100% DECARBONIZATION WITH 100% RENEWABLE ENERGY SYSTEMS

Through Power to Gas and Direct Electrification

Pedro A. Prieto

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By Pedro A. Prieto

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Abstract

As the world continues paving its way to the so called renewable energy transitions, mainly solar photovoltaic systems and wind power, there are some fundamental hurdles appearing in the horizon, despite of the overwhelming hype that these renewables are receiving in all the global media and also in the academic world to replace the fossil fuel systems.

The main alibi to promote this expansion is that the world goes straightforward to an unprecedented Global Warming and Climate Change, if drastic and urgent measures to reduce the CO2 emissions are not taken soon. There is still almost no solid reference in the different governments and in the industrial and capitalist world about the problem that also may represent soon the gradual depletion of fossil fuels and other resources, once they reach their maximum world production peaks (not when they are exhausted, which is a much more distant and imprecise date).

There is no sign or apparent willingness to appeal to consume less in helping to solve the problem (the feared and despised “degrowth” or “powerdown”, when voluntarily assumed). Very likely because accepting the premise that the world resources are finite, that they are subject to depletion and that they will reach a tipping point, when their extractions/productions will decay, automatically implies the announced death of capitalism, that demands infinite growth in a finite world like ours. In any case, the only reference mentions energy savings and efficiency improvements, by using more and more technology, thus forgetting that there has not been a single global reduction of any kind in the more than 150 years of industrial society , through which we have noticeably and continuously improved our efficiency (William Stanley Jevons and his famous paradox, still today in force).

Therefore, it seems more “digestible”, even within the enormity of the pollution problem of our planet, to say, we are going to eliminate the CO2, than accepting we have to change our production model. Even when it is proposed by using more and more technology, which is the main cause that has taken the world to this situation in less than 2 centuries of industrial civilization and less than half a century of technological civilization.

In one side, we can appreciate, despite of the avalanche of economic and technical statistics of huge progress in renewables, both in installed power and energy generated in the last 20 years, in reality their contribution has hardly dent in the fossil fuels contribution. Even more, despite of the successive crisis in the last three lustrum (the big economic crisis of 2008 and the Covid19 crisis in 2020), the fossil fuel energies continue their consumption growth in absolute values, beyond what renewables can offer.

On the other hand, the modern renewable energies, only produce electricity and this world, our world is basically a non electric one. Although some functions can be electrified in theory, like, for instance, the passenger cars fleet or the railways, and there are, in fact, a tsunami of investments in electric vehicles, many other social functions, have insurmountable difficulties to be served with electric energy. These are, the civil aviation, the maritime transportation, the heavy terrestrial

machinery for civil works and mining and heavy trucks for land transportation, the mechanized agriculture, the high fishing fleets, the armed forces or the cement and metallurgic industry, that in many cases cannot use electric smelting furnaces, except for few smelting of steel scrap and in few more cycles as each one degrades the output quality.

The third leg or hoof, which some renewables have started to timidly show behind the door is the one of massive energy storage and the granting of the security of supply under any circumstance and on demand, not as a function of wind blowing and sun shining. That is, the solving of the dire problem of intermittency of these systems.

In this document I shall not enter to assess this (until now) hidden elephant in the hardware store, but as soon as the renewable systems penetration increases in the electric networks (only in the electric networks), the elephant starts to break down hardware, so it is not possible to ignore it any longer. That is why, the final values are necessarily conservative and lower than what the forced oversdimensioning will oblige.

If we try to assess how to cover and transition with renewables, the 80% of total world primary energy used now in a non electric form and the uses of very unlikely or impossible electrification, we have to address this issue.

This document was created in 2019 and was stopped in April 2020, still lacking the review of the last chapter with the conclusions and the final summaries of the necessary energies of installed power in Terawatts(TW) and energy generated in Terawatts*hour (TWh) , by modern renewables, to get a 100% decarbonized world (in theory). As mentioned before, quite conservative figures, because the over-dimensioning of installed power and generated energy, necessary to store huge amounts of electricity to solve the storage and intermittence problems are not included in this work.

I started this document in Spanish and then I ended it in English, hoping t o publish it in a peer review scientific magazine. Afterwards, taking into account that most of the reviewers in the main publications are notoriously pro-renewables and the time and delays and objections that they may impose, I decided to put it in quarantine.

Later, as hydrogen ass a vector (or energy source as many still claim) was gaining momentum for a decarbonized world, some known academic and scientific colleagues, asked me for opinion and I delivered them this uncompleted document. I have not received any note from them commenting errors or wrong methodologies.

I know some have used or extracted some data with my permission (I am always pro-copyleft), that may have considered of interest. Finally, an academic has asked me permission to quote or cite the document and needs any public place to give access to his readers. This has prompted me to publish it in a friendly magazine 15-15-15, to which I am deeply grateful for their hospitality. However, I advance it has not been peer reviewed.

It is a calculated provocation to ask potential readers with some scientific knowledge, to help me to correct (to lower or higher) the final amounts of installed power and equivalent energy needed to get the 100% decarbonization. Error admitted and I will thank any communications helping to improve the final conclusion.

English is not my mother tongue and the document has not been reviewed by an English expert in these subjects, although I expect it will be clear enough for English speaking people.

It has been amazing how in these last two years, the mainstream media and the industrial and government powers-that-be have started to hype the so called “hydrogen economy”; that is as per the dominant media, the energy vector that will come to the rescue to solve the present huge economic activities that today move with or need with fossil energy, that cannot be electrified and this vector will help to replace fossils by using electricity in origin and combustion, when required, at the end.

In fact, both the USA programs linked to the Green New Deal, promoted now with the arrival of the democrat Joe Biden to the presidency of the United States, as well as the efforts of the European Union to pour huge investments in programs such as Next Generation EU and similar national programs, even they try to revitalize the production, strongly hit with the 2020 pandemic, still not overcome, they already openly talk, to invest in the hydrogen economy or in the “green hydrogen” (the one obtained from electrolysis with electricity 100% of renewable origin), as much as investments in wind power or solar PV.

There are also foreseen investments for programs to boost energy (electricity) storage systems, basically in batteries.

This document has included a chapter dedicated to obtaining synthetic natural gas. The reason is because the smarter among the ones in favor of decarbonization with more renewables and hydrogen, have noticed that hydrogen, known since more than two centuries ago and used since more than one century ago, although it has interesting, but limited uses and applications, has also low efficiencies in their production and over all, dire problems to be stored in a safe and feasible form, specially in the huge logistic storage facilities, being so flammable, with a very low energy density, both in weight, but specially in volume and finally because its big reactivity , specially with metals that have to confine it at high pressures or very low temperatures, to which they make them brittle soon.

So they have initiated another way: to convince us to generate hydrogen and then immediately transform it into a fuel or gas liquid more stable than hydrogen, by means of known chemical processes, like, for instance, ethanol or the so called synthetic natural gas (CH_4), by adding carbon from CO_2 by means of the Sabatier process. So they can score a double goal claiming they are helping to “sequester” CO_2 from the atmosphere, or at least to produce a liquid fuel that is baptized as “carbon neutral”, to be used in the many applications where it is required and the electricity is not feasible. And also, in the case of methane, to be transported and stored through conventional natural gas existing massive infrastructures.

That’s why this process is also assessed in Chapter 7, although it is a step more in the ladder of increasing complexity.

I admit that Chapter 8, devoted to the necessity of materials to achieve this “decarbonized economy” with 100% renewable energies, is clearly improvable, due to its brevity. But it gives an idea of the degree of difficulty and lack of emissions neutrality that the mining and other extractive refining and transport processes imply. The works of Alicia Valero, a doctor in Chemical Engineering in the University of Zaragoza and world expert in exergy in the mineral capital of planet Earth will be of much help to understand what we are facing to get a 100% decarbonized world by this way.

The conclusion that accompanies every abstract, is that we are facing a challenge very likely beyond our means. It is therefore an invitation to give a step forward: to rethink the required change of paradigm and our way of living towards a society eminently less consumerist. Starting, in a very first place by the most developed capitalist countries; to move to a much more austere society, focused in satisfying the minimum needs to have a human life with dignity, but leaving apart the many discretionary and superfluous expenses. Very easy to formulate, immensely difficult to carry out voluntarily. But if we do not do collectively and voluntarily, Nature will take care of placing all of us in the acceptable thresholds where all the living beings (not only humans) can considered themselves sustainable in the long term, without the forward escapes to which this industrial and technological society has accustomed us.

Disclaimer and commitment

This document offers exclusively physical data, chemical formulas and mathematical calculations, using the exact sciences, like data in Mtoe, or Mtoe/year, in TW or in Mwh , in m^3 or m^3/second, in tonnes of CO_2, etc., etc., which are much more difficult to manipulate, than volatile concepts like Levelized Price of Electricity (LCOE), $/Mwh, $/kg of H_2 or $/litre of gasoline and any type of money to energy equivalents, which are always subject of pre-assumed lifetimes of systems with a given pre-assured generation throughout time, market changes, volumes implied, geographical area or moment analyzed, the dollar as an immutable and unalterable universal currency etc.

In this sense, this is a scientific document, which is what recent movements fighting and demonstrating against Climate Change, ask politicians and businessmen to listen[1].

The study makes a top-down analysis, as we are talking of the need of a drastic change in our global system. It analyzes the energy consumed at global level from fossil fuels, the alternatives that modern renewables offer, considering that the biggest cause of Climate Change is the burning of the fossil fuels and the corresponding emissions.

The objective is the to analyze the technical feasibility to get completely free of CO_2 and other greenhouse gas emissions by using a massive deployment of renewable energies to replace fossil fuels, to avoid Climate Change and make the planet to derail.

Bottom up studies and analysis starting in a small scale and extrapolating later, may lead also to false assumptions, if do not consider the 'Beware of Scale' (BOS) factor and the changes that upward extrapolation may represent. What it may apparently serve for a country, or region, does not necessarily imply that can be extrapolated to the world. On the other hand, the present world is so inextricably interrelated, that analyzing solutions for only one region and country will not be useful any longer.

We do not advocate in this document for a conventional disclaimer, so common in every time more and more scientific papers, that the study finds that the conversion of fossil fuels to renewable energies is (or isn't) economically feasible or that the main barriers are still social and political, as if the economics of the data were scientific, being the economy a social science.

So, we will leave to the economists, preferably biophysical economists, rather than conventional or neoclassic economists, to extract economic conclusions, if any, from our presented physical data.

However, And as for the political (politicians) and social (people) stances, we believe that engineers and scientists cannot any longer ignore the impact of their decisions in these key sectors and shake off the political and social impacts of their conclusions, when we talk about energy, emissions and climate change and the world is at stake.

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[1] www.theguardian.com/environment/video/2019/sep/18/listen-to-the-scientists-greta-thunberg-tells-congress-video

In fact, we understand that many times, despite of the attempt to charge responsibility in the political and social stances, there is a clear intention to influence policymakers and businesses.

The document has tried to offer data in a readable and understandable language, with a minimum technical level, without compromising the required scientific level, because it tries to reach the university and high school audience these days concerned by the future in danger due to Climate Change. It also reviews in detail the common belief of the movements fighting Climate Change that modern renewables will take care of the decarbonization, with just political will or some subsidies and financing.

Chapter 1.
Introduction

Two important and opposed forces are occupying most of the debate in the global energy sector.

A. In one side, the conventional users of fossil fuels, which now power about 80% of our primary energy needs. This group can include the Climate Change deniers and also people pretending to work in the field of reducing emissions through different means, that may go from improvements in technology or efficiency or even those trying to succeed with Carbon Capture and Sequestration (CCS) or more recently Carbon Capture Utilization and Storage (CCUS).

B. In the other side, a growing group of individuals and organizations, claiming that we have lo leave the fossils urgently and make an energy transition as fast as possible. These persons and groups are very varied in their requests and proposals. From the ones that give themselves more time to transit to green energies to those that also accept as reasonable the different technologies to increase efficiency and use of CCS or CCUS.

The reasons argued by the Climate Change group are overwhelmingly the need to combat the ongoing Climate Change (CC) and its horrible effects. Most of the people is very well aware that fossils are finite, no one in this field appears to be concerned by anything else than the pollution and the emissions of the greenhouse gases effects.

C. An exception made of a very small and tiny group talking about the impending peak oil, gas or coal (in historic terms) and the also dire consequences of the post peak depletion rates, for the present way of living, is not basically considered within this second group. The Intergovernmental Panel for Climate Change (IPCC) has, in fact some scenarios, like the most alarming RCP 8.5, growing in emissions, from an ever growing consumption of fossil fuels up to year 2100, that peak oil warning groups consider will never happen for that cause, even most of the peak oil groups recognize the CC as a huge problem also. However, we shall not address this controversy here.

The debate of peak oil (supply) has swiftly but also smoothly been changed to `peak oil demand', trying to imply that for some reason and for the first time in 160 years of industrial civilization, the world will voluntarily reduce their energy consumption, be that the magic of energy savings or energy efficiency or any other type of technological achievement, forgetting always that the system is designed to grow on permanent basis.

The group of Climate Change then it is divided at the same time into two main groups.

D. The majority group is asking and demanding that we have to make a fast or very fast energy transition to urgently decarbonize our present energy and societal system. These groups have gained momentum with recent demonstrations of young people all over the world, but basically in Western and developed countries, like Extinction Rebellion (XR), Fridays For Future (FFF) and a myriad of others in different countries. Extinction Rebellion proposes, for instance full decarbonization by 2025[2], be then national I(i.e. Britain, where the movement started)or international. The FFF young people have told politicians (Greta Thunberg ass the most visible spokesperson) that they should panic on what they ave ahead. Their urgency so far, have prompted some official instances to launch programs to move in the same direction. Several European countries, regions and counties have made formal declarations of Climatic Emergence, that have not so far produced any result till now). Even the European Union, through its EU Commissioner for Energy and Climate Action, has proposed, at the end of 2018, to basically fully leave the EU free of emissions by 2050, while letting it grow economically at 2% throughout the period.[3]

It is worth mention that these groups are obviously very heterogeneous; some of them demand full decarbonization. Others suggest gradual emissions reductions, or in line with the last Paris Agreements on Climate Change. The target dates are also changing very much from group to group. Some demand just net-zero emissions, which is different (and more moderate) than full decarbonization and accept offsetting emissions with, for instance CCS or CCUS or the use of biofuels that are considered by some as zero-net emitters in the global life cycle.

E. There is a very minority group among people that has also CC as the main target to achieve, that proposes or believes that no modern renewables would ever reach the present level of energy consumption and facilities we are having today, even in a very uneven distribution, Pareto type. They are generally called degrowth or 'decroissance' people at different levels. That is, people that believes the only form to avoid a global collapse or even the so called Sixth Extinction, is to decrease in energy consumption to more or less drastic levels and do it voluntarily, better than forced by the facts or by Nature.

F. The group D above, demanding to get rid of greenhouse emissions as soon as possible, has even recently displaced th interest in the debate about deployment of modern renewables, although most of them trust, through many published papers, that we could, more or less, make the fossil fuels replacement by the so called clean energies, without big social and global disturbances, provided that we act now, we act and invest massively in installing modern renewables.

The experts believing in modern renewables as the key tool for that energy transition to decarbonize the present global economy, are divided in its turn, in two main groups:

G. Those that believe that we can achieve the energy transition with 100% renewable energies with different mixes and therefore get free from the dangerous emissions and stop the warming of the planet at different levels, but only in case of drastically changing our present consumeristic lifestyle and moving towards a stationary sort of global economy. [4]

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[2] www.vox.com/energy-and-environment/2019/4/24/18511491/climate-change-protests-london-extinction-rebellion

[3] https://europa.eu/rapid/press-release_SPEECH-18-6595_en.htm

[4] Energy and mineral peaks, and a future steady state economy. Antonio García-Olivares *, Joaquim Ballabrera-Poy Institut de Ciències del Mar, CSIC, Passeig Marítim de la Barceloneta, 37-49, Barcelona 08003, Spain.

The figures considered, in a world like ours, that already consumes about 14 billion tons of equivalent energy per year (BToes/year), which are equivalent to some 17 TW of permanent electric power, are floating around 10-12 TW of permanent electric power, in general, for reasons of efficiency and higher quality of the electricity versus the thermal processes.

They sometimes, mention the possibility of scarcity of some essential materials to get this gigantic revolution, but still in most cases remain optimistic that substitutes, alternative elements, technology improvements, energy savings, process optimization, etc. could make it possible at the end.

