab. [MJ/kWp]	Energy mat. & fab. [MJ/m2]
m-Si	China	345	1.687	20.45	9.89	1 980	398.96	26 500	5 339.7
CdTe	USA	450	2.475	18.18	8.20	650	118.18	10 500	1 909.0
CIS	Japan	144	1.228	11.73	0.30	1 050	123.12	17 600	2 063.7

Time [yrs.]	TAWP AT = 100 years	Grid carbon intensity [gCO2/kWh)]	Grid carbon int. (T.A.) [gCO2/kWh]	Secondary emissions [kgCO2/m2]	Secondary emiss. (T.A.) [kgCO2/m2]	PAS2050 general case 30 years
0	1	254.0	254.0	35.23	35.23	-
1	0.9918043	245.6	243.6	9.24	9.16	0.003330
2	0.9836389	237.2	233.3	9.24	9.09	0.003267
3	0.9755018	228.8	223.2	9.24	9.01	0.003233
(…)	(…)	(…)	(…)	(…)	(…)	(…)
28	0.7752386	18.5	14.4	9.24	7.16	0.002400
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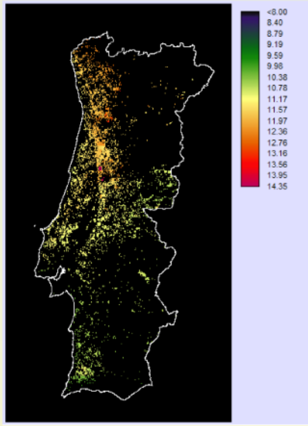
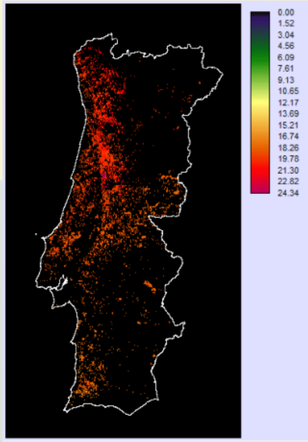
30	0.7589607	1.7	1.3	9.24	7.01	0.002333
	TAWP weighting factor	Lifetime average	Time-adjust. lifetime average	Lifetime total	Time-adjust. lifetime total	PAS2050 weighting factor
	0.8794	123.6	113.3	312.4	277.9	0.8450





RESULTS

Metric	Mono-Si			CdTe			CIS		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
CPBT Carbon Payback Time [years]	9.8	**11.2**	14.4	3.1	**3.6**	4.6	4.9	**5.5**	7.1
CPBT with sec. emissions [years]	16.7	**19.3**	24.3	10.6	**12.2**	15.5	16.0	**18.3**	23.0

The table on the left shows the limits and mean values for distributions of carbon payback times, with primary and both primary and secondary emissions. Above, two CPBT maps with the spatial distribution for mono-Si: top, primary emissions; bottom, total emissions. Velvet spots on the top map are the lowest yield areas, with irradiation not lower than 1500 kWh/m^2.yr^{-1}.

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A3 - Maps and Additional Tables

