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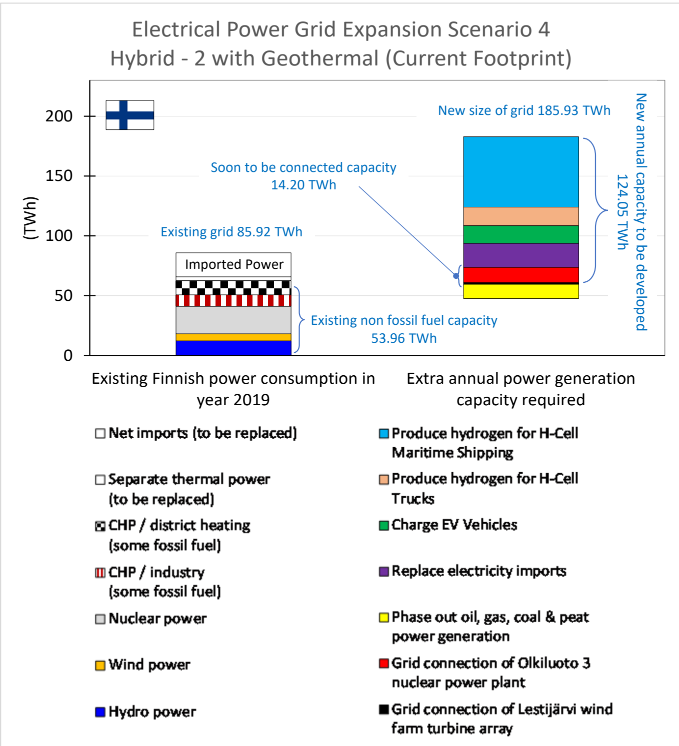
Assessment of the scope of tasks to completely phase out fossil fuels in Finland

Simon P. Michaux

Tere Vadén

J. M. Korhonen

Jussi T. Eronen



GEOLOGICAL SURVEY OF FINLAND **DOCUMENTATION PAGE**

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Authors
Simon P. Michaux (GTK)
Tere Vadén (BIOS)
J. M. Korhonen (LuT)
Jussi T. Eronen (UH, BIOS)

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Assessment of the scope of tasks to completely phase out fossil fuels in Finland

Abstract
Fossil fuel energy consumption and use in Finland was examined. Data for the year 2019 (the last year before Covid-19 pandemic quarantine requirements) was assembled for oil, gas, coal, nuclear, hydro, wind, solar, and biomass to energy systems, by application in Finland. The annual generation of electricity and how it was used in application was assessed.

Oil was the largest source of energy resource in Finland in 2019, accounting for 35.5 % of annual primary energy consumption (or 73 million barrels a year). Most of this oil was used to power Internal Combustion Engine (ICE) vehicles. To phase out these ICE vehicles, it was proposed that all trucks be hydrogen fuel powered, and all other vehicles be Electric Vehicles (EV's). To do this, Finland will be required to import/construct 162 186 hydrogen fuel celled trucks and produce 268 028 tonnes of hydrogen annually to fuel them. This will require 15.48 TWh to be delivered from the Finnish electricity grid. All other vehicles in the Finnish transport fleet are recommended to be Electric Vehicles. Finland will be required to import/construct 4.36 million EV's of various vehicle classes, containing 848 251 tonnes of lithium-ion batteries. To charge these batteries, an annual 7.91 TWh will be required to be delivered from the Finnish electricity grid. The concept of the Finnish transport fleet being fully supported by biofuels sourced from wood biomass was also examined, where 49.31 TWh of fuel would need to be produced annually. To supply enough wood biomass to achieve this, an annual volume of 40.3 Mm^3 of wood biomass would be required. Sustainable management of forestry biomass was discussed. The required volumes are not sustainable with current forestry practices and levels of wood use. However, biofuels could be the best way to maintain the aviation industry and the bioplastics industry.

The largest annual electricity generation supply system in Finland 2019 was nuclear power at 26.7 % (22.9 TWh), with a comparable quantity being imported, 23.3 % (20.04 TWh). Electricity generation from fossil fuels accounted for 13.9 % of the total. Electricity generated from Combined Heat and Power (CHP) plants accounted for 25.0 % (21.6 TWh) of total annual energy generation in 2019. When the soon to be operational Olkiluoto 3 nuclear power plant and the Lestijärvi wind farm are commissioned, an extra 14.20 TWh of annual capacity is added to the Finnish electricity power generation grid.

A series of 6 scenarios for Finland to phase out fossil fuels was developed, where recommendations for the expansion of annual capacity for the electrical power grid (as a consequence of substituting fossil fuel systems) ranged from 134.55 TWh to 17.76 TWh. All new electrical power capacity was recommended to be wind turbine generated.

If this extra capacity was sourced from wind power, this would require the construction and commissioning of a further number of Lestijärvi wind farms (a new wind farm being constructed which will annually supply 1.3 TWh), ranging from 104 new stations (47.13 GW installed capacity) to 13.3 stations (6.06 GW installed capacity).

An extra 29.16 TWh extra non-fossil fuel annual heat generation capacity is recommended to be developed, to replace fossil fuel sourced heating. If this 29.16 TWh was sourced just from wood biomass, an extra 17.60 Mm^3 of

Shallow geothermal low temperature heating was examined in conjunction with 4th generation heat pumps as a way of meeting residential heating requirements.

The task to phase out fossil fuels is perhaps the largest and most significant task the global industrial ecosystem has ever faced. It is required to have tangible physical results in the next years. All nation states, while each in unique circumstances, must meet these same challenges. Finland's net position to undertake this challenge may be one of the strongest in the world.

Keywords
Finland, sustainability, fossil fuel, electricity, renewable, wind, biomass, Electric Vehicle, hydrogen fuel cell, CHP, geothermal

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Signature/Simon P. Michaux
Associate Professor of Mineral Processing & Geometallurgy (GTK)

Signature/ J. M. Korhonen
Lappeenranta-Lahti University of Technology (LuT)

Signature/ Tere Vadén
Researcher (BIOS), Associate Professor

Signature/ Jussi Eronen
Associate Professor of long-term sustainability (University of Helsinki); Researcher (BIOS)

Signature/ Saku Vuori
Director, Science & Innovation (GTK)

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SUMMARY FOR POLICYMAKERS

Finland has a unique net position for the potential for continuing industrial production without the use of fossil fuels. However, the material and energy demand for attaining such a position are larger than current thinking and strategic planning allow. To replace all fossil fuels (oil, gas, coal, peat) in their various applications in Finland, a great deal of new Finnish industrial infrastructure is required to be financed, constructed, and then managed. This study examined what would be required to replace the Finnish fossil fuel industrial ecosystem as it is now. Data from 2019 was used as data from 2020 and 2021 has some unusual artefacts in it due to the impact of the quarantine requirements on the international energy and commodity markets.

The most logistically significant task is to phase out Internal Combustion Engine (ICE) vehicles and maritime shipping and replace them with Electric Vehicles (EV's) and hydrogen fuel cell (H_2-Cell) technologies. Within this, the hydrogen economy tasked to support the maritime shipping fleet was the largest task in terms of power draw. The sourcing of heat for industrial and domestic purposes was the next largest task. Direct and complete Finnish system replacement would resemble the following (Based on Scenario 4):

• To replace fossil fuel sourced electricity generation	11.92 TWh
• To replace fossil sourced industrial heat & district heat	29.1 TWh
• To replace fossil sourced residential heating	2.6 TWh
• To replace electrical power imports	20.04 TWh
• To power EV vehicles	10.76 TWh
• Electric vehicles	4.3 million units
• Li-ion batteries for EVs	195 GWh / 848 251 tonnes
• To produce hydrogen for H_2-Cell trucks	15.48 TWh
• H_2-Cell trucks	162 186 units
• To produce hydrogen for maritime shipping	58.77 TWh
Total	***138.67 TWh***

In comparison, domestic electricity production in 2019 was 65.82 TWh (consumption was 85.92 TWh). As an example, the production of 102.79 TWh (Scenario 4) would require building 79 new wind farms corresponding to the newly constructed Lestijärvi farm (1.3 TWh/a), or alternatively, 5 456 new wind turbines of 6.6 MW installed capacity (total 36.0 GW). Required stationary power storage to act as a buffer for this new wind generation station fleet of 80 stations, at just a conservative 4 week capacity would be 7.91 TWh.

As current annual wood harvests are already close to maximum sustainable levels, any significant increase in provision of liquid biofuel from wood biomass is possible only by reducing the biomass volume used by the forest industry. The 6 scenarios developed show the different options of how the various solutions could fit together. All 6 scenarios require some contraction of the existing forestry industry, where some biomass is harvested, but within recommended sustainable limits. Two studies of what was considered a sustainable annual biomass wood harvest were used. The National Resources Institute estimates a limit of 80.5 Mm^3 for annual long-term sustainable harvests (Luke 2021). Another study recommended this annual harvest be limited to 70 Mm^3 (WWF Finland 2015). Both recommendations were used in all 6 scenarios.

Avoidance of catastrophic climate change is possible only with rapid (within 10-15 years) end of fossil fuel use. In addition, the production of oil and gas are becoming more unreliable, creating bottlenecks and disruptions. Geopolitical events may cause the voluntary or involuntary cessation of imports from one or several international sources. Given the material and energy needs and the amount of available time, a significant reduction of societal demand for resources is something that needs to be taken seriously in any future scenario. In the following table we summarize six scenarios for a non-fossil fuel future in Finland.

FACTSHEET

Energy Source	Finnish primary energy consumption in 2019 (Exajoules EJ)	Finnish primary energy consumption in 2019 (TWh)
Oil	0,39	108,3
Natural Gas	0,07	19,4
Coal	0,15	41,7
Nuclear energy	0,2	55,6
Hydroelectricity	0,11	30,6
Renewables	0,18	50,0
Total	1,1	305,6

Fuel Source in 2019	Electricity (GWh)
Oil	267
Coal	4 115
Natural Gas	3 767
Other fossil	947
Peat	2 821
Total	11 917

Table 12. Finnish transport fleet in 2019

Vehicle Class EV	Number of Self Propelled Vehicles in 2019 Finnish Fleet (number)	Annual km traveled by average vehicle in Finland in 2019 (km)	Total km driven by class in 2019 Finnish Fleet (km)	Total km driven by class in 2019 Finnish Fleet (million km)
Trucks	162 186	20 606	3,34E+09	3 342
Buses	19 137	31 405	6,01E+08	601
Commercial Van	486 949	11 759	5,73E+09	5 726
Passenger Car	3 574 570	11 391	4,07E+10	40 718
Motorcycle *	278 534			
Total	4 521 376		5,039,E+10	47 045

4.5 million vehicles

47.0 billion km travelled in 2019

* Distance travelled by motorcycles not reported

Table 3 & 35 (merged). Finnish energy consumption in 2019

Existing System (using 2019 Data)	Electricity Capacity	Wood Biomass	Geothermal Heating
Existing Finnish electrical power demand (TWh)	85,92		
Existing electrical non-fossil fuel power production in Finland (TWh)	53,96		
Imported electric power	20,04		
Existing Annual Finnish Forestry Industry Harvest of Wood Biomass		72 Mm^3	
Existing Finnish biofuels production		625 (ktoe/year)	
Existing geothermal heating energy produced by heat pumps in Finland (TWh)			6,0

Table. 29 & 11 (merged). Extra power required to phase out fossil fuels

Task	Current use (TWh)	Required extra electricity production capacity needed (TWh)	Biofuel from Wood Biomass (Mm^3)
Replace power imports	20.04	20.04	
Short range vehicles, EVs		10.76	
Trucks, H_2-cell vehicles		15.48	
Maritime fleet, H_2 fueled		58.8	
Aviation fleet	9.77 (aviation jetfuel)		8.14
Heat generation (district & industrial heat)	93.6	29.16	
Domestic heat	17.69	2.60	
Total		136.81	

SCENARIOS TO PHASE OUT FOSSIL FUELS - SUMMARY

Scenario 1: Full Spectrum Electric (Current Footprint)

- All new power production & all transport electrical.
- To supply the extra 134.55 TWh, 104 new Lestijärvi scale wind farms constructed (1.3 TWh/a), i.e., 7 142 wind turbines of 6.6 MW capacity (47.13 GW in total).
- Required stationary power storage for buffer new wind generation station fleet @ 4 weeks capacity, 10.35 TWh.
- No extra wood biomass to be annually harvested.

Scenario 2: Max Biomass (Current Footprint)

- Finnish wood biomass used as much as possible in CHP plants and for biofuels (harvest additional 90.5Mm^3/a)
- ICE vehicles, including trucks, aviation and maritime shipping all powered with biofuels.
- To supply extra 17.76 TWh, 14 new Lestijärvi scale wind farms constructed (943 wind turbines of 6.6 MW capacity, 6.2 GW in total).
- Required stationary power storage for buffer new wind generation station fleet @ 4 weeks capacity, 1.37 TWh.
- Downgrade forest industry by -100% (assuming a harvest level of 80.5 Mm^3/a), and still have a biomass shortfall.

Scenario 3: Hybrid 1 (Current Footprint)

- Combination of electrical power from wind turbines with wood biomass fueled CHP plants supplying all heating requirements.
- To supply extra 102.79 TWh, 79 new Lestijärvi scale wind farms constructed (5 456 wind turbines of 6.6 MW capacity, 36.0 GW in total).
- Required stationary power storage for buffer new wind generation station fleet @ 4 weeks capacity, 7.91 TWh.
- Downgrade forest industry by -23.9% (assuming a harvest level of 80.5 Mm^3/a).

Scenario 4: Hybrid 2 with Geothermal (Current Footprint)

- Residential building heat through heat pumps sourcing shallow (300m) geothermal wells; industrial heat through wood biomass fueled CHP plants.
- Extra electrical power the same profile as Scenario 3, 102.79 TWh, 79 Lestijärvi scale wind farms (36.0 GW total installed capacity), 7.91 TWh buffer stationary storage.
- Downgrade forest industry by -9.04 % (assuming a harvest level of 80.5 Mm^3/a).

Scenario 5: No Action (No new capacity constructed; fossil fuels phased out)

- No new power generation capacity, all fossil fuels phased out. All new heating CHP wood biomass sourced.
- To meet the challenge, consumption demand for power consumption reduced by 47.96%. Half of existing non-fossil fuel power production re-tasked to production of hydrogen and the charging of EV batteries.
- Annual distance travelled by short range vehicles and trucks reduced by 66%. Annual distance travelled by maritime transport fleet reduced by 75%.
- Downgrade forest industry by -12.6% (assuming a harvest level of 80.5 Mm^3/a).

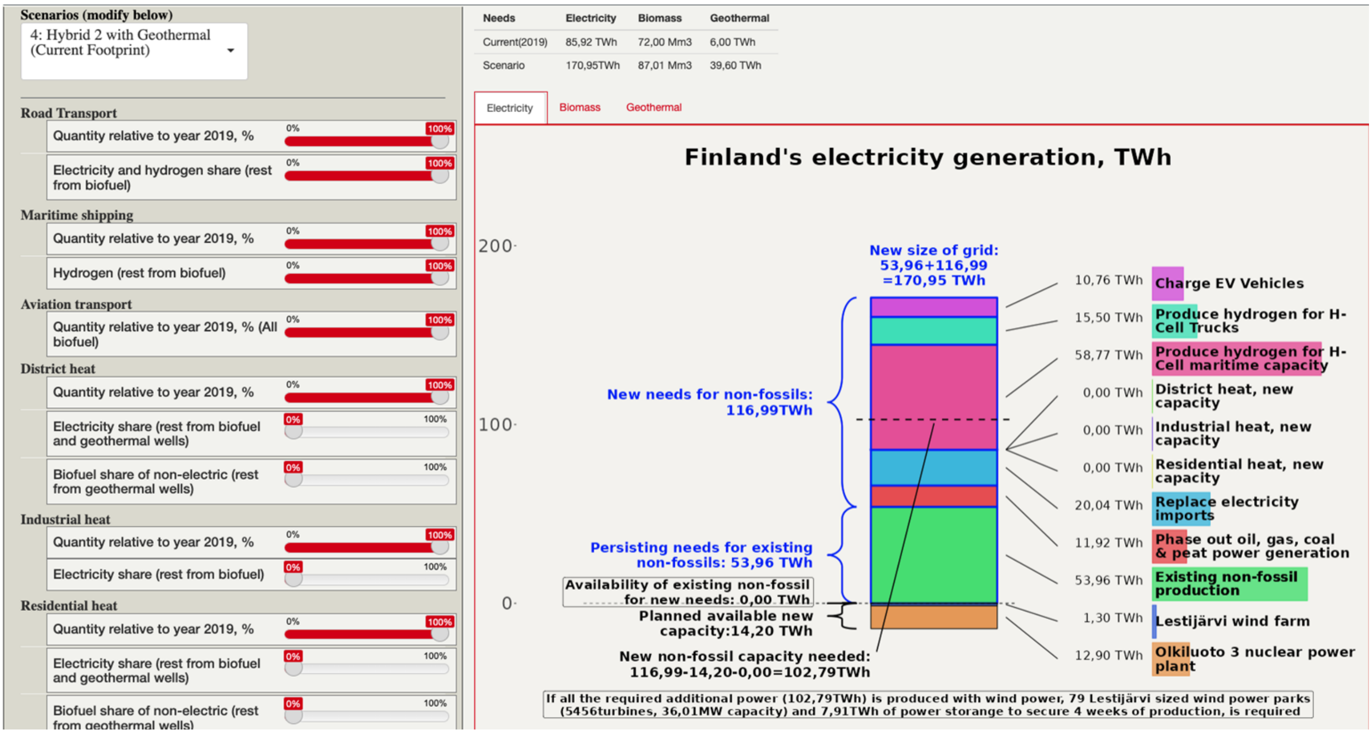
Scenario 6: Planned Sustainability (Managed Footprint Contraction 50%)

- Demand for power consumption reduced by 50%. Half of fossil fuel electrical power generation replaced. Residential building heat through heat pumps sourcing shallow (600m) geothermal wells; industrial heat through wood biomass fueled CHP plants.
- 50% of non-fossil fuel power production re-tasked to production of hydrogen and the charging of EV batteries (26.98 TWh). Annual distance travelled by short range vehicles, trucks and maritime transport fleet reduced by 50%.
- To supply the required extra 17.32 TWh, 13.3 new Lestijärvi scale wind farms constructed (918 wind turbines of 6.6 MW capacity, 6.06 GW in total).
- Required stationary power storage for buffer new wind generation station fleet @ 4 weeks capacity, 1.33 TWh.
- Downgrade forest industry by -3.39% (assuming a harvest level of 80.5 Mm^3/a).

BIOS FINNISH ENERGY SIMULATOR

On the basis of this report, BIOS Research Unit (https://bios.fi/) has published a web app (with both Finnish and English text), developed by Ville Seppälä. The purpose of the simulator is the same as in the report: to illustrate the possibilities and challenges of energy transition away from fossil fuels to low-emission energy production in Finland. The web app is used to calculate how the total Finnish energy consumption (electricity, transportation and traffic, heating) in 2019 could be produced without fossil fuels. The background data and assumptions for the tool come from this report. The weblink for the simulator is:

https://energialaskuri.bios.fi



Screenshot of https://energialaskuri.bios.fi

The user can adjust the amount of energy demand in each sector and choose between different forms of production (wind, biomass, geothermal). The app then shows the amount of needed total production, and the amount of needed new electricity production, amount of (wood) biomass and geothermal energy.
On the left side there is a pulldown menu, with the six pre-set scenarios from the report. By choosing a pre-set scenario, the simulator presents the amount and modes of energy production in that scenario. All of the preset scenarios can be modified by using the sliders on the left side. The results on the right-side change according to the values set by the sliders.

At the bottom of the left side there is a button for “Share your selections” which allows the user to create a link to the scenario (preset or modified) currently on view.

1 INTRODUCTION

Energy is the master resource. It allows and facilitates all physical work done, the development of technology and allows human population to live in high density settlements like modern cities. Energy (in Watt-hour or Wh) is the capacity to do physical work, and its consumption correlates directly with the real economy (Bradley & Fulmer 2008) which is the part of the economy that is concerned with actually producing goods and services, as opposed to the part of the economy that is concerned with buying and selling on the financial markets.

Power (in units of Watt or W) is energy per unit of time. Thus, energy is what makes change happen and can be transferred from one object to another. Energy can also be transformed from one form to another. Power is the rate at which energy is transferred.

Future projections of global energy demand are usually developed on past behavior, with no understanding of finite limits or depleting resources (see, e.g., Smil 2017 for details). Generally, reserves have been projected on past production and demand has been defined by population growth and economic GDP.

The modern world is heavily interdependent. Many of the structures and institutions we now depend upon function in a global context. Energy as a fundamental resource underpins the global industrial system (Fizaine & Court 2016, Meadows et al. 1972, Meadows et al. 2004, Hall et al. 2009, Heinberg 2011, Martenson 2011, Morse 2001, Ruppert 2004 and Tverberg 2014).

Energy is utilized by many sectors including residential, commercial, industrial, and transportation sectors. The industrial sector may be the most difficult to address as it requires large quantities of concentrated power that is sinusoidally clean and of consistent supply. Energy-supply reliability is expressed via long-term preservation of energy resource availability at a level comparable with the present level of electrical-energy supply from domestic energy resources, i.e. at least 75% of the present consumption. A great deal of work has been done to develop alternative systems of energy generation and delivery. These include solar power generated from photovoltaic solar panels, solar thermal systems involving using the focused heat of the sun to make steam, the use of moving water in hydro power generation and wind turbines in linked arrays. Also, there is a school of thought that the future of power generation should be nuclear.

Use of fossil fuels like coal, gas, and oil to generate energy in its various forms, all result in carbon emissions. Use of nuclear power to generate electricity has a very different carbon footprint but has its own challenges to remain viable at a large scale of application. Renewable sources like hydroelectricity have a very small materials footprint and produce very little carbon pollution (if at all) but can only be applied in specific and unusual geographic circumstances.

In previous work, the function of energy, and the logistical requirements to phase out fossil fuel-based energy systems and replacing them with non-fossil fuel systems was examined for the United States, Europe, China, and the whole Global ecosystem (Michaux 2021). This was approached by estimating what would be required to replace the entire existing system. To do this, the industrial ecosystem as it was in the year 2018, where all reported data for industrial actions, number of vehicles and physical work done, was used as a baseline to calculate the needed number on non-fossil fuel technological units.

The focus of this report is to repeat this work and assess what is required to phase out fossil fuels in Finland. This report will use the year 2019 for data collection and estimations of the size of the industrial ecosystem. The year 2019 was used as this was the last year before the Covid-19 pandemic quarantine measures, which devastated the industrial supply chain, and consumption demand of most resources. The data for the years 2020, and 2021 contain highly unusual signatures that could be artefacts of pandemic containment.

The report is limited to directly replacing the fossil fuel use of 2019 in Finland, leaving out air and maritime traffic, as these are international sectors where country-specific estimates are hard to come by. The report is also conservative in the sense that we don't project any structural (energy efficiency, energy saving, etc.) changes in energy systems, just use the situation and information available at current time. In addition, we will discuss the role of fossil feedstock in plastic and other chemical production, and the possibility of replacing those with other alternatives. Due to the resurfacing needs of supply security, we will also note Finnish dependency on uranium imports, and discuss the perspective of energy sufficiency, different from the perspective of replacing existing fossil fuel use.

Finland is a developed, industrial nation with a robust democracy and civil society, sometimes described as the most stable country in the world (The Fund for Peace, 2020). As part of the EU, Finland is committed to 40 % reduction in emissions from the levels in 2005 by 2030 (the EU "Fit for 55" program will increase the emission target to 55 %; OSF, 2021). In addition, the current government has set a target of carbon neutrality by 2035 (Finnish Government, 2019). As part of these targets, different industrial sectors have prepared detailed low-carbon roadmaps with the facilitation of the Ministry of Economic Affairs and Employment (MEAE, 2021). Together, these roadmaps form the most detailed picture of a low-carbon transition in the real economy in an EU country. Overall, the transition is highly dependent on increased electricity production and the electrification of industry processes. However, these roadmaps as well as other related public policy documents, such as the governments' energy and climate strategy, and the mid-term climate plan (Ministry of the Environment, 2020), do not address the material needs of the transformation (Majava et al., 2022). Consequently, the major question remains: What a full replacement of fossil fuels demands? For Finland, this directly concerns especially the energy, forest, and chemical sectors, although all major industry sectors need to acknowledge their material needs better for fossil-fuel free future.

Forests and wood biomass are particularly relevant for Finland, as they have two crucial roles with regard to climate. First, when undisturbed they function as carbon storage and when growing as carbon sinks. Second, products from harvested wood can replace fossil-based products (e.g., timber in construction instead of concrete, biofuel instead of fossil fuel in energy production). Unfortunately, these roles are, to an extent, mutually exclusive: if the harvested wood is used in products that release the carbon quickly (energy, paper, pulp, board, etc.), the carbon stored in the wood is emitted to the atmosphere and the carbon store lost. This trade-off is relevant, as Finland's emission reductions rely, to a large extent, on wood-based bioenergy (biofuel in traffic, wood in district heating, wood energy in forest industry), and as the carbon neutrality goal depends on existing forest carbon sinks. Depending on the modes of clean electricity production chosen when replacing fossil fuels, the effects to the demand of forest-based biomass and the forest sector will vary widely.

2 ENERGY PRODUCTION AND USE IN FINLAND

Finland has a unique energy mix, with established industry and natural resources. The opportunities and challenges in Finland are very different to many other nation states. Appendix A presents the Finnish share of the global market, for oil, gas coal, nuclear, hydro, renewables, biofuels, and electrical power consumption in the year 2019.

As shown in Appendix A, Finland is a relatively minor player on the world market for fossil fuel energy. A strong case can be made that the fossil fuels market in general are about to become very volatile, and possibly unreliable in supply delivery (Michaux 2019). This could mean that materials, metals, and manufactured component markets could become inelastic.

The following pages are to document energy consumption for Finland in the year 2019.

2.1 Primary Energy Sources and Use

Charting primary energy use is a way of comparing all energy sources directly, with the same units. Primary energy consumption measures the total energy demand of a country. It covers consumption of the energy sector itself, losses during transformation (for example, from oil or gas into electricity) and distribution of energy, and the final consumption by end users. It excludes energy carriers used for non-energy purposes (such as petroleum not used not for combustion but for producing plastics)

(https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Primary_energy_consumption)

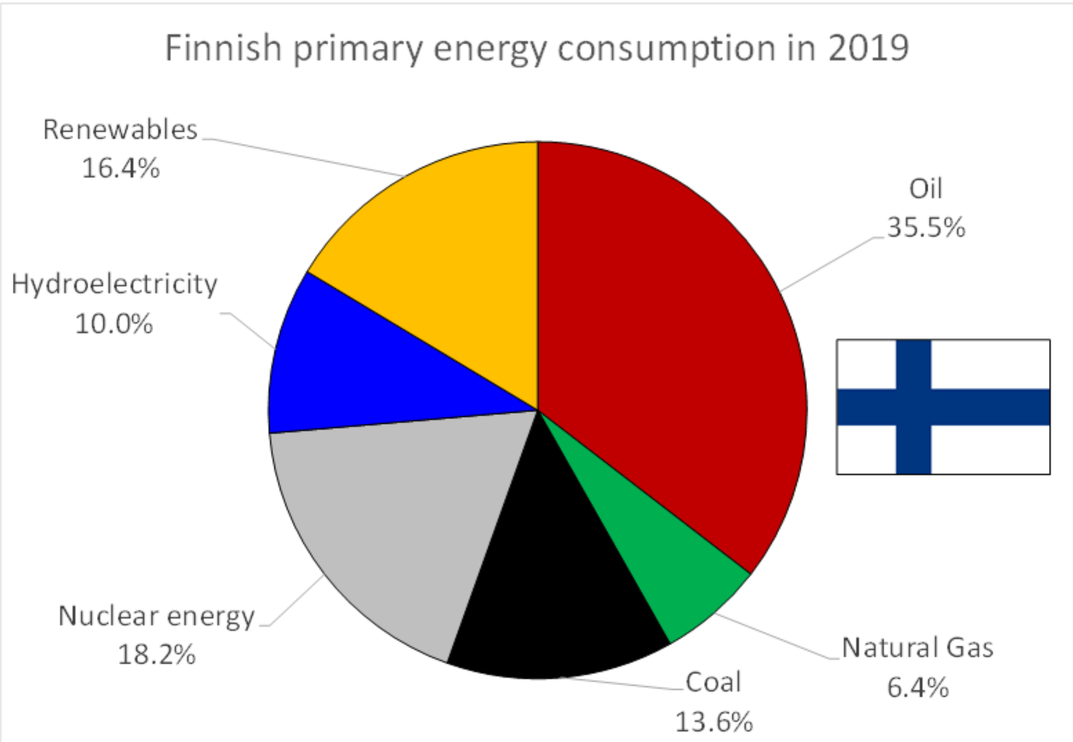


Figure 1. Finnish primary energy consumption in 2019 (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

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Energy Source	Finnish primary energy consumption in 2019 (Exajoules EJ)	Finnish primary energy consumption in 2019 (TWh)
Oil	0.39	108.3
Natural Gas	0.07	19.4
Coal	0.15	41.7
Nuclear energy	0.2	55.6
Hydroelectricity	0.11	30.6
Renewables	0.18	50.0
Total	1.1	305.6

1 Exajoule [EJ] = 277.7778 Terawatt hour [TWh]

Table 2. Finnish primary energy consumption in 2019 (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Energy Source	Finnish Energy Consumption in 2019	Units
Oil	73	(Million Barrels a year, Mbbl/yr)
Natural Gas	2.0	(Billion cubic metres, bcm^3)
Coal	0.15	Exajoules (EJ)
Coal	5 118 126	Estimated Tonnes (t)
Nuclear energy	0.2	Exajoules (EJ)
Hydroelectricity	0.11	Exajoules (EJ)
Renewables	18.4	Terawatt hours (TWh)
Wind	6.00	Terawatt hours (TWh)
Solar	0.20	Terawatt hours (TWh)
Other Renewables	12.2	Terawatt hours (TWh)

As can be seen, oil was the largest source of energy resource in Finland in 2019. Oil is used to manufacture petroleum products, which are used in transport applications and in some cases heating applications. Some chemical industries use a quantity of oil as a feedstock for manufacture (plastics, etc.).