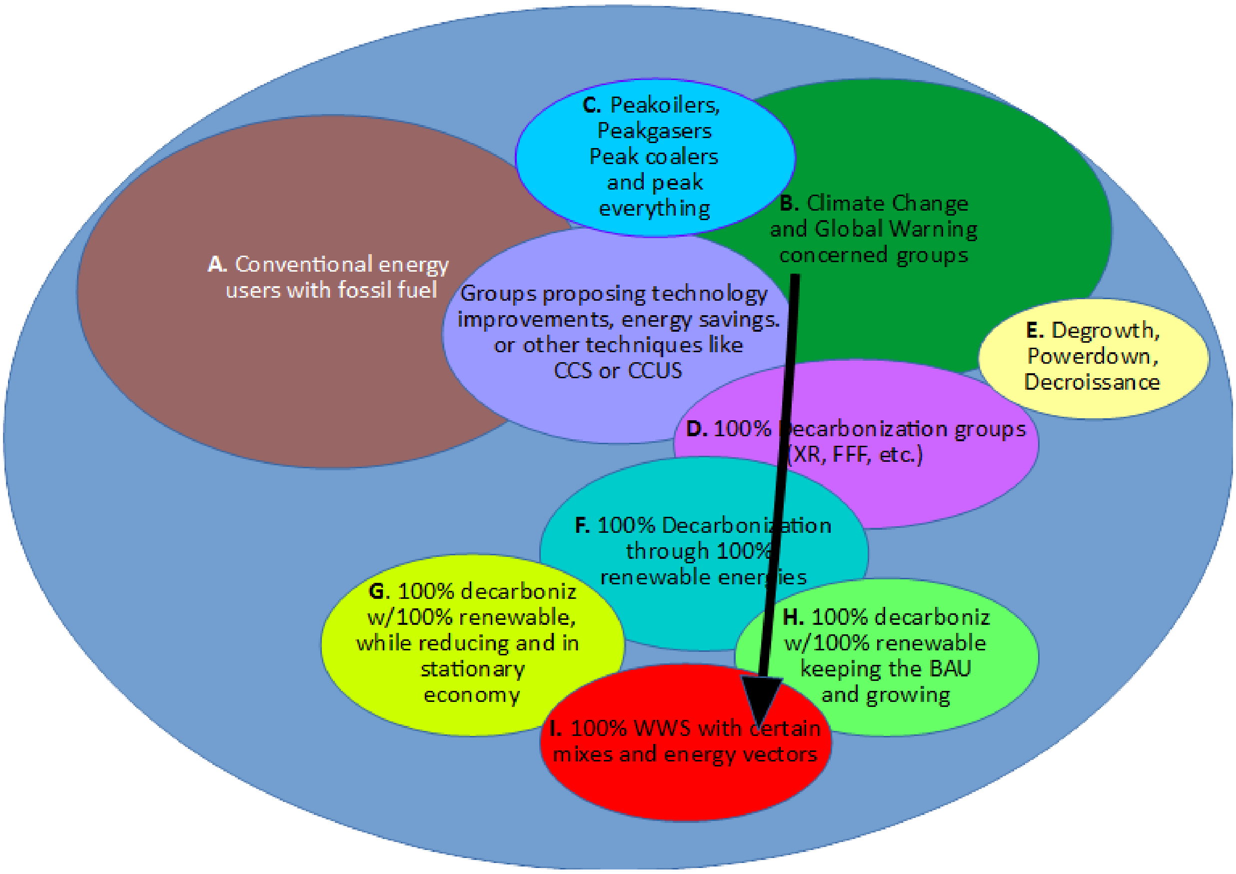

Figure 1. Approximate diagram of the most common positions with respect to Climate Change, emissions reductions or decarbonization and 100% renewables. We shall focus for our analysis in just the portion related to the use of energy vectors (red bubble) to carry out some processes, functions or activities that could not be directly electrified.

H. There is, however, an important group of researchers believing we can make the energy transition to renewables and thus tackle the problem of Climatic Change, but without putting in jeopardy the present economic system, which demands continuous economic and hence energy consumption growth in a foreseeable time. The most famous and representative is Mark Z.

Jacobson, in coauthorship with many others, with his different papers on 100% Wind Water and Solar (WWS).[5]

I. Among the intricate possibilities on energy and emissions that have been explained here In this paper, we shall address only the needs of a small portion on the processes and activities at global scale that very likely will need an energy vector to continue functioning more or less at similar level.

We shall investigate basically on the needs and energy costs of hydrogen, as the main vector for many of the processes, activities and applications that are not powered in electric form and that are very unlikely or impossible to directly electrify as well as the overall efficiency. And with these needs, the electricity needs to produce the hydrogen by electrolysis, considering the world will be (or must be) 100% renewable.

Additionally and being conscious that hydrogen as an energy vector has some severe logistic problems for massive storage and embrittlement, we shall investigate the needs and energy costs of synthetic natural gas (SNG) , as methane is much easier to handle and store massively and the amount of modern renewables to power the manufacturing of all the required SNG. And with it, the overall efficiency in terms of global logistics.

1.1. Power to Gas (PtG or P2G) as an energy vector, from renewable energies

It consists in generating a fuel form renewable energies in its totality -following the principles of 100% decarbonization-, that could both be used to serve processes, functions or activities in our present society, that cannot reasonably be electrified. Or also to massively store electricity when the intermittent energies of renewable systems are not available and the society demands electricity. In this document, we shall focus on the needs of fuels obtained from renewable electricity to be used in functions that cannot be (reasonably) electrified.

Apart from the energy and efforts to generate the fuel from chemical processes, it also generally implies additional efforts and energy to compress or liquefy the fuel for logistics, storage or convenient transport needs.

The most generalized forms to store electric energy is to pump up water between a lower dam and an upper one. The approximate losses are in the range of 30%, but this procedure will be limited because the huge land occupation of the already existing world dams for different purposes and environmental consequences.

Another possibility for electricity storage are the batteries or flying wheels, but they are difficult to store and manage the enormous amount of required energy, if to be 100% electric.

[5] http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html

Generating hydrogen via electrolysis is a form to convert electricity into a gaseous fuel, that could be used in processes, functions or applications that due to their energy intensity requirements, cannot be electrified, apart from the possibility to store it and use its energy content either in thermal form, after compressing or liquefying it, by combining it with oxygen (to burn it) or again converting it back into electricity, through a so called Fuel Cell. These are, in essence, one of the PtG possibilities.

Another form comes from using biogas, extracted, for instance, from wood and purify it with hydrogen, also obtained from renewable energy. A product that can be obtained from the pyrolysis of wood is methanol (CH_3-OH), that could also be obtained from a more complex mix of carbon monoxide and dioxide and hydrogen. These systems have not been developed much and we shall leave them apart.

Finally another PtG possibility is the methanation[6] or the production of natural gas in a synthetic form, called also Synthetic Natural Gas (SNG) from either carbon monoxide and hydrogen and /or carbon dioxide and hydrogen. The advantage of this process, regardless of the energy costs to obtain it, is that this methane will be considered net-zero emissions gas, and at the same time will be considered a form of capturing part of the excess of CO_2 now in the air.

We shall treat here the process of obtaining SNG from CO_2 and hydrogen through an exothermic reaction $CO_2+4H_2O\rightarrow CH_4+2H_2O-164$ kJ/Mol, known since more than a century as the Sabatier process.

[6] https://en.wikipedia.org/wiki/Methanation

Chapter 2. Methodology

We will use a simple method to analyze the global effort to achieve the target of free of emissions and the amount of modern renewables that will be required.

We will take the International Energy Agency (IEA) data of primary energy, the energy flows and the multiple transformations and refining processes, until obtaining energy of quality to be delivered to society.

But we will focus exclusively in its final stage; what the IEA calls **Total Final Consumption** in the different sectors. Other authors call it "final stage energy"[7] to imply that renewable already deliver energy directly in this "final stage" and thus, they have an advantage with respect with fossil fuels, when looking at this side of the equation.

From this final stage energy, we will then calculate how much of this comes from fossil fuels today and how much could reasonable be replaced by electricity and how much would need an energy vector to continue performing the present social functions.

The paper will not consider big increases in the use of biomass, with respect to present use of biomass at world level, as an alternative to net-zero emissions, in the replacement of fossil fuels.

The examples of biofuels obtained from corn in the USA, the ethanol from Brazil or the biodiesel from palm oil in the Southeast Asia rain forests and the levels of devastation and deforestation in these natural reservoirs and fertile soils, in few years, and the many articles (Pimentel, Patzek, etc.), showing the very low Energy Return on Investment of these solutions, do not allow us to even consider morally possible to exploit even more these resources for fuels.

We believe that proposals like the Lappeenranta University in Finland, with the Energy Watch Group, led by Christian Breyer, in their paper[8] stating:

> ***Sustainable biofuels and natural carbon sinks will offset emissions***
> *Biofuels will be produced only in a sustainable way on degraded lands. Globally, around 6.7 million km2 of degraded arid lands are available, on which 263 million tons of sustainable Jatropha plant oil could be harvested up to 2050. The potential to offset emissions range from 1 to 15 $tCO^2/(ha \cdot a)$. Up to 10 gigatons of annual natural carbon sinks might be created on jatropha basis on degraded land.*

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[7] Estimation of Global final-stage energy-return on investment for fossil fuels in comparison to renewable energy sources. Paul E. Brockway et al. https://www.nature.com/articles/s41560-019-0425-z

[8] Global Energy System Based on 100% Renewable Energy. Power Heat, Transport and Desalination Sectors. http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf

Are, in our opinion, utterly nonsense, in calling “sustainable” to planting a territory of arid lands, almost the size of Australia, to produce jatropha and biofuels from it, like in a three shifts factory, year over year.

We shall not address neither any substantial increase in the use of more hydroelectricity as renewable energy to cope with our insatiable demand of energy, as the main river basins of the world are already quite exploited and occupying fertile valleys (more than 80% in Europe).

The valleys are irreversibly damaged by a number of dams, more than 45,000 big ones, just in the 20th. century[9], for both agricultural uses, domestic use and industrial uses (among them the generation of electricity). Salinization affects to more than 20% of the irrigated soils.

Increasing pumping up systems as a way to store electric energy will also impoverished the already biologically died waters in many river basins, by making circular flows of water. So, we will not consider this in our study.

The vision of migrating fishes having to be lifted in a huge elevator pool in the Itaipu dam converts the pride of the dam guides showing it in an ecological sarcasm. Pedro Arrojo Agudo, Phd in Physics and professor of Fluid Mechanics in the University of Zaragoza, Goldman Prize and a world authority in water uses, declared: “in front of the Climatic Change we cannot expect to spend more water. This is suicide”[10]

So, in this document, we will focus basically in the modern renewables (Wind and Solar) as the basic tools to make the energy transition in search of a full decarbonization, by replacing the uses of fossil fuels and mainly in the areas that will require energy vectors.

Once we get the global figures of the fossil fuel uses in different sectors in the so called “final stage energy” or “Total Final Consumption” in words of the IEA, in Mtoe/year, we will analyze how many of those cannot be practically electrified in direct form and will need the use of an energy vector. Then ,we will make reverse engineering to calculate the energy to produce the energy vectors (hydrogen or SNG) and from this, we shall calculate the amount of modern renewables to be installed to produce the energy vectors in the amounts needed in TWh and finally installed TW.

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[9] World Commission on dams.

[10] www.infolibre.es/noticias/politica/2019/01/30/pedro_arrojo_ante_cambio_climatico_no_podemos_aspirar_gastar_mas_agua_eso_suicida_90577_1012.html

Chapter 3.
The energy consumed in the World

The best and simplest form to get a general overview, is the Sankey Diagram of the EIA. Unfortunately, the IEA updates this valuable with two-three years delay[11]. But to all effects, we will consider this picture as a reference.

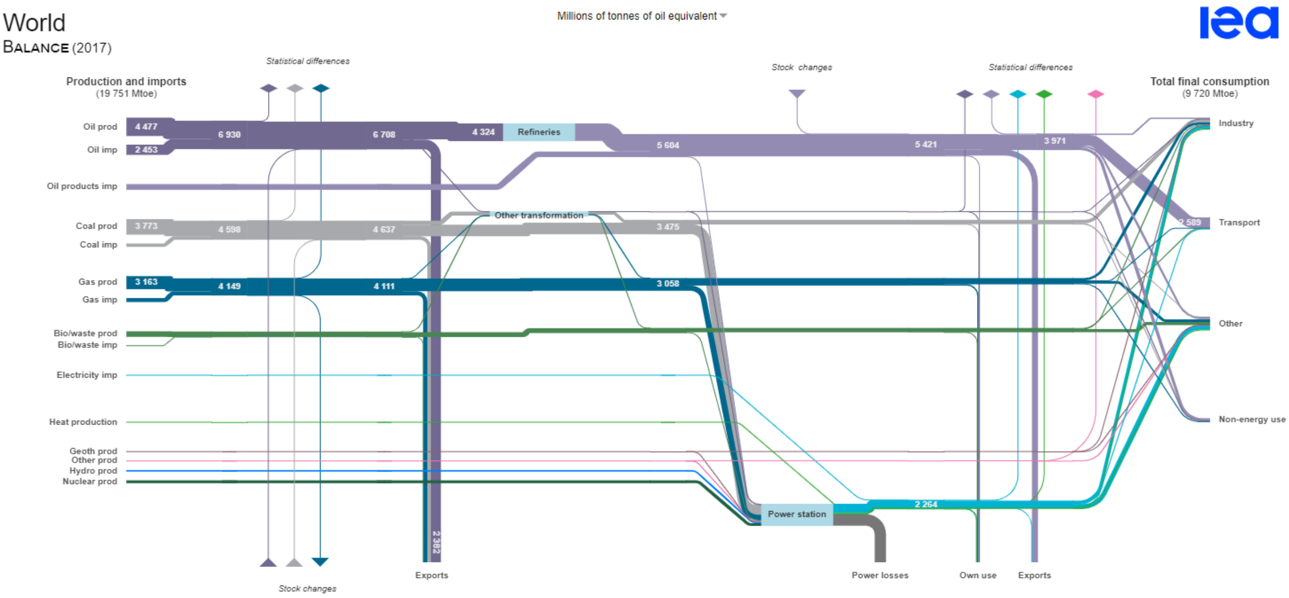

Figure 2. Sankey Diagram of the International Energy Agency 2017.

11 https://www.iea.org/sankey/

We can see in more detail the basic energy flows in the tables below

World Primary Energy			
Extraction	Mtoe	%	NRES/RES
Oil	4477	31,9	86,2
Coal	3773	26,9	
Natural Gas	3163	22,5	
Nuclear	687	4,9	
Biomass	1324	9,4	13,8
Geotherm	86	0,6	
Solar/Wind	171	1,2	
Hydroelectr.	351	2,5	
TOTAL	14032	100	

Entrance to the electric System 37,9% of primary energy			
Fuel	Mtoe	%	%
Coal	2374	44,7	85,7
Natural Gas	1264	23,8	
Oil	226	4,3	
Nuclear	687	12,9	
Biomass/Wast	200	3,8	14,3
Geothermal	72	1,4	
Solar/Wind	139	2,6	
Hydroelectr.	351	6,6	
TOTAL	5313		

Total Final Consumption (TFC)
9720 Mtoe

Industry: 29% TFC	Mttoe	%	NRES%
Oil	321	11,4	65,4
Coal	818	29,0	
Natural Gas	568	20,1	
Heat	138	4,9	
Biomass/Waste	207	7,3	
Geothermal	1	0,0	
Electricity	769	27,3	
TOTAL	2822	100	

Transport: 29% CFT	Mtoe	%	NRES%
Oil	2589	92,2	95,9
Coal	0	0,0	
Natural Gas	105	3,7	
Biomass/Waste	84	3,0	
Electricity	31	1,104	
TOTAL	2809	100	

Resid./Com.: 33% CFT	Mtoe	%	NRES%
Oil	433	13,5	43,0
Coal	152	4,7	
Natural Gas	644	20,1	
Heat	152	4,7	
Biomasss/Waste	747	23,3	
Geothermal	13	0,4	
Solar/Wind	31	1,0	
Electricity	1037	32,32	
TOTAL	3209	100	

Non Energy: 9% TFC	Mtoe	%	NRES%
Oil	643	73,1	100
Coal	51	5,8	
Natural Gas	186	21,1	
TOTAL	880	100	

Own Use (Self Consump.)	Mtoe	%	NRES%
Oil	211	25,8	75,7
Coal	80	9,8	
Natural Gas	291	35,6	
Heat	37	4,5	
Biomass/Waste	13	1,589	
Electricity	186	22,74	
TOTAL	818	100	

Table 1. Taken from the Sankey Diaram of the IEA (2017), it can be summarized as follows:

14.0 Btoe/year of primary energy are used

11,4 Btoe/year of primary energy are fossil fuels that the world expects to be "decarbonized"

86.2% of the primary energy is not renewable

81.3% of the primary energy is from fossil fuels.