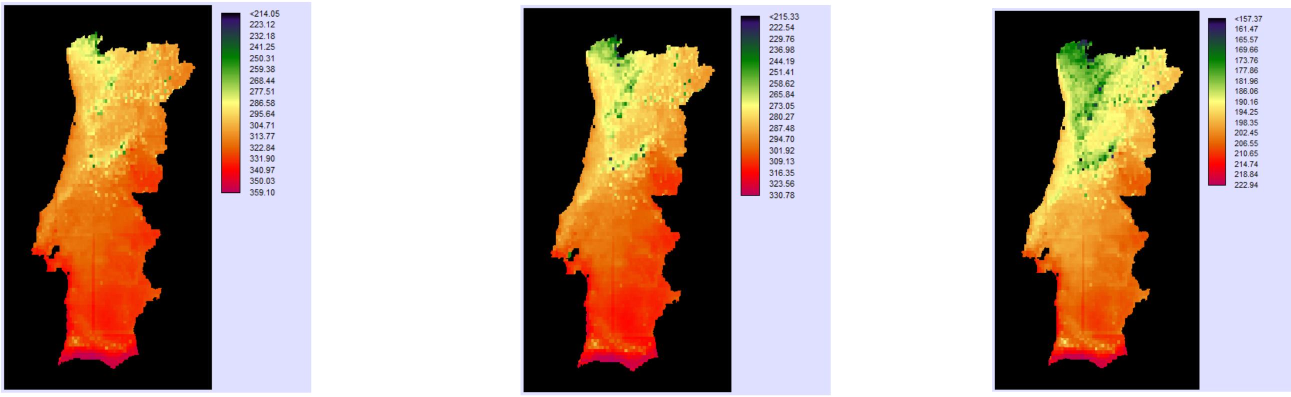

Figure A3.1 – PV yield in kWh/m2/year (Mono-Si, CdTe, CIS)

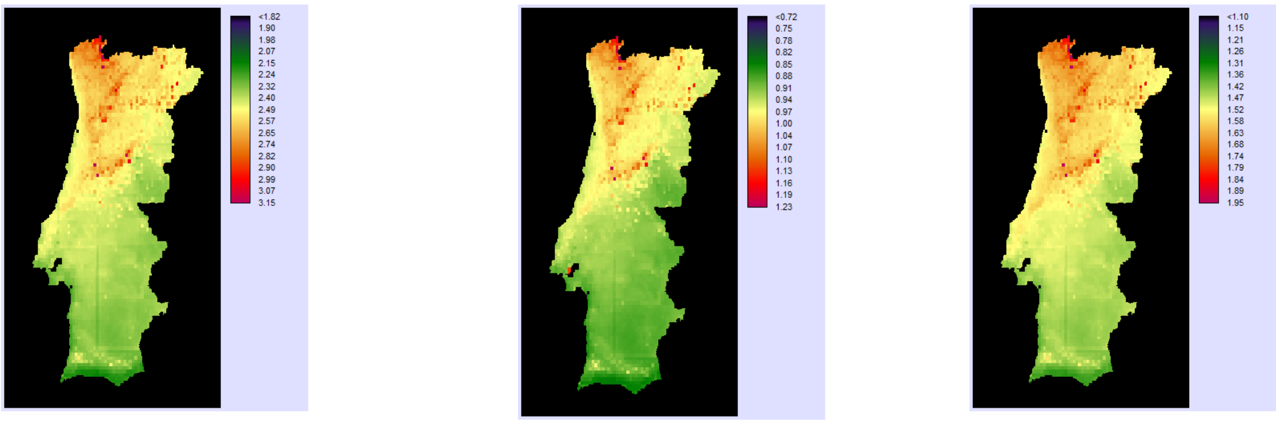

Figure A3.2 – Energy Payback Time in years (Mono-Si, CdTe, CIS)