Finland also exported approximately 9 Mt of oil products in 2019 (OSF 2019a). Replacing these exports is not considered in this report.

2.2 Electricity Generation

Figures 2 to 6 and Tables 3 to 6 show the generation of electricity by source, and then consumption by application in Finland for the year 2019.

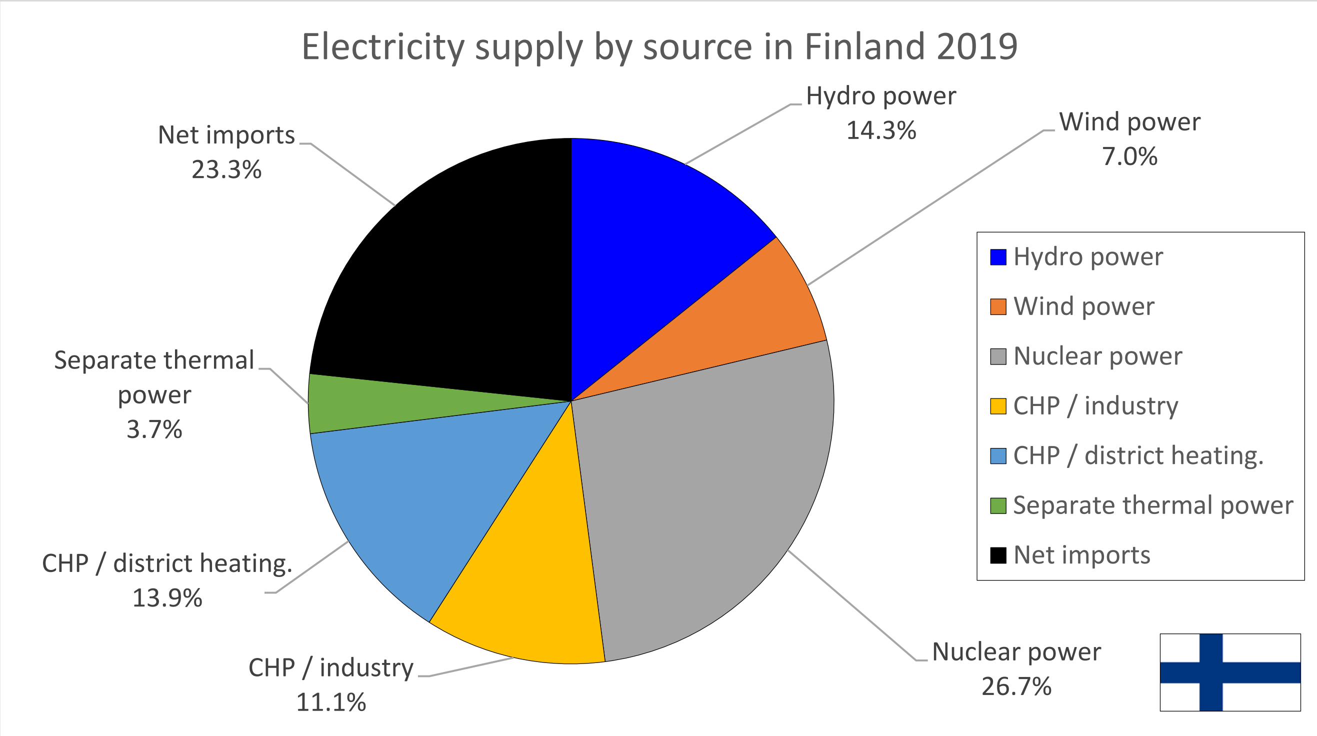

Figure 2. Electricity use in Finland (Source: Finnish Energy, Energy provision by source, https://energia.fi/files/426/Sahkon_hankinta_energialahteittain_2007-2020_web.xlsx)

Table 3. Electricity use in Finland (Source: Finnish Energy, Energy provision by source, https://energia.fi/files/426/Sahkon_hankinta_energialahteittain_2007-2020_web.xlsx)

Power Source	Electricity supply by source in 2019 (TWh)	Electricity supply by source in 2019 (%)
Hydro power	12.25	14.3 %
Wind power	6.02	7.0 %
Nuclear power	22.91	26.7 %
CHP / industry	9.58	11.1 %
CHP / district heating	11.98	13.9 %
Separate thermal power	3.14	3.7 %
Net imports	20.04	23.3 %
Total	85.92	100.0 %

The largest electricity generation supply system in Finland 2019 was nuclear power, with a comparable quantity being imported. Electrical power generation from fossil fuels accounted for 13.9 % of the total. The imports (20.04 TWh, 23.3% of annual consumption) will need to be replaced with a Finnish energy non-fossil fuel system. If projections of a tight energy market and a low energy future are correct (Michaux 2019 and 2021), then the nations producing this power for Finland will need that capacity domestically.

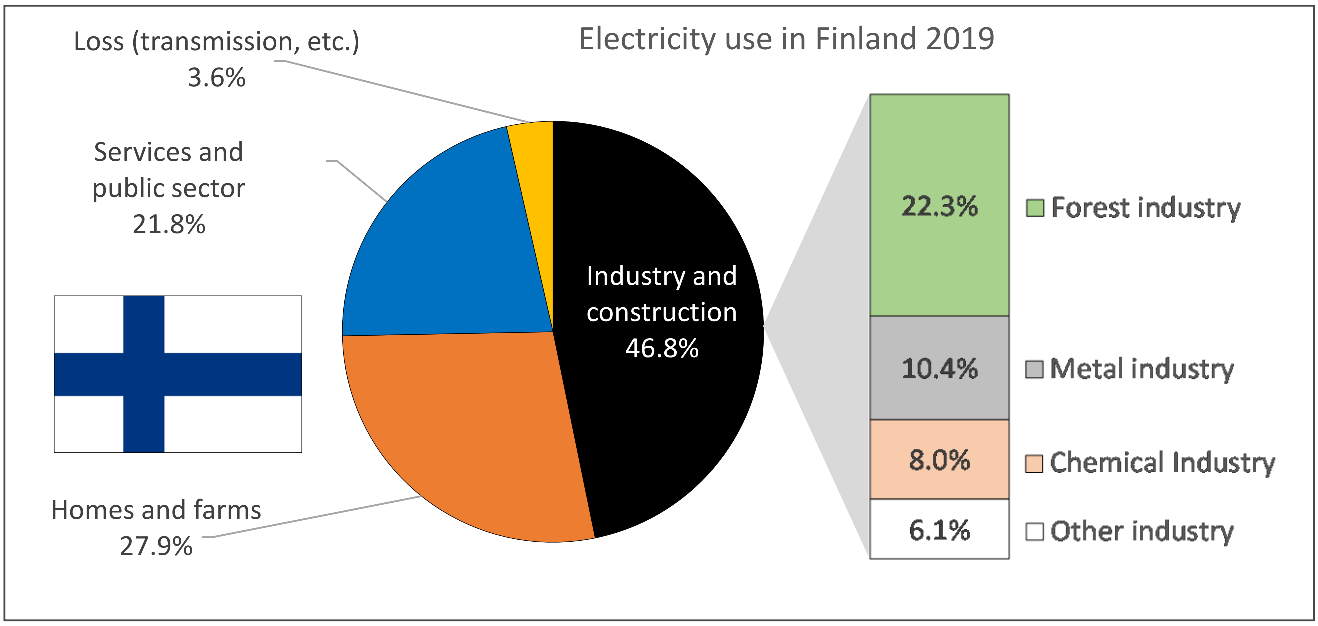

Figure 3. Electricity use in Finland (Source: Official Statistics of Finland: Energy supply and consumption https://pxnet2.stat.fi/PXWeb/pxweb/fi/StatFin/StatFin__ene__ehk/statfin_ehk_pxt_12vm.px/)

Power generated from Combined Heat and Power (CHP) plants accounted for 25.0 % of total annual energy consumption in 2019.

Table 4. Electricity use in Finland (Source: Official Statistics of Finland: Energy supply and consumption https://pxnet2.stat.fi/PXWeb/pxweb/fi/StatFin/StatFin__ene__ehk/statfin_ehk_pxt_12vm.px/)

Sector in Finland	Energy Consumption (GWh)	Energy Consumption (GWh)
Industry and construction	40 284	
Forest industry		19 226
Metal industry		8 963
Chemistry		6 885
Other industry		5 210
Homes and farms	24 020	
Services and public sector	18 726	
Loss (transmission, etc.)	3 062	
Total electricity use	86 092	40 284

Industry and construction accounted for 46.8% (40 TWh) of electricity consumption, with the largest industrial consumer being the forest industry. Domestic consumption accounts for 27.9 % (24 TWh annually).

Figure 4 and Tables 5 to 8 show the Finnish power plant fleet. The power plants shown are only the largest in the Finnish station fleet. There are approximately 445 power stations in Finland, ranging in installed capacity from 0.6 to 890 MW (Finnish Energy Authority, Power Plant Register, updated 12.1.2022).

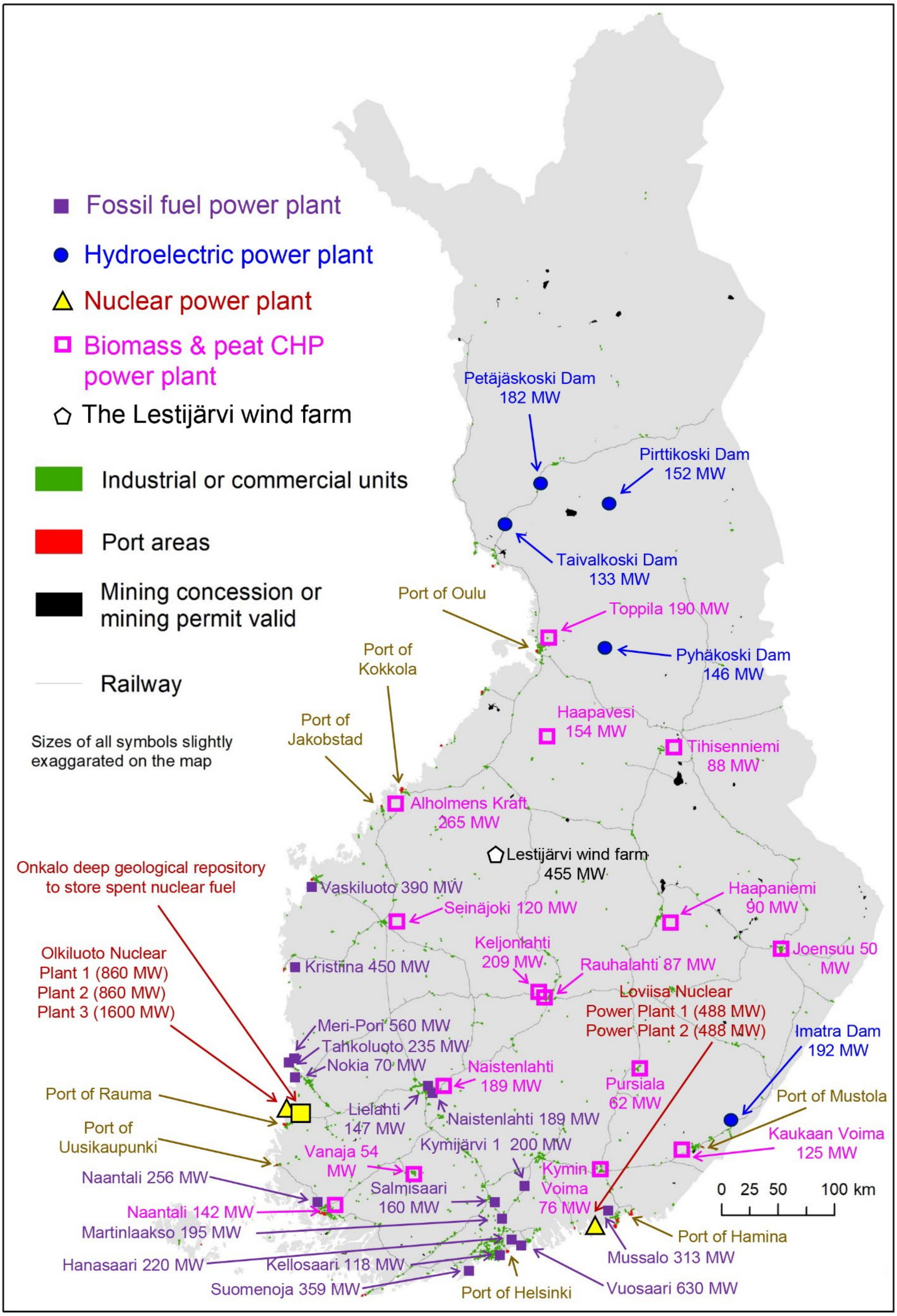

Figure 4. Map of main power stations in Finland (Source: GTK, Jussi Pokki, SYKE/ Corine Land Cover 2018, Mining Register)

Table 5. Fossil fuel power stations in Finland (Source: Global Energy Observatory)

Name	Location	Fuel	Capacity (MWe)
Hanasaari Power Station	Helsinki	Coal	220
Kellosaari Power Station	Helsinki	Fuel oil	118
Kristiina Power Station	Kristinestad	Coal and fuel oil	450
Kymijärvi 1 Power Station	Lahti	Coal, natural gas and biogas	200
Lielahti Power Station	Tampere	Natural gas	147
Martinlaakso Power Station	Vantaa	Coal and natural gas	195
Meri-Pori Power Station	Pori	Coal	560
Mussalo Power Station	Kotka	Natural gas and coal	313
Naantali Power Station	Naantali	Coal	256
Naistenlahti Power Station	Tampere	Natural gas, peat, wood and fuel oil	189
Nokia Power Station	Nokia	Natural gas	70
Salmisaari Power Station	Helsinki	Coal	160
Suomenoja Power Station	Espoo	Natural gas and coal	359
Tahkoluoto Power Station	Pori	Coal	235
Vaskiluoto Power Station	Vaasa	Coal and fuel oil	390
Vuosaari Power Station	Helsinki	Natural gas	630

Table 6. Nuclear power plant stations in Finland (Source: Global Energy Observatory)

Plant Name	Location	Type	Capacity (MWe)	Operational
Loviisa Nuclear Power Plant 1	Loviisa	VVER	488	1977–
Loviisa 2		VVER	488	1980–
Olkiluoto Nuclear Power Plant 1	Olkiluoto	BWR	860	1978–
Olkiluoto 2		BWR	860	1980–
Olkiluoto 3		EPR	1600	Construction finished

Note: if the average working lifespan of a nuclear power plant is 40 years, then all nuclear power plants in Finland apart from Olkiluoto 3, will be due for decommissioning soon. Life extensions are probable, however.

Table 7. Major hydropower plants in Finland (Source: Global Energy Observatory)

Station	Location	Capacity (MW)
Imatra Dam	Imatra	192
Petäjäskoski Dam	Rovaniemi	182
Pirttikoski Dam	Rovaniemi	152
Pyhäkoski Dam	Muhos	146
Taivalkoski Dam	Keminmaa	133

Table 8. Biomass and peat CHP power stations (Source: Global Energy Observatory)

Station	Location	Fuel	Capacity (MW)
Alholmens Kraft Power Station	Jakobstad	Biomass and peat	265
Haapaniemi Power Station	Kuopio	Biomass and peat	90
Haapavesi Power Station	Haapavesi	Peat	154
Joensuu Power Station	Joensuu	Biomass and peat	50
Kaukaan Voima Power Station	Lappeenranta	Biomass	125
Keljonlahti Power Station	Jyväskylä	Peat and biomass	209
Kymin Voima Power Station	Kouvola	Biomass and peat	76
Naantali Power Station	Naantali	Coal, natural gas, peat, biomass and RDF [1]	142
Naistenlahti Power Station	Tampere	Natural gas, peat, wood and fuel oil	189
Pursiala Power Station	Mikkeli	Wood and peat	62
Rauhalahti Power Station	Jyväskylä	Peat and wood	87
Seinäjoki Power Station	Seinäjoki	Peat and wood	120
Tihisenniemi Power Station	Kajaani	Peat	88
Toppila Power Station	Oulu	Peat	190
Vanaja Power Station	Hämeenlinna	Biomass, peat and natural gas	54

Note:

[1] Under construction

3 HEAT GENERATION IN 2019

While annual consumption of electrical energy in 2019 was 86.092 TWh, 93.55 TWh (93 546 GWh) of total energy was consumed by heating, in total. District heating consumed 38.1 TWh (38 142 GWh) and industrial consumption of heat energy was 55.4 TWh (55 404 GWh). Figures 5 and 6 (and Tables 9 and 6) show the heat generation by various sources and applications in Finland in the year 2019.

Table 9. Conventional thermal power in Finland 2019 (Source: Finnish Energy, Energy provision by source, https://energia.fi/files/426/Sahkon_hankinta_energialahteittain_2007-2020_web.xlsx)

Heat Power Source	Electricity supply by source (TWh)	Used fuels 2019 (TWh)
CHP / industry	9.58	12.42
CHP / district heating	11.98	13.99
Separate thermal power	3.14	9.11

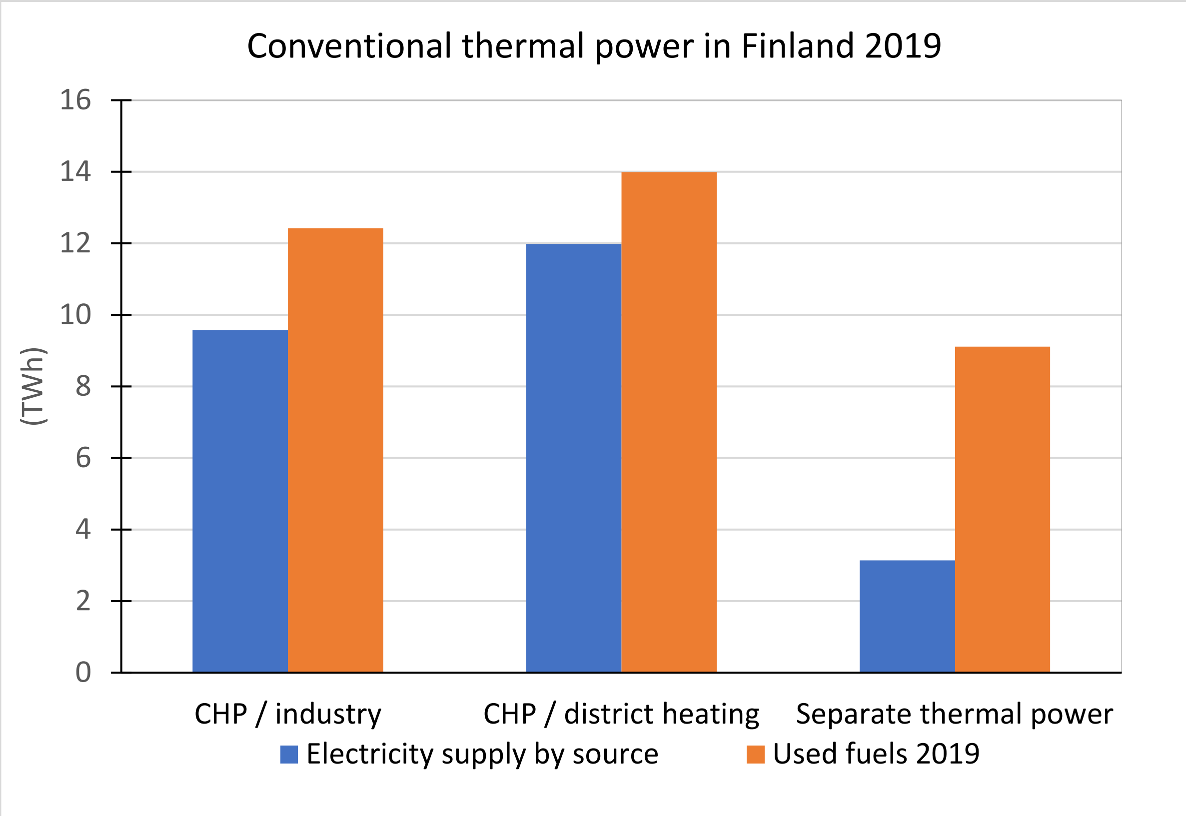

Figure 5. Conventional thermal power in Finland 2019 (Source: Finnish Energy, Energy provision by source, https://energia.fi/files/426/Sahkon_hankinta_energialahteittain_2007-2020_web.xlsx)

Heat is generated in Combined Heat and Power (CHP) plants, where heat and electricity are generated at the same time. This report seeks to show useful data in what was sourced for heating in terms of fuel, some of which was fossil fuel based (Table 10). To phase out fossil fuels, all energy sources of oil, gas, coal, and peat would need to be replaced with another source.

Black Liquor is a biomass fuel, sourced as lignin from trees (and some other chemical products). It is a side product of pulp production, which is often used in the paper industry. The source biomass, from which black liquor comes from, is logged timber when pulped. Almost all of it is used as energy in the forest industry.

Table 10. Heat generated in Finland in 2019 (OSF 2019b: Production of electricity and heat (Industrial and district heat). Appendix table 1. http://www.stat.fi/til/salatuo/2019/salatuo_2019_2020-11-03_tau_001_en.html)

Application in 2019	Fuel Source	Electricity (GWh)	District Heat (GWh)	Industrial Heat (GWh)	Total Heat (GWh)	Fuel used (GWh)	Fuel used (TJ)
Power Plants [1]	Oil	102	-	-	-	342	1 230
	Coal	603	-	-	-	1 725	6 210
	Natural Gas	112	-	-	-	301	1 085
	Other fossil [3]	461	-	-	-	1 255	4 518
	Peat	476	-	-	-	1 475	5 311
	Black Liquor	650	-	-	-	2 184	7 863
	Other wood-based	613	-	-	-	1 894	6 819
	Other renewable [2,4]	79	-	-	-	249	897
	Other sources [5]	46	-	-	-	253	911
	Total	3 142	-	-	-	9 678	34 842
Combined Heat and Power [6] CHP	Oil	165	158	416	574	906	3 260
	Coal	3 513	6 391	466	6 857	11 844	42 640
	Natural Gas	3 655	2 878	2 250	5 128	10 052	36 186
	Other fossil [3]	487	1 140	501	1 641	2 795	10 061
	Peat	2 345	4 363	2 518	6 881	11 093	39 937
	Black Liquor	6 100	204	28 630	28 834	44 154	158 956
	Other wood-based	4 447	7 517	7 350	14 867	23 514	84 650
	Other renewable [2,4]	652	1 264	597	1 861	3 305	11 898
	Other sources [5]	211	107	667	774	1 349	4 857
	Total	21 576	24 022	43 397	67 419	109 013	392 446
Heat Only [7]	Oil	-	617	1 693	2 310	3 200	11 521
	Coal	-	509	147	656	728	2 622
	Natural Gas	-	1 214	1 299	2 513	2 798	10 074
	Other fossil [3]	-	287	245	532	632	2 274
	Peat	-	1 309	753	2 062	2 439	8 779
	Black Liquor	-	15	686	701	813	2 926
	Other wood-based	-	5 759	4 644	10 403	12 297	44 268
	Other renewable [2,4]	-	514	408	922	1 124	4 047
	Other sources [5]	-	3 895	2 131	6 026	1 939	6 979
	Total	..	14 120	12 007	26 127	25 969	93 489
	out of which with exhaust scrubbers	-	2 552	802		..	..
Total	Oil	267	776	2 110	2 886	4 447	16 011
	Coal	4 115	6 900	614	7 514	14 298	51 472
	Natural Gas	3 767	4 092	3 549	7 641	13 151	47 345
	Other fossil [3]	947	1 427	747	2 174	4 681	16 853
	Peat	2 821	5 672	3 271	8 943	15 007	54 027
	Black Liquor	6 750	219	29 316	29 535	47 151	169 744
	Other wood-based	5 060	13 275	11 995	25 270	37 705	135 737
	Other renewable [2,4]	732	1 778	1 004	2 782	4 678	16 842
	Other sources [5]	258	4 003	2 798	6 801	3 541	12 747
	Total	24 717	38 142	55 404	93 546	144 660	520 777

1) Condensing power production from CHP counted in "Power plants (condensing, "lauhdevoima")"
2) Mixed fuels (such as recyled fuels) are counted in renewable and fossil fuels according to their fossil and bioregradable carbon content
3) Contains coke gas, coke, plastics, fossil waste as fuel, and fossil component in mixed fuels
4) Other renewable fuels include e.g. the bio-contribution of biofuels and biogas.
5) Contains hydrogen, electricity and industrial reaction- and secondary heat
6) Contains only pure CHP
7) Reduction-heat from condensing power and CHP counted in heat-only

In Table 10, total industrial and district heat energy generated for the year 2019 was 93 546 TWh. 61.6% of this heat (57 587 TWh) was sourced from some form of biomass (including wood based, black liquor, bio-contribution of biofuels and biogas). Shown in Table 10, 31.2 % (29 158 TWh) of heat generated was fossil fuel sourced (including oil, gas, coal, peat, coke gas, coke, plastics, fossil waste as fuel, and fossil component in mixed fuels).

In addition, 30.4 TWh of heating energy was generated for residential buildings (detached houses, terraced houses, blocks of flats, free-time residential buildings), out of which 2.6 TWh with fossil fuels (including peat) and 12 TWh with wood (giving a total of 14.7 TWh of heat generation with wood, peat, and fossil fuels). This is shown in Table 11, (which excludes district heating for residential buildings as data for district heating is included in Table 10).

Table 11. Consumption of heating energy in residential buildings
(detached houses, terraced houses, blocks of flats, free-time residential buildings), GWh
(OSF, https://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin ene asen/statfin asen pxt 11zr.px/)

Heating energy in Finnish residential buildings in 2019	All systems including electric heating (GWh)	Fossil fuels and peat for feedstock (GWh)	Fossil fuels, peat & wood biomass for feedstock (GWh)
Wood	12 042		12 042
Peat	29	29	29
Coal	1	1	1
Heavy fuel oil	8	8	8
Light fuel oil	2 366	2 366	2 366
Natural gas	242	242	242
Heat pumps	5 331		
Electric heat systems	10 401		
Total	**30 420**		
Fossil fuels and peat, total		**2 646**	
Fossil fuel, peat and wood, total			**14 688**

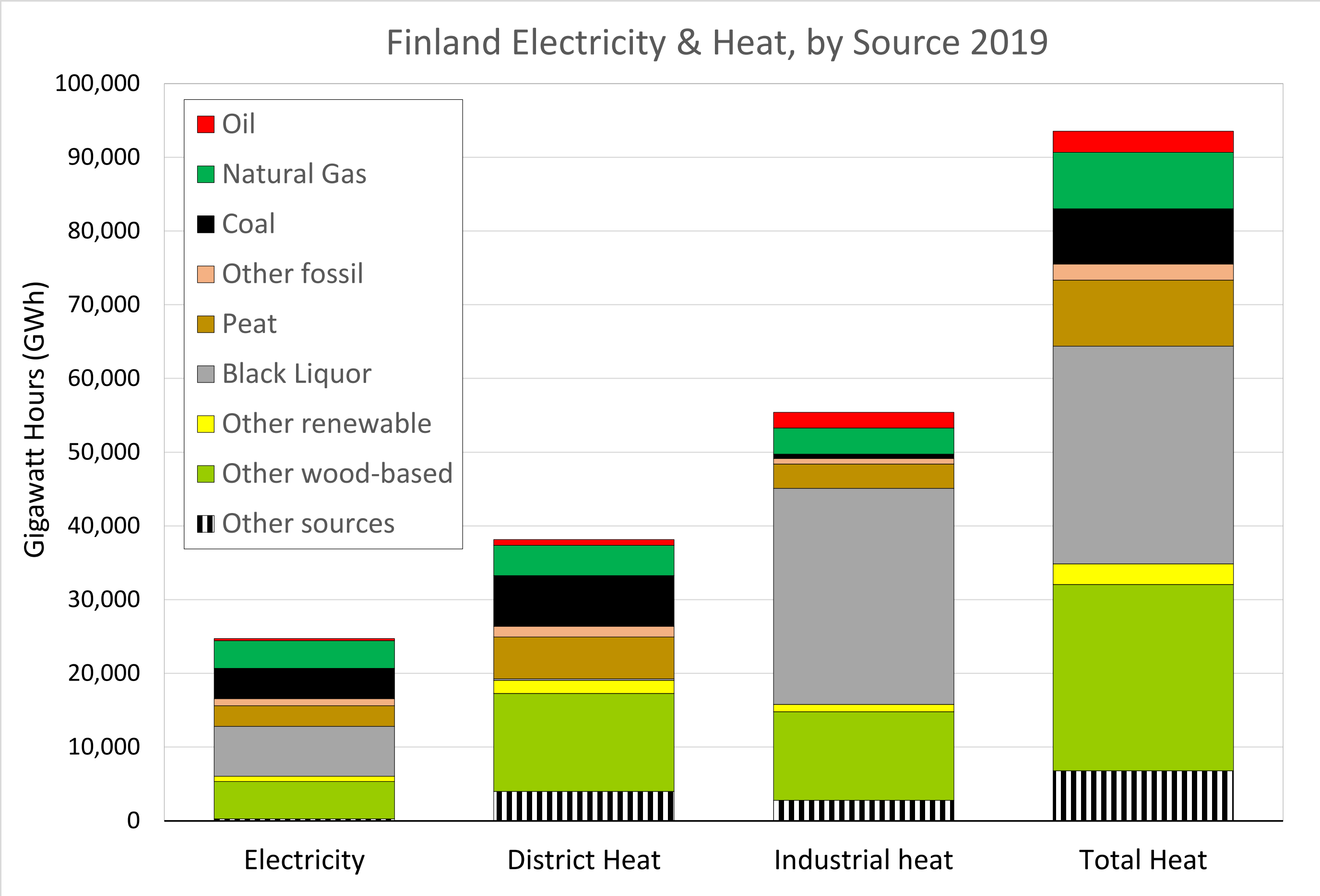

Figure 6. Finland electricity and industrial and district heat generation by source in 2019, (Source: Official Statistics of Finland (OSF): Production of electricity and heat. Appendix table 1. http://www.stat.fi/til/salatuo/2019/salatuo_2019_2020-11-03_tau_001_en.html)

Finland has a unique industrial and natural resource ecosystem. Not only does Finland have large areas of forest, and a small but highly educated human population, there is a strong industrial presence and a wealth of useful mineral deposits. Finland has a good capability in the refining of chemicals and smelting of metals (shown in Figure 7). This is often termed heavy industry, which often has high heat intensity requirements (Appendix E).