27.4% of primary energy from fossil fuels go to generate electricity.

72.7% of the world electricity is generated by fossil fuels

14.3% of the electricity is generated by renewable energies.

2.6% of the world electricity is generated by wind and solar energy

9,720 Mtoe/year is the energy consumed as Total Final Consumption or "Final Stage Energy" (that is, quality refined, ready-to-use energy, losses discounted).

69.3% of the primary energy reaches only the Total Final Consumption or Final Stage Energy from the total Primary Energy used worldwide

7,419 Mtoe/yr of the total Final Consumption or "Final Stage Energy" or 76.3% of the energy with quality in the end use are from fossil fuels.

Now, the work will focus in the 7,419 Mtoe/year used as Total Final Consumption or Final Stage Energy, that are provided by fossils and how we could get rid of them.

The main sectors using this quality energy from fossil fuels, in non electric form, are:

Industrial sector, with 1,845 Mtoe/year.
Transport sector, using 2,694 Mtoe/year.
Residential and Commercial (called "others by the IEA), with 1,381 Mtoe/year.
Non energy uses, take 880 Mtoe/year.
Own use (understood as self consumption of the energy web) takes 619 Mtoe/year.

The Science magazine calculated[12] in 2014 the sectors considered difficult to eliminate (hard-to-abate), from the point of view of CO_2 emissions. The article estimated that at least 9,200 million tons of CO_2 (Gton CO_2) hard-to-abate (unless a clean energy vector would be used instead of fossils), out of the 33,900 Gton C emitted in 2014 (in 2018 other sources [13]estimated over 37 Gton CO_2). This is some 30% of the total global emissions.

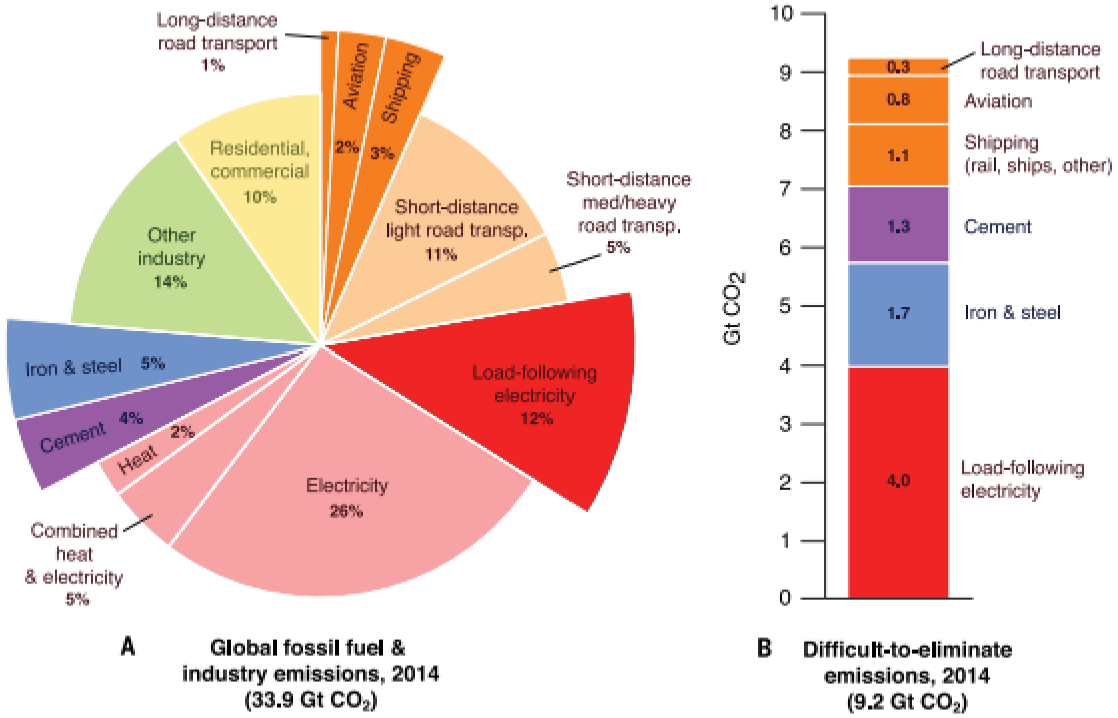

Figure 3. Sectors and activities emitting CO_2 (and hence logically consuming fossil fuels) that will be difficult to eliminate, unless there is an alternative use of an energy vector, generated from renewables. Source: Science Magazine. Net-Zero emissions energy systems. June 29th. 2018. Ibid

[12] Net-zero emission-energy systems. https://science.sciencemag.org/content/sci/360/6396/eaas9793.full.pdf

[13] https://www.scientificamerican.com/article/co2-emissions-reached-an-all-time-high-in-2018/

So, it should not be unrealistic to believe that 30% of the 7,419 Mtoes/year; that is, some 2,226 Mtoes/year of the Total Final Consumption or Final Stage Energy (energy already refined), would need a solution that is not electric. We shall try to refine this amount analyzing in detail some of theses processes today made with fossil fuels and difficult or impossible to electrify.

We shall keep this figure of 2,000+ Mtoe of fossil fuels that will need a 100% renewable supply of energy in a 100% decarbonized world by energy vectors, as the minimum level of fossil fuel energy, assuming a) that the global society intends to keep all the economic activities they are "hard to abate". because they are hard or impossible to electrify and b) that the society keeps stationary (without further and continuous growth) from the 2017 or 2020 consumption levels into the future.

Chapter 4.
An approach to the energy vectors required

Some of the global economy sectors which today are powered by fossil fuels, can be obviously electrified at given energy, infrastructure erection, capital costs, etc. which are far from being negligible, but that fall beyond this study, for the time being. We shall try to identify the processes, activities functions and applications that would reasonably require an energy vector to satisfy the present needs.

Among these activities, we list the following:

4.1. The air transport/civil aviation sector.

Some 26,000 planes fly around the world. Recently, on July 25th. 2019, a new record was set with more than 30,000 commercial flights in one single day and more than 30,000 planes of all types in the air in a given single moment. More than 4.5 billion people were transported by plane in 2019, so there is enough excess power to fly 6 out of 10 people living on the Earth every year[14]. At 100 people per plane on the average, that's 23 million people in the air in one day! We have thus created a virtual city in the air, the second largest city[15] on the Earth, just after Shanghai[16].

And airlines are planning to double[17] number of planes from 25,830 to 50,660 aircraft between 2018 and 2038.

The planes usually consume kerosene, a refined byproduct of oil as "final stage energy". The world energy consumption of fuel for aviation was in 2016 of 305 Mtoe as per the IEA[18]. They were considered responsible of 2% of the global emissions and are targeted these days by the young movements against Climate Change, for being one of the most intensive (not the most voluminous) greenhouse gas emitters.

We shall consider here that even Mark Z. Jacobson also proposed the hydrogen solution for this transport. Contrary to his work, we shall consider here that all long-haul aircraft will fly, if having to use some kind of free emissions energy, with electrolytic cryogenic or at least, highly pressurized gaseous hydrogen, also for all small-short range planes , instead his, in our view optimistic belief that all short-haul aircraft will fly by 2035 with Battery electric vehicles (BEV) or BEV-Hydrogen Fuel

[14] https://www.statista.com/statistics/262971/aircraft-fleets-by-region-worldwide/
[15] https://www.worldatlas.com/articles/the-10-largest-cities-in-the-world.html
[16] https://patzek-lifeitself.blogspot.com/2019/07/green-new-deal-v-constraints-delusions.html
[17] https://www.statista.com/statistics/262971/aircraft-fleets-by-region-worldwide/
[18] https://www.iea.org/statistics/kwes/consumption/

Cell(HFC) hybrids and for 2040 all the remaining new aircraft with BEV-HFC systems [19]. Being the HFC, in any case, needing the use of hydrogen.

We are not counting here the energy costs of the additional mining, manufacturing, installing and operating the gigantic new infrastructure.

Summary: 305 Mtoe/year to be replaced by an energy vector for this sector alone and without considering any growth in the sector.

4.2. The merchant fleets.

There are more than 50,000 cargo ships carrying goods. The energy spent basically in bunker oil fuel (in Navigation, as per the IEA terms) was around 262 Mtoe/year in 2016, as per the EIA[20]. They may easily reach to 300 Mtoe/year if we consider other types of recreational ships , in leisure ports, etc.

The Marine Environment Protection Committee (MEPC) confirmed in July 2018 that the new global sulfur limit for marine fuel of 0.50% m/m will apply from 1 January 2020. Some exemptions were allowed later, due to complexity of the measure if vessel are equipped with Exhaust Gas Cleaning Systems or scrubbers

Of course, a part of these fuels that are spent in sea transport, are to power the oil and gas tankers and in a 100% renewable world, this cargo ships could be deducted, but not all of them, unless the world managed to produce locally all the required fuels, which is very unlikely, due to the type of activity concentration in our modern world.

In this sense, the Total International Seaborne Trade in 2017 was of 10,702 million tonnes, of which 3,146 (about 30%) was for oil and gas.[21] To this, we have to add the coal transportation that represented 25.5% of the drybulk (mainbulk) commodities that totaled some 3,196 Mtonnes[22]. So 815 Mtonnes have to be added to the cargo ships that theoretically will be eliminated in a 100% free emissions world. This is an important 37% of all the International seaborne trade. So, we shall estimate from the present 300 Mtoe/year of fossil fuels spent today in navigation, could be reduced to 189 Mtoe/year in a 100% free emission scenario

On the other hand, other international seaborne trade products, such as cement, iron ore, bauxite/alumina and minerals and other metals, like copper will have to increase substantially, in this new 100% renewable scenario to erect, to continue supplying current activities and massively deploying new free emissions infrastructures and renewable systems, apart from maintaining and replace the virtually all the installed renewable base every 25 years.

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[19] Mark Z. Jacobson et al. 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All - Sector Energy Roadmaps for 139 Countries of the World. August 10th., 2017

[20] https://www.iea.org/statistics/kwes/consumption/

[21] https://unctad.org/en/PublicationsLibrary/rmt2018_en.pdf Page 19

[22] https://opensea.pro/blog/shipping-coal

We are not counting here the energy costs of the additional mining, manufacturing, installing and operating the gigantic new infrastructure.

Summary: 300 Mtoe/year is a conservative amount of fossil fuel energy to be replaced by an energy vector, for this sector alone, and without considering any growth in the sector.

4.3. The mechanized agriculture and fishing sector.

Here we have the Janus bi-facial paradox: agriculture demanding fuel for production and agriculture planting for producing biofuels. The later is a sign of the times (zeitgeist). The agricultural sector, by nature and by its dispersion on cultivated lands, is almost impossible to be electrified, despite of some pathetic attempts showing electric tractors and harvesters.

Energy consumption in agriculture has many fields, from fertilizing, plowing, tilling, irrigating, pumping, harvesting, drying, storing, packing, etc.

The more developed countries may have some electrification in water pumps or use for driers some biomass waste (i.e. in Spain dried olive bones burnt in furnaces to dry some other agricultural products) But mostly we can consider that distillate fuels or other fuels, propane or natural gas make the virtual total.

The recent developments of solar module arrays to power pumps in distributed areas, may have a relative impact in diminishing the needs of fossil fuels, but machinery (tractors, harvesters, shovels, tillers, trailers, etc.) are difficult, if not impossible to electrify. More than 25 million tractors operate worldwide, as per the World Bank data[23] and a growing number of harvesters, combined harvesters and trailers, as well as other millions of smaller diesel or gasoline powered agricultural machinery.

Finding data for the energy used in global agriculture is not easy. Data of Food and Agriculture Organization of the United Nations (FAO) is not much updated and some of the energy expenses may overlap with the data calculated with other sectors, like heavy terrestrial transport, desalination, non energy uses (energy used for fertilizers and pesticides) or industrial uses.

The figures given by the FAO on energy global consumption in agriculture slightly vary. According to the 3rd Assessment report of the Intergovernmental Panel on Climate Change (IPCC 2001) estimated that by 1995, agriculture accounted for about 3 per cent (9 EJ, which are 307 MToe) of global energy consumption, but more than 20 per cent of global Greenhouse Gas (GHG) emissions or 2% of the global primary use of energy and 10 EJ (341Mtoe/year)[24].

Other sources assign to agriculture a relatively small proportion of Total Final Consumption (Final Stage Energy) in both industrialized and developing countries. In OECD countries, for example, around 3-5% of total final energy consumption is used directly in the agriculture sector. In

[23] https://data.worldbank.org/indicator/AG.AGR.TRAC.NO

[24] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2935130/

developing countries, estimates are more difficult to find, but the equivalent figure is likely to be similar - a range of 4-8% of total final commercial energy use.[25]

A conservative figure for energy in agriculture would be a 3-4% of the 9,558 Mtoe/year of Total final Consumption (Final Stage Energy) (287-382 MToe/year)

With some more detail, the FAO differentiates for consumption in agriculture, figures are as follows:[26]

> In electricity, the global consumption in this sector was 613 TWh (52 Mtoe) in 2012. We shall not consider this energy as it is already provided in electric form.

For the rest:

Consumption in Agriculture FAOSTAT 2012		
all countries in the world		
Fossil Fuels	**I n TJ**	**In Mtoe**
Gasoil	4.520.246	108,0
Gasoline for engines	392.055	9,4
Natural gas (LNG Incl)	392.017	9,4
Liquefied Petr. Gas	145.164	3,5
Fuel Oil	61.852	1,5
Coal	1.008.935	24,1
Total	**6.520.269**	**156**
Energy for rrigation	185.915.798	4.440,4
Total Fossil Fuels	**198.956.335**	**4.751,9**

Table 2. Global energy consumption of fossil fuels in agriculture as per the FAO Statistics in 2012

To this, we have to add 60 Mtoes for fishing[27] and FAO also discriminates from this the energy for irrigation. Which is in the ballpark of the above global figures given also by FAO for all agriculture energy expenses.

Summary: A total 300 Mtoe/year seems to be a conservative figure for fossil fuels used in this sector, that will need to be replaced by an energy vector or carrier, for the difficulties to do them directly with in electric form.

4.4 The long distance heavy terrestrial transport and other mobility sectors.

The world had, as of 2015, some 947 million passenger cars and 335 million commercial vehicles in use . The annual production of passenger cars was 70.5 millions in 2018 and 25.1 million

[25] http://www.fao.org/3/x8054e/x8054e05.htm

[26] http://www.fao.org/faostat/es/#data/GN

[27] Fuel and energy use in the fisheries sector FAO Roe 2015 http://www.fao.org/3/a-i5092e.pdf

commercial vehicles[28]. The approximate rate of scrapping of motor vehicles in the last years was 47% with respect to the yearly production. So a 53% of the production resulted in new cars in use every year in average. Despite of the growing interest in electric cars , about 5.1 million cars were on the roads in 2018[29].

Although the International Organization of Motor Vehicle Manufacturers (OICA) does not provide data for 2018, we could assume here there must be some 1,1 billion passenger car in use and some 400 million commercial vehicles worldwide.

We will have to discriminate the huge amount of energy, that devoted to transportation in the world (2,533 Mtoe/year of oil and 102 Mtoe/year of natural gas in the form of refined energy (Total Final Consumption or Final Stage Energy), which include the above listed passenger car fleet, and the heavier transport systems that will most likely need an energy vector.

According to the IEA (WEO 2019 page 140, some 23% of the global oil (some 95 Mb/day or if we use the Figure 1 above 4,127 Mtoes of the Total Final Consumption or "Final Stage Energy" of oil, the 23% of it, is consumed by cars and 17% by trucks. So, we can assume in rough figures that some 940 Mtoes of Total Final Consumption of already refined oil go to the cars and 702 Mtoes are used by trucks.

In this work, we shall try to differentiate the passenger car sector (including the heavy SUVs), which is now in the headlines because the plans to electrify the whole sector and will focus on the sections which are more difficult to electrify, like buses (despite the attempts of China to electrify its fleet like commercial vehicles, which we understand could not extrapolate for the difficulties with the battery weights and the poor useful load vs dead-weight ratios), that make a global 9.3% of the bus transport fleet[30]

Other buses, a 7.8% of the total, are hybrid vehicles and a 4.1% powered by biodiesel. The rest is powered by either diesel or natural gas in its distinct forms. We shall consider here some 75% of the world buses are powered by fossil fuels and would require an energy vector like H_2 or SNG, if they have to get rid of fossil fuels.