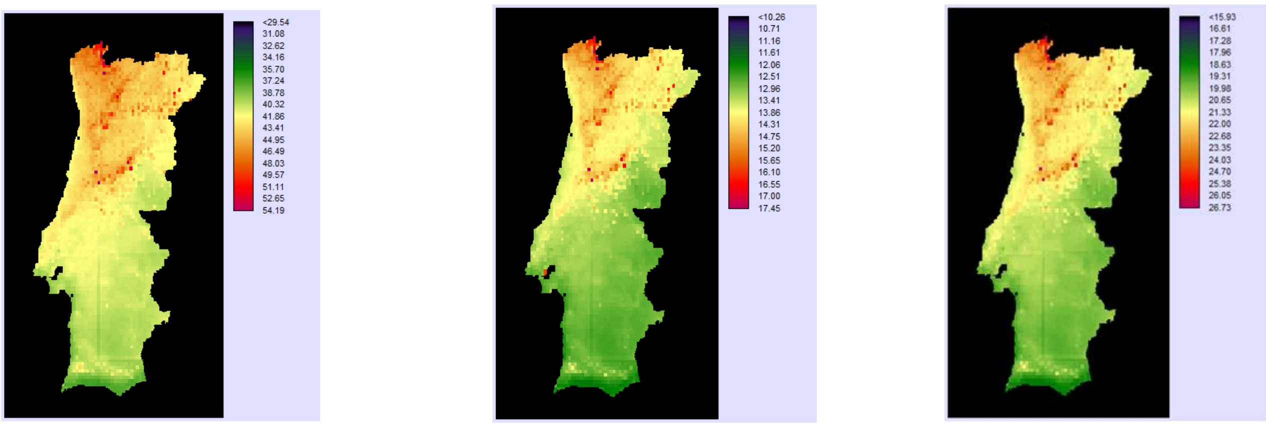

Figure A3.3 – Carbon Footprint in gCO2e/kWh (Mono-Si, CdTe, CIS)

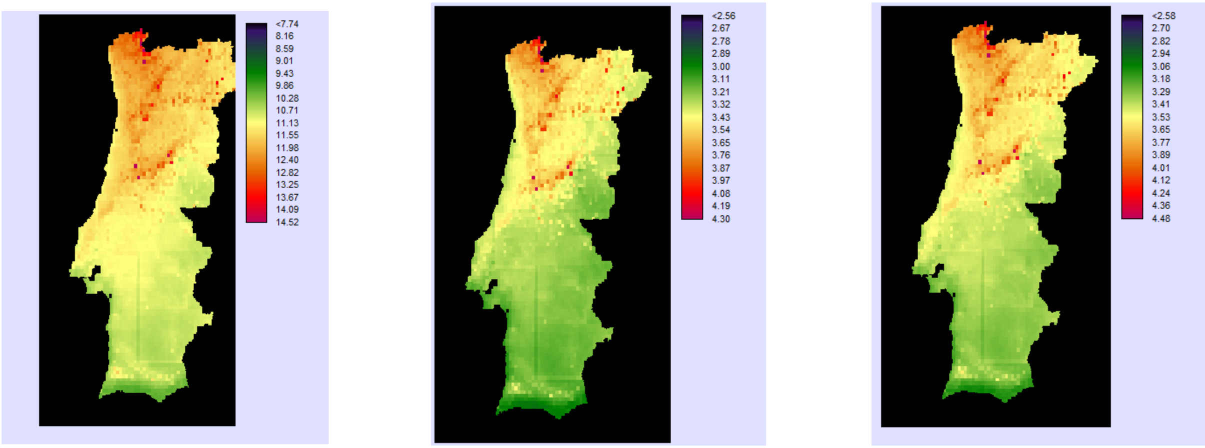

Figure A3.4 – Carbon Payback Time in years (Mono-Si, CdTe, CIS)