As the task to phase out fossil fuels is at hand, the practicalities of manufacturing the required substitute technology are a relevant strategic area to develop. To phase out Internal Combustion Engine (ICE) vehicles, Electric Vehicles and their batteries are one of several options. Currently, industrial capability to produce metals, chemicals and components for batteries is present only in a few nation states internationally. Finland has the potential to form a fully vertically integrated battery ecosystem around the beginning of the battery value chain. Figure 8 shows the battery relevant industrial capability in Finland at the time this report was written. Figure 9 after that shows the battery metal mineral deposits and operating mine sites. While Finland represents a very small share of the global market, the opportunity is there to develop a fully functional battery mineral-to-chemical Finnish industrial ecosystem. Even better, the capability to support this ecosystem with non-fossil fuel power exists in Finland, in ways that are not possible elsewhere.

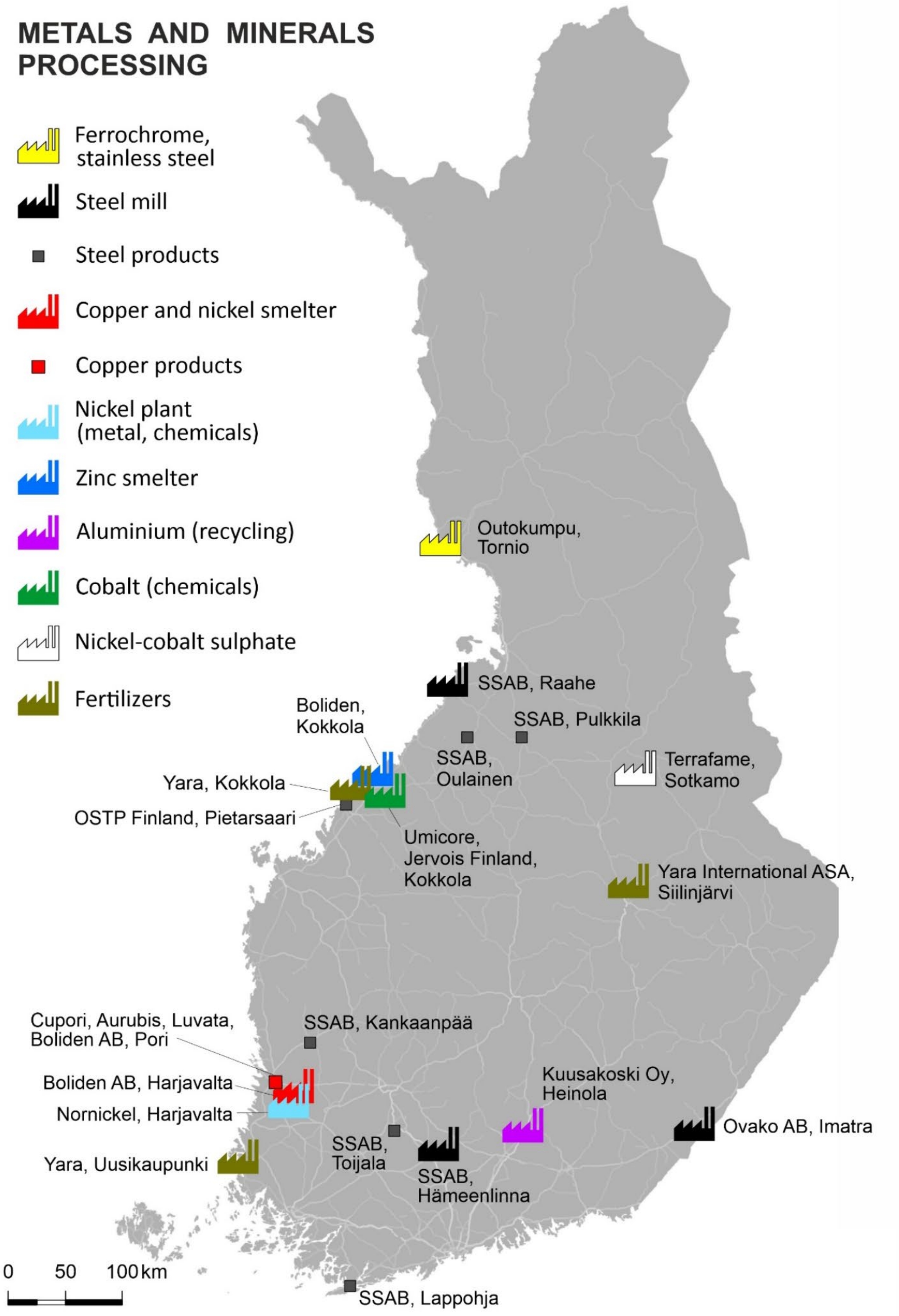

Figure 7. Map of the metal production industrial ecosystem in Finland (Source: GTK, Jussi Pokki)

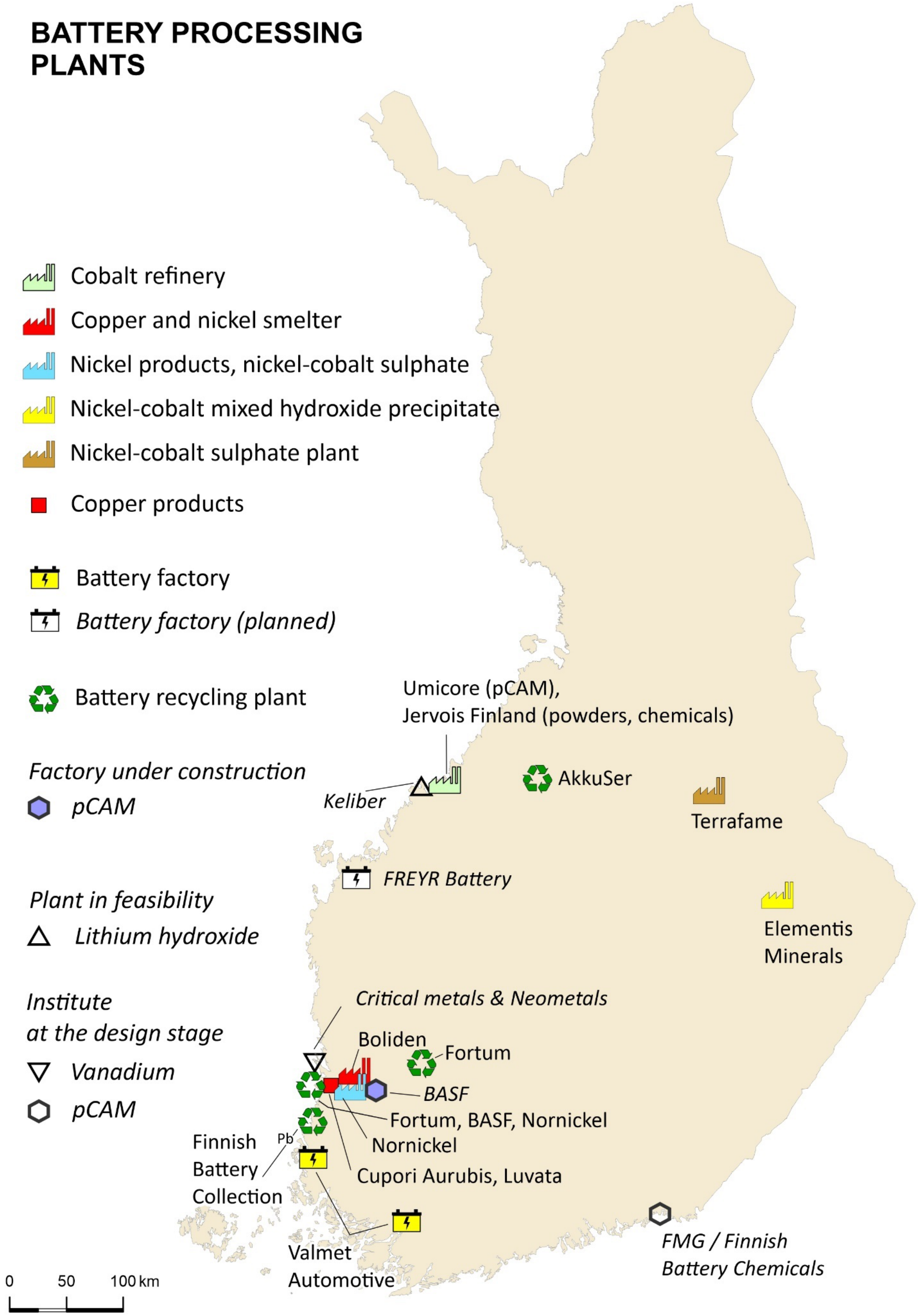

Figure 8. Map of battery industrial ecosystem in Finland (Source: GTK, Jussi Pokki)

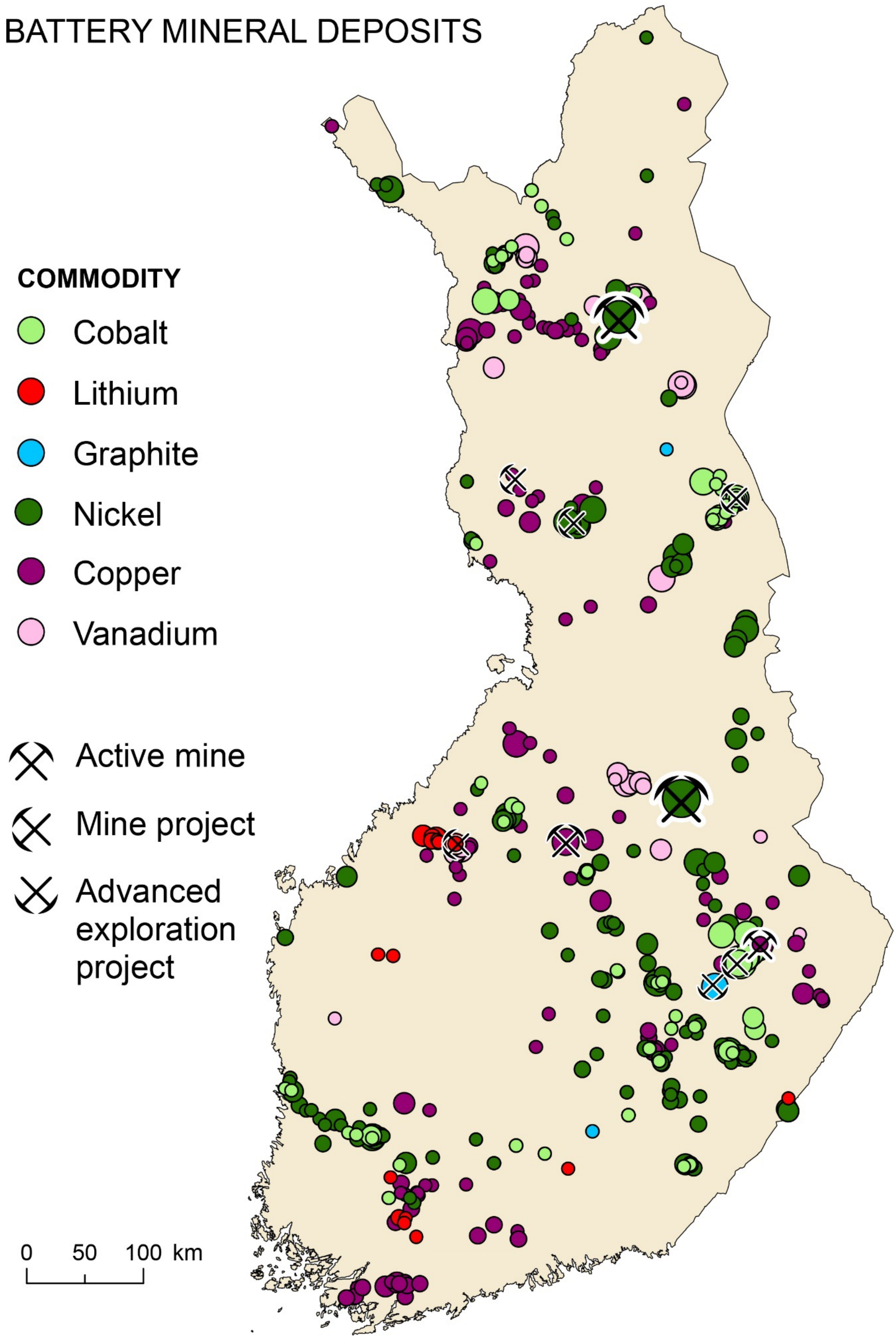

Figure 9. Map of battery mineral deposits and mines in Finland (Source: GTK, Jussi Pokki)

4 TRANSPORTATION IN 2019

Here we will consider the replacement of the fossil fuel use in Finnish transportation. The biggest item is vehicle transport. In addition, we will consider rail transportation, which is already largely electrified. Aviation and maritime shipping were also examined, but not included in the assessment of fossil fuel replacement.

4.1 Finnish Vehicle Transport Fleet

The number of vehicles by class and distance travelled in the Finnish transport fleet in 2019 is shown in Table 12. Appendix B shows the number of vehicles in the global fleet.

Table 12. Finnish vehicle fleet by class in 2019 (Source: Statistics Finland,
Number of vehicles: https://pxnet2.stat.fi/PXWeb/pxweb/fi/StatFin/StatFin__lii__mkan/statfin_mkan_pxt_11ib.px/
Distance travelled: http://www.stat.fi/til/tiet/2019/tiet_2019_2020-04-15_tie_001_fi.html)

Vehicle Class EV 	Number of Self Propelled Vehicles in 2019 Finnish Fleet (number)	Annual km traveled by average vehicle in Finland in 2019 (km)	Total km driven by class in 2019 Finnish Fleet (km)	Total km driven by class in 2019 Finnish Fleet (million km)
Trucks	162 186	20 606	3,34E+09	3 342
Buses	19 137	31 405	6,01E+08	601
Commercial Van	486 949	11 759	5,73E+09	5 726
Passenger Car	3 574 570	11 391	4,07E+10	40 718
Motorcycle *	278 534			
Total	4 521 376		5,039,E+10	47 045

4.5 million vehicles

47.0 billion km travelled in 2019

* Distance travelled by motorcycles not reported

The data shown in Table 12 will now be used to estimate the required size of a Finnish EV fleet and the Finnish hydrogen fuel cell fleet.

4.2 Finnish Rail Transport Network

Tables 13 to 15 show the data for the Finnish train network. Most of rail traffic is already electric, with diesel locomotives operating mainly on low-traffic routes and in hard-to-electrify areas like harbors, industrial locations and logistic hubs. Currently, there are plans for increasing the role of rail traffic through improvements in the most heavily used passenger and freight routes (mainly in Southern Finland), upgraded logistic terminals for freight, and electrifying existing sections of rail (Valtioneuvosto 2021).

Table 13. Energy consumed by the Finnish rail network in 2019 (Source: Official Statistics of Finland (OSF): Railway Statistics. Helsinki: Statistics Finland. http://www.stat.fi/til/rtie/meta_en.html)

Total energy consumption, petajoule	3,36
Electricity consumption, mill. kWh	671
Electricity consumption, petajoule	2,41
Light fuel oil, mill. litres	26,5
Light fuel oil, petajoule	0,95

Table 14. Distance traveled in the Finnish rail network in 2019 (Source: Official Statistics of Finland (OSF): Railway Statistics. Helsinki: Statistics Finland. http://www.stat.fi/til/rtie/meta_en.html)

Finnish Rail Network in 2019	Train kilometres (km)	Locomotive kilometres (km)
Diesel tractive stock total	5 381	14 306
Diesel locomotives	3 499	11 963
Diesel railcars	1 882	2 343
Electric tractive stock total	46 090	58 402
Electric locomotives	27 880	32 940
Electric railcars	18 210	25 462
Total	51 471	72 708

Table 15. Number of locomotives in the Finnish rail network for 2018 (data for 2019 not yet available) (Source: Official Statistics of Finland (OSF): Railway Statistics. Helsinki: Statistics Finland. http://www.stat.fi/til/rtie/meta_en.html)

Steam locomotives	NA
Diesel locomotives	217
Diesel railcars and railbuses	16
Electric railcars	218
Electric locomotives	173
Light rail motor tractors	61
Passenger stock	1 226
Freight stock	8 763
Passenger kilometres (1000 pkm)	4 534 608
Weight of freight (1000 t)	40 721
Tonnekilometres (1000 tkm)	11 174 893

4.3 Finnish Domestic Aviation Transport

According to the most recent greenhouse gas emission inventory, the fuel consumption for international aviation was 35.166 TJ and for Finnish domestic aviation 2.811 TJ in 2019 (Traficom Publications 2021 and Official Statistics Finland: http://www.stat.fi/til/uvliik/). Given that 1 Terajoules = 0.000278 Terawatt Hour, Finnish domestic consumption of aviation fuel was 9.77 TWh.

A more complete discussion of Finnish Aviation transport is discussed in Appendix F.

4.4 Finnish Maritime Shipping Transport

In 2019 the Finnish maritime shipping industry exported 48 million tons of cargo, imported 53.3 million tons of cargo, and travelled 404 000 000 000 ton-kilometers (OSF; http://www.stat.fi/til/uvliik/), where:

- 296 000 000 000 ton-kilometers were exports
- 105 000 000 000 ton-kilometers were imports
- 200 000 000 ton-kilometers were domestic

Maritime shipping grade fuel consumed in the year 2019 was 2 300 000 tons (Salanne et al. 2021).

4.5 Vehicle fleet split between EV and Hydrogen fuel cell systems

This section examines the question of when an Electric Vehicle system would be more appropriate than a hydrogen fuel cell system, and vice versa. A more complete discussion of this topic is shown in Appendix C. The numbers shown here are from the comparison of a fully electric vehicle global vehicle fleet to a fully hydrogen powered H_2 fuel cell global vehicle fleet (Michaux 2021). This included all vehicles, trains, and maritime shipping for the entire global fleet.

Table 16 compares the quantity of electricity required to charge the batteries of an entirely EV global fleet of vehicles (Scenario A in Michaux 2021) compared to the electricity required to produce the required annual mass of hydrogen needed to fuel an entirely H_2 fuel cell global fleet of vehicles (Scenario C in Michaux 2021). As can be observed, the hydrogen solution requires between 2 and 4 times the electricity for it to be implemented. This has important implications. To deliver this extra electricity, 2 to 4 times the installed capacity in power generation needs to be constructed. This would not be a trivial matter.

Table 16. Comparison the annual electrical energy to be generated to charge a global fleet of pure EV vehicles to the electrical power to produce the annual mass of hydrogen to fuel a global complete H_2 cell vehicle fleet (Michaux 2021)

Vehicle	Required annual electrical energy to be generated to charge a global fleet of pure EV vehicles, assuming a 10% loss in transmission between power station and charging point (TWh)	Electrical energy to produce the annual required mass of hydrogen to fuel a global complete H2 cell vehicle fleet, assuming a 10% loss in transmission between power station and H2 manufacture site (TWh)	Ratio of electric energy needed to charge a global fleet of pure EV vechicles to the electric power needed to produce enough of H2 to power a global fleet of Fuel Cell vehicles
Class 8 Truck	3 564.3	7 503.7	2.1
Bus & Delivery Truck	1 597.5	3 710.4	2.3
Light Truck & Van	2 988.6	9 203.9	3.1
Passenger Car	1 545.9	2 494.5	1.6
Motor Cycle	26.5		N/A
Maritime Shipping	945.9	2 983.4	3.2
Rail Transport	226.6	1 066.5	4.7
Sum Total	10 895.2	26 962.4	2.5
			Average Ratio

However, there are distinct advantages of a hydrogen fuel system over the electric vehicle system. Table 17 shows the mass of energy storage required to be on board the vehicle while operating. The mass of the battery needed to power the EV vehicle was compared against the mass of the H_2 fuel tank needed to power the fuel cell vehicle, for each vehicle class. The mass of the needed hydrogen tank was assumed to have a storage density for 700 bar compressed hydrogen to be 5.7 wt% (like the Toyota Mirai passenger car). Clearly, the hydrogen fuel cell solution has a much lighter mass energy storage than the EV solution, by an average multiplier of 3.2.

Table 17. Comparison the estimated mass of energy storage of an EV vehicle (a Lithium-Ion Battery) to the estimated mass of the energy storage of a fuel cell vehicle (compressed H_2 tank at 700 bar pressure) of the same class doing a similar task (Michaux 2021)

Vehicle	Scenario A - EV Vehicles		Scenario C - Hydrogen Fuel Cell Vehicles	Ratio between mass of EV battery and mass of H_2 tank
	Estimated needed capacity of the EV battery in the vehicle (kWh)	Estimated mass of lithium ion battery in vehicle, @230 Wh/kg (kg)	Estimated weight of 700 bar pressure compressed hydrogen storage tank @ 5.7 wt% storage density (kg)	
Class 8 Truck	450.0	1,957	563	3.5
Bus & Delivery Truck	227.5	896	474	1.9
Light Truck & Van	42.1	183	123	1.5
Passenger Car	46.8	203	70	2.9
Motor Cycle	21.5	80	N/A	N/A
Rail Freight Locomotive	65,000	282,609	75,789	3.7
<u>Maritime Shipping</u>				
Small Vessel	14,269.5	62,041	16,689	3.7
Medium Vessel	358,397.3	1,558,249	419,178	3.7
Large Vessel	4,977,739.7	21,642,347	5,821,918	3.7
Very Large Vessel	11,614,726.0	50,498,809	13,584,475	3.7
			Average:	3.2

Table 18 shows the same comparison as Table 16, but instead of compressed hydrogen gas, storage is in the form of liquid hydrogen in cryogenic tanks. This has been presented as liquid hydrogen has a much smaller mass and volume of storage system for the same unit of mass of hydrogen fuel. The EV storage system mass ratio to liquid hydrogen storage system is approximately 9:1. This would be important for the large, long range vehicles like very large ships. The engineering and logistics of liquid hydrogen are much more complex than compressed hydrogen gas. The viability of the system should consider all of these issues.

Table 18. Comparison the size of energy storage of an EV vehicle (a Lithium-Ion Battery) to the size of the energy storage of a fuel cell vehicle (cryogenic liquid H2 tank) of the same class doing a similar task

Vehicle	Estimated needed capacity of the EV battery in the vehicle (kWh)	Estimated mass of lithium ion battery in vehicle, @230 Wh/kg (kg)	Estimated mass of cryogenic liquid hydrogen storage tank @14 wt% storage density (kg)	Ratio between mass of EV battery and mass of cryogenic liquid H_2 tank
Rail Freight Locomotive	65,000	282,609	30,857	9.2
<u>Maritime Shipping</u>				
Small Vessel	14,269.5	62,041	6,795	9.1
Medium Vessel	358,397.3	1,558,249	170,665	9.1
Large Vessel	4,977,739.7	21,642,347	2,370,352	9.1
Very Large Vessel	11,614,726.0	50,498,809	5,530,822	9.1

The energy content of hydrogen has clear implications. A fuel cell vehicle will be able to have a much greater range and capacity to carry cargo and passengers than an EV. So, the fuel cell is more appropriate for long range and cargo transport applications. Due to the extra electrical power required to produce the hydrogen, all short-range vehicles should be EV systems. Based on the above, it is recommended in this report that:

- All passenger cars, commercial vans, buses, and motorcycles are Electric Vehicle systems
- All trucks are hydrogen fuel cell systems

5 CALCULATION OF SCOPE AND ELECTRIC POWER REQUIREMENTS OF THE FINNISH ELECTRIC VEHICLE FLEET

The calculation steps to estimate the extra electrical energy required to charge a Finnish EV fleet, if all passenger cars, commercial vans, buses, and motorcycles are Electric Vehicle systems is shown in Figure 10.

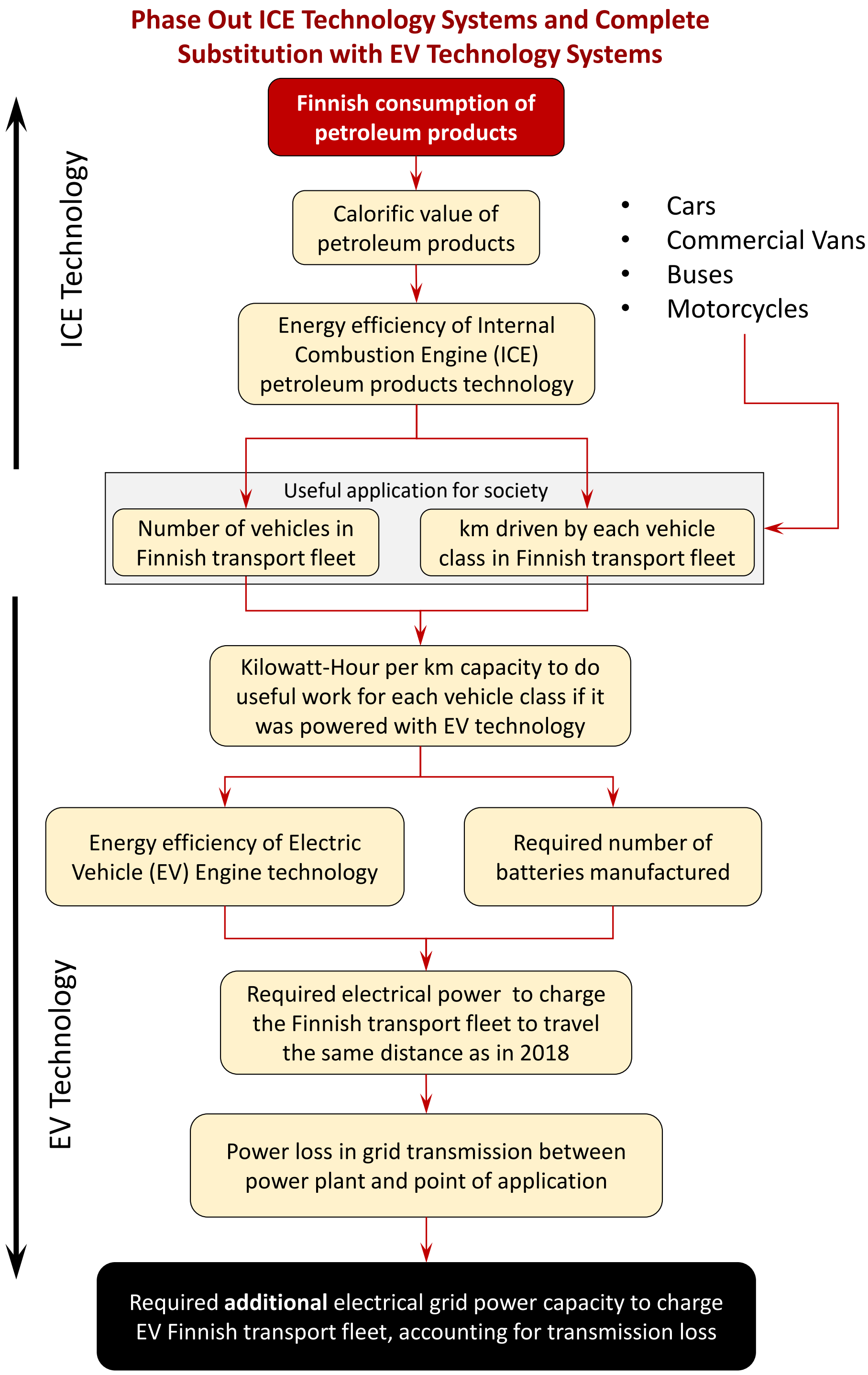

Figure 10. Required calculations for the steps to phase out ICE vehicles and substitute them with EV's (Image: Simon Michaux)

Given the outcomes of Section 6.1 (see below), it is recommended that all short-range vehicles are electrified. This includes passenger cars, commercial vans, buses, and motorcycles. Trucks are recommended to be powered by the hydrogen fuel cell systems.