As for the cars, they will need a complete additional study, because the roadmaps to a possible energy transition, change considerably from source to source. While the IEA still forecasts some 21% of the global oil demand for 2040 for cars, with a global car park approaching to 2 billions[31] some other sources and governments expect a 100% park of Electric Vehicles (EV's) for 2050 or even before. We will take an optimistic approach and will concede that 80% of the global fleet is going to be fully electric and 20% will be hydrogen powered with fuel cells.

And we shall assume that the trucks will be all of them using an energy vector.

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[28] http://www.oica.net/category/production-statistics/2018-statistics/

[29] https://en.wikipedia.org/wiki/Electric_car_use_by_country

[30] www.uitp.org/sites/default/files/cck-focus-papers-files/Statistics%20Brief_Global%20bus%20survey%20%28003%29.pdf

[31] IEA WEO 2019. Page 140

Global passenger travel by light-duty vehicles, bus, rail, and two- and three-wheeled vehicles reached nearly 24 trillion passenger miles in 2012 (the most recent year with detailed international travel statistics)[32].

Assuming no growth in the sector when decarbonization reaches its full extent, the energy vector needs will be of 188 Mtoe for the hydrogen powered cars (20% of the 940 Mtoes calculated by the IEA for cars that in the future will be powered by hydrogen and fuel cells) with fuel cells and 702 Mtoes for the trucks, as calculated above..

The assumption that all the world rail transport can be electrified is quite overoptimistic, although we have left it outside the calculations of the replacement of rail transport powered by coal or oil derivatives by energy vectors. It will probably be more realistic and feasible, if any, the direct electrification, despite having 34 countries without any rail network.

Even the European Union, the most developed and advanced continent in terms of railways electrification, has merely a 54% of the railways electrified. China follows with 46% of their rail network. But the USA has a merely 1% of their rail network electrified, and has abandoned close to two-thirds come down of the historic peak rail network length of 409,000 Km and is even below the world average of rail network electrification, that has electrified 46,570 Km. out of the 1,370,782 Km. of rail networks worldwide, a mere 3.4%.[33]

So, this leaves global rail transport outside of the calculations of energy vector needs, and assumes 100% electrification, which is very much in the optimistic side.

Summary: A total of 890 Mtoe/year from fossil fuels just for transport and mobility used in this sector to be replaced by an energy vector for the difficulties to do them directly with in electric form.

4.5. Industry sectors.

4.5.1. The cement industry.

The IEA gives in figure 1 above the data of 307 Mtoes of oil, 808 Mtoes of 827 Mtoes of coal, 538 Mtoes of gas and 136 Mtoes of heat from fossil fuels in the industry sector as Total Final Consumption. That makes a total of 1,808 Mtoe/year of refined, final stage energy (energy of quality) from fossil fuels that need to be replaced by either electricity from renewables or by a credible and reliable energy vector if we have in mind the full decarbonization.

Although IEA does not segregate by specific activity and sometimes is difficult to get the data , very likely, coal is clearly more used in iron and steel and metallurgy industries. A good portion of gas may be used for industrial processes and heat is very likely used for industrial processes requiring high temperatures.

[32] https://www.eia.gov/todayinenergy/detail.php?id=26192

[33] https://en.wikipedia.org/wiki/List_of_countries_by_rail_transport_network_size

Cement mixers can also be electric, but very unlikely in practice. Not as much the cement factories. Cement trucks are very common, but they are difficult to desegregate from the total number of trucks.

The cement industry consumes 350 million tons of coal-equivalent fossil and alternative fuels [34], which are equivalent to 171 Mtoe/year. The cement processes uses in general, the worst and most polluting type of fuels, like petroleum based wastes, miscellaneous wastes, chemical and hazardous wastes, apart from coal, fuel oil, coke and natural gas. In some cases, they use biomass residues.

Summary: A total of 171 Mtoe/year from fossil fuels used in this sector to be replaced by an energy vector or carrier for the difficulties to do them directly in electric form.

4.5.2. The iron and steel industry and civil works heavy machinery and the mining sector fossil fuel consumption.

The iron and steel industry consume fossil fuels basically in the different furnaces and may use electricity in other electro-intensive sector, like aluminum production or in the roll mils and motors. In 2010, the iron and steel industry and the aluminum industry in the USA consumed close to 1,400 trillion Btu (TBtu) from them less than 300 TBtu were electric. The fossil fuels basically represented some 1,000 TBtu. Or 25.2 Mtoe/year in fossil fuels[35]. The USA was in 2010 approximately the 5% of the world production. A gross estimate using the same percentage of fossil fuels with respect the total energy consumed implies that some 500 Mtoes/year were consumed in 2010 for that iron, steel and aluminum.

The fact that these industries are not easy to electrify in the furnaces area is the recommendation of the IEA and also the EIA to accelerate energy and material efficiencies by improving the scrap collection and recycling.

The electric arc furnaces, induction furnaces or dielectric heaters that could ,in theory, electrify this type of production high temperature industrial processes, usually do not smelt iron and other metals, they just melt existing steel, which is originally made with hundreds of combinations of alloys (about 5-10 metals) to make the steel flexible or inflexible, very strong, very resistant to rust and so on. Melting a bunch of scrap steel, it will be some mix of kind of flexible, not so strong, prone to rust, so perhaps not usable for car manufacturing or some appliances.

Blast furnaces have to run 24x7, newer ones last at least 20 years. They must keep running or their brick lining shatters, so electricity is not suitable and will demand full reliability to avoid the furnaces be damaged by a brownout or blackout. 70% of steel is made from iron, not recycled steel.

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[34] Use of alternative fuels in cement industry. Nickolas J. Themelis. Columbia University. https://www.researchgate.net/publication/263714046_Use_of_alternative_fuels_in_cement_industry

[35] https://www.eia.gov/todayinenergy/detail.php?id=16211

The civil works heavy machinery is very varied and complex and in some cases, the number of different machines is overwhelming: articulated trucks, dozers, draglines shovels, excavators. Loaders of many types, tractor scrappers, backhoe loaders or telescopic handlers. For civil works specially in cities, it is more common to use electric powered devices, like lifting cranes for buildings.

From the mining machinery, we will have to consider a double effect: in one side, in a world already and theoretically stabilized with 100% renewables, we will have to discount the heavy machinery used to extract coal and to mine the heavy bituminous oils in places like Athabasca in Canada and the drilling and extraction equipment in conventional oil and gas wells and in the unconventional shales in the United States and other countries, which is a considerable amoount.

On the other hand, the extra effort in equipment and machinery to explore, extract minerals, crush, pulverizing, etc. process metals, refine, melt, preform,etc. for the energy transition to a 100% renewable world will increase also in an important form, which is difficult to estimate in advance.

According to Allied Market Research[36] about 66% of the global mining equipment market goes to metal mining and mineral mining and the rest went to coal mining in 2017. It is expected that by 2025, the metal and mineral mining will increase its share to a some 75%.

The number of equipment for mining is in some cases similar to those of the heavy equipment and transport used for the civil works sector. They have of course, some differentiated equipment, like the huge off-highway trucks, essential for transport minerals from the open pit mines to the crushing and refining processes.

Although some of these machines can in theory be electrified in mining by wired systems (batteries will be utterly nonsense and with a ridiculous gross to net carrying capacity), like the gigantic machine to extract coal in Germany, and some underground hard rock or long-wall subterranean mining in very specific circumstances of stabilized mines, mostly in developed countries, most of them cannot simply be electrified. The depletion of more and more mine pits and the lower ores of many of them, as we dig more and more, make impractical to electrify the every minute longer tracks from the extraction point to the next processing centers.

An indicator of the energy intensity that mining requires sometimes, can be obtained from the Chilean copper sector. According to Cochilco[37] in its 2019 annual report, the copper activity in Chile consumed 82,594 TJ of fuels in 2018 and 94,153 TJ in electricity. This is 1.9 Mtoe/year of fossil fuels and $2.61*10^{13}$ w*h; that is, 26.1 TWh of electricity. Considering that Chile consumed 80.2 TWh, this alone represent some 32% of the total national electric demand.

We shall take the fuel consumption only (1.9 Mtoe/year) as a reference for further calculation

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36 https://www.alliedmarketresearch.com/mining-equipment-market

37 www.cochilco.cl/Lists/Anuario/Attachments/20/AE2019avance.pdf

Chile produced 5.831 Million tons of fine copper in 2018, which was the 28% of the world copper. It is reasonable to extrapolate that world copper production could require some 7 Mtoe/year of fossil fuels to process the 20 million tons world copper.

The mining production can be classified in mineral fuels (85.2%), that will be discarded here, industrial minerals (4.7%), non ferrous metals (0.6%) and iron and ferro-alloys (9.5%). In 2016 the total world production was 16.9 billion metric tons[38]. The 14.2% or 2.3 billion metric tons of this huge amount were industrial minerals, non ferrous metals and iron ferro-alloys. These portions will have to be increased substantially in a scenario of 100% free emissions/100% renewables, because they are heavily demanding iron and steel, copper and many other metals, including scarce elements from rare earths and precious metals for the electronic industry.

Although not all the industrial minerals need the same energy by weight or volume extracted, a simple proportion with copper will give a fossil fuel consumption of 805 Mtoes for all the mining sector.

Summary: 805 Mtoe/year to be replaced by an energy vector for the sector alone and without considering any growth in the sector.

4.6 The armies (Navy and air forces included).

Although it is very difficult to estimate the energy consumption of the armies of the world, we could infer an approximate amount form the most studied and analyzed country: the United States. According to this source[39] the USA spends about 1% of its energy consumption in the military. Its energy consumption is 2.300 Mtoe/year (BP 2018). So, the military spend some 23 Mtoe/year. About three-fourths are oil (17.3 Mtoe/year of refined oil in the form of final stage energy. basically for mobility. So, we shall assume that this is the portion more difficult to electrify. If we consider that the US represents the 35.6% of all the world military spending (SIPRI), if we extrapolate, we can consider that the energy spent in the military which will not be possible to replace unless there is an efficient energy vector, amounts to 48.6 Mtoe/year.

This consumption will easily increase substantially as the conflicts for conventional fossil fuel resources are mounting and the mobility will increase consequently.

Summary: A total 50 Mtoe/year from fossil fuels used in this sector to be replaced by an energy vector for the difficulties to do them directly with in electric form, should the Armies of the world convey to a 100% free emissions/100% renewable world.

4.7 The non energy uses sector.

In this sector, which is using fossil fuels generally as feedstock, there are 870 Mtoe/year, from them 645 Mtoes/year from oil alone. The rest of uses take gas and coal. The non energy uses are

[38] http://www.world-mining-data.info/wmd/downloads/PDF/WMD2018.pdf

[39] https://www.resilience.org/stories/2007-05-21/us-military-energy-consumption-facts-and-figures

usually the elaboration of fertilizers, pharmaceuticals, pesticides, lubricants, greases, plastics and over all, something vital for land transport: asphalts.

On the other hand, non energy products today obtained from longer chains of oil or coal derivatives, will have a very costly replacement, even if they are tried from the SNG obtained from methanation, with renewable energies, as natural gas has shorter CH molecule chains than sometimes are required.

Some of these non energy uses, except asphalts, could be made from biomass, but this will imply more cultivation or more extraction from existing biomass in prairies or forests. Many could be done by means of producing synthetic natural gas from hydrogen and CO_2 and with renewable energies, like fertilizers pharmaceutical pesticides or plastics. For some others, like lubricants or greases usually made from hydrocarbons with longer hydrogen molecules, the replacements would be more difficult and of course, much more costly in energy terms, if they have to be obtained from SNG as feedstock.

We shall consider here only a percentage of the 870 Mtoes, assuming that we could get rid of most of the plastic bags. The industry was consuming for plastics in 2010 some 2.5% of all oil and a 3.6% of natural gas of the Total Final Consumption. A combined amount of 161 Mtoe/year.[40]

We shall leave also aside of the calculations of the energy vector or carrier requirements for the asphalts, with an open (tough important) question mark on how it is going to be substituted or replaced from oil.

As a side note, we shall mention that the elimination of any oil product obtained at present in the refineries with the different mixes in the fractioning sections , without considering in full all other refined byproducts, will imbalance seriously the whole production of the refineries.

That is the case, for instance, of the gasoline and/or diesel for passenger cars. In Spain, the elimination of gasoline and diesel for the 23 million passenger cars, will only reduce in a 24% the approximately 60 million tons of oil of yearly consumption [41] and will imbalance the refineries very much, if they still have to produce all the other oil derivatives.

So, we shall detract the energy of asphalts here (102 Mtoe/year)[42]

Summary: A total 768 Mtoe/year from fossil fuels used in this sector to be replaced by an energy vector for the difficulties to do them directly with in electric form.

[40] http://large.stanford.edu/courses/2010/ph240/hamman1/

[41] Pedro A. Prieto Consideraciones sobre el vehículo eléctrico en España. 2019.

[42] http://www.factfish.com/statistic/bitumen+asphalt,+consumption+for+non-energy+uses

4.8. Overall Summary of all energy requirements that would likely need an energy vector or carrier for a 100% free emissions world with 100% renewable systems.

We can conclude that in a conservative mode, some 2,500 Mtoe of global processes and activities carried out in our present world society will be hardly electrified. Should we expect to keep them producing and without emitting any greenhouse gases

SECTOR	**In Mtoe**
The air transport/civil aviation	305
The merchant fleets.	300
The mechanized agriculture and fishing.	300
The long distance heavy terrestrial transport and other mobility.	890
The cement and iron and steel industries and civil works heavy machinery and the mining sector fossil fuel consumption.	1,476
The armies (Navy and air forces included).	50
Non energy uses.	768
TOTAL	3,489

Table 3. Summary of the energy equivalent to carry out processes and functions that are difficult or impossible to electrify and today are made with fossil fuels, so they would eventually need the use of an energy vector or carrier

Chapter 5. Hydrogen as energy vector, produced from renewable energies. A complete life cycle efficiency.

Despite hydrogen being the most abundant element in the Universe, unfortunately cannot be found isolated and free on Earth, but always associated to other atoms; therefore, it always costs energy to split and isolate it.

There are several methods to extract hydrogen from elements containing atoms of hydrogen. It can be made by electrolysis from water, using electric energy between a cathode and an anode ,by means of the following reaction

Oxidation: $2H_2O\ (l) \rightarrow 4H^+(aq) + O_2\ (g) + 4e^-$
Reduction: $2H_2O\ (l) + 2e^- \rightarrow H_2(g) + 2OH\ (aq)$
Total reaction in the cell: $2H_2O\ (l) \rightarrow 2H_2\ (g) + O_2\ (g)$

However, the present society and the industry finds more efficient to obtain hydrogen through the steam reforming, through the following process: $CH_4 + H_2O \longrightarrow CO + 3H_2$ and then $CO + H_2O \longrightarrow CO_2 + H_2$

According to Wikipedia, 96% of the hydrogen produced globally is obtained by steam reforming with methane + water or by carbon gasification in a much lesser extent. Only a 4% of hydrogen is obtained by electrolysis[43]. Only a tiny fraction of less than 5% of the global produced hydrogen already takes 8 GW of installed electric capacity to make this job.