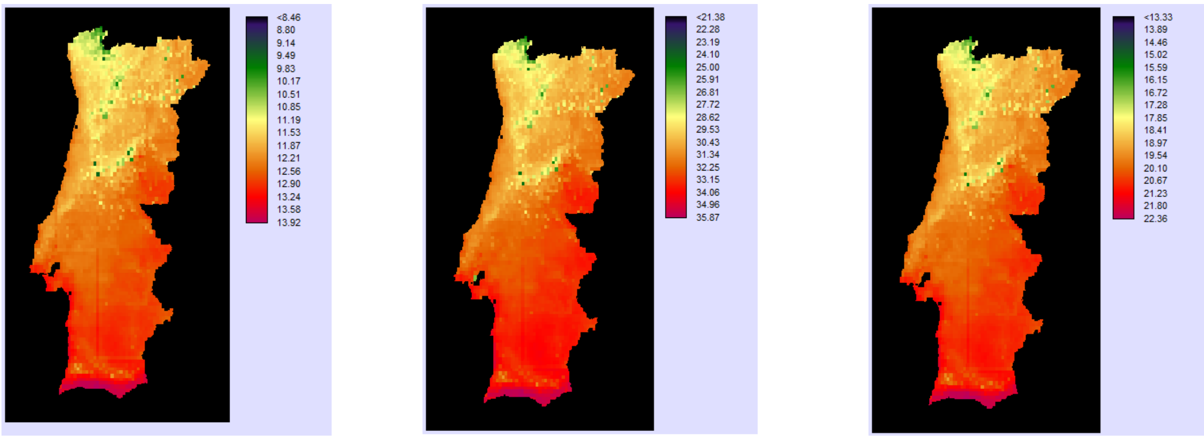

Figure A3.5 – EROI ratio (Mono-Si, CdTe, CIS)

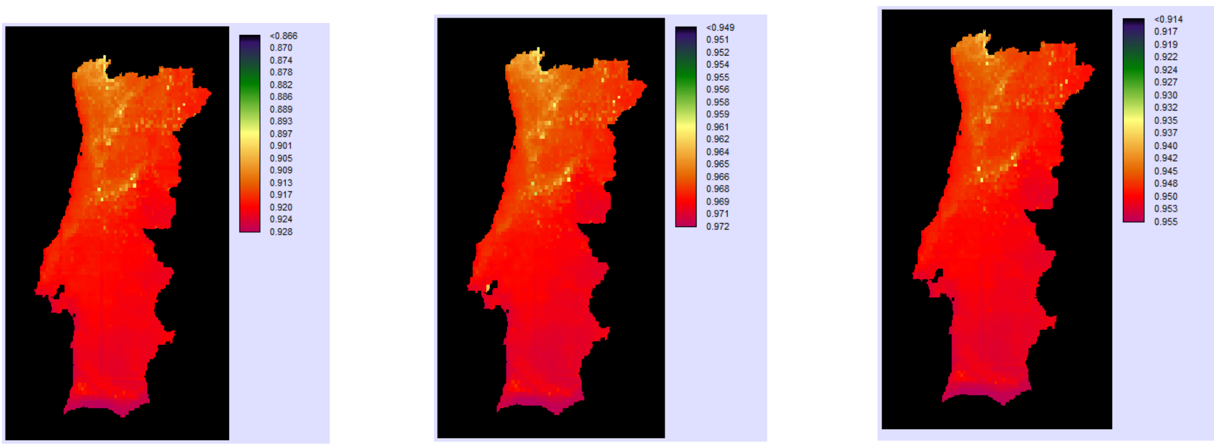

Figure A3.6 – NTG ratio (Mono-Si, CdTe, CIS)