The following tables provides a list of current electric vehicles (EV), with battery size, efficiency, average range, and a range of ranges in the city, and out on the open freeway. The range is between driving in sub-zero temperatures with heating on and driving in the warm with no air conditioning. All the vehicles listed can achieve longer ranges on road trips, if driven in an economical way. Table 19 shows that on average, a passenger car (car) consumes 0.19 kWh/km, or for every kilometer traveled, the vehicle needs 0.19 kWh, where current lithium-ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019).

Table 19. Electric Vehicle Passenger car range and distance per kWh capacity
(Source: data taken from United States Environmental Protection Agency, Electric Vehicle Database https://ev-database.org/car/1125/Kia-e-Niro-64-kWh, and Cleantechnica https://cleantechnica.com updated October 17th, 2018)

Manufacturer	Model	Battery Capacity (kWh)	Distance per kWh (km/kWh)	Range Average (km)	Range in City (km)		Range in Freeway (km)	
					Min Distance (km)	Max Distance (km)	Min Distance (km)	Max Distance (km)
Smart	EQ for-four	16.7	0.13	88.5	96.5	144.8	64.4	80.5
Mitsubishi	i-MiEV	15	0.12	88.5	88.5	136.8	56.3	88.5
Volkswagen	e-up!	18.7	0.13	104.6	104.6	160.9	72.4	88.5
BMW	i3	27.2	0.17	168.9	168.9	257.4	120.7	152.9
KIA	Soul EV	30	0.13	177.0	177.0	265.5	120.7	152.9
Hyundai	Ioniq	28	0.10	201.1	185.0	289.6	136.8	177.0
Volkswagen	e-Golf	32	0.14	201.1	193.1	297.7	136.8	185.0
Renault	Zoe	37	0.16	233.3	225.3	345.9	160.9	209.2
KIA	Niro EV Mid-Range	39.2	0.17	233.3	241.4	362.0	168.9	217.2
Nissan	Leaf 2018	38	0.17	241.4	233.3	362.0	168.9	217.2
Hyundai	Kona Electric	40	0.17	249.4	241.4	378.1	168.9	225.3
Tesla	Model 3 (Standard)	52	0.15	329.8	345.9	571.2	257.4	345.9
Tesla	Model X 75D	72.5	0.18	329.8	337.9	490.7	241.4	289.6
Mercedes	EQC (2019)	70	0.21	345.9	370.1	539.0	265.5	337.9
Chevrolet	Bolt *	60	0.47	378.1	-	410.3	-	345.9
Opel	Ampera*	60	0.47	378.1	-	410.3	-	345.9
Hyundai	Kona Electric (64 kWh)	64	0.19	386.2	386.2	595.3	281.6	362.0
Tesla	Model S 75D	72.5	0.22	386.2	378.1	555.1	281.6	362.0
Jaguar	i-Pace	85	0.25	402.3	402.3	579.2	281.6	362.0
Tesla	Model 3 (Long Range)	78	0.17	490.7	466.6	708.0	345.9	458.6
Average		46.79	0.19	270.71				

* Opel Ampera is the EU version of the Chevy Bolt, and figures are taken from the EPA site, where a range of ranges is not available, just city and highway ranges.

The Mitsubishi i-MiEV is not currently available, but is sold as Citroen C-Zero and Peugeot Ion.

All figures for range are rounded to 0 or 5.

Table 20 shows the specifications of electric commercial vans. These vehicles are in production and specifications are readily available. An average energy consumption for a Light Truck/Van vehicle to be used is 0.23 kWh/km, where current lithium-ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019).

Table 20. Electric Vehicle commercial van (Light Truck/Van) range and distance per kWh capacity (Source: https://evcompare.io/search/)

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (km/kWh)	Engine Torque (Nm)	Engine Horsepower (hp)
Citroen	Berlingo Electric	170	22,5			
Iveco	Daily Electric	280	91	0,33	300	107
Nissan	e-NV200	200	40	0,2	254	107
Peugeot	Partner electric	170	22,5			
Renault	Kangoo Z.E.	270	33	0,28	225	59
Renault	Master Z.E.	120	33	0,12	225	76
SAIC Maxus	EV-80	230	53	0,23	320	136
		Average (Light Truck/Van)	42,14	0,23		

Table 21 shows the estimated specifications of EV pick-up trucks like the Tesla Cybertruck. None of these vehicles have been released yet and specifications have had to be estimated from manufacture press releases. An average energy consumption for a Light-Duty vehicle to be used is 0.31 kWh/km.

Table 21. Electric Vehicle Light-Duty Vehicle (Pick-up truck) range and distance per kWh capacity

Manufacturer	Model	Date of Release	Possible Battery Capacity (kWh)	Estimated Range (miles)	Estimated Range (km)	Power Horsepower (hp)	Estimated Distance per kWh (km/kWh)	Source (Manufacturer website)
Chevrolet Silverado / GMC Hummer Electrics	Hummer EV SUT	2021	200	400	643,6	1000	0,31	https://www.gmc.com/electric-truck/hummer-ev
Ford	Electric Ford F-150	2022		300	482,7			https://insideevs.com/reviews/377328/ford-f150-electric-truck-details/
Tesla	Cybertruck			500	804,5			https://www.tesla.com/en_gb/cybertruck
Rivian	R1T	2021	105	230	370,07		0,28	https://rivian.com/r1t
			135	300	482,7		0,28	
			180	400	643,6		0,28	
Lordstown	Endurance	2021				600	0,25	https://lordstownmotors.com/pages/endurance
Bollinger	B2	2020	142	200	321,8	614	0,44	https://bollingermotors.com/bollinger-b2/
Nikola	Badger	2022	160	300	482,7	455	0,33	https://nikolamotor.com/badger
Average (Light-Duty Vehicle	- Pick up truck)		153,67				0,31	

Table 22 shows the specifications of EV buses to transport lots of people. Only two examples are shown here (7900 Volvo and BYD K9), but these two models represent a large proportion of the current EV bus fleet. Specifications are from manufacturer's press releases. An average energy consumption for a Transit Bus, Paratransit Shuttle, or School Bus EV vehicle to be used is 1.32 kWh/km, where current lithium ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b).

Table 22. Electric Vehicle Bus (Transit Bus, Paratransit Shuttle, School Bus) range and distance per kWh capacity (Source: Volvo 7900 Electric specifications, www.volvobuses.co.uk and BYD 2020, www.byd.com)

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (km/kWh)	Engine Torque (Nm)	Engine Horsepower (hp)
Volvo	7900 Electric	200	150 200 250	1,25	400	160
BYD Auto	BYD K9	250	310	0.9-1.8	700 1100 3000	245 410 490

Average (Transit Bus, Paratransit Shuttle, School Bus)	227,5	1,32

Table 23. Electric Vehicle HCV Trucks (Refuse Truck, Medium Duty Delivery Truck, Large Duty Rigid Delivery Truck, Laong Haul Semi-Trailer Class 8) range and distance per kWh capacity (Source: Liimatainen et al 2019)

Manufacturer	Commercial Name	Type	Maximum Weight (tonnes)	Battery Capacity (kWh)	Range (km)	Energy Consumption (kWh/km)
Mitsubishi	eCanter	medium duty	7,5	82,8	120	0,69
BYD	T7	medium duty	11	175	200	0,88
Freightliner	eM2 106	medium duty	12	325	370	0,88
Volvo	FL Electric	rigid	16	100-300	100-300	1
Renault	D Z.E.	rigid	16	200-300	300	1
eMoss	EMS18	rigid	18	100-250	100-250	1
Mercedes-Benz		rigid	26	212	200	1,06
Renault	D WIDE Z.E.	rigid	26	200	200	1
Tesla	Semi	semitrailer	36		480-800	1,25
BYD	T9	semitrailer	36	350	200	1,75
Freightliner	eCascadia	semitrailer	40	550	400	1,38

Average Medium Duty (Delivery Truck)	194,3	0,82
Average Rigid (Refuse Truck, Large Rigid Delivery Truck)	206,0	1,01
Average Semi Trailer (Class 8 Truck)	450,0	1,46

Long haul trucks (HCV) have a capacity of 1.44 kWh/km, (noting that this from the less aerodynamic heavy duty truck traveling at 90 km/h) (Earl *et al* 2018). Tesla manufacturers are releasing the Tesla Semi HCV class 8 long haul truck, which is quoted at having a capacity of 1.24 kWh/km (2.0kWh/mile) (Source: Tesla Semi PR release: https://www.tesla.com/semi), and Sripad & Viswanathan 2017). A more recent study reports an average energy consumption for a Long Haul Class 8 Truck EV vehicle to be used is 1.46 km/kWh (Liimatainen *et al.* 2019).

Table 23 shows the estimated specifications of electric trucks of various classes. An average energy consumption for a Refuse Truck EV vehicle to be used is 1.01 km/kWh. An average energy consumption for a Delivery Truck EV vehicle to be used is 0.82 km/kWh, where current lithium-ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019).

5.1 Power capacity required accounting for EV efficiency drivetrain loss

To determine the needed electrical energy for an EV to travel a given distance, the efficiency of the electric system to translate power stored in the battery to physically moving the vehicle needs to be determined (Ehsani *et al* 2018). The overall energy efficiency of an electric vehicle is estimated as 73%, comparing energy stored in the battery and the wheels turning (Malins 2017). This is far more efficient than any of the ICE technologies. The sources of lost energy in the system is listed below:

- Energy storage and distribution in battery: Approximately 5% energy losses
- Inversion AC/DC: Approximately 5% energy losses
- Battery Charge efficiency: Approximately 5% energy losses
- Inversion DC/AC: Approximately 5% energy losses
- Engine efficiency: Approximately 10% energy losses

The loss of energy depends on a number of situational based contributing factors. The battery technology is evolving quickly, and the following is often dependent on age. Looking at the unadjusted (for transmission loss) direct electrical power for buses in the Finnish transport fleet to travel the same distance as in 2019 (601 million km, or 6.01 x 10^8 km), the KiloWatt-Hour energy to distance consumption would be 731 million kWh. This is then adjusted for an EV 73% system efficiency to become a little over 1 billion kWh (1.002 x 10^9 kWh, or 1.002 TWh) (shown in Table 23), to calculate the needed power to reside in batteries.

5.2 Power capacity required accounting for transmission loss between power station and application

So, 1.002 terawatt hours (TWh) is required to charge EV buses to be delivered annually to the point of charging in many places in the Finnish electric power grid (Table 23). Electricity must be transmitted from large power plants to the consumers via extensive networks. The transmission over long distances creates power losses. A major part of the energy losses comes from Joule effect in transformers and power lines. The energy is lost as heat in the conductors, which is included in the energy efficiency of the power generation source. Once the power has been generated, it has to be transmitted through the distribution network.

Considering the main parts of a typical Transmission & Distribution network, here are the average values of power losses at the different steps (IEC 2007):

- 1 - 2% – Step-up transformer from generator to Transmission line
- 2 - 4% – Loss in energy due to resistance of transmission wires and electrical equipment
- 1 - 2% – Step-down transformer from Transmission line to Distribution network
- 4 - 6% – Distribution network transformers and cables

In addition, a further 7-10% electrical power can be lost, which could be caused by congestion, which occurs when the normal flow of electricity is disrupted by device constraints or safety regulations (Singh 2014 and Schneider Electric 2016). The true impact of this would vary considerable between different electrical grids around the world, where collecting this information was beyond the scope of this study. As such this was not included in calculations.

The overall losses between the power plant and consumers are then in the range between 8 and 15% (IEC 2007). For the purposes of this report, an average value of 10% in power loss during transmission will be used. This conservative value could account for future efficiency gains in some instances.

So, 1.002 terawatt hours is adjusted to become 1.102 terawatt hours (1.10 x 10^9 kWh) of energy needed to be supplied at the point of electricity generated (power plant) to charge the needed number of self-propelled vehicles EV batteries.

5.3 Estimated energy consumption of a complete EV transport fleet in 2019

To estimate the electric energy that would be consumed if the transport fleet was electric, the following information was compiled:

- The number of vehicles in system in the year 2019 (Table 11)
- Different vehicle classes (cars, trucks, etc.) and their proportions in the whole fleet (Table 11)
- The distance each vehicle class traveled in the year 2019 - km (Table 11)
- The electrical energy consumption per unit distance for each vehicle class – kWh/km (Tables 18 to 22)

Table 24 shows this information compiled together. To support a Finnish EV fleet (comprised of all vehicles except trucks), then an extra 10.8 TWh of electrical annual electricity generation is required to be installed into the Finnish electric power grid. This does not include the hydrogen economy. In a previous estimation by Nordea Bank (Kostiainen 2022), 10 TWh was required for electrification of passenger traffic in Finland.

Table 24. Estimated kilowatt hours needed to charge the projected Finnish EV in 2018.

Vehicle Class EV	Number of Self-Propelled Vehicles in 2019 Finnish Fleet (number)	Annual km traveled by average vehicle (km)	Total km driven by class in 2019 Finnish Fleet (km)	KiloWatt-Hour power to distance consumption vehicles were EV (kWh/km)	Electrical power to be generated (kWh)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Buses	19 137	31 405	6.01E+08	1.22	7.31E+08	8.04E+08
Commercial Van	486 949	11 759	5.73E+09	0.23	1.32E+09	1.45E+09
Passenger Car	3 574 570	11 391	4.07E+10	0.19	7.74E+09	8.51E+09
Motorcycle	278 534			0.11		
Total	4 359 190		4.705.E+10		9.78.E+09	1.08.E+10
	4.36 million vehicles (without trucks)		47.05 billion km travelled in 2018			10.8 TWh

Table 25. Estimated number and mass of Li-Ion batteries (NMC-811) for all self-propelled vehicles in the Finnish fleet

Vehicle Class EV	Number of Self Propelled Vehicles in 2019 Finnish Fleet (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Trucks	NA	NA	NA	NA	NA	NA	NA
Buses	19 137	206,1	226	3 944 136	1,16	896,1	17 148
Commercial Van	486 949	42,1	206	20 521 422	0,23	183,2	89 224
Passenger Car	3 574 570	46,8	270	167 289 876	0,19	203,5	727 347
Motorcycle	278 534	12	322	3 342 408	0,08	52,2	14 532
Total	4 359 190			195 097 842			848 251
	4.36 million vehicles (without trucks)			195.1 GWh of Batteries		Total Li-Ion battery mass 848 251 tonnes	

Table 25 estimates the number of batteries, assuming all units are NMC-811 lithium-ion chemistry. Assuming all batteries would be NMC 811 chemistry is an assumption and makes the outcome a crude estimate. At the time of writing this report, the work needed to estimate a market proportion split of the different battery chemistries has not yet been done. In future work, an estimate of the market share in 2040 of the 5 lithium-ion battery chemistries already published (IEA 2021) will be used to extend this calculation.

Based on a Finnish transport fleet of 4.5 million vehicles, split into different vehicle classes, 195.1 GW of batteries will be needed to power the EV fleet. If all batteries were using NMC 811 chemistry with an energy density of 230 Wh per kilogram (IEA 2019), then that 195.1 GW of batteries would be 848 251 tonnes.

5.4 Stationary power storage as buffer for intermittent power supply from wind turbines

The intermittent nature of renewable energy can be mitigated with measures like connecting lots of renewable power stations together and optimizing their power delivery through one system (Droste-Franke 2015). Power storage systems are mostly required to ensure consistent supply to the grid during the long periods of reduced sunlight hours and reduced wind where it is needed, for solar and wind turbine stations.

The most flexible storage in application is a large battery storage power station (U.S. Department of Energy 2020). This is a type of energy storage power station that uses a group of batteries to store electrical energy. In addition, there are many other options, including gravity-based (pumped) storage, storing energy as heat, and so on. For simplicity, this report will just use Lithium-Ion battery power storage stations. As of 2020, the maximum power of battery storage power plants is an order of magnitude less than pumped storage power plants, the most common form of grid energy storage.

Steinke *et al* 2012 put forward the recommendation for a fully renewable powered Europe to have 2 days of power storage, plus 10%, for the whole system capacity. This study was to examine all power requirements for Europe to be 100% renewable. The Droste-Franke (2015) study proposed a 1 month of energy storage to keep the grid up during seasonal variations (for the whole system capacity). This was seen as a reasonably conservative estimate (where some suggestions were as long as 10 weeks) and was selected for use in this report.

Currently, pumped-storage hydropower (PSH) provides 98% of all the existing electrical energy stored in the world (Mongird *et al* 2019). While the volume of electrical power from renewable sources is relatively small this is a manageable issue. Once renewable power becomes a larger share of power generation, infrastructure will be needed in electrical power storage. The required power storage that is proposed later in this report (Section 13) is much larger than what is currently in place. Due to the number of required power storage stations, it is impractical to plan for more pumped storage stations as they are very geographically limited. There are other options, but the most flexible is the battery storage power station concept.

As of 2020, the largest battery storage power station in the world was the Australian Hornsdale Power Reserve, adjacent to the Hornsdale wind farm, built by Tesla (Parkinson 2017a). The plant is operated by Tesla and provides a total of 129 megawatt-hours (460 GJ) of storage capable of discharge at 100 MW into the power grid. Its 100 MW output capacity is contractually divided into two sections: 70 MW running for 10 minutes and 30 MW with a 3-hour capacity. In construction of the EV batteries themselves, Samsung 21–70-size cells were used (Parkinson 2017b). The system helps to prevent load-shedding blackouts (ElectraNet 2018) and provides stability to the grid (grid services) while other slower generators can be started in the event of sudden drops in wind or other network issues.

6 CALCULATION OF SCOPE AND ELECTRIC ENERGY REQUIREMENTS OF A HYDROGEN FUEL CELL VEHICLE FLEET

Given the outcomes of Section 4.6, it is recommended that all long-range vehicles are to be powered by the hydrogen fuel cell systems. The classification of long range could be used to describe any vehicle that travels more than 100 km (intercity for example) or any heavy vehicle that must operate for a long time. This would mean that all trucks would be supported by and take up the majority share of the Finnish hydrogen economy.

As the first step to estimate the quantity of hydrogen that would be needed annually to fuel the Finnish trucking fleet, an example of a hydrogen fuel cell heavy duty truck was selected and examined.

6.1 Hydrogen Fuel Cell Heavy Duty Truck

The Hyundai Motor Company have produced and commercialized a heavy-duty hydrogen fueled truck (FuelCellsWorks 2020). The first 50 manufactured units are being sent to Switzerland in Q3 of 2020 with a planned total of 1 600 XCIENT trucks to be manufactured by Hyundai by 2025.

The XCIENT H-cell fueled truck is powered by a 190 kW hydrogen fuel cell system with dual 95 kW fuel cell stacks. Seven large hydrogen fuel tanks offer a combined storage capacity of 32.09 kg of hydrogen. The driving range of the XCIENT truck is quoted by Hyundai as being 400km (assuming the 4X2 model with refrigerated up-fit configuration while operating 34 tonne truck + trailer). This provides a hydrogen fuel consumption efficiency of 8.02 kg/100km. These specifications were developed based on a balance between the optimal requirements from the potential commercial fleet customers. Refueling time is approximately 8-20 minutes.

So, a Class 8 H_2 Fuel Cell Heavy Duty Truck to travel 400 km, it would carry as an energy store a 32.09 kg tank of hydrogen. In comparison, a Class 8 Electric Vehicle Heavy Duty Truck (pure EV) would need a 584 kWh lithium ion battery, of mass of 2.540 tonne (where the energy density of Li-Ion batteries is assumed to be 230 Wh/kg – IEA 2019). This shows there to be a large difference in mass of an energy storage between the systems.

Table 26. Specifications of the XCIENT Fuel Cell Heavy Duty Truck
(Source: Hyundai Motor Company, FuelCellWorks 2020)

Item Model	XCIENT Fuel Cell truck
Vehicle Type	Cargo (Chassis Cab)
Cab Type	Day Cab
Drive System	LHD/4X2
Dimensions (mm)	
Wheel Base	5130
Overall (Chassis Cab)	
Length	9745
Width	2515 (2550 with side protector), Maximum allowable width 2600
Height	3730
Weight (kg)	
Max. Gross Combination Weight	36 000 as pull-cargo
Max. Gross Vehicle Weight	19 000 as rigid truck
Front/Rear	8 000/11 500
Empty Vehicle Weight (Chassis Cab)	9 795
Calculated Performance	
Drive Range	Accuarte range to be confirmed later
Max. Speed	85 km/hr
Powertrain	
Fuel Cell Stack	190 kW (95 kW x 2 EA)
Battery	661 V / 73.2 kWh - by Akasol
Motor/Inverter	350 kW / 3 400 Nm - by Siemens
Transmission	ATM S4500 - by Allison / 6 forward speeds and 1 reverse speed
Rear Axle ratio	4.875
Hyrdogen Tank	
Filling Pressure	350 bar
Capacity	32.09 kg H_2 (available hydrogen amount at SOF 100%)

Note - Hyundai Motor Company reserves the right to change specifications and equipment without prior notice

The number of trucks in the 2019 Finnish transport fleet was 162 186 (Table 12), and the distance they traveled in the calendar year 2019 was 20 606 km. If all of these trucks were XCIENT Fuel Cell Heavy Duty Trucks (Table 26), then the required annual quantity of hydrogen could be estimated to be 268 028 tonnes (Table 27).

Hydrogen is produced using electrolysis, powered with non-fossil fuel-based electricity (IRENA 2019, IRENA 2018 FCH 2019, COAG 2019, and ITM 2017). That hydrogen is stored and distributed throughout society to be the basic energy of choice in parallel with electricity. Hydrogen is to be used as a fuel source to power vehicles like passenger cars, trucks, and ships with the use of fuel cells (probably PEM cells). Some hydrogen could also be used in turbines (same technology as gas turbines) to generate electricity and heat, which could be used in a variety of applications domestically and industrially.

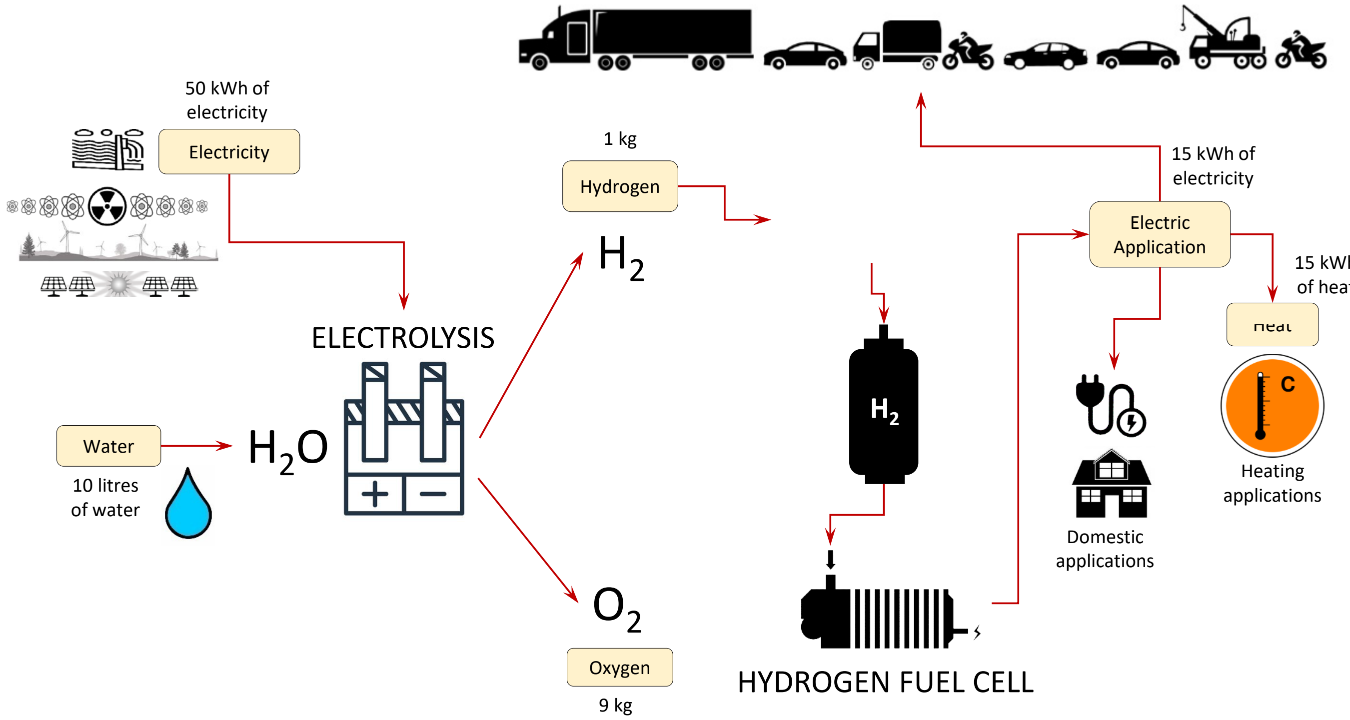

Figure 11. Production and use of 1kg of hydrogen in the proposed Hydrogen Economy (Image: Simon Michaux) (Data taken from EIA)

Hydrogen Physics (Thomas 2018)

- 1kg of H_2 ↔ 11.1 Nm^3 ↔ 33.3 kWh (LHV) and 39.4 kWh (HHV)
- High mass energy density (1kg H_2 = 3.77 liters of gasoline)
- Low volumetric density (1 Nm^3 H_2 = 0.34 liters of gasoline)

Hydrogen Production from water electrolysis (~ 5 kWh/Nm^2 H_2) (Thomas 2018)

- Power: 1 MW electrolyzer 200 Nm^3/h H_2 ↔ ±18 kg/h H_2
- Energy: +/- 50 kWh of electricity ↔ 1kg H_2 ↔ 11.1 Nm^3 ↔ ±10 liters demineralized water
- Compressed H_2 in tank storage at pressure 700 bar requires 2.5 kWh/kg

Energy production from a hydrogen PEM fuel cell from hydrogen (+/- 50% efficiency) (Thomas 2018)

- Energy: 1kg of H_2 ↔ 15 kWh

Assuming 50 kWh/kg to produce hydrogen with electrolysis (IRENA 2018, FCH JU 2017), and 2.5 kWh/kg to compress the hydrogen into 700 bar pressure storage tanks (Thomas 2018), the estimated quantity of electricity to produce the estimated annual required mass of hydrogen for Finland, would be 15.48 TWh (Table 27).

Table 27. Annual quantity of hydrogen for trucks in Finland for the year 2019

Vehicle Class Trucks Hydrogen Cell	Units	Outcome
Number of Self Propelled Vehicles in 2019 Finnish Fleet	(number)	162 186
Annual km traveled by average vehicle (apply ratio 0.368)	(km)	20 606
Total km driven by class in 2019 Finnish Fleet	(km)	3,34E+09
Consumption of hydrogen if vehicle was a FCEV	(kg/100 km)	8,02
Consumption of hydrogen if vehicle was a FCEV	(kg/km)	0,0802
Quantity of H_2 for all global vehicles in that class to travel the same distance as was done in 2019	(kg)	2,68E+08
	(tonnes)	268 028
Required Electric power to manufacture H_2 with electrolysis (@ 50kWh/kg)	(kWh)	1,34E+10
Required Electric power to compress H_2 into tanks at 700 barr pressure (@ 2.5 kWh/kg)	(kWh)	6,70E+08
Required annual electric power generation assuming 10% grid transmission loss between power station and electrolysis unit and compression unit	(kWh)	1,55E+10
	(TWh)	15,48

6.2 Calculation of Scope and Electric Power Requirements of a Hydrogen Fuel Maritime Shipping Fleet

It will be a challenge to phase out fossil fuels in the maritime industry. The volumes of cargo and commodities moved are truly vast and the distances travelled are longer than any other transport system currently in use (Michaux 2021). Multiple options to phase out fossil fuels have been proposed (EFTE 2018), ranging from fully EV, to sail assisted and nuclear propulsion (currently used in large military vessels like aircraft carriers). Several hybrid systems have also been proposed. Thinking outside the box, a solution could be engineered where large ships are propelled by sail, assisted by EV in port, where each sail could function like a solar panel, could be engineered. This conceptual idea is not available at this time, however. For the purpose of this report, the fully electric propulsion system, powered by a hydrogen fuel cell is modeled.

Diesel propulsion system is the most commonly used marine propulsion system converting mechanical energy from thermal forces (MAN Energy Solutions 2019). Diesel propulsion systems are mainly used in almost all types of vessels, including small boats and recreational vessels. In conventional power system arrangements, the ship's propellers are driven by a diesel propulsion engine while the supply of electricity for the other shipboard loads is transmitted via the shipboard generators (Figure 12).