The IEA, in an analysis[44] titled The Future of Hydrogen, a report prepared for the meeting of G20, that took place in Osaka, Japan in June 2019, probably more updated, reports a growing demand of hydrogen. It points out that the interests resides in its versatility and can help by itself or by producing SNG, to power homes and feed industry, and into fuels for cars, trucks ships and planes in direct form. In summary, to replace fossils where the human processes are consuming them today and are difficult to be replaced by electricity (hard-to-abate sectors)

[43] https://en.wikipedia.org/wiki/Hydrogen_production
[44] https://webstore.iea.org/download/direct/2803?fileName=The_Future_of_Hydrogen.pdf

The present uses of hydrogen as per the IEA document are very telling:

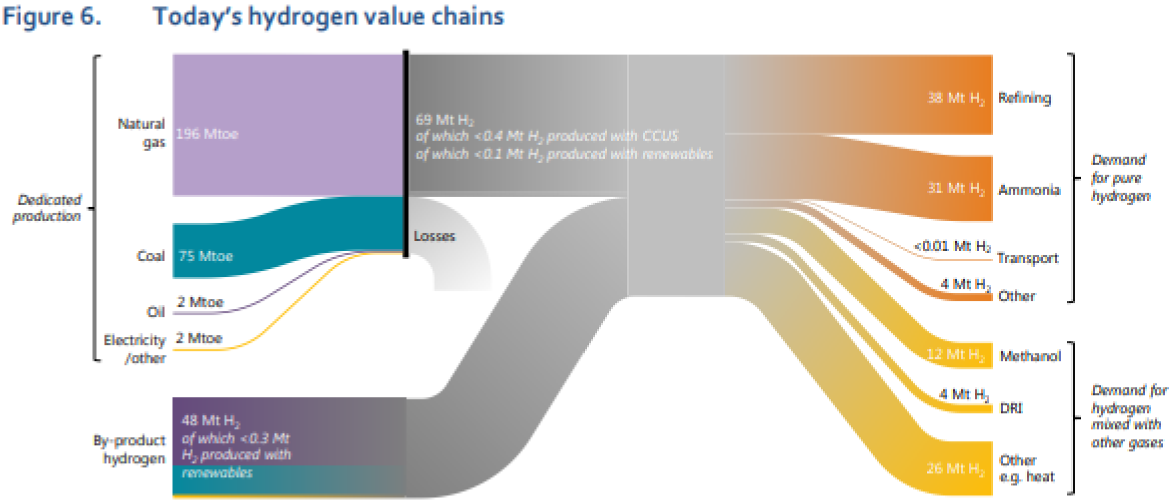


Figure 4. Today's hydrogen Value Chains. Source. The Future of Hydrogen. IEA Ibid. Page 32

In 2018, the world produced 69 million tons (MtH_2) of "pure hydrogen". This is hydrogen with very low levels of impurities.

The water used for electrolysis needs to be quite pure, so, the majority of processes to generate hydrogen demand a previous water purification step. The electrolysis costs energy. According to Medeas[45] the European research group that investigated the energy transition in Europe to a world low in emissions, every m3 of water requires some 0.025 MJ or some 6.9 kWh per ton or m^3 of water to desalinate it and deionize it and leave it ready for electrolysis. Other sources indicate more efficient processes that could lower this figure to 3 kWh/m^3 of water. Claims that reverse osmosis could lower this have to be analyzed in the light of more expensive and less durable equipment

The obtained hydrogen has several nicknames, depending on the origin of the feedstock.

- Black hydrogen is the one coming from coal.
- Gray hydrogen is the one coming from natural gas.
- Brown hydrogen is coming from lignite.
- Blue hydrogen is the one coming to capture CO2 emitted by any installation in the called CCUS.
- Green hydrogen is the one coming from electricity from renewable energy.

Figure 4 above leaves clear the tiny amount of blue and green hydrogen.

For the production of the 69 MtH2, some 273 Mtoe of natural gas, coal and oil are required. This is as much as 2% of all the world primary energy.

2 Mtoe of electricity are being used to produce hydrogen by electrolysis.

[45] https://www.medeas.eu/

Less than 0.7% of the total energy to produce hydrogen comes from renewable energies or generation plants with fossil energy equipped with the CCUS system.

The IEA report indicates that the present hydrogen economy implies the emission of 830 Mt CO_2/year. This is 2.3% of all global CO_2 emissions.

As we saw above, 96% of the hydrogen is generated by fossil fuels, but 54% of all the generated hydrogen at world level, goes in its turn, to transform, adapt and refine the lengths of different molecules of fossil fuels for different uses.

The required change for an energy transition with the aim to get a 100% decarbonized world by 100% renewable systems is therefore, telluric. The present feedstock from fossils will have to disappear in a 96% and taken over by renewables and water..But the many thermal and pressure processes to get the proper chemical conversions and to carry out certain catalytic processes will require much more energy either from electricity from renewables or from hydrogen from electricity from renewables.

But it will also require a drastic change in the use of the present 54% of the hydrogen produced, that will not go to refine and treat the molecules of fossil fuels to adapt them to the Total Final consumption. This will not be any longer necessary, in the long term and will represent a saving in the present hydrogen destinations.

5.1. Energy equivalences between hydrogen and the most common fossil fuels and its comparison with hydrogen.

From the table 2 below, we can observe, as a rough comparison, that most of the common already refined fossil fuels, in its Total Final Consumption stage or Final Stage Energy, have about 3 times less energy content per unit of mass (kg) than hydrogen, when considering the most favorable case of Higher Heating Values (HHV), rather than Lower Heating Values (LHV).

Kerosene 3.06 times; Diesel 3.16; fuel oil 3.22 or crude oil 3.16 times less energy content by unit of mass than hydrogen (MJ/tonne). These are some types of fuels that for many applications, will be difficult to eliminate to get the total decarbonization or a free emissions world, among them, in some of the main uses of the table 2.

As a preliminary conclusion, we could say that in order to eliminate 3 Mtoe/year from fossil fuels we would need to generate and replace them with at least 1 MtH_2 ,as an energy vector.

Of course, generating hydrogen by electrolysis is not the only energy cost of having hydrogen as energy vector. This fuel needs, almost compulsory, due to its very low energy density, to be handled (transported, stored, etc.), by either compressing it at 700 bars or liquefying it at -253ºC.

Compression of hydrogen to 700 bar, which is agreed upon as an international standard pressure for the storage of gaseous hydrogen for automotive cars, for instance implies some losses of a minimum 20% of the hydrogen energy content[46].

Storage of liquefied hydrogen is taking a much higher energy toll. Current systems spend some 12 kWh per kg.of LH_2, although they expect to lower this consumption to 8 kWh per kg of LH_2 in much bigger plants[47]. This is a burden of a minimum 30% of the H_2 HHV energy content, because there must be added some other energy expenses to refrigerate the tanks or deposits and other expenses related to security and safety handling.

To summarize, we will use as an equivalent energy content, that for every 2 Mtoe of fossil fuels needed to be replaced by hydrogen as energy vector, we must use 1 Mtoe of hydrogen.

Fuel Energy Density

Liquid Fuel	Uses	MJ/litre	Litre/Tonne	MJ/tonne
LPG	propane	25.3	1960	49,600
LPG	butane	27.7	1750	49,100
LPG	mixture	25.7	1928	49,600
Gasoline	aviation	33.0	1412	49,600
Gasoline	automotive	34.2	1360	46,400
Kerosene	power	37.5	1230	46,100
Kerosene	turbine fuel	36.8	1261	46,400
Kerosene	lighting	36.6	1270	46,500
Heating Oil		37.3	1238	46,200
Diesel Oil	automotive	38.6	1182	45,600
Diesel Oil	industrial	39.6	1135	44,900
Fuel Oil	low sulphur	39.7	1110	44,100
Fuel Oil	high sulphur	40.8	1050	42,900
Refinery Fuel		40.9	1050	42,900
Naphtha		31.4	1534	48,100
Lubricants		38.8	1120	43,400
Bitumen		44.0	981	42,700
Solvents		34.4	1229	44,000
Waxes		38.8	1180	45,800
Crude Oil		38.7	1160	44,900
Ethanol		23.4	1266	29,600
LNG	-160C & 300kPa	25.0	2174	54,400

Table 3. Energy density of different fossil fuels and most common uses of these fuels. Source:http://w.astro.berkeley.edu/~wright/fuel_energy.html and energy density, specific energy of hydrogen in its different forms. Source: https://en.wikipedia.org/wiki/Energy_density

[46] https://www.sciencedirect.com/topics/engineering/compressed-hydrogen
[47] https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf

5.2. Green hydrogen production (water + electricity by electrolysis)

The electrolysis also requires high quality water, besides electricity. There are some 9 liters of water to produce 1kgH_2 and there is oxygen as a byproduct.

At small scale, oxygen can be used for medical purposes in the health sector, and a higher scale in industrial processes.

If all the present 69 MtH_2 generated today would have to be produced by electrolysis, the water demand will be of 617 million m^3, which are equivalent to the 1.3% of all the water needs of the energy sector and twice the present water needs to produce hydrogen from methane, by means of the steam reforming process[48] (345 Mm^3 of water for 52 MtH_2).

The EIA acknowledges that the use of fresh water for electrolysis can be a problem in certain water-stressed areas. They estimate that desalination is the best process in these cases, by reverse osmosis at an extra cost of 3-4 kWh/m^3. The extra electricity required to desalinate these 617 Mm^3 of water per year, will be in the order 2.5 TWh more, a small additional percentage to the electricity of the electrolysis itself.

However, the environmental effect of desalinate 617 Mm^3 of seawater and the need to send the brine through long pipes back to the seas can be of substance. The world has now close to 20,000 desalination plants, producing 34,675 million m^3 of fresh water, but at the expense of shipping 51,380 million cubic meter of brine back to the sea[49].

At the present very limited hydrogen production level, if it has to be done by desalinating seawater, would need to increase the world plants in 2% (about 400 more desalination plants).

But of course, the world production of hydrogen in a scenario of 100% decarbonization with 100% renewables to replace the processes, functions and applications that cannot be electrified will demand much more energy and much more water, if it has to be made 100% by electrolysis.

The energy content of hydrogen per unit of mass is 120.1 MJ/kgH_2 and the specific energy is 8.5 MJ/litre in liquefied form (-253ºC, 1 bar)[50].

5.3. Conclusions of the requirements to cover non electrificable fossil fuel functions by means of hydrogen as energy vector or energy carrier.

[48] IEA. The Future of Hydrogen. Page 43.

[49] The State of Desalination and Brine Production: A Global Outlook. Edward Jones et al. Elsevier. https://www.sciencedirect.com/science/article/pii/S0048969718349167

[50] IEA. The Future of Hydrogen. Page 35

Therefore, as a first general approach, let's grossly assume that form the 7,419 Mtoes/year that the world is using in non electric form in the Total Final consumption of Final Stage Energy, as per the table 3 above, we would need to replace some 3,548 Mtoes of fossil fuels by hydrogen as energy vector, to avoid theoretical overlapping of some activities and also to be in the ball park of the Science percentage of emissions hard to abate"

Let's reduce the amount of energy to 2,000 Mtoe/year that will need an energy vector for processes and functions that cannot be electrified. As assumed at the end of Chapter 3. This for the sake of simplicity, to avoid theoretical overlapping between the different considered processes and functions and to be in the ballpark of what Science considers (see figure 3) to be the "hard to abate emissions" , which are a 27% of all global emissions (9,200 GtC of the 33.9 GtC considered). The 2,000 Mtoe are also a 27% of the 7,295 Mtoe of Final Energy Consumption of Final Stage Energy that are today using fossil fuels.

Note: In a scenario of 100% emissions free or full decarbonization with 100% renewables,, whatever fossil fuel energy is reduced here to the effect of calculations of energy vector and the required installed power of renewable energy, will be accounted in the Chapter 7 for the renewables needed for electrification of all the rest of activities.

We will require then the production of 1,000 MtH_2/year to replace the 2,000 Mtoe of functions that cannot be electrified..

As mentioned and calculated by the IEA[51], if the today's dedicated hydrogen output (69 MtH_2) would have to be obtained with electricity by electrolysis, from electricity would result in an electricity demand of 3,600 terawatt hours (TWh).

So, the electricity needed to obtain 1,000 MtH_2 will be of 52,173 TWh just for this purpose. This is roughly 2 times the global electricity demand of 2018 (26,614.8 TWh)[52]

This astonishing amount of energy, just to replace few fossil fuel functions as energy vector, does not include

> The losses of hydrogen in its containers, through time, with leaking rates depending so much of the type of containers cylindrical , polymorph or toroidal, that demand very expensive four-layers structure. Steel is very affected by embrittlement. Aluminum-alloys are used, lined internally with plastic lining and wrapped externally in a protective layer of carbon fiber-reinforced plastics[53]. Complex technologies not at the disposal of every country.
>
> The existing containers and pipes for liquid Natural Gas (LNG) will not suffice. A large LNG tanker losses 0.2% of its total volume per day, but "store hydrogen in the same kind of tank will lose 5% of the contents every day to vaporisation".To get down to the same boil off

[51] IEA. The Future of Hydrogen. Page 43.

[52] BP Statistical Review of World Energy 2019.total World Electricity Generation 2018

[53] https://www.sciencedirect.com/topics/engineering/compressed-hydrogen

rate, the insulation of the hydrogen tank must be about 10 times more efficient than an LNG tank. In fact it needs a system that is gas tight form the outside as well as the inside with no chance of the air finding its way into insulation- if it does it will condense, and this will suck yet more air in"[54]

Admitting that with several times more expensive and costly ducts and deposits than those used today for natural gas, the losses of hydrogen via leaks could be reduced to a 0.2%/day. Massive handling of energy requires a vast network of deposits, where the energy now can be maintained ready for use (this includes the strategic reserves for every country). Additionally, what is valid for the gas and oil to be sometimes stored in huge subterranean caverns, depleted gas or oil formations or salt formations, it will not be suitable for hydrogen, that will have to create the whole massive storage facilities on the ground and ex-novo.

The minimum time for oil and gas in strategic reserves is considered for between 90 and 120 days of an average national consumption in these complex handling processes. This imply that for equivalent amounts of energy being stored at the disposal of society, the losses of hydrogen will reach a 20% in 100 days of storage. Any final global amount of hydrogen, will have to be multiplied by 1.2. This irrespective of the dire environmental problems of leaking the 20% of all the hydrogen produced in a 100% renewable economy.

The hydrogen used to manufacture ammonia, used basically for agriculture as precursor of nitrogenous compounds. This use will likely increase the need of ammonia if biofuels are going to take a part of the existing fossil fuel processes. Ammonia is also used for plastics, explosives, textiles and pesticides or to purify water.

The gigantic amount of energy required to erect the required additional infrastructures, throughout all the process chains, from the supply sector, to handling and to the demand sectors.

The need to either highly over-dimensioning the installed power of renewables and the creation of a vast electric global grid infrastructure to send energy from where it is being produced in a given moment to where is needed and is not being produced. Or otherwise, the additional huge investments in massive electric storage to face the need of a full dispatchable energy to the global society when is required, from the intermittent renewable energy systems.

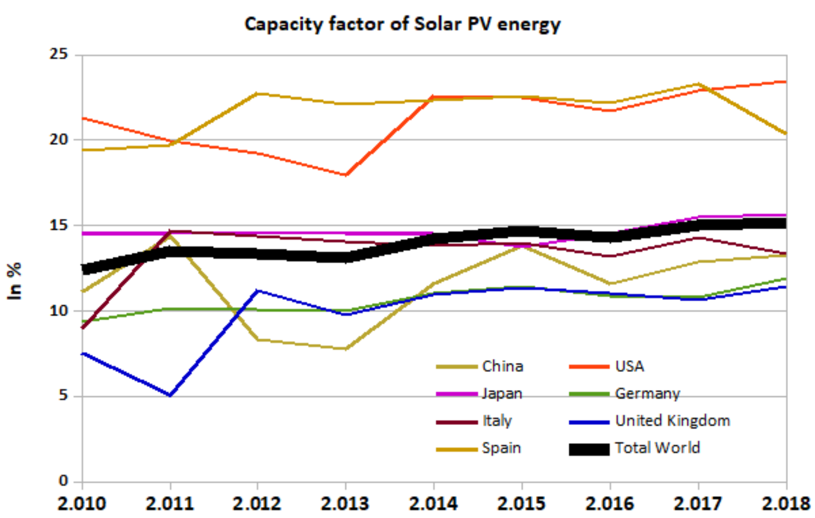
Now, let's see how much installed power would be required to supply this electricity, if it has to be done in a 100% free emissions scenario, powered by 100% renewable energies.

[54] https://escolaeuropea.eu/news/environmental-news/from-lng-to-hydrogen-pitfalls-and-possibilities/

5.4. Electric installed power required by hydrolysis as an energy vector if supplied by solar Photovoltaic (PV) systems

If we try to do it with solar PV systems, the capacity factor at present is a mere 15.2% globally.
In the last 8 years, despite the many claims of impressive progress, the reality is that it has improved 2 percentage points. The real world has little to do with the claims of efficiencies obtained in controlled situations and in labs.

We shall assume here that the technology may improve 2 more percentage points and calculate for solar PV at global level and calculate the need of solar PV installed power with a capacity factor of 17% (meaning the number of peak-hours the solar PV systems really work in a year of 8.760 hours; that is, about 1,490 hours in a year.



The conclusion is that we shall need some 35 TW of installed power to generate the required 52,174 TWh per year to generate enough hydrogen as energy vector or carrier, just to provide hydrogen for 2,000 Mtoes of fossil fuels that need an energy vector or carrier. This is about 368 times more global solar PV installed power than what it was installed in 2018 (95,566 MW).