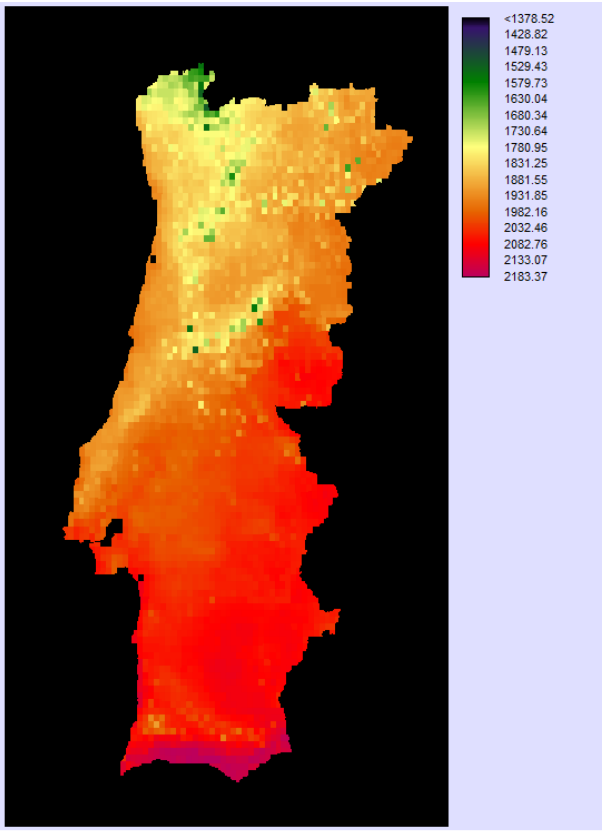

Figure A3.8 – Irradiation map in kWh/m2/year

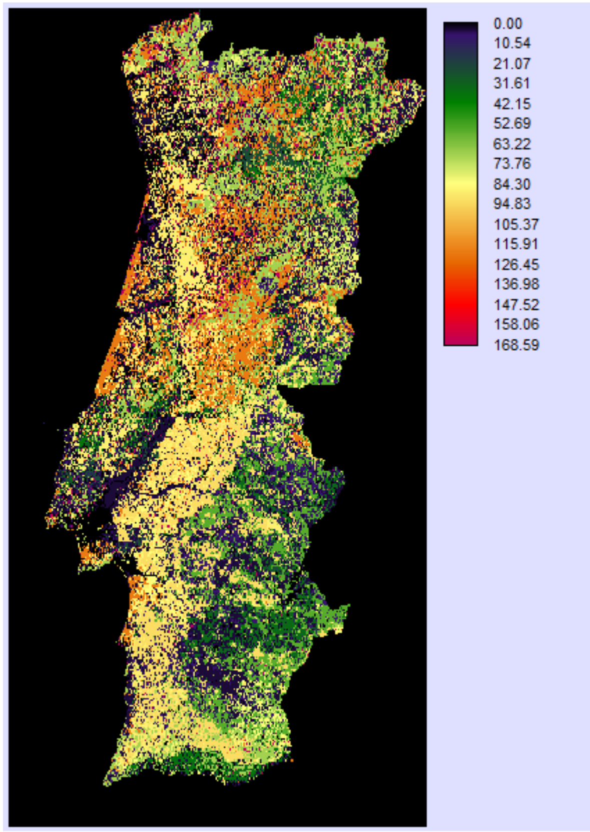

Figure A3.7 – CO_2 emissions map in Mg/hectare

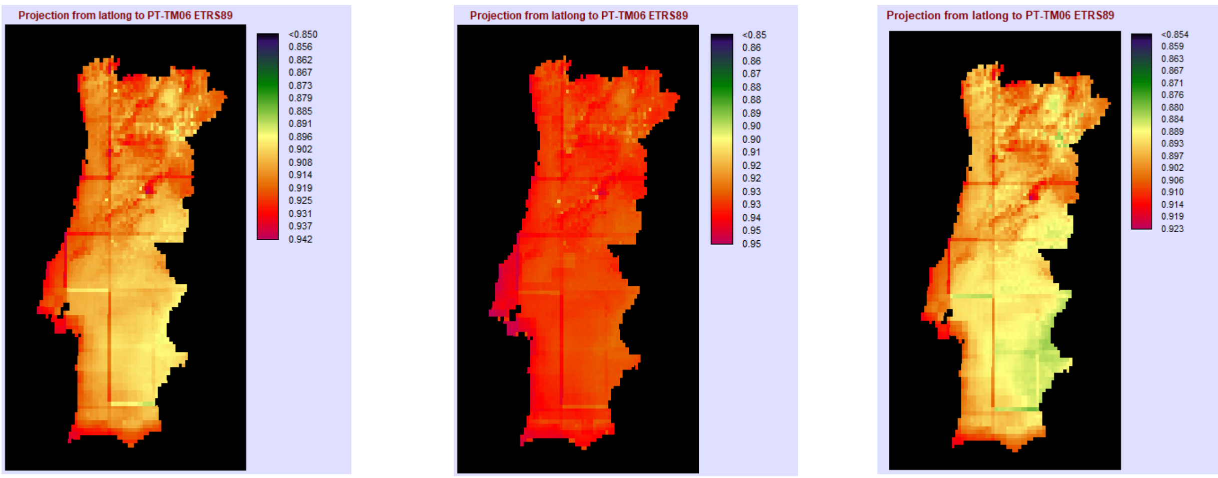

Figure A3.9 – Total PV error maps given by PVGIS (Mono-Si, CdTe, CIS)