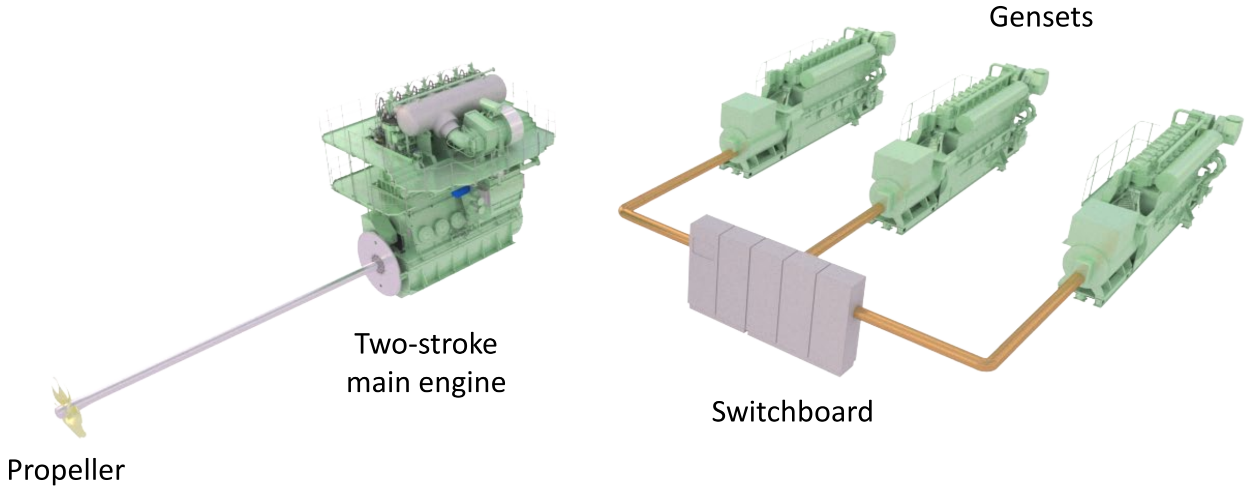

Figure 12. Traditional diesel-mechanic propulsion of a large merchant vessel
(Source: MAN Energy Solutions 2019)

In electric propulsion systems, the energy used to drive the propellers becomes an electrical load meaning that the generators can take care of all shipboard loads. Electric propulsion systems utilize electrical power to drive propeller blades for propulsion. From commercial and research ships through to fishing vessels, over the last five years, electric propulsion has gained momentum in a wide range of marine applications across Europe and in Japan. The basic configuration of the electric propulsion system is shown in Figure 13.

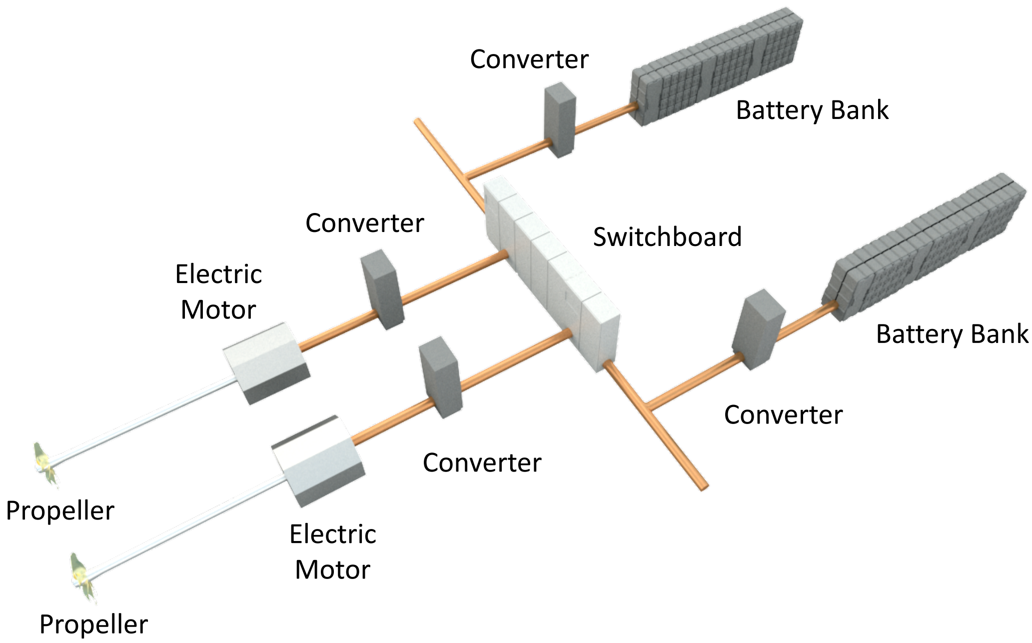

Figure 13. Pure battery electric propulsion system for a maritime shipping vessel
(Source: MAN Energy Solutions 2019)

There is a considerable difference in energy density: the energy density of diesel marine fuel oil (or bunker oil) is 12 750 Wh/kg (Table H.1 in Appendix H), whereas current lithium-ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b). This results in differences in energy storage mass and volume, and as a result an EV system will take up more ship gross tonne capacity than an ICE system. Even if battery technology became 10-fold more efficient, it would still be only have 1/6th the energy density of diesel fuel oil. This is partially balanced out by a difference in energy transfer efficiency, where diesel ICE is 38% and EV propulsion is approximately 73% (the numbers are not clear for large ships at the time of writing this report). It is for this reason that it was proposed to model shipping as a Hydrogen fuel cell system, given that the mass of energy storage (battery vs. hydrogen fuel tank) is smaller (see Appendix C), where the electric propulsion system is supplied with electricity generated by a PEM fuel cell unit.

Maritime shipping grade fuel consumed in the year 2019 was 2 300 000 tons (both light and heavy fuel oil) (Salanne et al., 2021).

- Given that the energy density of diesel (marine gas oil) calorific content is 12.75 kWh/kg, or 45.9 MJ/kg (Table H.1, Appendix H), the Finnish maritime shipping industry consumed 29.3 TWh of energy in the year 2019.

- Given that energy efficiency of an ICE diesel engine is 38% (Table H.3, Appendix H), then 11.14 TWh of useful work was done by the Finnish maritime shipping fleet in the year 2019.

- If all ships had an electric propulsion system, where its energy efficiency was the same as an Electric Vehicle system is taken at 73% (Malins 2017), then the sum total of all Finnish ships would require 15.3 TWh of energy supply to do the same useful work done as what was done in 2019.

- If each ship in Finland was powered with an electric propulsion system, that is supplied with electricity generated by a PEM fuel cell unit, then an annual sum total of hydrogen would be needed. Given for each 1 kg of hydrogen, 15 kWh of electricity is generated by a PEM hydrogen cell, then 1,017,671 tonnes of hydrogen (1.02×10^9 kg) are needed annually for the Finnish maritime shipping fleet.

- Given it requires 50 kWh of electrical energy to generate 1kg of hydrogen, and 2.5 kWh of electrical energy to compress that hydrogen into 700 bar pressurized tanks for storage (Zuttel 2004 and Rivard *et al* 2019), then 53.4 TWh of electrical energy is needed each year to produce hydrogen ($52.5 \times 1.02 \times 10^9 = 53.43$).

- Assuming a 10 % loss in grid transmission between the power station and the hydrogen production facility, 58.77 TWh of electrical power will need to be generated each year to service the Finnish maritime fleet, with the production of hydrogen (53.43 x 1.1 = 58.77).

7 CALCULATION OF EXTRA NON-FOSSIL FUEL ELECTRICAL ENERGY GENERATION TO PHASE OUT FOSSIL FUEL POWER IN FINLAND

The physical work done in Finland using fossil fuels as an energy source in the year 2019, is shown in Figures A1 to A9 and Tables A1 to A8 in Appendix A. Table 28 shows the electrical energy generated using fossil fuels as a feedstock raw material.

Table 28. Electricity generated in Finland in 2019 sourced from fossil fuels (drawn from Table 6)

Fuel Source in 2019	Electricity (GWh)
Oil	267
Coal	4 115
Natural Gas	3 767
Other fossil [3)]	947
Peat	2 821
Total	11 917

Assembling data from different parts of this report, Table 29 shows an estimate of the required extra electrical energy generation capacity required annually to phase out fossil fuels. To replace fossil fuel sourced electrical energy generation, 11.92 TWh of non-fossil fuel energy generation capacity is required. In addition, in 2019, Finland imported 20.04 TWh of energy from abroad. The nations that are producing this electrical energy and selling it to Finland, will struggle to continue this supply in a post fossil fuel world. It is recommended that this 20.04 TWh is delivered from internal power generation sources. In addition to substituting the fossil fuel power generation, to deliver enough electrical energy to charge the batteries of an Electric Vehicle fleet (passenger cars, buses, commercial and vans), 10.8 TWh (Table 24) of annual capacity is required. Also, to manufacture enough hydrogen to support the fleet of trucks (powered by hydrogen fuel cells), 15.48 TWh of annual capacity is required (Table 27).

Table 29. Required extra annual electrical energy generation to phase out fossil fuels in Finland

Required Extra Annual Electrical Energy Generation	(TWh)	Source
Phase out fossil fuel sourced energy generation	11.92	Table 28
To replace imports	20.04	Table 3
To power EV vehicles	10.76	Table 24
To produce hydrogen to power H-Cell vehicles	15.48	Table 27
To produce hydrogen to power maritime shipping	58.77	Section 6.2
Total	116.97	

The total of 116.97 TWh of annual energy is required for the replacement whole Finnish ICE transport fleet as it was in 2019. Expanding the solar, hydroelectricity and biomass energy generation sectors all face practical and logistical bottleneck limitations. Solar power in Finland may not be reliable due to available sun hours and the duration of time panels would be covered in snow. Hydroelectric power is very dependent on geographic locations, where most suitable locations already have a hydroelectric power generation station operating, and both new and existing hydroelectric power plants need to consider multiple local issues (like nature conservation, land stewardship, biodiversity etc. see e.g. Grill et al. 2019, Soininen *et al.* 2019). Biomass to waste in CHP plants will have to be examined carefully due to sustainability and land stewardship issues (See Section 9).

8 SCOPE AND BIOMASS REQUIREMENTS OF A POSSIBLE FINNISH BIOFUEL VEHICLE, AVIATION AND MARITIME FLEET

Finland has the unique situation where a large proportion of its territory is covered in forest, that can be managed as harvestable biomass. Some of this biomass can be used to produce biofuels. There is a great deal of interest in the possibility of Finland producing biofuel from biomass as a way of substituting petroleum in ICE vehicles. Table 30 shows the current production of biofuels in Finland.

Table 30. Current status and development of Finnish companies' production of biofuels. (Source: Modified from AFRY 2021)

Companies and Factories	Production Capacity		Planned New Capacity		Capacity to be Developed by 2030	
	Domestic (ktoe/a)	Foreign (ktoe/a)	Domestic (ktoe/a)	Foreign (ktoe/a)	Domestic (ktoe/a)	Foreign (ktoe/a)
Neste Oyj	**480**	**2730**	**210**	**2835**	**690**	**5565**
MyDiesel [1]	480	2730	210	2835	690	5565
St1 Oy	**15**	**<1**	**25**	**245**	**35**	**245**
Etanolix [2]	10	<1		10	10	10
Bionolix [3]	<1				<1	
Cellunolix	5		25	25	25	25
Göteborg HVO				210		210
UPM-Kymmene Oyj [4]	**130**			**500**		**630**
Lappeenranta	130				130	
Kotka/Rotterdam				500		500
Other Actors						
BioEnergo			30		30	
Pori			30		30	
Nordfuel			40		40	
Haapavesi			40		40	
Total	625	~2730	305-805	3080-3580	925-1425	5810-6310

1 - MyDiesel is mostly PFAD and waste oils from food production
2 - St1 Etanolix is produced from food waste
3 - St1 Cellunolix is produced from saw dust
4 - UPM-Kymmene produces diesel and naphtha from tall-oil in Lappeenranta

The biomethane/biogas potential from waste in agriculture and waste management is estimated to be 11-15 TWh (MEAE, 2020). Finnish petroleum product consumption in 2019 was the following: (OSF: http://www.stat.fi/til/ehk/meta.html)

Gasoline Petrol ("bensiini") in 2019

- 1 398 315 tons
- 1 864 420 m^3
- 61 945.4 Terajoules (where 1000 tons of gasoline = 44.3 terajoules)
- 17.21 TWh (where 1 terajoule = 0.00028 terawatt hours)

Diesel in 2019

- 2 608 711 tons
- 3 087 232 m^3
- 112 144 Terajoules (where 1000 tons of gasoline = 44 terajoules)
- 31.15 TWh (where 1 terajoule = 0.00028 terawatt hours)

Summing gasoline and diesel together, 48.36 TWh (17.21 TWh + 31.15 TWh = 48.36 TWh) of fuel would need to be produced to match 2019 annual consumption.

As an approximate estimate, one cubic meter (1 m^3) of wood biomass could be used to produce 2 MWh of energy, and the further conversion step to produce liquid biofuel from this energy has an average conversion efficiency of 0.6 (Forsström *et al.*, 2012). Combining these together gives:

$$\emptyset = (X / 0.6)/2 \qquad \text{Equation 1}$$

Where:
X = amount of liquid fuel needed, in (TWh)
Ø= needed amount of biomass fuel sourced from wood, in (Mm^3)

So, the biomass annually sourced from wood required to produce enough biofuel to substitute for petroleum sourced gasoline and diesel for the Finnish transport fleet in 2019, would be 40.3 million cubic meters of wood [(48.36TWh/0.6)/2 = 40.3 Mm^3]. The maximum sustainable harvest of wood biomass from Finnish forests is somewhere between the estimates of 80.5 Mm^3/per annum (Luke 2021) to 70 Mm^3/per annum (WWF Finland 2015). In 2019, the forest industry used 72 Mm^3 of wood (Luke 2021). Given the range of sustainable harvest levels and current forestry practices, the needed wood biomass for biofuels substituting petroleum products could only be sourced by radically reducing the wood use in forest industry (approximately by 50 percent).

8.1 Biofuel for the Aviation Industry

It is possible to produce fossil-equivalent jet fuel from biomass. This could be the most practical way to maintain the aviation industry after fossil fuels. Currently, commercial biofuel is produced from various vegetable oils and animal fats (Neste, 2022). Production from lignocellulosic (wood, harvest residues) sources is more complicated, but possible (see Appendix G). Both electric and hydrogen systems have engineering limitations. Conventional jet fuel is produced by refining petroleum crude. Its composition depends on the raw crude oil, but is typically around 20% paraffins, 40% isoparaffins, 20% naphthenes and 20% aromatics (Blakey, Rye & Wilson, 2011). Each of these components plays a critical role in providing specific fuel characteristics. The ASTM has approved the certification of seven different technology platforms used to produce sustainable aviation fuel for use in commercial aviation, without restrictions. These are described in Appendix G, Table G1.

8.2 Biofuel for the Maritime Shipping Industry

The Finnish maritime shipping industry consumed 2 300 000 tons (both light and heavy fuel oil) in the year 2019 (Salanne et al., 2021). Given that the energy density of diesel (marine gas oil) calorific content is 12.75 kWh/kg, or 45.9 MJ/kg (Table H.1, Appendix H), the Finnish maritime shipping industry consumed 29.3 TWh of energy in the year 2019. Using Equation 1, it can be estimated that 24.42 Mm^3 of wood sourced biomass would be needed to annually produce the corresponding amount of biofuel.

9 SUSTAINABILITY OF BIOMASS TO GENERATE HEAT AND ELECTRICITY

In terms of energy sufficiency, security, and sustainability, it is necessary to investigate the limits to energy generation from biomass. In Finland, the main biomass source is wood. Other possible sources include agricultural waste products, food waste, rapeseed oil, and straw (AFRY 2021). We will concentrate on wood, below, as it is the only source with major possibilities for expanded use. Heat and electricity can be produced by burning biomass. This option is attractive for two general reasons. First, in some uses biomass or products derived from biomass, such as ethanol or biodiesel, can function as drop-in replacements for fossil fuels. Diesel and ethanol are already being produced from wood-based sources in Finland (AFRY 2021). In other cases, biomass, such as wood, only needs drying and chopping up to be ready for use. Often the plants, such as CHP plants utilizing wood need to be fine-tuned for that purpose, but in places like Finland with long traditions of wood use in energy production, skills and technology exist readily.

The second reason is due to current carbon emission accounting, as formulated in the UN Kyoto protocol and subsequent regulation. When trees are harvested, the forest loses the carbon stored in the trees (and, additionally, in many forms of forestry, such as clear-cutting, some carbon is lost from the forest soil). If the harvested wood is used for short lived products, such as energy, paper, pulp, and board, the carbon is released within a few years. The emissions are reported in national accounting on the LULUCF (land use, land use change and forest) sector. In countries like Finland with large, forested areas, the LULUCF sector is typically a carbon sink, and the emissions due to the use of harvested wood diminish the amount of this sink. Crucially, as the emissions are recorded in the national LULUCF accounting, the energy or heat producer using the wood (for instance, by burning it for energy) does not have to report the resulting CO_2 emissions and thus evades paying for emissions. In addition to these general reasons, in places like Finland wood use is attractive due to its availability. In 2019, wood sourced fuel accounted for 28 % of energy total consumption. The fact that Finland has achieved its EU target of 38 % renewable energy use by 2020, is dependent on wood sourced energy. This means that 57 % of harvested wood was used as energy in 2019 (Luke 2021). Especially forest industry relies on wood energy: ca. 87 % of the energy used by the forestry sector in Finland was renewable, mainly consisting of energy derived from the wood that is not contained in the end product (Jegoroff, Arasto & Tsupari, 2021).

However, there are two major problems regarding wood biomass use. The first problem concerns the climate and biodiversity effects of wood consumption, and the second the availability of sustainably harvested wood. Despite the loss of carbon from rapidly degrading products, the substitution of wood for fossil fuels may be advantageous to the climate if and when the forests grow back. Benefits from substitution vary depending on the details of both the substituted fossil material and the used biomass (Sterman *et al*. 2018; Agostini, Giuntoli & Boulamanti 2014; Soimakallio *et al*. 2021; Kalliokoski *et al*. 2020). In terms of climate goals, the timeframe of carbon re-uptake is crucial (Skytt, Englund & Jonsson 2021; Helin *et al*. 2016; Soimakallio *et al*. 2016). For urgent climate mitigation, the use of biomass should be limited to feedstocks that have re-uptake times within the timeframe of the Paris agreement (Norton et al. 2019).

In Finland, forest growth is relatively slow, implying long carbon re-uptake times. Consequently, the substitution factor (i.e., how much greenhouse gas emissions is avoided when a wood-based product is used instead of another product to provide the same function) tends to be less than 1 tC/tC (Hurmekoski *et al*., 2019), while the substitution factor should be around 2.0 -2.4 tC/tC in order for increased loggings to produce climate benefits (Seppälä *et al*. 2019). In terms of carbon accounting, a similar effect is seen in that one ton of carbon in harvested wood reduces the carbon sink in forests on average by 1.7 tons (Finnish Climate Change Panel, 2019).

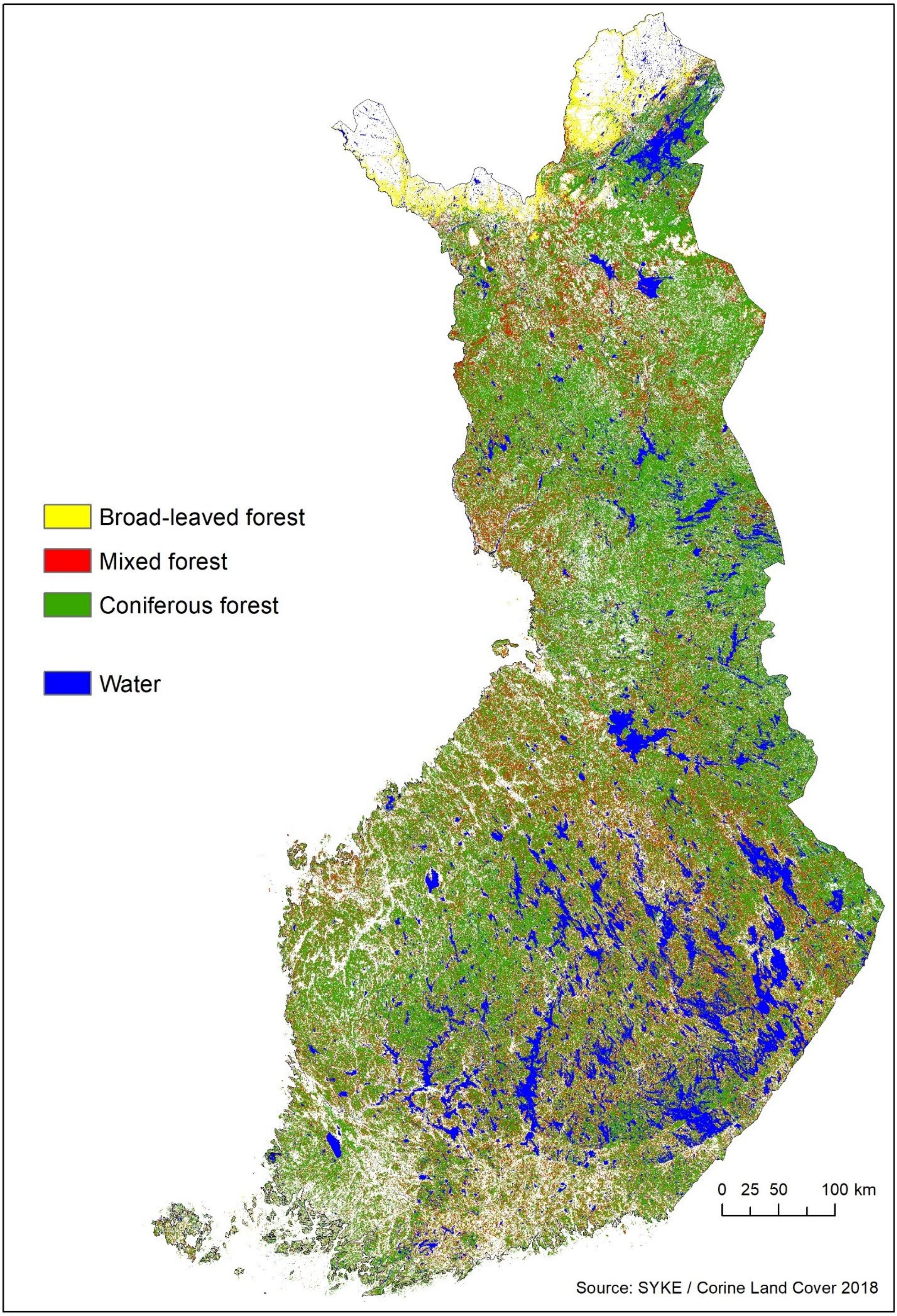

Figure 14. Map of forestry biomass in Finland (Source: GTK, Jussi Pokki, SYKE/Corine Land Cover 2018)

In sum, with current forestry practices and logging levels it is "exceptionally unlikely (cumulative P ≤ 1%) that the wood utilization in Finland provides significant unit reductions in net carbon emissions within the upcoming 100 years." (Soimakallio *et al.* 2016). Thus, if the motivation for phasing out fossil fuels is the mitigation of climate change, increased wood use may, without further developments, be counterproductive.

Table 31. Forest types in Finland, data from Figure 14

Land Classification	Area (km^2)	Proportion of Finnish land area (%)
Broad-leaved forest	10 358	2.7 %
Coniferous forest	149 804	38.3 %
Mixed forest	45 363	11.6 %
Water (lakes and rivers)	33 468	8.6 %
Transitional Woodland/Shrub	33 798	8.6 %
Total	272 791	69.8 %

The second major problem is a dynamic but definite limit to available sustainably harvested biomass. In 2019, the annual growth of forests was 110 Mm^3/a (million cubic meters per annum), giving a long-term maximum harvest amount of 80,5 Mm^3/a, with actual loggings being 72 Mm^3 (Luke 2021). It should be noted that this maximum rate only evaluates the sustainability of wood production, and does not include ecological sustainability, such as questions of biodiversity. In some areas, logging levels have been exceeding the sustainable maximum (Vaahtera et al. 2021). The low-carbon roadmaps by sectors of Finnish industry (energy, forest, chemical and traffic sectors) rely on increased wood use up to 140 Mm^3 (Majava et al, 2022); the roadmap of the forest sector alone contains a wood use of 90 Mm^3, overstepping current sustainable harvest levels, thus dictating a model of intensified forestry practices intended to increase growth (Luke 2020).

Given the limit for wood availability, there are two possibilities for delivering the wood needed for phasing out fossil fuels. Either the wood use by the forest sector must decrease, or imports must be increased. In 2019 Finland imported 10 Mm^3 of wood (Luke 2021), mostly from Russia (at the time of writing, imports from Russia have been discontinued). The importing of wood brings its own problems. First, again, is the question of sustainability. In terms of sustainable development goals, a practice where a highly developed country imports biomass in order to reach carbon neutrality is problematic (Beuchelt & Nassl 2019). A climate mitigation strategy where Finland, one of the most forested countries in the world, can attain its climate goals only through importing biomass, is clearly not scalable.

According to the official numbers by the National Resource Institute (Luke, 2021) the maximum economically sustainable level of harvesting that does not jeopardize future use is currently 80,5 Mm^3. This number does not consider issues of ecological sustainability, such as biodiversity. Given current forestry practices, it is likely that the ecologically sustainable level of loggings is lower, as forestry is the most important cause of regional extinction in Finland and an increasing number of forest species have become endangered (Hyvärinen *et al*., 2019). In a report published by WWF Finland in 2015, the maximum harvest level compatible with ecological sustainability was estimated to be 70 Mm^3. A level of over 80 Mm^3 of harvesting is also too high to guarantee Finnish climate targets, as it would result in declining carbon sinks in forests (Finnish Climate Change Panel, 2019).

10 CALCULATION OF EXTRA NON-FOSSIL FUEL HEAT GENERATION CAPACITY TO PHASE OUT FOSSIL FUELS IN FINLAND

The heat energy generated from fossil fuel sources for industrial and district heat in 2019 is shown in Table 32. This 29.16 TWh will have to be generated from non-fossil fuel sources.

Table 32. Industrial and district heat generated in Finland in 2019 sourced from fossil fuels (drawn from Table 10)

Fuel Source in 2019	District Heat (GWh)	Industrial heat (GWh)
Oil	776	2 110
Coal	6 900	614
Natural Gas	4 092	3 549
Other fossil [3)]	1 427	747
Peat	5 672	3 271
	18 867	10 291
Total		29 158

Of the industrial and district heat energy generated in Finland in 2019 (93 546 TWh), 29.16 TWh was generated using fossil fuel sources (oil, gas, coal, and peat). So, this 29.16 TWh should be generated using non-fossil fuel sources. One proposed source is biomass, wood in particular. The calorific value of dry wood is on average 4 kWh/kg (depending on the type of wood, Forsström et al. 2012), and as harvested 2.5 kWh/kg. Table 33 shows the energy content of wood harvested from forestry as biomass. The basic density (ratio of oven-dry mass and green volume) of wood varies between species (e.g., Scots pine 285 kg/m^3, spruce 400 kg/m^3, birch 475 kg/m^3; Alakangas et al., 2016).

Table 33. Wood Harvested as Bio Mass - Combustion Heat and calorific energy content
(Source: https://www.engineeringtoolbox.com/wood-biomass-combustion-heat-d_440.html)

Biomass in the form of wood harvested from forestry	Moisture (%)	Calorific Value (kWh/kg)	Approximate Combustion Values (btu/lb)	Approximate Combustion Values (kJ/kg)	Approximate Combustion Values (kcal/kg)
Immediately after felling (Green)	50-60%	2,5	4000	9300	2220
After being stored for one year (under good conditions)	25-35%	3,9			
After being dried for several years (under good conditions, or oven dry)	15-25%	4,5	7000	16300	3890

Note: by volume wet wood has about 85% of the energy of oven-dry wood
by weight wet wood has less than half - 42% - of the energy of oven-dry wood
One weight unit of wood has enough energy to evaporate 6 weight units of water.

As an average, one m^3 of wood gives 2 MWh of energy in a CHP station, roughly one third as electricity and two thirds as heat (Alakangas et al. 2016, 69). This is shown as Equation 2.

$$\Theta = Y/2 \quad \text{Equation 2}$$

Where:
Y = amount of heat needed, in (TWh)
Θ= needed amount of biomass fuel sourced from wood, in (Mm^3)

Using this value for estimation, the production of 29.16 TWh (Table 32) of district and industrial heat sourced from wood biomass would require 14.58 Mm^3 wood (using Equation 2: 26.16/2=14.58). If half (5.15 TWh) of industrial heat is high-temperature heat that requires liquid biofuels (using Equation 1), the need for wood would be 16.29 Mm^3. (29.16-5.15 = 24.01, 24.01 TWh using Equation 1 gives 12 Mm^3 of wood, the remaining 5.15 TWh using Equation 2 gives 4.29 Mm^3 of wood, 12+4.29=16.29). Adding the replacement of residential heat from fossil fuels and peat at 2.6 TWh would require an additional 1.3 Mm^3 of wood.

Wood biomass produced in 2019 gave approximately 105 TWh of energy, which was 28 percent of total energy consumption. In 2019, approximately 72 million cubic meters of wood from forests were felled (Luke 2021). If CHP plants were used to generate the needed extra heat, an expansion of 14.58 Mm^3 (16.29 Mm^3 if liquid fuels are needed for high-temperature industrial heat) of wood harvest would be required. There is some debate being conducted about the appropriate and sustainable rate of harvesting biomass in Finland (see section 9 above). It is not clear if this increase of approximate 20.3 % is currently feasible.