Figure 6. Capacity factor of the main countries of the wind energy installed power and the world average and evolution since 2010 through 2018. Source BP Statistical Review of World Energy 2019 and own elaboration.

5.5. Electric installed power required by hydrolysis as an energy vector if supplied by wind energy systems

If it has to be done with wind energy, the capacity factor at present is a mere 26.9% globally.

In the last 8 years, despite the many claims of impressive progress, the reality is that it has improved 3 percentage points.

We shall assume here that the technology may improve 4 more percentage points, specially as more offshore wind parks are being installed (offshore parks have also inconveniences and higher costs) and calculate the global need of wind installed power with a capacity factor of 30%

(meaning the number of peak-hours the wind power systems really work in a year of 8.760 hours; that is, about 2,628 hours in a year, which we consider an optimistic assumption.

The conclusion is that we shall need some 20 TW of installed power to generate the required 52,174 TWh per year to generate enough hydrogen as energy vector or carrier, just to provide hydrogen for 2,000 Mtoes of fossil fuels that need and energy vector or carrier.

This is about 406 times more global wind installed power than what it was installed in 2018 (49,172 MW).

We leave to the reader any possible combination of solar PV and wind energy.

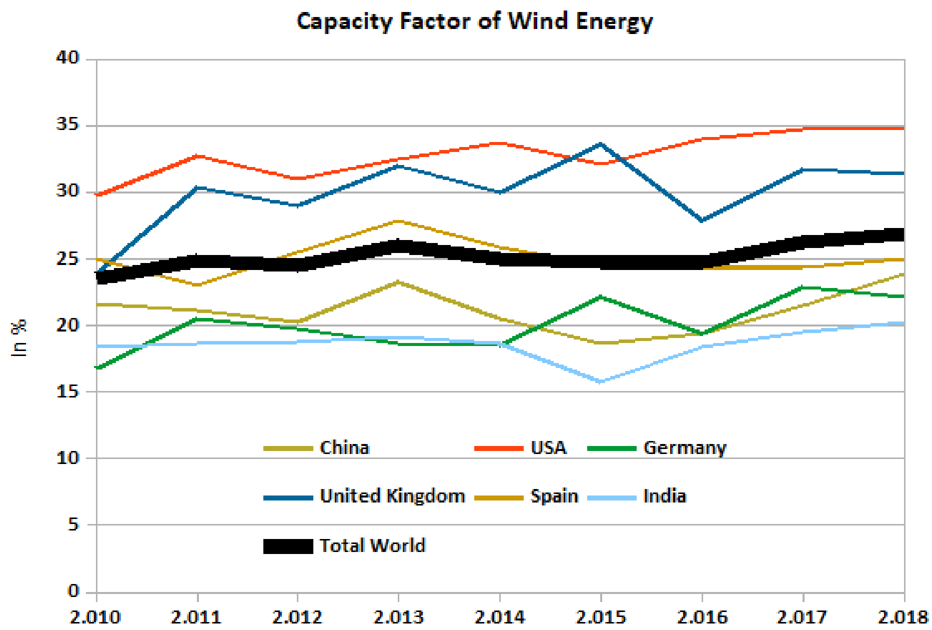


Figure 6. Capacity factor of the main countries of the wind energy installed power and the world average and evolution since 2010 through 2018. Source BP Statistical Review of World Energy 2019 and own elaboration.

Chapter 6.
Synthetic natural gas (snc) as energy vector, obtained by methanation from renewable energies. A complete life cycle efficiency

Methanation is a process consisting in taking CO_2 and hydrogen and obtain methane (natural gas). The most known process is known as the Sabatier process.

It is extremely curious that a procedure discovered and developed by Sabatier and Senderens[55] in 1902, has not been, until recently, a chemical and catalytic anecdote in our developed society (it needs a nickel, ruthenium of aluminum oxide catalyzer). The chemical reaction is as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

What is obtained here is called Synthetic Natural Gas or SNG. The main reasons to use this process are the consideration that using CO_2 from the atmosphere or from the exhaustion of some fossil fuel burning plants, will somehow alleviate the increasing amount of this gas in the atmosphere. The CH_4 so obtained is considered therefore net-zero emissions, when it is burnt back, because it was previously generated by capturing CO_2. And it has the advantage with respect to hydrogen, as energy vector or energy carrier, that it can be transported, handled or stored much easier than hydrogen, that requires either some 700 bars for compression or -253ºC for liquefaction, to gain some energy content per volume and do not have the dire problems of embrittlement that hydrogen has. And most of the existing infrastructures of natural gas could be used, without any problems, contrary to what happened with hydrogen.

The abundance of natural gas in deposits is so abundant, that it finds more efficient the reverse process: to obtain hydrogen from methane by the so called steam reforming process, as follows:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \text{ and then } CO + H_2O \rightarrow CO_2 + H_2$$

We shall study here the overall efficiency cycle and the energy required to obtain methane from CO_2 and H_2. And we will use data of existing plants of catalytic methanation, which is the cheapest in this moment, with fixed bed reactors. Other concepts as three-phase methanation, micro-reactors or biochemical conversion will be left outside, for being mainly in development.[56]

[55] https://www.sciencedirect.com/topics/engineering/methanation

[56] Renewable Power-to-Gas: A Technological and Economic Review. Manuel Gotz et al. https://www.storeandgo.info/fileadmin/downloads/2015-08-03-Review_Artikel_PtG_Renewable_Energy_2015.pdf

We shall not consider here the energy expenses to clean first upstream the CO_2 from impurities that could harm the nickel catalysts, like sulphur containing components, very usual in the exhaustion of fossil fuel plants or the energy spent in CO_2 removals, if any, once the SNG is obtained or heat integration energy expenses.

Biogas will be another theoretical source of CO_2 for methanation, as it contains a considerable amount of this gas (30-50% of CO_2).

Considering that the scenario is 100% free emissions world made with 100% renewable energies, we shall consider only the capture of CO_2 from atmosphere and not in the huge thermal plants, that will have to disappear in the final stage of this scenario. Although the CO2 content in the air was 280 parts per million (ppm) now it has reached 415 ppm and mounting.

So, the feedstocks to be considered here will be water for electrolysis and hydrogen production (per kg. of H_2 produced 8 kg of O_2 are also produced than can be partially reused or diverted to other sectors), and the CO_2 from the 415 ppm of the atmosphere.

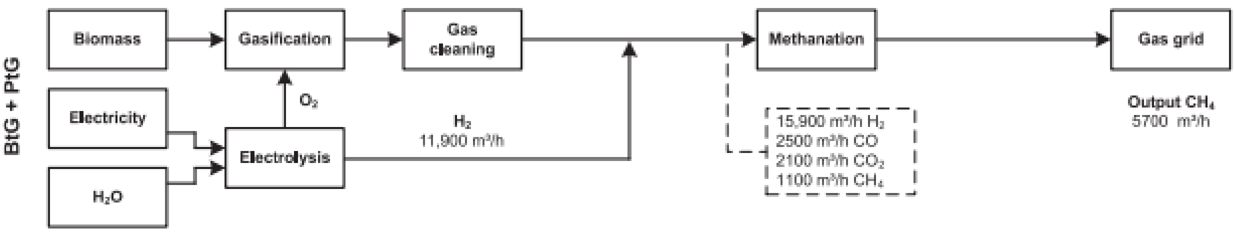


Figure 8. Example of methanation using biomass, renewable electricity and water to make electrolysis to produce SNG. Source: Renewable Energy 85 (2016) 1371-1390. Renewable Energy Elsevier. Renewable Power-to-Gas: A technological and economic review. Manuel Götz et al.. Fig. 10 Increase in CH4 production for Biomass-to Gas by integrating H_2 from wind and sun power.
https://www.storeandgo.info/fileadmin/downloads/2015-08-03-Review_Artikel_PtG_Renewable_Energy_2015.pdf

In the above scheme, it is observed that in order to produce 5,700 m^3 of SNG per hour, 11,900 m^3 of hydrogen per hour need to be applied as feedstock, as well as 2,100 m^3 per hour of CO_2.

In summary, we could conclude that every m^3 of SNG produced by this method, will require
2.09 m^3 of hydrogen
0.37 m^3 of CO_2
0.44 m^3 of CO and even
0.02 m^3 of CH4 also in the process.

We shall focus exclusively here in the hydrogen and CO_2 energy costs for its production.

Now, what is needed to replace the present fossil fuels that cannot be used in electric form and need this SNG as energy vector or carrier, are the 2,000 Mtoe of global processes or functions, already mentioned and calculated in Chapter 5.3 above.

According to the BP Statistical Review of World Energy 2019, in the approximate conversion factors:

1 m^3 of natural gas is equivalent to 0.86 kg of oil.
1 billion m^3 of natural gas are equivalent to 0.860 Mtoe

Therefore, we would need to produce 2.3 trillion m^3 of SNG as energy vector or carrier to replace 2,000 Mtoes of fossil fuels, whose processes and functions cannot be directly replaced by electricity. This is 62% of the present global natural gas production (3.848 trillion m^3)

6.1. The hydrogen required for methanation of 2,000 Mtoes of fossil fuels

In figure 8 above, 5,700 m^3 of SNG will demand 11,900 m^3 of hydrogen. The hydrogen density is 0.089 kg/m^3 at 0ºC and 1 bar.

The production of 5,700 m^3 of SNG as per in figure 8 above, will demand 1,059 kg of H_2. That is, every kg of H_2 as feedstock will yield in this process 5.38 m^3 of SNG.

The global required production of 2.3 trillion m^3 of SNG will demand the production of 397 MtH_2.

The IEA estimates that if the present annual world production of the 69 MtH_2 would have to be made completely by electrolysis, it would demand 3,600 TWh. Therefore, the production of 397 MtH_2 would require an electricity demand from 100% renewables of 20,713 TWh . Almost the world electricity demand in 2018 (26,615 TWh), just to replace 2,000 Mtoes of fossil fuels whose processes and functions cannot be directly electrified.

6.2. The CO_2 required for methanation of 2,000 Mtoes of fossil fuels

The carbon dioxide (CO2) is a colorless gas, now in 415 ppm in the air. It is not a toxic gas in itself in this concentration, but necessary for many plant vital functions. It weights 1.976 kg per cubic meter. Its boiling point is .57ºC and the fusion point is -70ºC.

As per the figure 8 above, to obtain 5,700 m^3 of SNG some 2,100 m3 of CO_2 will be required.

Therefore, the 2.3 trillion m^3 of SNG required for methanation, as seen above, will demand the capture of 847,000 million m^3 of CO_2. One tonne of CO_2 occupies 500 m^3. So, to replace 2,000 Mtoe with 2.3 Tm^3 of SNG, we will need 1,695 $MtCO_2$. This is roughly twenty times less than what is emitted by anthropogenic causes every year, tough it is already an important amount. In this point, some considerations have to be highlighted:

> On one hand, to rescue some 1/20 of all world CO_2 emissions, it would be very good, but it represents in itself a huge task, even if trying to capture it where it leave in higher

concentrations, at the exhaust of many industrial plants and they are quite evenly distributed worldwide.

On the other hand, one of the bigger CO_2 emitters is the transport sector, and its inherent mobility makes things very difficult to materialize and use for methanation.

We have already mentioned that the process of figure 8 implies some other energy expenses and complex additional processes that we will not address here, but have to be kept in mind for methanation.

The target of full decarbonization implies that every analysis of CO_2 in the long term has to be considered as captured from the atmosphere ni the present 415 ppm.

To analyze the energy that costs the acquisition of 1 tonne of CO_2 from the air, is a complex issue. There are many paper documenting the price of capturing (CCS or CCUS) one tonne of CO_2, but they vary widely and many offer improvements and costs reductions in the future.
We shall focus no the article of David W. Keith in Joule magazine, titled "Process for Capturing CO2 from the atmosphere"[57].

The capture of CO_2 is a complex process requiring filters, sorbents, pellets, films of certain types to facilitate reactions and catalysis, from water to calcium carbonate, various reactors, calciners and steam and gas turbines, etc.

The scheme of the used infrastructure and basic reactions can be summarized as follows:

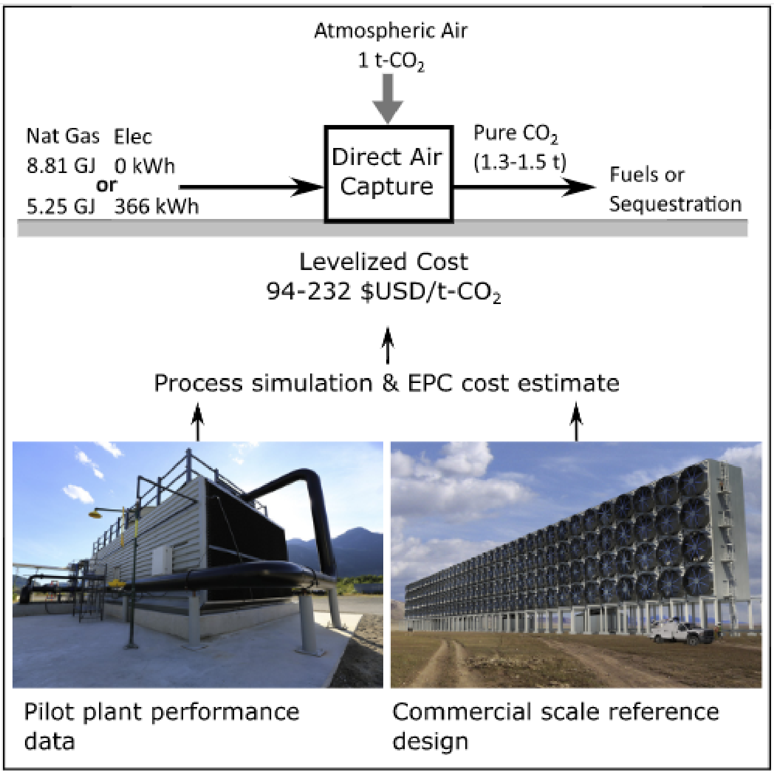


Figure 9. Processes to capture CO2 from the atmosphere. Source: A Process for Capturing CO2 from the Atmosphere, by David W. Keith. Ibid.

It is worth noting the complexity to capture CO_2 and the number of consumable materials to get the required reactions and that the plants need to be changing and replacing. We shall leave these extra costs apart for simplicity.

[57] https://www.sciencedirect.com/science/article/pii/S2542435118302253

The next table is a brief summary of the above mentioned plant, designed to produce 171 tonnes of CO_2/hour. The table offers the material inputs or feedstocks or consumables needed for the 171 tonnes of CO_2/hour. Also the amounts that will be needed to produce the above mentioned 1.695 million tons of CO_2 per year to cope with the methanation needs, necessary to produce the 2.3 Tm3 of SNG necessary to replace just 2,000 Mtoe/year of fossil fuels that carry out today processes and functions we have considered cannot be electrified and will need and energy vector.
It is worth noting the intensive use of methane to produce CO_2 in present plants.

We have assumed that the generation of the gas turbine can be conveniently replaced by an equivalent electric power coming from renewables in a 100%.

The energy consumption of this plant is considered of 315 GJ/h of CH_4, which equals to 87.5 MWh/h or 766,500 MWh/year. We shall consider that if electricity takes this function and assuming that the efficiency of the gas turbine is 38%, the electricity required for this plant will be 291,117 MWh/year. This is 0,291 Twh/year.

In order to produce the required 1,695 $MtCO_2$/year some 1,131 plants of this size will have to be installed worldwide. The electric consumption will be in the order of 330 TWh/year. Needless to say that we are not counting the additional energy to bring to produce, install and maintain the required plants nor the rest of the huge material inputs and consumables required ($CaCO_3$ or water, among others)

		CO2 grade of purity obtained	CO2 output in tonnes/hour	Required million tonnes of CO2/year
		97.12%	171	1695
		O2 1.36%	Byproducts of the CO2 obtention	
		N2 1.28%		
		H2O 14.99%		
		Equip. For CO2	MW	Some 1,131 plants of this size will be required to produce the CO2 for the methanation required for the SNG as a energy vector or carrier
		Pellets reactor	3.4	
		Water Showers	0.3	
		Air Contactor	9.2	
		CO2 Absorber	0.4	
		Quicktime Mix Tank	0.2	
		Aux	2.6	
		Calciner	0.8	
		CO2 Compressor	22	
		Oxygen preheat	13.3	
		Steam Slaker	3.6	
		Gas Turbine	-46	
		Steam Turbine	-9.8	
		315GJ (87.5 MWh) gas turb	87.5	
		Total	0	
Products	**Inputs in t/h**	**Processes for CO2**	Material inputs in tonnes per tonne of CO2	Required inputs in Mt/year for 1,695 Mt CO2
CaCO3	3.4	As makeup		
CaCO3	4.5	As seed		
CaCO3	6.0	As seed to pellets reactor		
Total CaCO3	**13.9**		0,081	138
CH4	**6.3**	315 GJ/h for Gas Turbine	0,037	62
H2O	531	Water knockout	3,105	5.263
O2	58.5	Oxygen preheat	0,342	580
Note: If Gas turbine has to be replaced by electricity from renewables, then 291,117 MWh/year will be needed, assuming a present 38% gas turbine efficiency				

Table 4. Summary of the energy and material needs of a typical CO_2 production plant from the atmosphere. Source: A Process for Capturing CO2 from the Atmosphere, by David W. Keith. Ibid.