Table A3.1 – Carbon and carbon dioxide stocks for selected COS2018 land-use *classes*

Map No.	Map filenames (raster, vector)	COS2018 Lg	COS2018 n1	NIR_global_2019 (UNFCCC) Land use categories	AGB	BGB	Litter	Total Carbon (Mg/hectare)	Total CO2 (Mg/hectare)
1	COS2018-AGRICULTURA-VINHAS	2.2.1.1 Vinhas	2.Agricultura	Vineyards	3.34	2.87	0.33	6.54	23.98
2	COS2018-AGRICULTURA-CULT-TEMP-PAST-ASSOC-VINHA	2.3.1.1 Culturas temporÃ¡rias e/ou pastagens melhoradas associadas a vinha	2.Agricultura	Vineyards	3.34	2.87	0.33	6.54	23.98
3	COS2018-AGRICULTURA-OLIVAIS	2.2.3.1 Olivais	2.Agricultura	Olive groves	7.85	1.15	0.33	9.33	34.21
4	COS2018-AGRICULTURA-CULT-TEMP-PAST-ASSOC-OLIVAL	2.3.1.3 Culturas temporÃ¡rias e/ou pastagens melhoradas associadas a olival	2.Agricultura	Olive groves	7.85	1.15	0.33	9.33	34.21
5	COS2018-AGRICULTURA-POMARES	2.2.2.1 Pomares	2.Agricultura	Other permanent crops	8.46	1.48	0.33	10.27	37.66
6	COS2018-AGRICULTURA-CULT-TEMP-PAST-ASSOC-POMAR	2.3.1.2 Culturas temporÃ¡rias e/ou pastagens melhoradas associadas a pomar	2.Agricultura	Other permanent crops	8.46	1.48	0.33	10.27	37.66
7	COS2018-AGRICULTURA-CULT-TEMP-SEQ-REGADIO	2.1.1.1 Culturas temporÃ¡rias de sequeiro e regadio	2.Agricultura	Rainfed annual crops/Irrigated annual crops (exc. Rice)	0.31	0.31	0.33	0.95	3.48
8	COS2018-AGRICULTURA-AGRIC-PROTEG-VIVEIROS	2.4.1.1 Agricultura protegida e viveiros	2.Agricultura	Rainfed annual crops/Irrigated annual crops (exc. Rice)	0.31	0.31	0.33	0.95	3.48
9	COS2018-AGRICULTURA-ARROZAIS	2.1.1.2 Arrozais	2.Agricultura	Rice paddies	0.31	0.31	0.33	0.95	3.48
10	COS2018-AGRICULTURA-MOSAICOS-PARCEL-CULTURAIS-COMPLEXOS	2.3.2.1 Mosaicos culturais e parcelares complexos	2.Agricultura	Rainfed annual crops/Irrigated annual crops (exc. Rice)	0.31	0.31	0.33	0.95	3.48
11	COS2018-AGRICULTURA-COM-ESPAÇOS-NAT-SEMI-NATURAIS.rst	2.3.3.1 Agricultura com espaÃ§os naturais e seminaturais	2.Agricultura	Rainfed annual crops/Irrigated annual crops (exc. Rice)	0.31	0.31	0.33	0.95	3.48
12	COS2018-PASTAGENS-PAST-ESPONTANEAS	3.1.2.1 Pastagens espontÃ¢neas	3.Pastagens	All grasslands	0.53	0.94	0.41	1.88	6.89
13	COS2018-PASTAGENS-PAST-MELHORADAS	3.1.1.1 Pastagens melhoradas	3.Pastagens	All grasslands	0.53	0.94	0.41	1.88	6.89
14	COS2018-VEGETACAO-ESPARSA	7.1.3.1 VegetaÃ§Ã£o esparsa	7. EspaÃ§os descobertos ou com pouca vegetaÃ§Ã£o	All grasslands	0.53	0.94	0.41	1.88	6.89
15	COS2018-MATOS-MATOS	6.1.1.1 Matos	6.Matos	Schrublands	8.78	4.96	4.94	18.68	68.49