11 GEOTHERMAL POTENTIAL TO SUPPLY ENERGY FOR DISTRICT HEATING

In 2019, residential building heating (excluding electric heating and ambient heat, e.g., heat pumps) accounted for 14.7 TWh energy consumption (OSF, https://www.stat.fi/til/asen/meta.html). One of the current approaches for heat production is using Combined Heat and Power (CHP) plants, fueled with wood biomass. There is a discussion regarding what is a genuinely sustainable rate of the harvesting of wood biomass from Finnish forests (see Section 9 above). It would be most useful to reduce the load CHP plants need to produce.

Geothermal energy could provide an alternative solution for renewable heat energy production. The utilization of geothermal energy for heating has increased in Europe over the last few years (Garabetian *et al.* 2020). In the Nordic countries, excluding Iceland, shallow geothermal utilization for heating is the most widely used geothermal resource. Shallow geothermal is defined as low enthalpy energy utilization from relative shallow depths; 100 to 400 m below ground level. Usually, a heat pump is needed to raise the fluid temperature to a reasonable level for heating purposes. According to the Official Statistics of Finland (retrieved in 2019) approximately 5.3 TWh of heating energy was produced by heat pumps in Finland in 2017. The heat pump energy production is increasing approximately 0.5 TWh annually (The Finnish Heat Pump Association 2018).

District heating is the most common heating system in Finland. Current heating network requires fluids of temperatures approximately 70-120^{0}C. Newly developed 4th generation district heating system can function on temperatures as low as 40-50^{0}C (Østergaard *et al* 2022 & Lund *et al* 2018). If a heat pump is used, then electrical power is required to run the pump. The electrical energy required is equivalent to approximately 1/3rd of the heat energy generated by the pump in Watt-hours. Conventionally, shallow geothermal wells were not considered economic for heat or energy production, where temperatures approximately 70-120^{0}C were needed. This new generation of district heating system makes the shallow geothermal borehole viable, where heat could be produced using fluids in the temperature range 40-50^{0}C.

A study was conducted by the GTK (Arola *et al.* 2019) to examine the potential for the use of shallow geothermal to supply heat energy to Finnish society.

The study calculated the energy which could be utilized from one 300 m deep borehole, then extrapolated that result in various geographical and geological locations across Finland. The stationary heat flux through the borehole wall was also calculated. The theoretically utilizable energy amount of one borehole area ranged in from 0.6 GWh (1.4 MW renewable power) in the North of Finland to 4.5 GWh in the South of Finland (9.6 MW renewable power). The sum of thermal energy stored into the ground was estimated to approximately be 300 to 350 petawatts (PWh), or 3 to 3.5 x 10^{15} Wh (Arola *et al.* 2019). The theoretical potential of shallow geothermal energy is enormous in Finland and geothermal energy has the potential to be utilized for space heating and cooling significantly more than currently is done.

Combined district heating production and industrial heat production was 93.6 TWh in Finland in 2019 (OSF, 2019). District heating in 2019 was 38.1 TWh and residential building heating was 14.7 TWh. Hence, theoretically the energy which is stored to the first 300 m of Finnish ground could provide heating energy for the whole country for next 3500 years. This calculation ignores the effect of continuous renewable power, which provides, for practical purposes, infinite heat flow. This heat flow should be added to the total energy reservoir as well. Hence, the real theoretical potential is larger than a calculated energy storage.

Arola *et al*. (2019) study examined the potential for 300 m deep holes. The deeper the geothermal borehole, the more energy it could provide.

The spacing of geothermal boreholes is very important to understand. While geothermal energy is renewable potentially over several thousands of years, in the short term it can be overutilized. From a thermodynamical view, heat flows form hot to cold. If too much heat is taken out of a given borehole, then its localized heat reservoir could be temporarily exhausted. Over time, this heat could be replenished. This shows that the number of boreholes and the heat drawn from them needs to be managed.

If boreholes are too close to each other and too much heat is drawn from them, then one borehole could tap energy from the heat reservoir of another borehole close by. As an example, if two boreholes were 100 m apart, they would not influence or interact. If boreholes were as close as 15 to 25 m apart, then they could influence each other over time (depending on the energy utilization and thermogeological circumstances. The area influenced by geothermal heat extraction varies significantly case by case). A practical balance needs to be found between the needed heat being harvested against the long-term management of the heat reservoir.

Appendix I shows a more complete discussion on shallow geothermal as well as the study done for Helsinki.

11.1 Shallow geothermal potential maps for Finland

Figure 15 shows the shallow geothermal potential map for Finland, renewable heating power in the ground. Figure 16 shows the thermal energy stored in the ground. The “Shallow geothermal potential dataset” describes the low enthalpy geothermal potential that can be extracted from the uppermost 300 meters of the ground and be used for space heating and/or cooling. The term “ground” is used to refer to both the crystalline bedrock and to the quaternary sediments that overlay it. The shallow geothermal potential was estimated computationally by simulating heat transfer in the ground using an axisymmetric borehole model. The energy which can be utilized from one 300 m deep borehole was calculated. The stationary heat flux through the borehole wall when the wall temperature was set to 0 °C was also calculated.

The calculated shallow geothermal reserve will be able to replace Finland's district heat production for thousands of years. This is very conservative approach because it does not assume that heat flux does not produce new energy.

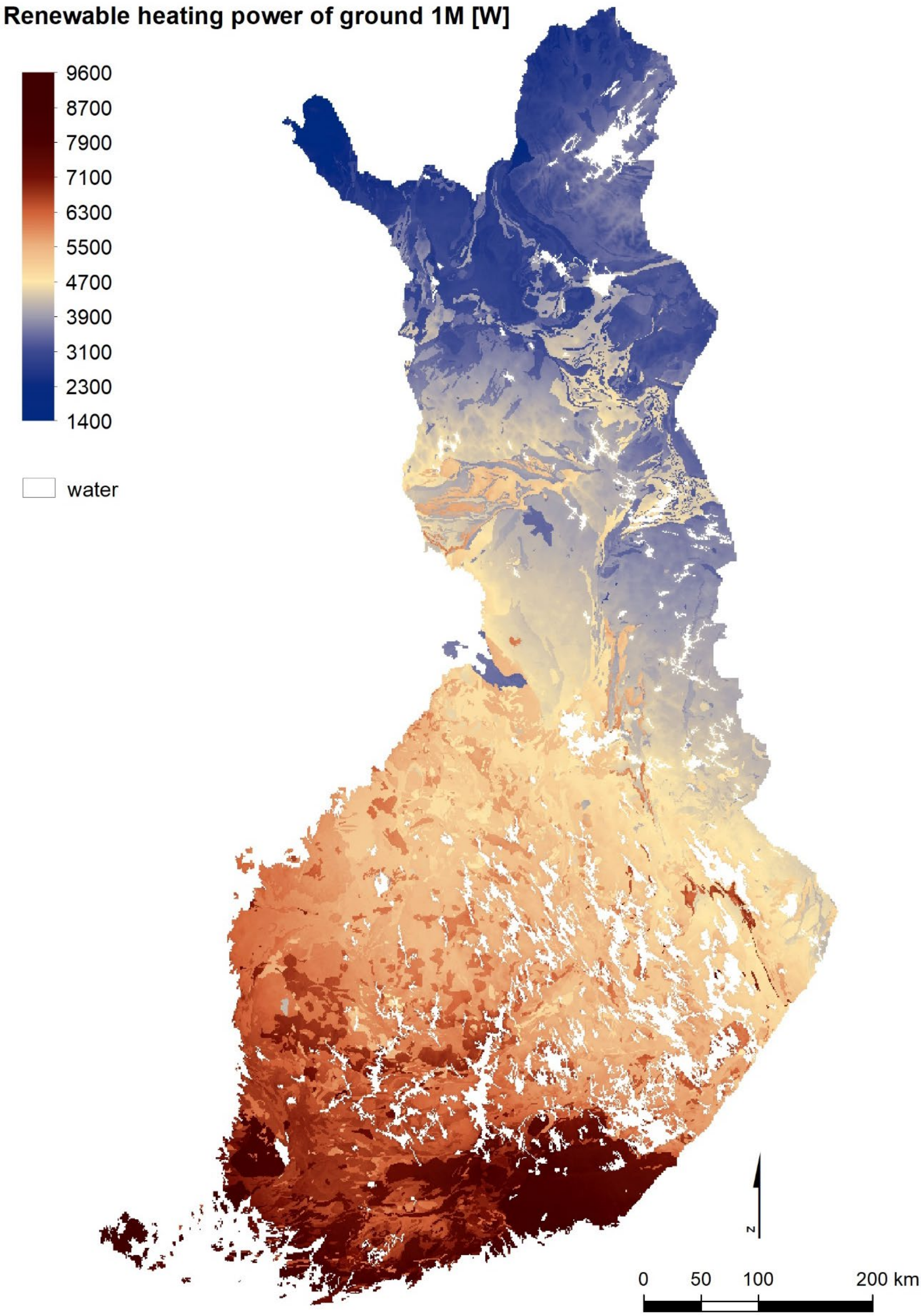

Figure 15. Shallow geothermal potential map for Finland, Renewable heating power in the ground, units renewable heating power (W) per 1 km^2 (Source: Arola *et al.* 2019)

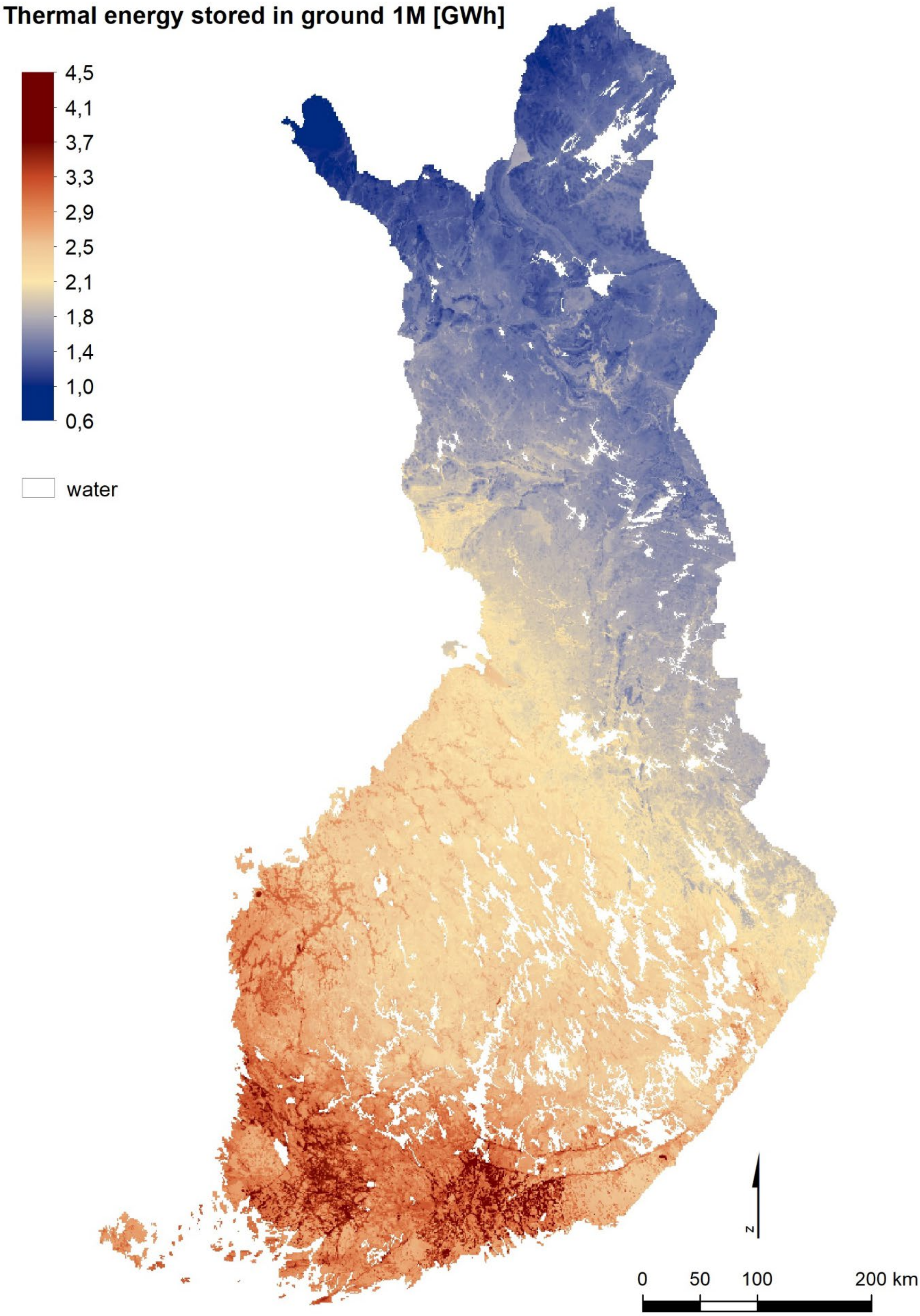

Figure 16. Shallow geothermal potential map for Finland, thermal energy stored in the ground, units heat energy (GWh) per 1 km^2 (Source: Arola *et al.* 2019)

11.2 Deep geothermal potential

Finland has the potential to produce economically viable heating energy from deep geothermal wells. Figure 17 shows a series of maps that describe the depth where 70 °C would be achieved. From that point to deeper theoretically utilizable energy, so called heat in place, has been calculated and showed in 1 km thick slices. For example, 70°C will be achieved at the depth of 5600 m. Then the temperature at this location at the depths of 6000 m, 7000 to 10 000 m was calculated. The temperature difference at the depth range 5600-6000 m, 6000-7000 m (etc.) was calculated and then heat in place was calculated based on temperature difference and thermogeological parameters. The amount of deep geothermal energy utilizable from Finnish ground is excellent. If current existing technology could be improved to generate electricity from 70°C fluids, then Finland could generate geothermal energy also.

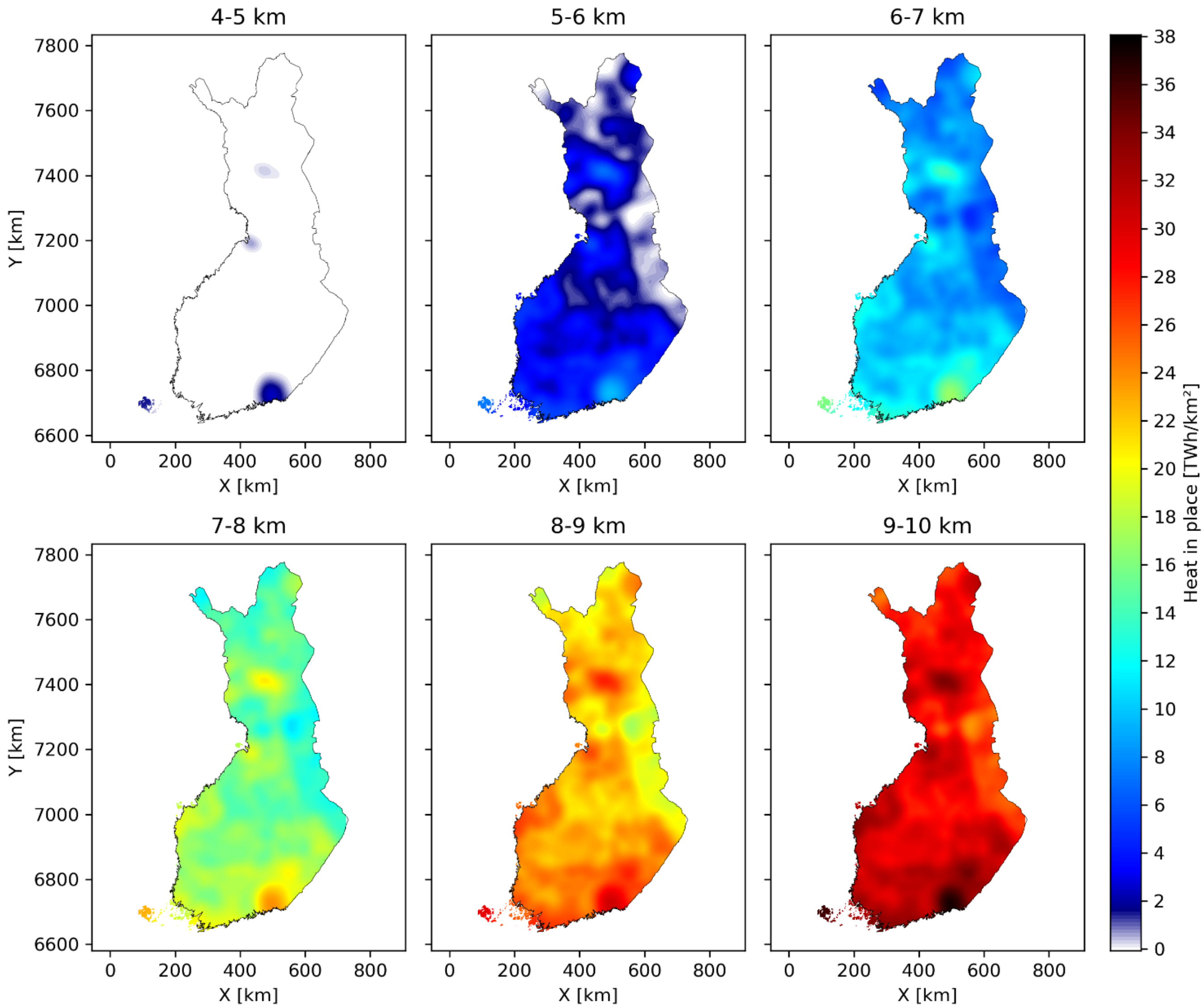

Figure 17. Deep geothermal potential in Finland (Source: Arola *et al.* 2019)

11.3 Helsinki's geo-energy potential

A study was conducted in 2017 by the Helsinki Geoenergy Potential project group (Kallio et al. 2019), which examined the potential for heating, using shallow and medium deep well geothermal energy in Helsinki. Although the temperature levels of the earth's shallow depths are low compared to the depths in the deeper part of the earth's crust, the geoenergy reserve of the shallow depths is so large that it could theoretically cover Helsinki's heating needs (approximately 7 TWh/a) for several decades. Over time, the heat reservoir would be depleted at this rate of heat withdrawal (quantity of heating energy available was calculated: heat is withdrawn until the borehole wall temperature is gradually reduced to 0 ^{0}C from its natural temperature in next 50 years). If heating was only drawn for part of the seasonal year (winter) and the remainder of the year was used to allow the heat reservoir to replenish, this resource could be managed to last much longer. The calculation was based on infinite geothermal energy well model where so many geothermal wells will be installed that the energy flux remains constant despite the numbers of borehole drilled.

However, this would require that the entire land area of Helsinki be drilled full of geothermal wells deeper than 300 meters every 20 meters. The number of boreholes this concept would require is 25 boreholes / hectare, or an approximate number of 522 000 boreholes which are 300 m deep. This would also require the Helsinki area to be re-engineered and restructured to accommodate these wells, and the heat harvesting units on top of each well. This is not a trivial task.

Table 34 and Figure 18 show the amounts of thermal energy bound to the three different depth ranges, as well as the amounts of geoenergy available from them in the heat wells and the amounts of heating energies obtained from the heat pumps.

Table 34. Summary of the geoenergy potential maps (Source: Kallio et al. 2019)

Depth Spacing [m]	Thermal energy bound to the bedrock	Geoenergy for use in heat wells	Heating energy from heat pumps
0-150	128 MWh/year/hectare (2.65 TWh/year)	122 MWh/year/hectare (2.57 TWh/year)	183 MWh/year/hectare (3.86 TWh/year)
0-300	292 MWh/year/hectare (5.98 TWh/year)	234 MWh/year/hectare (4.76 TWh/year)	351 MWh/year/hectare (7.14 TWh/year)
0-1000	1518 MWh/year/hectare (30.71 TWh/year)	765 MWh/year/hectare (15.91 TWh/year)	1148 MWh/year/hectare (23.87 TWh/year)

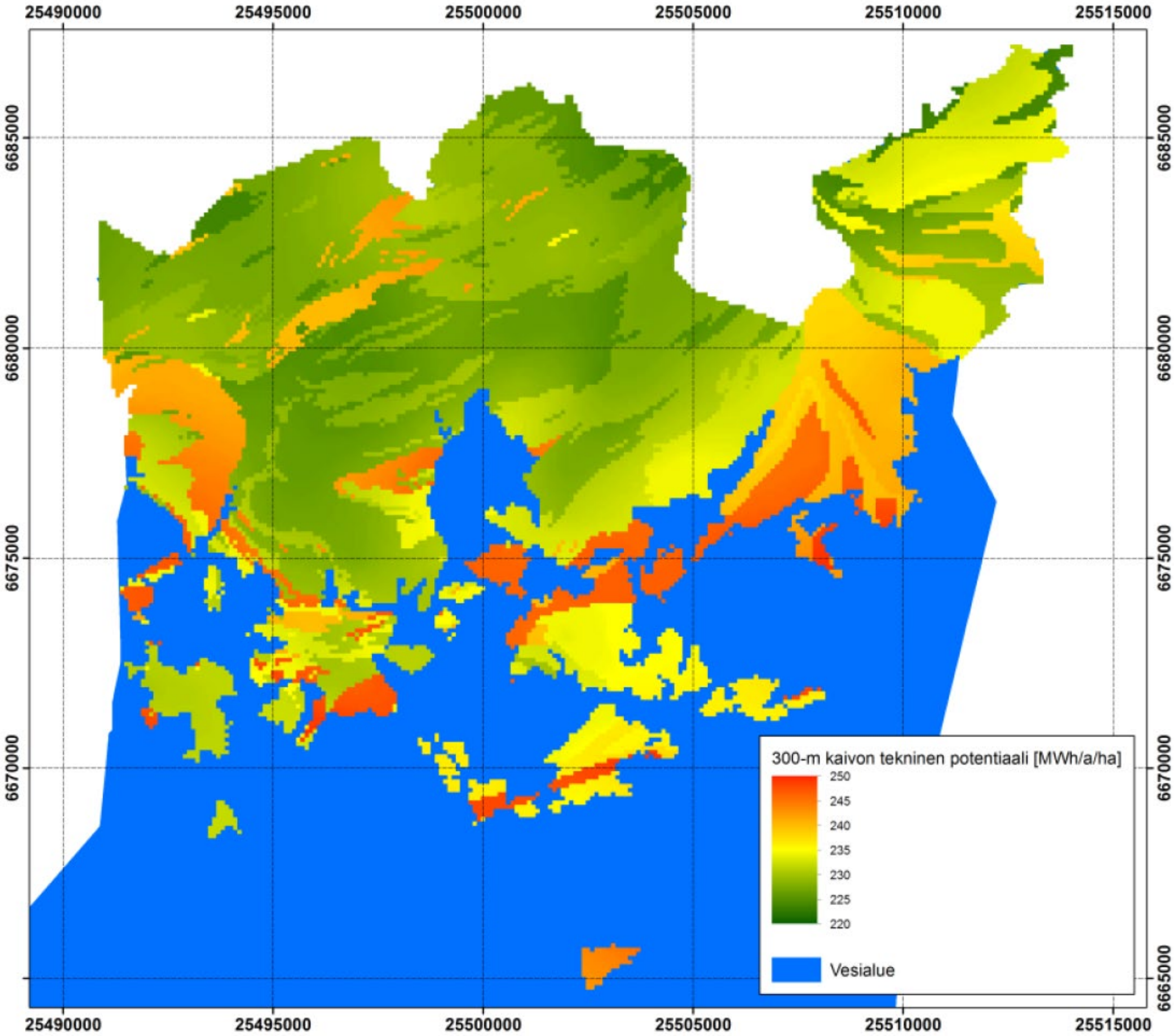

Figure 18. Technical geoenergy potential for 300 m deep heat wells. The map describes how much geoenergy from Helsinki could be obtained from a maximum of one hectare for 50 years without freezing the rock if Helsinki were one large thermal well field. The sum of all cells is about 4.76 TWh/a. The coordinate system is ETRS-GK25FIN. (Source: Kallio et al. 2019)

Current district heating network is planned for temperatures of 70 to 120 °C. Currently shallow geothermal does not provide enough heat for heat pumps so that it would be economically viable to utilize for district heating purposes. But there is a solution, the 4th or 5th generation district heating networks which operate at lower temperatures and include waste heat production and heat storage systems (Østergaard *et al* 2022 & Lund *et al* 2018).

In practical terms, there are two options for much wider geothermal utilization in Finland:

a) Drilling deeper well boreholes which would allow the utilization of higher temperature reservoirs. This requires technical improvements in both drilling and heat extraction to be economically viable.

b) Re-engineering the Helsinki energy distribution schemes towards lower temperature district heat networks and increase heat storage system capacity significantly.

12 SUMMARY OF FINNISH DATA ON ENERGY GENERATION AND USE FOR 2019

- Finnish 2019 electric energy consumption 85.92 TWh in 2019
  - Of which only 11.49 TWh was fossil fuel based (13.9 % of total)
  - Of which 53.96 TWh was generated with non-fossil fuel systems
  - 8.65 TWh fossil fuels + 2.84 TWh peat = 11.49 TWh to replace
  - Of which 20.04 TWh imported
  - *Total to be replaced: 31.5 TWh*

- Finnish 2019 industrial and district heat generation was 93.6 TWh in 2019
  - Of which 20.2 TWh was fossil fuel based
  - 7.5 TWh was generated from coal
  - 7.6 TWh was generated from gas
  - 8.9 TWh was generated from peat
  - *Total to be replaced: 29.1 TWh*

  - Industrial heat was 55.4 TWh in 2019
    - Of which 7.0 TWh was generated from conventional fossil fuels
    - 3.2 TWh generated from peat
    - 10.2 TWh fossil fuels + peat (7.0+3.2)

  - District heat was 38.1 TWh in 2019
    - Of which 13.2 TWh was generated from fossil fuels
    - 5.7 TWh generated from peat
    - 18.9 TWh fossil fuels + peat (13.2+5.7)

- Residential heat (excluding electric heating and ambient heat, e.g., heat pumps) was 14.7 TWh in 2019
  - 12 TWh generated from wood fuels
  - 2.6 TWh was generated from fossil fuels
  - *Total to be replaced: 2.6 TWh*

- Finnish vehicle transport fleet
  - Total fleet of 4.5 million vehicles travelled 32.71 billion kilometers in 2019
  - Trucks: 162 186 trucks travelled 4.56 billion kilometers
  - Buses: 19 137 buses travelled 299.5 million kilometers
  - Commercial vans: 486 949 commercial vans travelled 3.39 billion kilometers
  - Passenger Cars: 3.57 million passenger cars travelled 24.1 billion kilometers
  - Motorcycles: 278 534 motorcycles travelled 388.6 million kilometers
  - *Electricity for trucks as hydrogen vehicles, 15.5 TWh*
  - *Electricity for all others as EV vehicles, 10.8 TWh*

- Finnish maritime transport
  - 2 300 000 tons of light/heavy fuel oil
  - *Electricity 58.77 TWh as a full hydrogen fleet*

- Finnish rail transport network
  - Locomotive electricity consumption 0.671 (TWh)
  - Passenger kilometers 4 534 608 (1000 pkm)
  - Freight transported 40 721 (1000 tonne)
  - Freight tonnekilometers 11 174 893 (1000 tkm)

- Finnish aviation
  - International aviation consumed 35.17 TJ and domestic aviation 2.81 TJ
  - *To be replaced: 9.77 TWh of aviation fuel (see appendices F & G)*

13 SCENARIOS TO PHASE OUT FOSSIL FUELS IN FINLAND

The solutions in this report have been assembled into several combinations and are presented in six scenarios. In the scenarios all ICE vehicles were substituted with EV's and Hydrogen Fuel Cell vehicles, where all long range or heavy action vehicles (trucks) are powered by hydrogen fuel cells. All other vehicles will be Electric Vehicles. The extra electrical energy to charge the EV batteries and produce the required hydrogen was estimated and added to the proposed electrical power grid expansion, using the outcomes from Section 5 and 6. The Finnish rail system is already 95% electric, thus changes in the rail system were not included in the scenarios. The Finnish maritime shipping fleet was transformed from a diesel fueled ICE fleet to a hydrogen cell powered fleet.

Table 35. The existing scope of the Finnish domestic system in 2019

Existing System (using 2019 Data)	Electricity Capacity	Wood Biomass	Geothermal Heating
Existing Finnish electrical power demand (TWh)	85.92		
Existing electrical non-fossil fuel power production in Finland (TWh)	53.96		
Existing heat production in Finland (TWh)	93.55		
Existing Annual Finnish Forestry Industry Harvest of Wood Biomass		72 Mm^3	
Existing Finnish biofuels production		625 (ktoe/year)	
Existing geothermal heating energy produced by heat pumps in Finland (TWh)			6.0

13.1 Nuclear powered electricity generation

Nuclear power in Finland is about to get a boost from the commissioning of a Generation III+ nuclear power plant with the third reactor of the Olkiluoto Nuclear Power Plant in Finland. This plant is located on Olkiluoto Island, on the shore of the Gulf of Bothnia, in the municipality of Eurajoki in west coast of Finland.

The Olkiluoto plant consists of two boiling water reactors (BWRs), each producing 890 MW of electricity. A third unit (Olkiluoto 3) will be the EPR reactor (a type of third generation with capacity of 1600 MW). Unit 3 is expected to be online in February 2022 (Pukkila 2020) and has been under construction since 2005. Assuming a 92 % availability (World Nuclear Association 2019) for this 1600 MW reactor, this station could contribute 12.9 TWh annually to the Finnish electrical power grid. This new plant will be considered in this study for all scenarios. Any new nuclear plants in addition to this were not considered.