As a summary, in order to produce the 2.3 trillion m3 of Synthetic Natural Gas required as a vector to replace 2 Btoe of fossil fuels per year (many other energy inputs derived of the infrastructure erections and material inputs excluded), the electricity required will be as follows:

20,713 TWh for the production of the 428 MtH_2 required for that process.

330 TWh for the production of the 1,695 MtCO_2 required for that process.
A total of 21,043 TWh of 100% renewable electricity will be demanded.

6.3. Electric installed power required by methanation if supplied by solar PV systems.

Based in the same principles than analyzed in Chapter 3.5. and figures 5 above, with the Capacity Factors improved to 17% in the case of solar PV, the systems will work 1,490 hours a year at nominal capacity. The required installed power will be of 15 TW of solar PV modules for that purpose.

6.4. Electric installed power required by methanation if supplied by wind power systems.

Based in the same principles than analyzed in Chapter 3.5. and figures 5 above, with the Capacity Factors improved to 30% in the case of wind power, and with the considered mixes of 50% onshore and 50% offshore, the systems will work 2,628 hours a year at nominal capacity. The required installed power will be of 8.5 TW of wind power systems for that purpose.

Chapter 7. The renewables needed for electrification of all the rest non electric processes and functions.

Now it is time to analyze the rest of the activities consuming today fossil fuels, that have been presumed here it will be directly electrified, to get a 100% decarbonized word with 100% renewables.

We shall divide this task into two big differentiated groups.

7.1. Electrification of the electric plants generating with fossil fuels.

In one side, we shall analyze the renewable energy necessary to transform the electric sector to a 100% renewable system. To this purpose, we shall make the following assumptions on the table 2 above, taken from the IEA Sankey Diagram of the figure 2 above:

Entrance to the electric System 37.9% of primary energy		
Fuel	Mtoe	%
Coal	2374	44,7
Natural Gas	1264	23,8
Oil	226	4,3
Nuclear	687	12,9
Biomass/Waste	200	3,8
Geothermal	72	1,4
Solar/Wind	139	2,6
Hydroelectric	351	6,6
TOTAL	5313	

	Estimated losses in conversion In Mtoe	Generated electricity in bars In Mtoe	Estimated losses in transport In Mtoe	Electricity delivered to TFC or Final Stage Energy in Mtoe	lectricity Mtoe to TFC from fossils to be replaced by Renewables 100,00 %
Coal	1614	760	76	684	1261
Natural Gas	695	569	57	512	
Oil	154	72	7	65	
Nuclear	447	240	24	216	
Biomass/ Waste	128	72	4	68	
Geothermal	45	27	1	25	
Solar/Wind	0	139	7	132	
Hydroelectric	0	333	17	317	
TOTAL	3083	2212	193	2020	

Table 5. Electric production in the world, with the input in Primary Energy by type of fuel in Mtoe and the electric output also in Mtoe, but of Total Final Consumption energy or Final Stage Energy. Source: IEA Sankey Diagram of world energy 2017. The conversion efficiencies from primary energy into Total Final Consumption or Final Stage Energy, given in world average and calculated by the author and shown in the table, based on well known estimated averages. For natural gas, it is considered higher than for other thermal uses due to Combined Cycle Gas fired plants. For biofuels and waste it has been considered the average conversion efficiency of thermal plants. For renewables it has been taken an optimistic assumption of only 5% losses to the Total Final Consumption in transport. We calculate also the nuclear energy finally delivered as TFC, but we shall leave apart the nuclear energy from this study.

The amount of electricity from fossil fuel origin to be electrified is 1,261 Mtoes of Total Final Consumption or Final Stage Energy.

According to the BP, 1 tonne of oil equivalent equals to 12 Mwh. Therefore, 1,261 Mtoe of pure electricity, after losses, at the Total Final Consumption of Final Stage Energy will demand 15,132 TWh.

7.2. Electric installed power required to replace fossil fuels now producing electricity, if supplied by solar Photovoltaic (PV) systems.

Based in the same principles than analyzed in Chapter 3.5. and figure 5 above, with the Capacity Factors improved to 17% in the case of solar PV, the systems will work 1,490 hours a year at nominal capacity. The required installed power to supply 15,132 TWh will be of 10 TW of solar PV modules for that purpose.

7.3. Electric installed power required to replace fossil fuels, now producing electricity, if supplied by wind power systems.

Based in the same principles than analyzed in Chapter 3.5. and figures 5 above, with the Capacity Factors improved to 30% in the case of wind power, and with the considered mixes of 50% onshore and 50% offshore, the systems will work 2,628 hours a year at nominal capacity. The required installed power to supply 15,132 TWh will be of 5.7 TW of wind power systems for that purpose.

7.4. Electrification of the rest of the processes and functions powered by fossil fuels.

In the other side, we shall analyze the renewable energy necessary to electrify the Total Final Consumption that is supplied by fossil fuels, which is 7,419 Mtoes/year, but excluding from it the fossil fuels that have been replaced in previous chapters of this study by energy vectors (2,000 Mtoe/year). That is, the task is to analyze the electric energy from 100% renewables that will replace the 5,419 Toe of Total Final Consumption or Final Stage Energy; the energy of quality and already refined, but in fossil fuel form.

The energy to be electrified from the Total Final Consumption, that is using fossil fuels, as per the table 2 above, taken from the IEA Sankey Diagram of the figure 2 above is as follows:

FOSSIL FUELS AT TFC LEVEL			Fossil Fuels of TFC to be replaced by energy vectors	Balance of fossil fuels of TFC to be directly electrified
Industry: 29% TFC	**Mtoe**	**%**	**Mtoe**	**Mtoe**
Oil	321	17,4		
Coal	818	44,3		
Natuiral Gas	568	30,8		
Heat	138	7,5		
TOTAL	**1.845**	100		
Transport: 29% TFC	**Mtoe**	%		
Oil	2.589	96,1		
Coal	0	0,0		
Natural Gas	105	3,9		
TOTAL	**2.694**	**100**		
Resid./Com.: 33% TFC	**Mtoe**	**%**		
Oil	433	31,4		
Coal	152	11,0		
Natural Gas	644	46,6		
Heat	152	11,0		
TOTAL	**1.381**	**100**		
Non Energy Uses	**Mtoe**	**%**		
Oil	643	73,1		
Coal	51	5,8		
Natural gas	186	21,1		
TOTAL	**880**	**100**		
Own Use	**Mtoe**	**%**		
Heat	37	6,0		
Natural Gas	291	47,0		
Coal	80	12,9		
Oil	211	34,1		
TOTAL	**619**	**100**		
GRAND TOTAL:	**7419**		**2000**	**5419**

Table 6. Total Final Consumption or Final Stage Energy from fossil fuels to be 100% electrified. Source: Source: IEA Sankey Diagram of world energy 2017.

If in this paper we assume that only 2,000 Mtoes of the world Total Final Consumption of Final Stage Energy are going to use energy vectors, then the balance of all fossil fuels used in 2017 that would require 100% transformation into renewable sources for a 100% decarbonization will be 5,419 Mtoe. As mentioned above, according to the BP, 1 tonne of oil equivalent equals to 12 MWh. Therefore, 5,419 Mtoe will demand 65,028 Twh for a 100% decarbonized world with 100% renewable energies. At the above calculated capacity factors of solar PV (17%) and wind energy

(30%) at global level, the solar PV installed power to cover these functions will be 44 TW and the wind power would need 25 TW.

7.5. Total electric energy needed to replace fossil fuels generating electricity and in other fossil fuels directly consumed as such in the Total Final Consumption or Final Stage Energy functions.

The total electric energy needed to replace all the fossil fuels (apart from the electricity we calculated in chapter 5 to make some functions through hydrogen as energy vector and alternatively chapter 6 to make the same functions though SNG as energy vector), can be summarized as follows:

	Mtoes	Twh Equiv	Required Installed Power RES100% in TW	
Total fossil fuels to decarbonize 100% with 100% renewables in TFC	**7419**			
2,000 Mtoes "hard to abate"to decarbonize by using hydrogen as energy vector	2000	52174	35 20	If solar PV If Wind
2,000 Mtoes "hard to abate" to decarbonize by using methanation as energy vector	2000	21043	15 9	if Solar PV If Wind
Balance of Mtoes of TFC to be directly electrified at 1 Toe = 12 Mwh		65028	44 25	if Solar PV If Wind
Total electricity needed for a 100% decarbonization with 100% renewables	5419	117202	79 45	Hydrogen with solar PV Hydrogen with wind
		86071	59 34	Methanation with solar PV Methaation with wind

Table 7. A Summary of the electricity global needs in TWh and global installed renewable additional power in TW for a 100% decarbonized world at present equivalent energy consumption levels if to be done with 100% modern renewables.

Therefore, the electric energy needs for a 100% decarbonized world with 100% renewables are between 117, 202 TWh and 86,071 TWh. This is approximately between 3 and 4.5 times the global electricity demand (26,615 TWh) of 2018, as per the BP Statistical Yearbook of World Energy 2019 (data of 2018).

Chapter 8.
A brief analysis of material's needs

To get an idea of how many materials would be needed to embark in the 100% decarbonization targets with 100% renewables, let's analyze, for instance, few materials and components needed of the renewable infrastructure. Environmentalists should start acknowledging the material efforts of the mining, transporting, manufacturing, transporting again, installing and maintaining the renewable systems, because they do not come from the sky or from zero emissions, so far.

8.1. Copper

Just the copper intensity by power generation type:

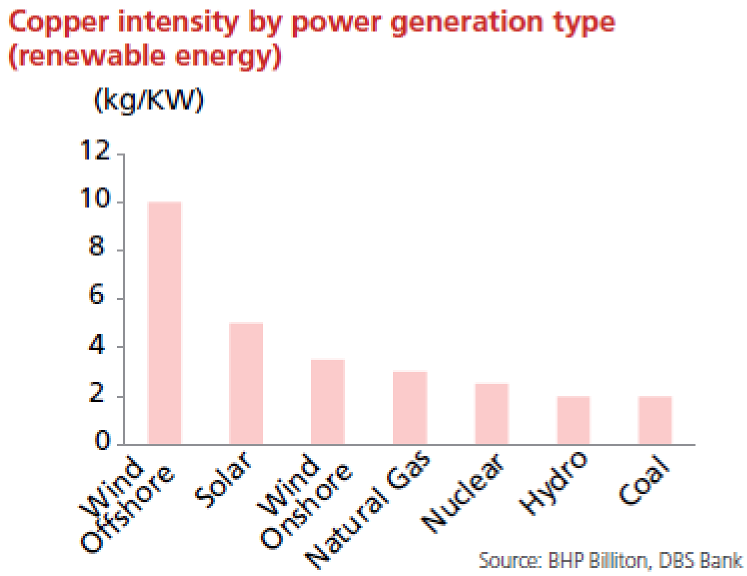


Figure 7. Copper intensity per generation type. Source: Copper and its Electrifying Future. DBS Group Research, Asian Insights Office[58]

As for the use of given generation power systems, the solar PV and the wind power systems are very intensive, due to its distributed architecture.

According to figure 7, an assumption of 50% onshore and 50% offshore future installations, will demand approximately 6.5 Tonnes of copper for each MW of installed wind power. Solar is close to 5 Tonnes of copper per installed MW. This assumption is made based on the future prospects of more offshore installations, for reasons of more stable generation and lower visual impact in the

[58] https://www.dbs.com/aics/pdfController.page?pdfpath=/content/article/pdf/AIO/102018/181008_insights_copper_SparX.pdf

inhabited land, although at present, in 2018, just 10% of the wind power had been installed in offshore in the European countries.[59]

So, the installed power demand shown below in the conclusions of 76.8 to 96.8 TW of solar PV power or alternatively 44 to 55.5 TW in the case of wind power (electric network infrastructure needs excluded, which will be far from negligible), will either demand between 384 and 484 million tonnes of copper in the case of solar PV or between 286 and 360 million tonnes of copper respectively for solar PV or wind power.

According to the USGS[60], the world production was 21 million tonnes of copper in 2018 and the reserves were of 830 million tonnes.

So the effort to decarbonize 100% the present economy with 100% renewables it will take between 14 and 22 times the total present world copper production.

The copper demand for that 100% decarbonization effort will consume the world known reserves in between 3 and 1.7 replacements.

8.2. Steel for wind generators

A typical tower for a 3 MW generator contains 335 tons of steel[61].

As per the final calculations of a 100% decarbonization with wind in the conclusions below, we will need about 50 TW of 3 MW wind generators.

This will imply the need of 5,583 million tons of steel. The global steel production in 2018 was 1,808.6 million tons[62].

So, the renewable effort for a 100% decarbonization with wind will demand more than 3 times the present annual world production.

8.3. Concrete/cement for wind generators.

A concrete base for a 3 MW onshore wind turbine may demand 1,200 metric tons of concrete.[63] As per the final calculations of a 100% decarbonization with wind in the conclusions below, we will need about 50 TW of 3 MW wind generators. This will imply the use of 20,000 million tonnes of concrete.

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[59] Wind Europe. Wind energy in Europe 2018. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf

[60] https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-coppe.pdf

[61] https://www.visualcapitalist.com/climate-smart-mining-minerals-for-climate-action/

[62] www.worldsteel.org/media-centre/press-releases/2019/Global-crude-steel-output-increases-by-4.6--in-2018.html

[63] https://www.visualcapitalist.com/climate-smart-mining-minerals-for-climate-action/

The global production of cement (which still has not the aggregated paste with sand and other ingredients) was 4,100 million metric tonnes in 2018[64].

So, the renewable effort for a 100% decarbonization with wind will demand about 4 times the present annual world production of cement.

8.4. Blades for wind generators.

a 3 MW typical wind turbine with the most common use of 3 blades in the rotor. Blades are made of fiber-reinforced composites, made with glass fiber and some resins, polymers or carbon fiber, as the size of the blades and the stress with the wind is now so big that they need very low density materials, with high strength and stiffness. The weight may be of 40 tonnes of this sophisticated and hard to recycle materials. A 100% theoretically decarbonized world with the present energy consumption and powered by wind, wit the above taken assumptions, will need some 666 million tons of composites.

The world produced in 2018 some 1.13 million tonnes of glass fiber.[65] and 75,000 metric tons of carbon fiber[66]

The necessary leapfrog to jump from present global production to the production required to serve a 100% renewable world with wind is clear enough.

8.5. Other materials, rare earths, etc. for wind generators.

A 3MW typical wind generator may contain as much as 2 tons of complex elements taken from rare earths (i.e. neodimium and praseodimium) and other components as zinc, molybdenum, etc., as well as aluminum (about 3 tons) in some parts of the nacelle and equipment. An extrapolation on the above assumptions for a 100% decarbonized world with 100% renewables with wind power will demand 33 million tons of rare earths.

The world production of rare earth in 2018 was 170,000 tonnes. The 100% wind power solution will demand almost two centuries of present world production and one-fourth of the known world reserves[67].

8.6. Renewables?

The worst thing is that what we have considered here renewable energies, in reality are rather complex non renewable equipment, able to capture, for a limited period of time (one human life generation or 25 years in the best case), intermittent renewable energy flows from nature.

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[64] https://www.statista.com/statistics/219343/cement-production-worldwide/
[65] http://compositesmanufacturingmagazine.com/2019/01/2019-state-of-the-industry-report/
[66] https://acmanet.org/composites-industry-overview/
[67] https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2019-raree.pdf

The expression “renewable energies” is one of the most successful language hijacking by technology of the last years.[68]

8.7. Recycling materials

As for the hopes deposited in the so called “circular economy” the present recycling rates are still symbolic and very poor at global level. A global study[69] concluded that “only 6% of all materials processed by the global economy are recycled and contribute to closing the loop. If all biomass is considered a circular flow regardless of production conditions, the degree of circularity increases to 37%”.