16	COS2018-FLORESTAS-FLOR-SOBREIRO	5.1.1.1 Florestas de sobreiro	5.Florestas	Quercus suber	20.4	2.94	2.04	25.38	93.06
17	COS2018-FLORESTAS-FLOR-AZINHEIRA	5.1.1.2 Florestas de azinheira	5.Florestas	Quercus rotundifolia	8.37	4.92	2.04	15.33	56.21
18	COS2018-FLORESTAS-FLOR-CASTANHEIRO	5.1.1.4 Florestas de castanheiro	5.Florestas	Other broadleaves	30.79	13.34	1.85	45.98	168.59
19	COS2018-FLORESTAS-FLOR-OUTROS-CARVALHOS	5.1.1.3 Florestas de outros carvalhos	5.Florestas	Quercus spp.	15.87	4.69	1.85	22.41	82.17
20	COS2018-FLORESTAS-FLOR-EUCALIPTO	5.1.1.5 Florestas de eucalipto	5.Florestas	Eucaliptus spp.	17.97	4.2	1.85	24.02	88.07
21	COS2018-FLORESTAS-FLOR-OUTRAS-FOLHOSAS	5.1.1.7 Florestas de outras folhosas	5.Florestas	Other broadleaves	30.79	13.34	1.85	45.98	168.59
22	COS2018-FLORESTAS-FLOR-ESPECIES-INVASORAS	5.1.1.6 Florestas de espÃ©cies invasoras	5.Florestas	Other broadleaves	30.79	13.34	1.85	45.98	168.59
23	COS2018-FLORESTAS-FLOR-PINHEIRO-MANSO	5.1.2.2 Florestas de pinheiro manso	5.Florestas	Pinus pinea	18.79	1.46	2.41	22.66	83.09
24	COS2018-FLORESTAS-FLOR-PINHEIRO-BRAVO	5.1.2.1 Florestas de pinheiro bravo	5.Florestas	Pinus pinaster	26.74	3.14	2.96	32.84	120.41
25	COS2018-FLORESTAS-FLOR-OUTRAS-RESINOSAS	5.1.2.3 Florestas de outras resinosas	5.Florestas	Other coniferous	14.51	1.76	2.96	19.23	70.51
26	COS2018-SUPERF-AGROFLORESTAIS-SAF-DE-SOBREIRO	4.1.1.1 SAF de sobreiro	5.Florestas	Quercus suber	20.4	2.94	2.04	25.38	93.06
27	COS2018-SUPERF-AGROFLORESTAIS-SAF-DE-AZINHEIRA.rst	4.1.1.2 SAF de azinheira	4.SuperfÃ-cies agroflorestais	Quercus rotundifolia	8.37	4.92	2.04	15.33	56.21
28	COS2018-SUPERF-AGROFLORESTAIS-SAF-DE-OUTROS-CARVALHOS	4.1.1.3 SAF de outros carvalhos	4.SuperfÃ-cies agroflorestais	Quercus spp.	15.87	4.69	1.85	22.41	82.17
29	COS2018-SUPERF-AGRFLORESTAIS-SAF-DE-PINHEIRO-MANSO	4.1.1.4 SAF de pinheiro manso	4.SuperfÃ-cies agroflorestais	Pinus pinea	18.79	1.46	2.41	22.66	83.09
30	COS2018-SUPERF-AGROFLORESTAIS-SAF-OUTRAS-ESPECIES	4.1.1.5 SAF de outras espÃ©cies	4.SuperfÃ-cies agroflorestais	Quercus spp.	15.87	4.69	1.85	22.41	82.17
31	COS2018-SUPERF-AGRFLORESTAIS-SAF-SOBREIRO-COM-AZINHEIRA	4.1.1.6 SAF de sobreiro com azinheira	4.SuperfÃ-cies agroflorestais	Quercus suber	20.4	2.94	2.04	25.38	93.06
32	COS2018-SUPERF-AGROFLORESTAIS-SAF-OUTRAS-MISTURAS	4.1.1.7 SAF de outras misturas	4.SuperfÃ-cies agroflorestais	Quercus spp.	15.87	4.69	1.85	22.41	82.17