In addition to this, the world's first deep geological repository for the final disposal of spent nuclear fuel is being built in Olkiluoto (Gil 2020, McEwan & Savage 1996, Deign 2012). This facility (called Onkalo) is near the Olkiluoto Nuclear Power Plant in the municipality of Eurajoki in Finland and is being constructed by Posiva. The facility is expected to be operational in 2023.

If the average working lifespan of a nuclear power plant is 40 years, then all nuclear power plants except Olkiluoto 3 are due for decommissioning very soon (see Table 6). This is something to keep in mind when planning for future power grid capacity.

13.2 Wind power electricity generation in scenarios

All new operational extra power generation capacity to phase out fossil fuels will be electrical in nature and is replaced by wind turbine renewable power generation. There are not enough sunshine hours in Finland to justify widespread solar (also the panels would be covered in snow during the winter season where power is needed). Adding new hydroelectric power plants could be difficult as all suitable geographical sites could be used already, with few green field sites available in Finland.

Wind turbines have an overall conversion efficiency of 30% to 45% (Abu-Rub et al 2014). The size and effectiveness of wind turbines has evolved considerably even in the last few years. Commissioning a wind turbine is getting more complicated, as the turbines get larger. Individual blades can be 80 tonnes in weight and more than 50m in length (Siciliano 2017). This creates a difficult logistical problem in transporting the turbine parts from the factory to the site of operation.

As of July 2018, global wind installed power generation capacity was 597 GW (WWEA 2019 and Global Energy Observatory 2018). Installed power generation capacity is related to the number and size of physical power stations that are operating and supplying electricity to the grid.

To quantify new electrical wind power generation the new Lestijärvi wind farm station is used as an example to deliver annual electricity to the Finnish power grid. Construction of a large wind farm (455.4 MW installed power capacity, with 69 wind turbines, 6.6 MW capacity each, with a maximum height of 240 meters each) in the Lestijärvi municipality in Western Finland has started and is planned to be operational in the year 2025 (YLE news, Construction begins on Finland's largest wind farm, https://yle.fi/news/3-12196240). The farm is estimated to produce over 1.3 TWh of electricity annually. This assumes a capacity factor (average power output divided by maximum power capability) of 33 %, which was the average capacity factor for wind power in Finland in 2019 (Tuulivoimayhdistys 2022). A 400-kilovolt transmission line is currently being installed at the location.

Wind powered electrical energy has shown to be highly intermittent (Fares 2015 and EIA 2015), as power generation depends on wind conditions. Furthermore, wind power is considered non-dispatchable because it is a variable power source, meaning that its electrical output depends on many factors, such as wind speed, air density, turbine characteristics, and more. All these factors also change depending on location of the site. Wind speed must also be in a certain range (depending on the turbine), above 3.5 m/s in order to generate electricity, and below 25 m/s to avoid damage to the turbine (Huang et al 2014). When taking multiple wind farm's intermittency into consideration, it would make sense that the reliability would somewhat increase, but in reality this doesn't appear to be the case. For example, between October 2006 and February 2007 there were 17 days when the output from Britain's 1632 windmills was less than 10% of their capacity. During that period there were five days when output was less than 5% and one day when it was only 2% (McKay 2008).

The difficulty associated with integrating variable sources of electricity stems from the fact that the current power grid was generally designed around the concept of large, controllable, steady supply electric generators (J.M.K.C. *et al* 2017). In current industrial practice, the grid operator uses a three-phase planning process to ensure power plants produce the required amount of electricity at the appropriate time to meet electric demand consistently and reliably. Because most grids in 2019 have very little storage capacity, the balance between electricity supply and demand must be always maintained to avoid a blackout or other cascading problems.

Intermittent renewables are challenging because they disrupt the conventional methods for planning the daily operation of the electric grid. Their power fluctuates over multiple time horizons, forcing the grid operator to adjust its day-ahead, hour-ahead, and real-time operating procedures. Wind power is by far the primary energy source that is most in need of high-quality energy storage options. Thus, for this power source to be viable, large battery banks and other solutions to overcome the intermittency will also need to be built as part of the up-front development costs.

13.3 Scenario 1: Full Spectrum Electric (Current Footprint)

In this scenario, all new solutions are electrical in nature and require a large expansion of the existing Finnish electrical power grid (Table 35 and Figure 19). As there is no practical solution for electric aviation that can be applied to large aircraft at the time of writing this report, this scenario omits the aviation industry.

13.3.1 Proposed in Scenario 1

- Finland will be required to import/construct 162 186 hydrogen fuel celled trucks and produce 268028 tonnes of hydrogen annually to fuel them. This will require 15.5 TWh to be delivered from the Finnish power grid.

- All other vehicles in the Finnish transport fleet are recommended to be Electric Vehicles. Finland will be required to import/construct 4.36 million EV's of various vehicle classes, containing 848 251 tonnes of lithium-ion batteries. To charge these batteries, an annual 10.76 TWh will be required to be delivered from the Finnish power grid (Section 5). The size and scope of the needed EV battery charging station network was not included in this study.

- Maritime shipping fleet are H_2-Cell and form the hydrogen economy with trucks (Section 6). To accommodate this, the electrical energy needed to be generated to manufacture this hydrogen using electrolysis was estimated at 58.77 TWh. It is assumed that the capability to produce both the required electricity to charge the EV batteries and hydrogen to fuel H_2-cell vehicles was developed in Finland.

- The rail network is already 95% electric powered as part of existing electricity demand and is not considered in this study.

- All heating requirements, district (18.87 TWh), residential (2.6 TWh) and industrial (10.29 TWh) was supplied with electrical heating systems (total 31.76 TWh).

- To supply the required extra 134.55 TWh, 104 new Lestijärvi scale wind farms constructed (@ 1.3 TWh annual capacity), or 7 142 wind turbines of 6.6 MW capacity, 47.1 GW installed capacity in total.

- Required stationary energy storage to buffer support new wind generation station fleet @4 weeks capacity was 10.35 TWh (Section 5).

- No extra wood biomass to be annually harvested is required as all new systems are electrical in form.

- Given there was no extra wood biomass harvesting required in this scenario, there was the potential expansion of the current forestry industry by +11.8% (if sustainable annual harvest is 80.5 Mm^3 wood harvest [Luke 2021]). Downgrade the current forestry industry by -2.8% (if sustainable annual harvest is 70 Mm^3 wood harvest [WWF Finland 2015]).

Table 36. Scenario 1 to phase out fossil fuels, Full Spectrum Electric (Current Footprint)

Finnish Annual Production and Consumption	Scenario 1 **Full Spectrum Electric (Current Footprint)**		Comments
	Electricity Capacity (TWh)	Wood Biomass (Mm^3)	
Existing Finnish electrical power demand (A)	85.92		
Existing electrical non-fossil fuel power production in Finland (B)	53.96		
Planned New Available Electric Power Capacity (C)			
Grid connection of Lestijärvi wind farm turbine array	1.30		
Grid connection of Olkiluoto 3 nuclear power plant	12.90		
Total	**14.20**	-	
New Electric Power Capacity Required (D)			
Replacing fossil fuel power generation	11.92	-	
Replacing power imports	20.04	-	
Total	**31.96**	-	
Transport Fleet Phase out of ICE Technology (E)			
Electric vehicle fleet	10.76	-	
Hydrogen production for vehicle fleet	15.50	-	Trucks are H_2-Cell
Hydrogen production for maritime shipping	58.77		Maritime shipping is H_2-Cell
Biofuel for vehicles Biofuel for aviation transport Biofuel for Maritime shipping			Aviation industry shut down (no viable soluton outside biofuels)
Total	**85.03**	-	
New Heat Generation Capacity (F)			
District Heat	18.87		
Residential Heat	2.60		
Industrial	10.29	-	
Low Temperature (50%)	5.15	-	
High Temperature (50%)	5.15	-	
Total	**31.76**		
Net Total [(Demand A+E+F)-(Production B+C) = New Capacity Required]	**134.55 (TWh)**		All new electrical power is wind generated
Required stationary power storage for new wind generation station fleet @ 4 weeks capacity	**10.35 (TWh)**		Current thinking suggests this should be battery banks
Number Lestijärvi scale wind farms @ 1.3 TWh annual capacity	104 Stations		Geographical siting not considered
Number of 6.6 MW capacity wind turbines	7 142		
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 80.5 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3		Potential expansion of forestry industry by +11.8%	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -2.8%	

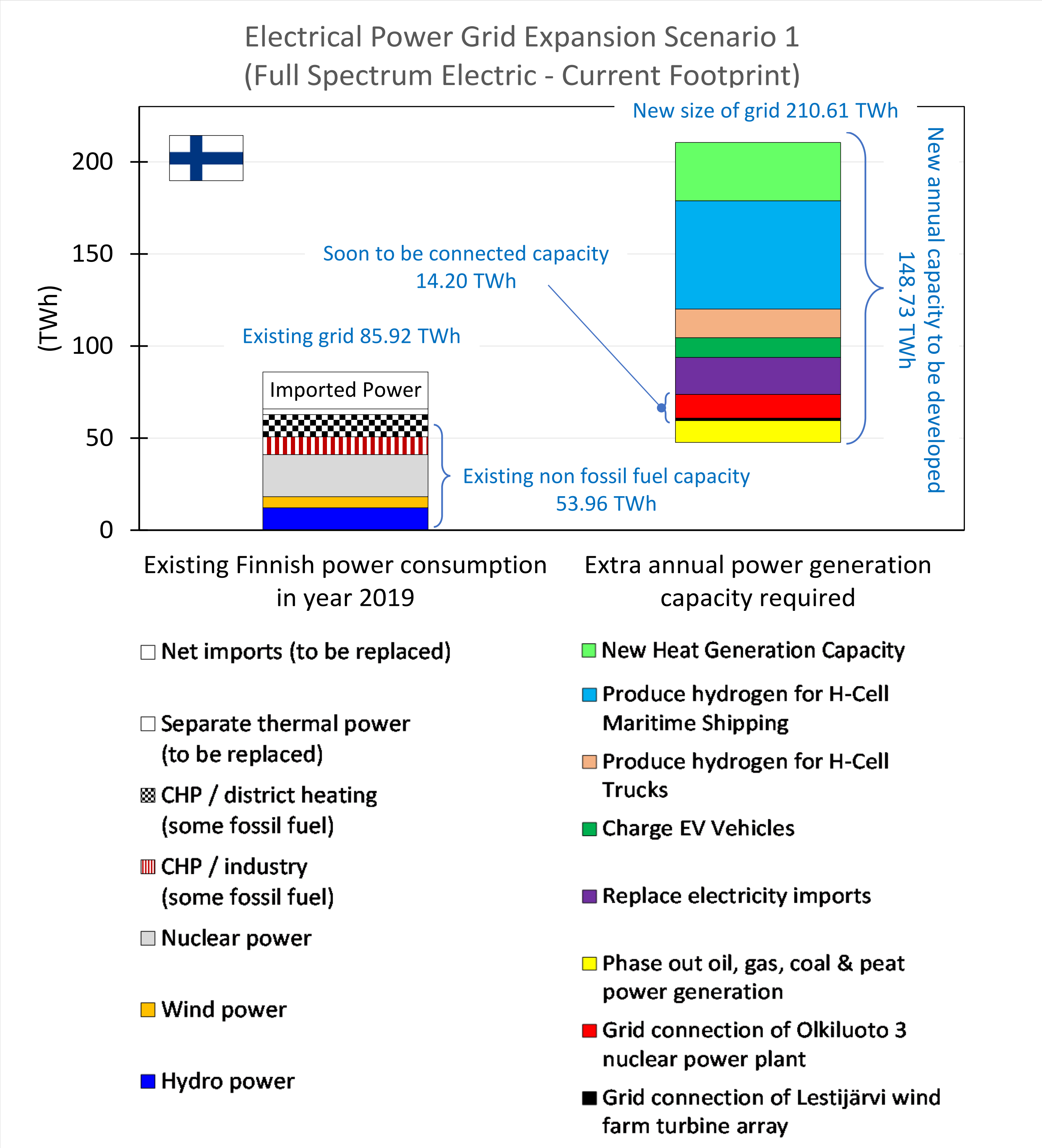

Figure 19. Extra annual electrical energy generation capacity required to phase out fossil fuels for Scenario 1: Full Spectrum Electric (Current Footprint)

13.4 Scenario 2: Max Biomass (Current Footprint)

Some consider biomass and biofuels to be the best solution to phase out fossil fuels and ICE technology (Table 36 and Figures 20 and 21). Biomass is grown each year, and as long as the harvest is kept small enough to allow the forests to recover in a timely fashion, could be considered renewable.

13.4.1 Biomass

In this scenario, biomass is used as much as possible to fuel CHP plants and to produce biofuels. Biofuels produced from wood biomass harvested from Finnish forests was estimated for both the aviation industry and the maritime industry, using the outcomes of Section 8. The extra biomass required was then added to the biomass harvested for CHP plants generating heat. This scenario estimated the quantity of wood biomass needed, then considered two sustainability limitations. The biomass annually sourced from wood required to produce enough biofuel to substitute for petroleum sourced gasoline and diesel for the Finnish transport fleet in 2019, would be 40.3 million cubic meters of wood [Equation 1: (48.36TWh/0.6)/2 = 40.3 Mm^3].

Finnish domestic consumption of aviation fuel in 2019 was 9.77 TWh (Traficom Publications 2021). By applying Equation 1, the mass of biomass needed to service the Finnish Aviation fleet was estimated. Approximately 8.14 Mm^3 of wood would be needed to annually produce biojet fuel for the current Finnish aviation industry [(9.77 TWh/0.6)/2 = 8.14 Mm^3 of wood]. This number is probably too low, as aviation fuel is of higher grade than typical biofuels (ethanol and biodiesel).

Assuming that biofuel produced for shipping was just as energy efficient as marine gas oil, then 29.3 TWh of biofuels would be needed annually to service the Finnish maritime shipping fleet. By applying Equation 1, this mass of required biomass was estimated. 24.42 Mm^3 of wood sourced biomass would be needed annually to produce fuel for the current Finnish maritime traffic [(29.3 TWh/0.6)/2 = 24.42 Mm^3 of wood].

One estimate of the sustainable annual rate of harvesting wood biomass from Finnish forests was 80.5 million m^3 (Luke 2021). A second estimate reported the sustainable annual rate of harvesting wood biomass from Finnish forests was 70 million m^3 wood harvest (WWF Finland 2015).

13.4.2 Proposed in Scenario 2

- All ICE vehicles (including trucks) were now powered with biofuels produced from wood biomass harvested from Finnish forests (Section 8) (40.3 Mm^3 of wood).
- All aircraft (8.14 Mm^3 of wood) and the entire maritime shipping fleet (24.42 Mm^3 of wood) are fueled with biofuels produced from wood biomass harvested from Finnish forests (Section 8)
- All extra heat requirements are CHP biomass sourced.
- To supply the required extra 17.76 TWh, 14 new Lestijärvi scale wind farms constructed (@ 1.3 TWh annual capacity), or 943 wind turbines (6.6 MW capacity, 10.5 GW installed capacity in total).
- Required stationary energy storage to buffer support new wind generation station fleet @ 4 weeks capacity was 1.37 TWh (Section 5).
- Either downgrade the current forestry industry by -100%, and still have a -10.7 % biomass supply shortfall (if sustainable annual harvest is 80.5 Mm^3 wood harvest), or downgrade the current forestry industry by -100%, and still have a -27.4 % biomass supply shortfall (if sustainable annual harvest is 70 Mm^3 wood harvest).

Table 37. Scenario 2 to phase out fossil fuels, Max Biomass (Current Footprint)

Finnish Annual Production and Consumption	Scenario 2 Max Biomass (Current Footprint)		Comments
	Needed Extra Electricity Capacity (TWh)	Wood Biomass (Mm^3)	
Existing Finnish electrical power demand (A)	85.92		
Existing electrical non-fossil fuel power production in Finland (B)	53.96		
Planned New Available Electric Power Capacity (C)			
Grid connection of Lestijärvi wind farm turbine array	1.30		
Grid connection of Olkiluoto 3 nuclear power plant	12.90		
Total	**14.20**	-	
New Electric Power Capacity Required (D)			
Replacing fossil fuel power generation	11.92	-	
Replacing power imports	20.04	-	
Total	**31.96**	-	
Transport Fleet Phase out of ICE Technology (E)			
Biofuel for vehicles	-	40.3	All vehicles are biofuel powered
Biofuel for aviation transport	-	8.14	
Biofuel for Maritime shipping	-	24.42	
Total		**72.86**	
New Heat Generation Capacity (F)			
District Heat (18.87 TWh) (Equation 2)		9.44	All extra heat requirements are CHP biomass sourced
Industrial Heat (10.29 TWh) (Half Equation 1 + Half Equation 2)		6.87	
Residential Heat (2.6 TWh) (Equation 2)		1.30	
Total		**17.60**	
Net Total [(Demand A+E+F)-(Production B+C) = New Capacity Required]	**17.76 (TWh)**	**90.5 (Mm^3)**	All new electrical power is wind generated
Required stationary power storage for new wind generation station fleet @ 4 weeks capacity	**1.37 (TWh)**		Current thinking suggests this should be battery banks
Number Lestijärvi scale wind farms @ 1.3 TWh annual capacity	14 Stations		Geographical siting not considered
Number of 6.6 MW capacity wind turbines	943		
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 80.5 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -110.7%,	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -127.4%	

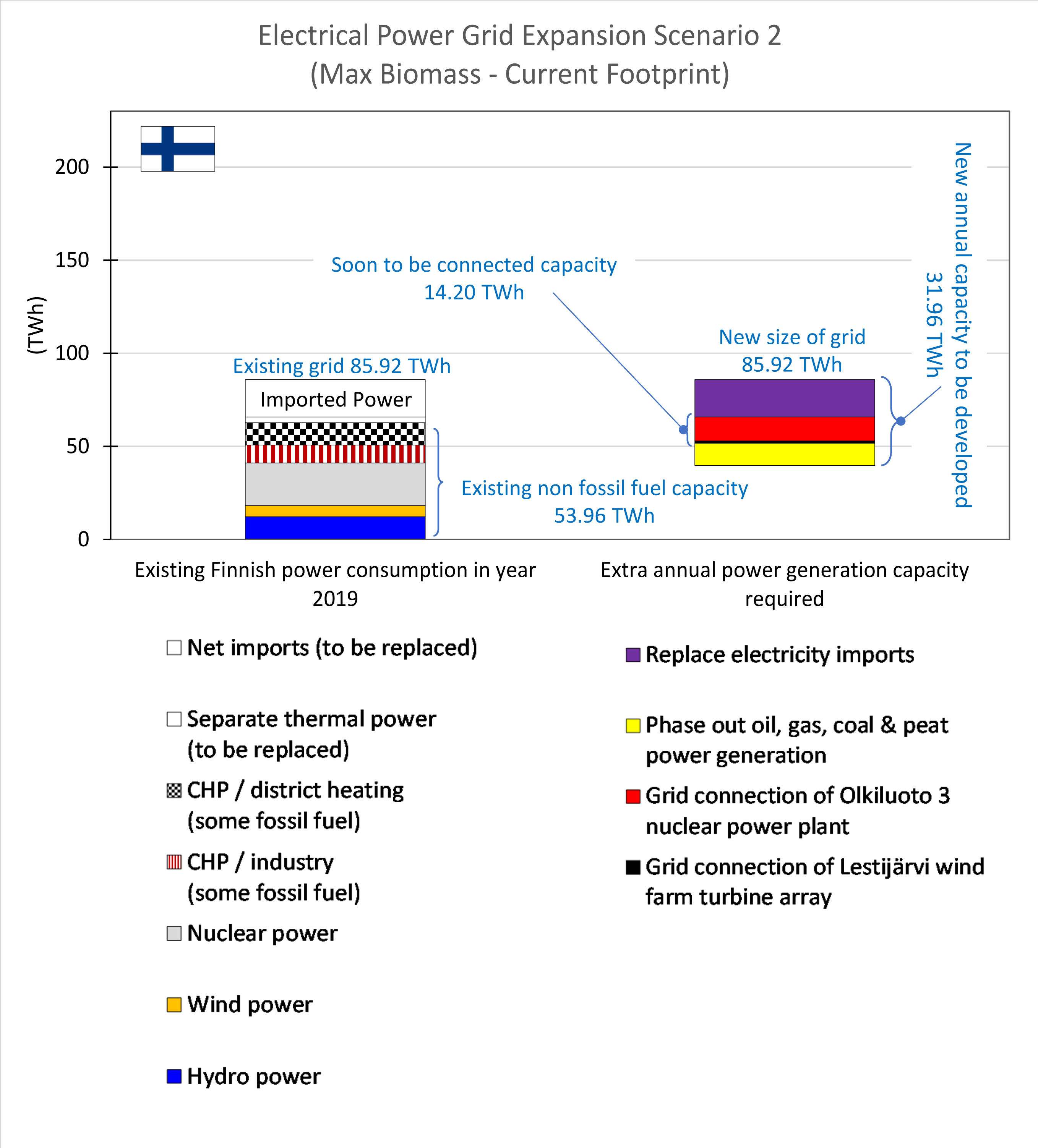

Figure 20. Extra annual electrical energy generation capacity required to phase out fossil fuels for Scenario 2 to phase out fossil fuels, Max Biomass (Current Footprint)

A missing element in all studies regarding the sustainable rates of biomass harvesting, is the dependency on industrial petrochemical fertilizers, herbicides, and pesticides. These are usually produced using gas (to produce ammonia) and phosphate rock, which are finite non-renewable natural resources. For this to be truly sustainable, then fertilizer would have to be produced inside Finland, and preferably organic in form.

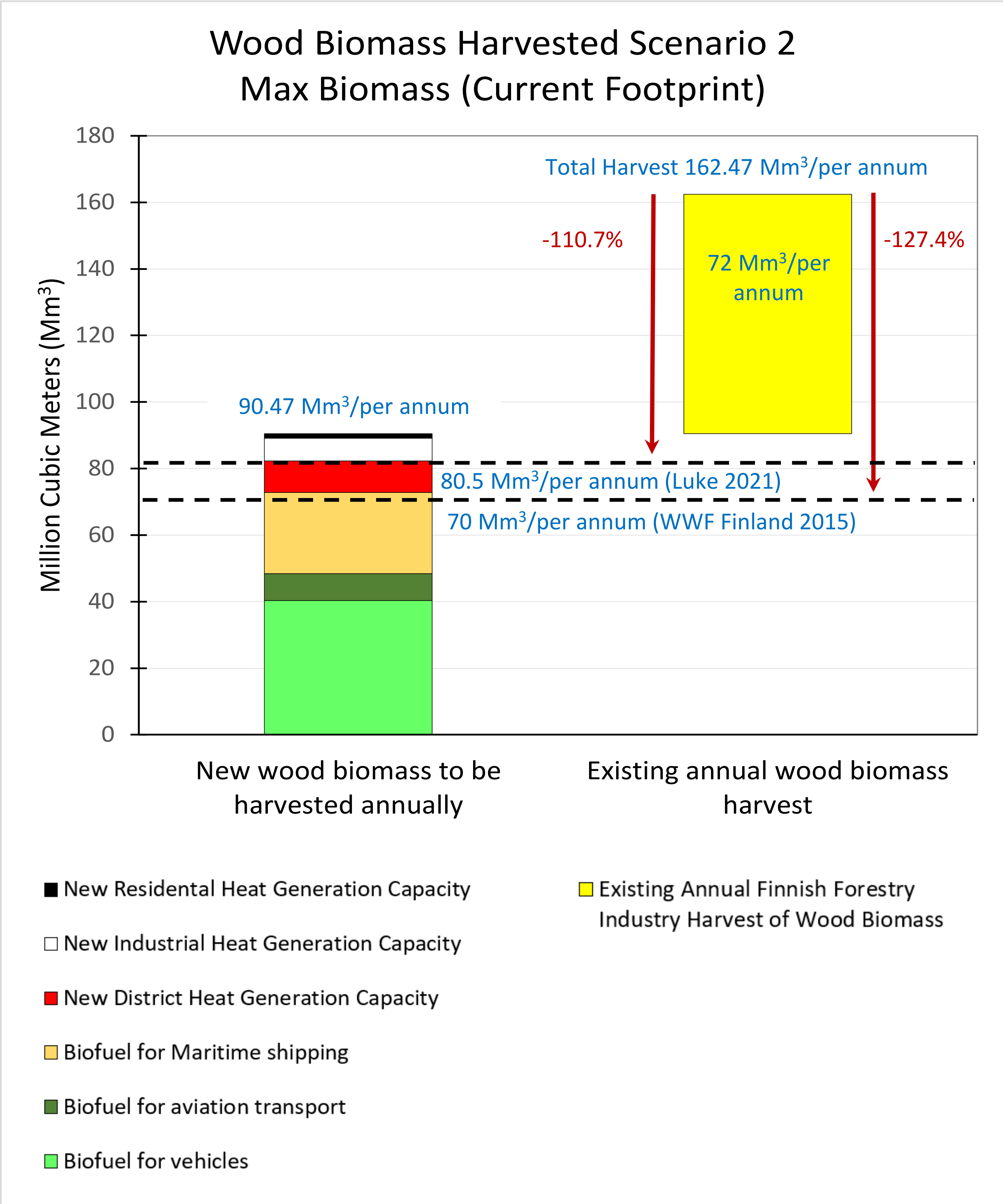

Figure 21. Extra annual wood biomass harvest required to phase out fossil fuels for Scenario 2: Max Biomass (Current Footprint)

As Figure 21 shows, the existing forestry industry would have to be discontinued, and there would still be a shortfall of required annual supply of biomass. Clearly, this scenario is not practical. It has been developed to show that biomass and biofuels have their limitations.

13.5 Scenario 3: Hybrid - 1 (Current Footprint)

In this scenario, a combination of electrical energy sourced from wind turbines is combined with heat and energy generated from wood biomass fueled CHP plants (Table 37 and Figures 22 and 23). This would mean that less new capacity would be required from the expanded Finnish power grid.

13.5.1 Proposed in Scenario 3

- All systems are designed to meet current demand and most of society is not changed. All vehicles, aircraft and ships do the same physical work and travel the same distance. The ability to meet current power demands for existing tasks is maintained.
- The vehicle transport fleet is split between EV's and H_2-Cells as per the recommendations from Section 6.
- All short-range vehicles (for example passenger cars and commercial vans) are EV's (Section 5). To accommodate this, the extra electrical energy needed to be generated to charge the batteries was estimated. The size and scope of the needed EV battery charging station network was not included in this study. It was also assumed that the 4.3 million vehicles were EV's.
- Trucks and maritime shipping fleet are H_2-Cell and form the hydrogen economy (Section 6). To accommodate this, the electrical energy needed to be generated to manufacture this hydrogen using electrolysis was estimated. It is assumed that the capability to do this in Finland at this scale is developed in Finland.
- All heating requirements, residential, district and industrial was supplied wood biomass fueled CHP plant heating systems. It is assumed all extra biomass needed is sourced as wood from forests.
- All aircraft are fueled with biofuels produced from wood biomass harvested from Finnish forests. It is assumed that the capability to do this, at this scale is developed in Finland.
- To supply the required extra 102.79 TWh, 79 new Lestijärvi scale wind farms constructed (@ 1.3 TWh annual capacity), or 5 456 wind turbines (6.6 MW capacity, 35.0 GW installed capacity in total).
- Required stationary energy storage to buffer support new wind generation station fleet @ 4 weeks capacity was 7.91 TWh (Section 5).
- The extra wood biomass to be annually harvested from Finnish forests would be 25.74 Mm^3.
- To meet the extra wood biomass demand and still maintain sustainability targets, either downgrade the current forestry industry by -23.9% (if sustainable annual harvest is 80.5 Mm^3 wood harvest [LUKE 2021]) or downgrade the current forestry industry by -38.5% (if sustainable annual harvest is 70 Mm^3 wood harvest [WWF Finland 2015]).