The figure could also increase if we get rid of the fossil fuels, but many of the materials used in the so called Green Economy have very low recycling rates.

The UN Metals Status Report Summary[70] gives a very good idea of the recycling rates in the global society of all the elements in the periodic table.

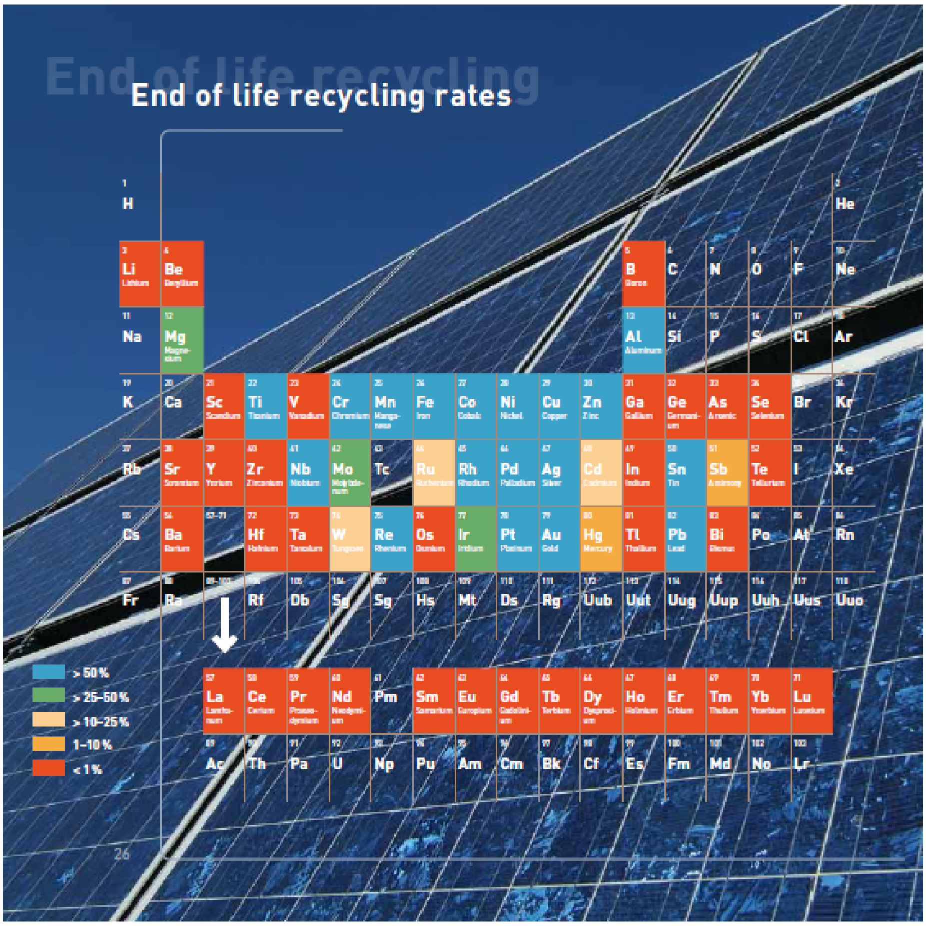

Figure 8. Recycling rates of the elements of the periodic table. Source: United Nations Environmental Program. (UNEP). Metal Stocks and Recycling Rates.

The possibility of having a complete circular economy goes against the entropy laws . The increasing complexity of some of the modern goods, like smart phones, with more than 20 different rare elements and complex alloys on them and the global dispersion of the units, the geographical, temporal, social, economic and other difficulties, makes very difficult to close the cycles and return to recycling units the materials previously dispersed.

[68] https://www.bbc.com/news/technology-49197595

[69] How Circular is the global Economy?. An asesement of Material Flows, Waste Production and Recycling in the European Union and the World in 2005. Willi Haas et al. Research and Analysis

[70] https://www.resourcepanel.org/reports/recycling-rates-metals

Recycling also costs energy, and the more dispersed are the elements, the more energy is required to take them to the recycling sites. Although in general and specially in the rprecious or scarce metals,, the energy expense of recycling is less than mining per tonne of recovered material, this study has not analyzed or included the energy costs of mining or recycling.

Chapter 9. Conclusions

9.1. Summary of renewable energy and renewable installed power needs

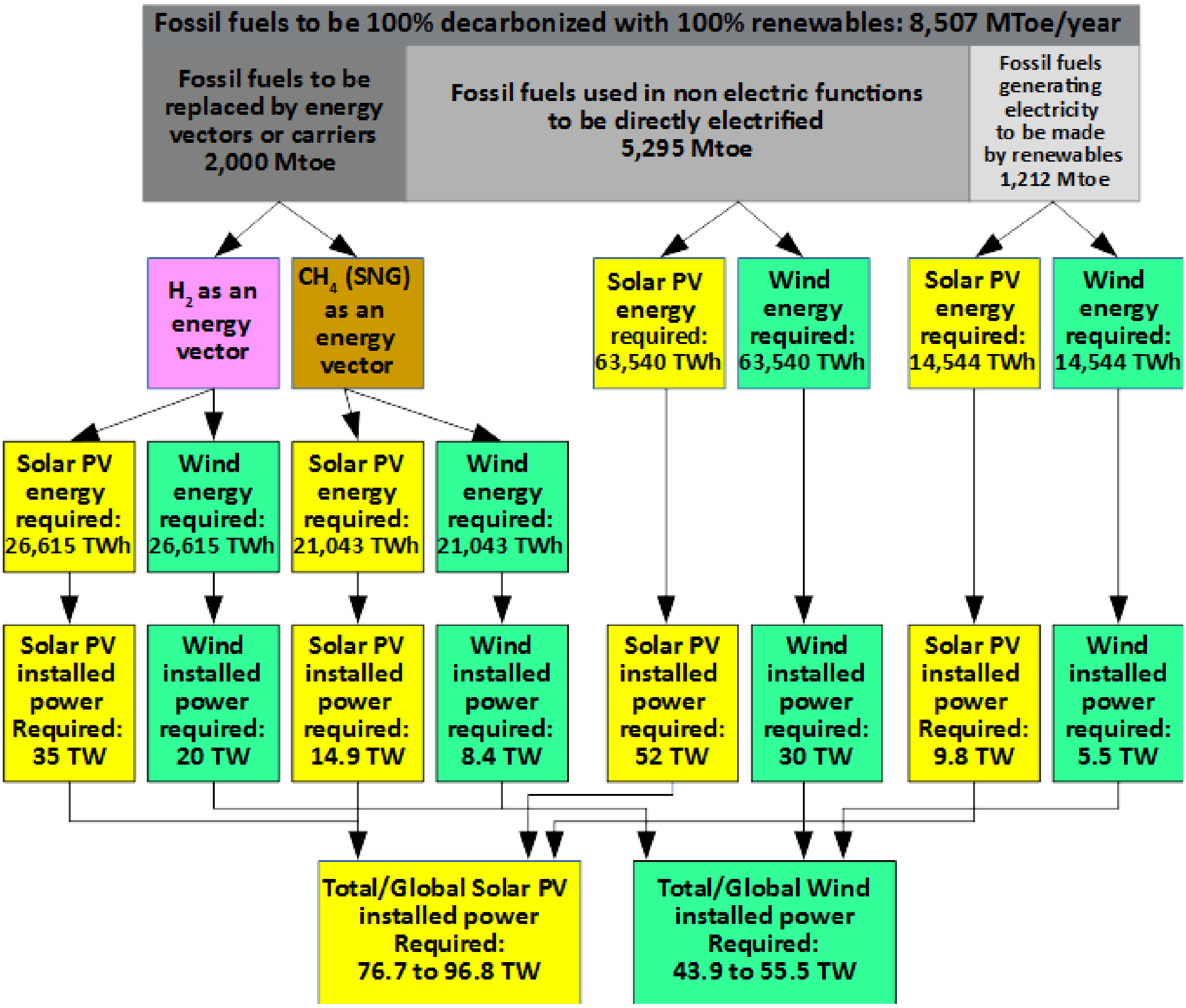

Figure 9. Diagram of a potential conversion of the global economy from a fossil fueled one to a 100% renewable energy.

9.2. Economic growth must/will end.

The above analysis has been made ignoring many energy elephants in the global room. One is the energy costs or the erection of all these infrastructures, which must include the construction of buildings, factories, increase in water consumption, road infrastructures, etc.

The own extra raw materials that the not so green economy will demand if we are moving to a 100% renewable world,as briefly explored in Chapter 8 above, if we still pretend having the economy in motion and using the same amount of raw materials for present uses, is also to be considered.

The increase in the size of the global electric network is also another big additional energy input we have deliberately ignored in this limited study, but that cannot be ignored , if we are to embark in this huge and now almost impossible venture.

But with all, the biggest problem ahead if we really want to decarbonize our world, is the political and social prevalent system of permanent economic growth. We have not intentionally considered in this limited study the impact of a "moderate" growth, as per the governments and businesses demand, of, for instance, a 2-3% per year (of course, accumulative). Should we have considered that, the materials needs would have to be mathematically duplicated every 35 or 25 years respectively and of course, the figures will have skyrocketed to impossible scenarios.

We will never reach, very likely the 20 billion cars on the roads, be them powered by Internal Combustion Engines (ICEs) or as Electric Vehicles (EVs).

We will never reach the 9 billion tourists in a year from the present 4.5 billions of today, but not because flygskam[71] fashion and some rich people get ashamed now of flying in polluting commercial flights or because a German parliamentary of the Greens proposes to limit to three international flights a year per German[72], when they are telling with this that three or less trips will be acceptable and if needed more they can buy to other non traveler fellow and continue traveling.

We will never reach this gargantuan figures and impossible roadmaps that the economic system forces us to take. But it won't be because plausible initiatives, but absolutely disconnected from this impossible economic system, destined to crash sooner than later.

Time to tell from the technical and scientific arena this real "inconvenient truth" to governments, politicians and also, why not, to the environmentalists and young protesters asking for their future life and still thinking, most of them, that renewables will come to the rescue if only politicians push the proper button.

We are astonished to observe how most of the scientists, with some honorable exceptions, are silent, precisely in front of this elephantian challenge, while continue offering scientific promises and smart calculations of a brilliant New Green Deal (GND)[73] with zero emissions in a Business As Usual (BAU) growth mode, ignoring that no efficiency or technological improvement will ever offset.

Time to come down to terms, starting from the most consumeristic zones.

[71] https://www.bbc.com/worklife/article/20190718-flygskam

[72] https://www.cleanenergywire.org/news/debate-curbing-aviation-emissions-gains-traction-germany

[73] https://es.wikipedia.org/wiki/Green_New_Deal

List of Acronyms

BAU: Business as Usual.
BEV: Battery (powered) Electric Vehicles.
BOS: Beware of Scale.
BP: British Petroleum.
Btu: British Thermal Units. A measure of energy.
CC: Climate Change.
CCS: Carbon Capture and Sequestration.
CCUS: Carbon Capture Utilization and Storage
CH: A hydrocarbon molecule.
CO_2: Carbon dioxide.
EJ: Exa-Joules
EU: European Union.
EV: Electric Vehicle.
FAO: Food and Agriculture Organization of the United Nations.
FFF: Fridays For Future (Greta Thunberg Inspired movement).
GHG: Greenhouse Gases.
GND: Green Bew Deal.
HFC: Hydrogen Fuel Cell systems or vehicles.
HHV:Higher Heating Values. Higher range of an energy content.
ICE: Internal Combustion Engine.
IEA: International Energy Agency.
IPCC: International Panel for Climatic Change.
LCOE: Levelizez Cost of Electricity.
LHV: Lower Heating Values. Lower range of an energy content.
LNG: Liquefied Natural Gas.
MEPC: Marine Environment Protection Committee.
Mtoe: million tonnes of oil equivalent.
MW: Megawatts
Mwh: Megawatts*hour
OECD: Organization for Economic Cooperation and Development.
OICA: Organization of Motor Vehicle Manufacturers.
PtG: Power-to-Gas. A form to get a gas fuel from electricity.
PV: Photovoltaic.
P2G: Power-to-Gas. A form to get a gas fuel from electricity.
RCP: Representative Concentration Pathway (IPCC scenario).
SIPRI: Stockholm International Peace Research Institute.
SNG: Synthetic Natural Gas or synthetic methane.
TFC: Total Final Consupmtion, as understood by the IEA (or Final Stage Energy)
TW: Terawatts.
TWh: Terawatts*hour.
UNEP: United Nations Environmental Program.
USA: United States of America.
USGS: United States Geological Survey.

WEO: World Energy Outlook of the IEA. A yearly report on energy.
WWW: Wind, Water and Solar.
XR: Extinction Rebellion

Tables of equivalences and correlations of physical units

We offer here the basic equivalences given by the BP Statistical Yearbook 2018, which are well known to those familiarized with energy and power equivalents.

Approximate conversion factors

Crude oil*	To tonnes (metric)	kilolitres	barrels	US gallons	tonnes/ year
From			**Multiply by**		
Tonnes (metric)	1	1,165	7,33	307,86	–
Kilolitres	0,8581	1	6,2898	264,17	–
Barrels	0,1364	0,159	1	42	–
US gallons	0,00325	0,0038	0,0238	1	–
Barrels/day	–	–	–	–	49,8

*Based on worldwide average gravity.

Products	To convert barrels to tonnes	tonnes to barrels	kilolitres to tonnes	tonnes to kilolitres
		Multiply by		
Liquefied petroleum gas (LPG)	0,086	11,60	0,542	1,844
Gasoline	0,120	8,35	0,753	1,328
Kerosene	0,127	7,88	0,798	1,253
Gas oil/ diesel	0,134	7,46	0,843	1,186
Residual fuel oil	0,157	6,35	0,991	1,010
Product basket	0,125	7,98	0,788	1,269

Natural gas (NG) and liquefied natural gas (LNG)	To billion cubic metres NG	billion cubic feet NG	million tonnes oil equivalent	million tonnes LNG	trillion British thermal units	million barrels oil equivalent
From			**Multiply by**			
1 billion cubic metres NG	1,000	35,315	0,860	0,735	34,121	5,883
1 billion cubic feet NG	0,028	1,000	0,024	0,021	0,966	0,167
1 million tonnes oil equivalent	1,163	41,071	1,000	0,855	39,683	6,842
1 million tonnes LNG	1,360	48,028	1,169	1,000	46,405	8,001
1 trillion British thermal units	0,029	1,035	0,025	0,022	1,000	0,172
1 million barrels oil equivalent	0,170	6,003	0,146	0,125	5,800	1,000

Units

1 metric tonne = 2204.62 lb.
= 1.1023 short tons
1 kilolitre = 6.2898 barrels
1 kilolitre = 1 cubic metre
1 kilocalorie (kcal) = 4.1868 kJ = 3.968 Btu
1 kilojoule (kJ) = 0.239 kcal = 0.948 Btu
1 British thermal unit (Btu) = 0.252 kcal = 1.055 kJ
1 kilowatt-hour (kWh) = 860 kcal = 3600 kJ = 3412 Btu

Calorific equivalents

One tonne of oil equivalent equals approximately:	
Heat units	10 million kilocalories 42 gigajoules 40 million Btu
Solid fuels	1.5 tonnes of hard coal 3 tonnes of lignite amd sub-bituminous coal
Gaseous fuels	See Natural gas and LNG table
Electricity	12 megawatt-hours

One million tonnes of oil or oil equivalent produces about 4400 gigawatt-hours (=4.4 terawatt hours) of electricity in a modern power station.

1 barrel of ethanol = 0.58 barrels of oil equivalent
1 barrel of biodisel = 0.86 barrels of oil equivalent

1 tonne of ethanol = 0.68 tonne of oil equivalent
1 tonne of biodiesel = 0.88 tonne of oil equivalent

Other terms

Tonnes: Metric equivalent of tons

About the author

Pedro Prieto: Creator and co-editor of CrisisEnergetica.org since 2003. Member of the ASPO International panel since 2006 and vice-president of AEREN (Association for the Study of Energy Resources). Some of his best known essays are: *Kyoto or Upsala* (Club de Amigos de la UNESCO, 2005), A tale of energy terror-ism (Club de Amigos de la UNESCO, 2003), *The Jungle Book*. AEREN, 2004. He is co-author with Professor Charles A. S. Hall of *Spain's Photovoltaic Revolution*: T*he Energy Return on Investment* (Springer, 2013), the first in-depth study of the rate of energy return on large-scale photovoltaic systems in a developed country.