Table A3.2 – Primary Energy Factor (PEF) calculation

IEA Sankey diagrams Portugal						2.5	0.4	PEF for electricity imports				
Year	**Power plants PES (Mtoe)**	**Imports (Mtoe)**	**PES + (Imports/0.40)**	**Elec. from p. plants**	**Elec. from p. plants + Imports (Mtoe)**	**PES in MJ**	**Elec. output in kWh**	**PEF (MJ/kWh)**	**PEF (MJ/MJ)**	**EtaG**	**Convert Mtoe to TJ**	**Convert Mtoe to GWh**
2013	7.82	0.7	**9.5700**	**4.35**	**5.05**	4.00696E+11	58731500000	**6.82**	**1.90**	**0.53**	41870	11630
2014	7.96	0.62	**9.5100**	**4.47**	**5.09**	3.98184E+11	59196700000	**6.73**	**1.87**	**0.54**	41870	11630
2015	8.49	0.69	**10.2150**	**4.41**	**5.10**	4.27702E+11	59313000000	**7.21**	**2.00**	**0.50**	41870	11630
2016	9.04	0.4	**10.0400**	**5.09**	**5.49**	4.20375E+11	63848700000	**6.58**	**1.83**	**0.55**	41870	11630
2017	9.61	0.47	**10.7850**	**4.96**	**5.43**	4.51568E+11	63150900000	**7.15**	**1.99**	**0.50**	41870	11630
2013-2017 avg.								**6.90**	**1.92**	**0.52**	41870	11630

Table A3.3 – Grid emission reductions with time using the TAWP of Kendall (2012).

Year	FESEN 2018	TAWP worksheet (AH = 50 yrs)	TAWP polynomial regression 3rd deg (AH = 50 yrs.)	
0	258		1	258.0
1	249.4		0.98376	245.3
2	240.8		0.96753	233.0
3	232.2		0.95129	220.9
4	223.6		0.93504	209.1
5	215		0.91876	197.5
6	206.4		0.90245	186.3
7	197.8		0.88609	175.3
8	189.2		0.86967	164.5
9	180.6		0.85317	154.1
10	172		0.8366	143.9
11	163.4		0.81993	134.0
12	154.8		0.80316	124.3
13	146.2		0.78627	115.0
14	137.6		0.76926	105.9
15	129		0.75211	97.0
16	120.4		0.73481	88.5
17	111.8		0.71735	80.2
18	103.2		0.69971	72.2
19	94.6		0.6819	64.5
20	86		0.66389	57.1
21	77.4		0.64567	50.0
22	68.8		0.62724	43.2
23	60.2		0.60858	36.6
24	51.6		0.58969	30.4
25	43		0.57054	24.5
26	34.4		0.55113	19.0
27	25.8		0.53145	13.7
28	17.2		0.51149	8.8
29	8.6		0.49123	4.2
30	0		0.47066	0.0
Sum	**3999**	**3360**		**3357**
Yearly Avg.	**133.3**	**112.0**		**111.9**