Table 38. Scenario 3 to phase out fossil fuels, Hybrid - 1 (Current Footprint)

Finnish Annual Production and Consumption 	Scenario 3 Hybrid - 1 (Current Footprint) Electricity Capacity (TWh)	Wood Biomass (Mm^3)	Comments
Existing Finnish electrical power demand (A)	85.92		
Existing electrical non-fossil fuel power production in Finland (B)	53.96		
Planned New Available Electric Power Capacity (C)			
Grid connection of Lestijärvi wind farm turbine array	1.30		
Grid connection of Olkiluoto 3 nuclear power plant	12.90		
Total	**14.20**		
New Electric Power Capacity Required (D)			
Replacing fossil fuel power generation	11.92		
Replacing power imports	20.04		
Total	**31.96**		
Transport Fleet Phase out of ICE Technology (E)			Trucks are H_2-Cell Maritime shipping is H_2-Cell All aircraft are biofuel powered
Electric vehicle fleet	10.76		
Hydrogen production for vehicle fleet	15.50		
Hydrogen production for maritime shipping	58.77		
Biofuel for aviation transport		8.14	
Total	**85.03**	**8.14**	
New Heat Generation Capacity (F)			All extra heat requirements are CHP biomass sourced
District Heat (18.87 TWh) (Equation 2)		9.44	
Industrial Heat (10.29 TWh) (Half Equation 1 + Half Equation 2)		6.87	
Residential Heat (2.6 TWh) (Equation 2)		1.30	
Total		**17.60**	
Net Total [(Demand A+E+F)-(Production B+C) = New Capacity Required]	**102.79 (TWh)**	**25.74 (Mm^3)**	All new electrical power is wind generated
Required stationary power storage for new wind generation station fleet @ 4 weeks capacity	**7.91 (TWh)**		Current thinking suggests this should be battery banks
Number Lestijärvi scale wind farms @ 1.3 TWh annual capacity	79 Stations		Geographical siting not considered
Number of 6.6 MW capacity wind turbines	5 456		
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 80.5 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -23.9%	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -38.5%	

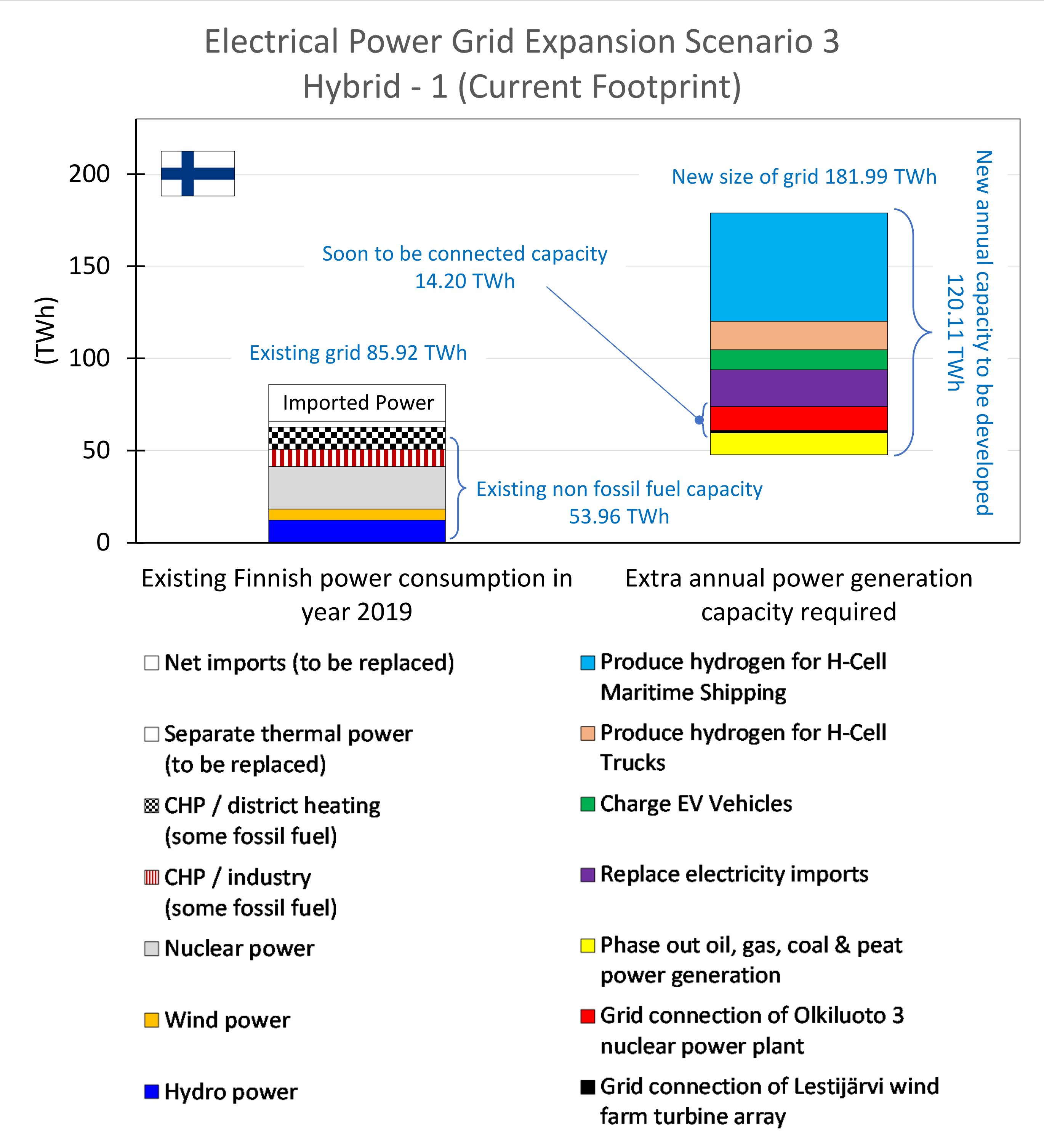

Figure 22. Extra annual electrical energy generation capacity required to phase out fossil fuels for Scenario 3: Hybrid - 1 (Current Footprint)

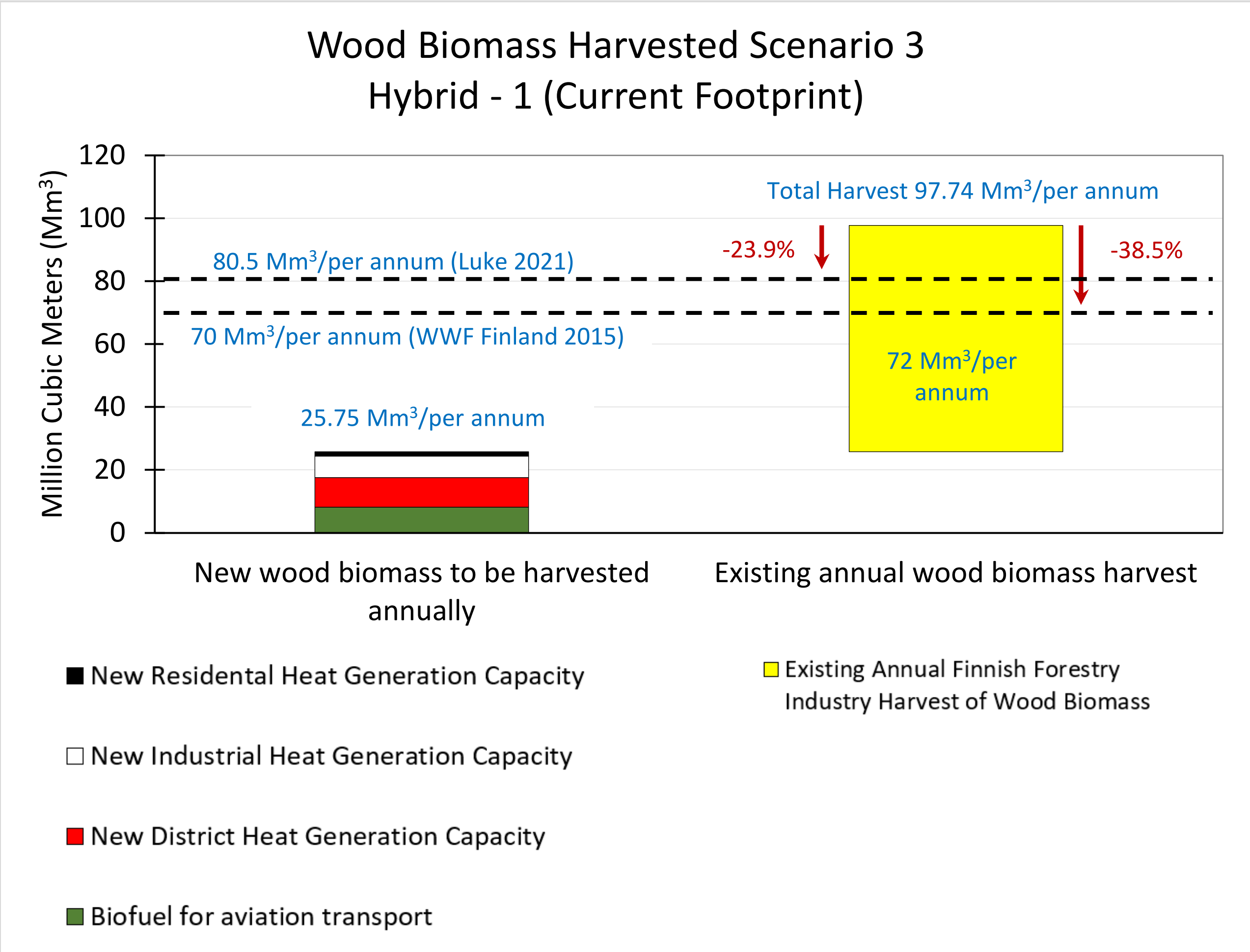

Figure 23. Extra annual wood biomass harvest required to phase out fossil fuels for Scenario 3: Hybrid - 1 (Current Footprint)

In 2019, the annual harvest of biomass was 72 Mm^3 (Luke 2021). The national Resource Institute estimates a sustainable annual harvest limit of 80.5 Mm^3 (Luke 2021). The other study recommends that the sustainable annual harvest is 70 Mm^3 wood harvest (WWF Finland 2015). Both studies and their recommendations are included in the scenarios for this report.

In Scenario 3, an extra 24.43 Mm^3 of wood biomass is to be harvested each year.

- If the sustainable harvest limit was 80.5 Mm^3, then the wood mass available for other tasks outside of Scenario 3 would be 54.8 Mm^3 (80.5-25.7 = 54.8). This means the existing forestry industry would reduce production to 54.8 Mm^3 each year from 72 Mm^3, which would be 76.1% of its existing capacity. This would entail a 23.9% contraction in industry production (54.8/72 = 76.1% and 100-76.1 = 23.9).

- If the sustainable harvest limit was 70 Mm^3, then the wood mass available for other tasks outside of Scenario 3 would be 44.3 Mm^3 (70.0-25.7 = 44.3). This means the existing forestry industry would reduce production to 44.3 Mm^3 each year from 72 Mm^3, which would be 61.5% of its existing capacity. This would entail a 38.5% contraction in industry production (44.3/72 = 61.5% and 100-61.5 = 38.5%).

13.6 Scenario 4: Hybrid – 2 with Geothermal (Current Footprint)

In this scenario, shallow geothermal wells were considered for the heating of residential buildings. The practical outcome would be that less energy would be required to be sourced from wood biomass CHP plants for heating. This in turn would mean that the biomass harvest could be smaller overall, making sustainability targets more achievable (Table 38 and Figures 24 and 25).

13.6.1 Geothermal

Scenario 4 is the same as Scenario 3, with one difference. The residential heating of buildings was supplied by utilizing shallow geothermal energy, using the outcomes of Section 11. In 2019, 14.7 TWh of heat from wood and fossil fuels was consumed for residential heating purposes, and fossil fuel-based district heating provided 18.87 TWh. It is assumed that this 33.56 TWh is now supplied from a shallow geothermal well network.

The study that assessed the potential for shallow geothermal bore holes to be used for building heating in Helsinki (Kallio *et al* 2019), used 300m deep wells in a 20 m spacing (25 wells per hectare), and assumed that all heat from the system is exhausted in 50 years (after which there would be a natural recharging time period and no energy is drawn for the system for heating). This study (Kallio *et al* 2019) is discussed in more detail in Appendix I.

This geothermal well heating system would be extended to all the high population density areas in Finland (where the geothermal heating potential is assessed for its usefulness in a local region context). To drill so many holes to that depth would require efficiency performance advancements from drilling technology. If the bore hole grid spacing could be widened, then each well would have a reduced influence on its neighboring wells. The best grid spacing for long term sustainability should be examined in a separate study. This study assumed that the geothermal heat reservoir would be locally exhausted in 50 years.

The possible outcome of extending the borehole grid spacing should be examined. This would mean that that much more heating energy could be accessed for longer and make the system more sustainable long term. Also, draw energy for heating only in the coldest part of winter and use the rest of the year to recharge the local reservoir from the regional geothermal heat reservoir. The energy in each 300 m deep borehole would be harvest using a 4th generation heat pump, which would allow more useful heating delivered from lower temperature fluids.

What is proposed here is a large task with logistical and engineering challenges. The whole building heating system for multiple cities would have to be re-engineered and retooled. To put this in practical context, if 100 drilling rigs operated in parallel, and each drilled one 300m deep well a day, it would require approximately 14.5 years.

13.6.2 Biomass

The outcome of using shallow geothermal wells for heating is that, compared to Scenario 3, 10.73 Mm^3 of wood biomass does not have to be annually harvested from Finnish forests. So, the extra 25.74 Mm^3 wood biomass seen in Scenario 3 is reduced to 15.01 Mm^3 in Scenario 4.

All remaining heating needs (industrial) are sourced from biomass fueled CHP plants.

13.6.3 Proposed in Scenario 4

- All systems are designed to meet current demand and most of society is not changed. All vehicles, aircraft and ships do the same physical work and travel the same distance. The ability to meet current energy demands for existing tasks is maintained.

- The vehicle transport fleet is split between EV's and H_2-Cells as per the recommendations from Section 6.

- All short-range vehicles (for example passenger cars and commercial vans) are EV's (Section 5). To accommodate this, the extra electrical energy needed to be generated to charge the batteries was estimated. The size and scope of the needed EV battery charging station network was not included in this study. It was also assumed that the 4.3 million vehicles were EV's.

- Trucks and maritime shipping fleet are H_2-Cell and form the hydrogen economy (Section 6). To accommodate this, the electrical energy needed to be generated to manufacture this hydrogen using electrolysis was estimated. It is assumed that the capability to do this in Finland at this scale is developed in Finland.

- All fossil fuel and wood based residential and fossil-based district heating requirements (33.6 TWh) was supplied from shallow geothermal wells, 300m deep, in a 20m spacing grid across all populated areas in Finland, supported by 4th generation heat pumps. Energy would only be drawn from wells in winter, and the rest of the year is used to replenish the reservoir to extend its useful life. It is assumed that this heating network is already constructed and is modeled as a completed system.

- Industrial heating requirements was supplied wood biomass fueled CHP plant heating systems.

- All aircraft are fueled with biofuels produced from wood biomass harvested from Finnish forests. It is assumed that the capability to do this, at this scale is developed in Finland.

- To supply the required extra 102.79 TWh, 79 new Lestijärvi scale wind farms constructed (@ 1.3 TWh annual capacity), or 5 456 wind turbines (6.6 MW capacity, 36.0 GW installed capacity in total).

- Required stationary energy storage to buffer support new wind generation station fleet @ 4 weeks capacity was 7.91 TWh (Section 5).

- The extra wood biomass to be annually harvested from Finnish forests would be 15.01 Mm^3.

- To meet the extra wood biomass demand and still maintain sustainability targets, either downgrade the current forestry industry by –9.04% (if sustainable annual harvest is 80.5 Mm^3 [Luke 2021]) or downgrade the current forestry industry by -23.6% (if sustainable annual harvest is 70 Mm^3 [WWF Finland 2015]).

Table 39. Scenario 4 to phase out fossil fuels, Hybrid - 2 with Geothermal (Current Footprint)

Finnish Annual Production and Consumption	Scenario 4			Comments
	Hybrid - 2 with Geothermal (Current Footprint)			
	Electricity Capacity (TWh)	Wood Biomass (Mm^3)	Shallow Geothermal wells (TWh)	
Existing Finnish electrical power demand (A)	85.92			
Existing electrical non-fossil fuel power production in Finland (B)	53.96			
Planned New Available Electric Power Capacity (C)				
Grid connection of Lestijärvi wind farm turbine array	1.30			
Grid connection of Olkiluoto 3 nuclear power plant	12.90			
Existing geothermal heating energy produced by heat pumps in Finland			6.0	
New Electric Power Capacity Required (D)				
Replacing fossil fuel power generation	11.92			
Replacing power imports	20.04			
Total	**31.96**			
Transport Fleet Phase out of ICE Technology (E)				
Electric vehicle fleet	10.76			
Hydrogen production for vehicle fleet	15.50			Trucks are H_2-Cell
Hydrogen production for maritime shipping	58.77			Maritime shipping is H_2-Cell
Biofuel for aviation transport		8.14		All aircraft are biofuel powered
Total	**85.03**	**8.14**		
New Heat Generation Capacity (F)				
District Heat (18.87 TWh) (hetaing reqruiements kept the same, but are re-engineered)			18.87	Domestic heat supplied by 4th generation shallow geothermal systems (300m deep)
Industrial Heat (10.29 TWh) (Half Equation 1 + Half Equation 2)		6.87		
Residential Heat (14.7 TWh) (Society heatng requirements kept the same, but are re-engineered)			14.69	Industrial heat requirements are CHP biomass sourced
Total		**6.87**	**33.56**	
Net Total [(Demand A+E)-(Production B+C) = New Capacity Required]	**102.79 (TWh)**	**15.01 (Mm^3)**	**33.56 (TWh)**	All new electrical power is wind generated
Required stationary power storage for new wind generation station fleet @ 4 weeks capacity	**7.91 (TWh)**			Current thinking suggests this should be battery banks
Number Lestijärvi scale wind farms @ 1.3 TWh annual capacity	79 Stations			Geographical siting not considered
Number of 6.6 MW capacity wind turbines	5 456			
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 80.5 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -9.04%		
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -23.6%		
Number of geothermal wells			Approx 522 000 boreholes, 300m deep, just in Helsinki	In a grid 20m apart, 25 boreholes per hectare for populated areas

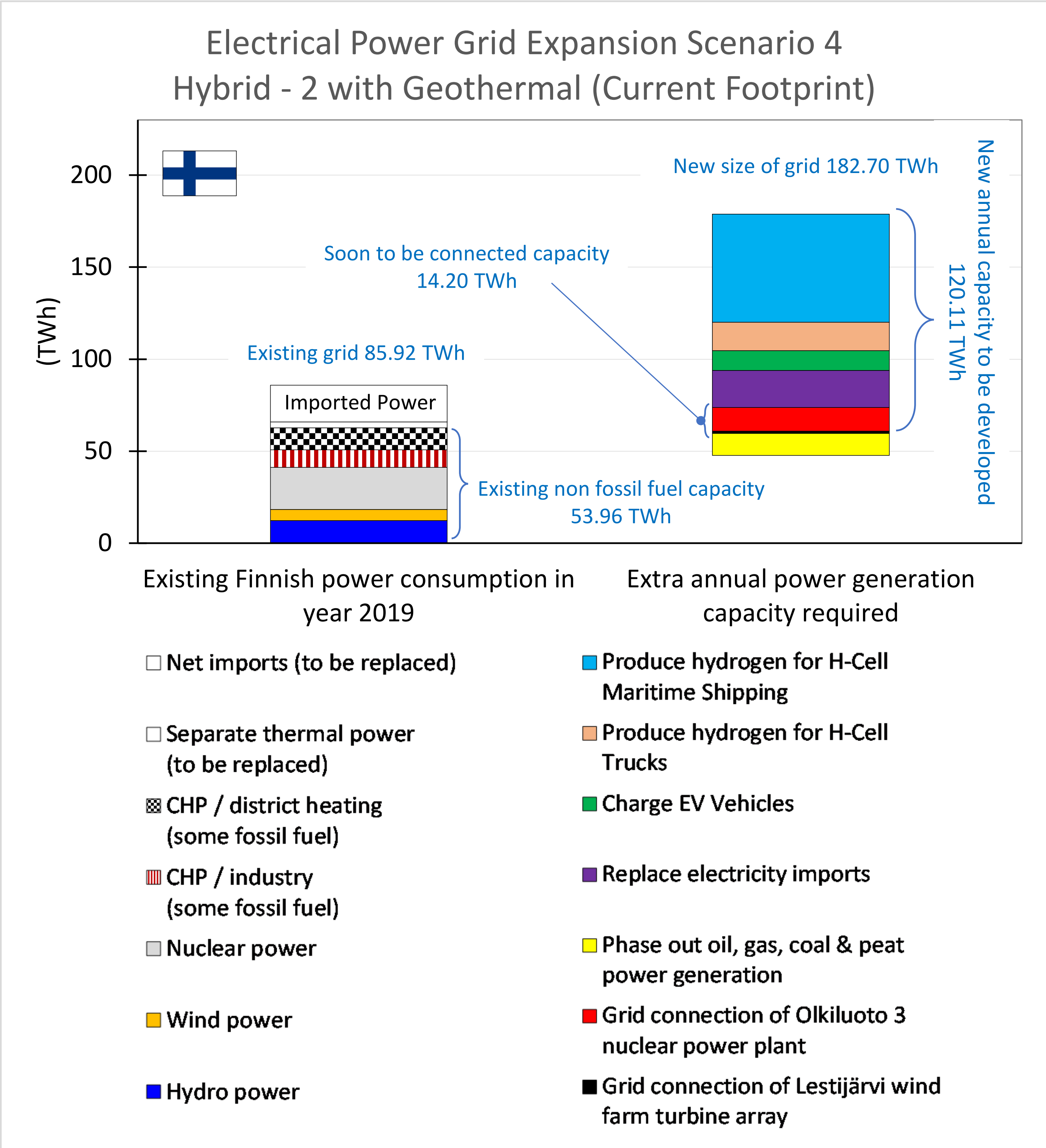

Figure 24. Extra annual electrical energy generation capacity required to phase out fossil fuels for Scenario 4: Hybrid – 2 with Geothermal (Current Footprint)

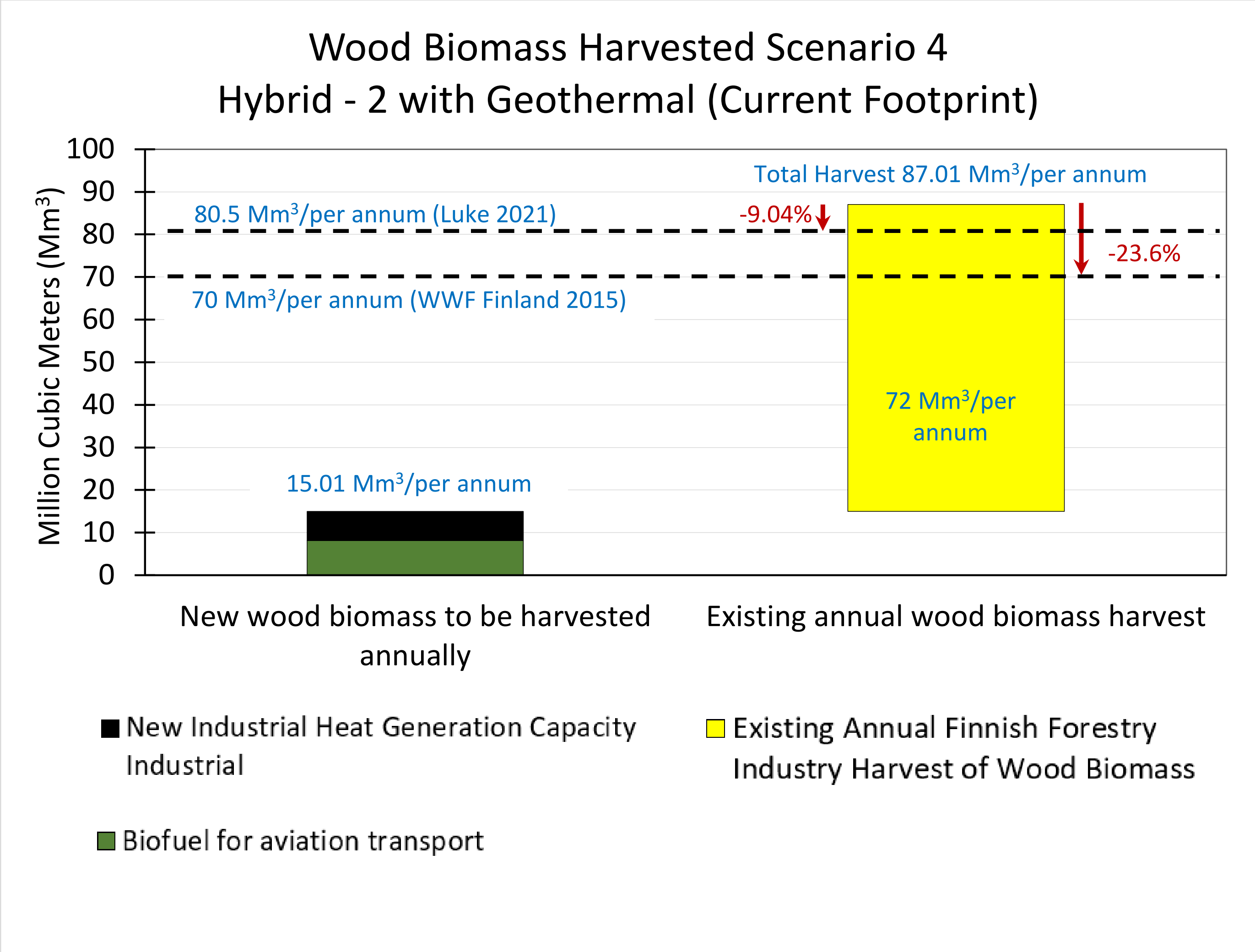

Figure 25. Extra annual wood biomass harvest required to phase out fossil fuels for Scenario 4: Hybrid - 2 with Geothermal (Current Footprint)

13.7 Scenario 5: No Action (No new capacity constructed; fossil fuels phased out anyway)

This scenario was designed to examine what would possible options be if no new non-fossil fuel energy generation capacity was constructed, but fossil fuels of all kinds were phased out anyway (Table 39 and Figures 26 and 27). The purpose of this scenario was to reflect the kind of problem solving if no future planning was acted upon.

It was assumed that both the Olkiluoto 3 nuclear power plant, and the Lestijärvi wind farm turbine array were both connected to the grid, adding 14.20 TWh to the Finnish annual energy generation capacity. The annual Finnish electrical energy supply reduced by 31.96 TWh to 53.96 TWh, which is a 37.2 % contraction (see below). To meet the challenge, the following adjustments were made, in a triage problem solving context, where Finnish society came together to meet an emergency like situation. Energy consumption for existing applications (85.92 TWh) is reduced by 47.96% to 44.71 TWh annually. 17.14% of existing non-fossil fuel power production is tasked to new applications. Thus 9.25 TWh (53.96 - 44.71 = 9.25) was then available for other tasks. The transport fleet was then contracted in scope and activity, where EV's and hydrogen could be produced using the now available 23.45 TWh (9.25 + 14.20).

13.7.1 Proposed in Scenario 5

- Fossil fuels were no longer used. All fossil fuel energy systems were taken offline, reducing the available grid size by 11.92 TWh. All electrical energy imports were discontinued. 20.04 TWh goes offline and was not replaced. The Finnish system will lose 31.96 TWh of annual capacity delivered but would gain 14.2 TWh (Olkiluoto 3 and Lestijärvi). The new Finnish grid capacity was 68.38 TWh.

- No new electrical power generation capacity was constructed.

- No new geothermal heating for residential buildings capacity was constructed.

To meet this challenge, Finnish society was restructured in an unplanned triage fashion as follows:

- Demand for electricity consumption for existing applications (85.92 TWh) was reduced by 47.96% to 44.71 TWh.

- 17.14% of existing non-fossil fuel electricity production (53.96 TWh – 44.71 TWh = 9.25 TWh) was re-tasked to new applications (26.98 TWh). This allowed new applications like the production of hydrogen and the charging of EV batteries to be possible.

- The physical work done, and annual distance travelled by short range vehicle transport fleet was reduced by 66%. So, 33.3% of the existing passenger cars, buses, vans (etc.) are EV and are charged from the grid.

- The physical work done, and annual distance travelled by truck transport fleet (heavy vehicles) and long range) was reduced by 66%. So, hydrogen to power 33.3% of the existing truck fleet was produced.

- The physical work done, and annual distance travelled the Finnish maritime shipping transport fleet was reduced by 75%. So, hydrogen to power 25% of the existing shipping fleet was produced.

- No aviation biofuel production capability was developed, and the industry was shut down.

- Heating requirements stay the same. All new heating heat requirements to replace fossil fuels are CHP biomass sourced, using existing infrastructure. This will require an extra annual 17.61 Mm^3.

- To maintain sustainability targets, downgrade the current forestry industry by -12.6% (if sustainable annual harvest is 80.5 Mm^3), or by -27.2% (if sustainable annual harvest is 70 Mm^3).

Table 40. Scenario 5 to phase out fossil fuels, No Action (No new capacity constructed; fossil fuels phased out anyway)

Finnish Annual Production and Consumption	Scenario 5		Comments
	No Action (No new capacity constructed, fossil fuels phased out anyway)		
	Electricity Capacity (TWh)	Wood Biomass (Mm^3)	
Existing Finnish electrical power demand (G)	85.92		
Existing electrical non-fossil fuel power production in Finland (P = G - H)	53.96		(85.92 - 31.96 = 53.96)
Electric Power Capacity Lost (H)			Fossil fuels are no longer used. 11.92 TWh goes offline and not replaced. Imports discontinued. 20.04 TWh goes offline and not replaced.
Fossil fuel power generation ceases	-11.92		
Imports of power is discontinued, with no replacement	-20.04		
Total	**-31.96**		
Planned New Available Electric Power Capacity			17.14% of existing non-fossil fuel power production (53.96 TWh - 44.71 TWh = 9.25 TWh) is tasked to new applications
Grid connection of Lestijärvi wind farm turbine array (Q)	1.30		
Grid connection of Olkiluoto 3 nuclear power plant (R)	12.90		
Existing power grid tasked to new applications	9.25		
Total	**23.45**		
Projected Electrical Consumption (Scenario 5)			
Existing electrical power demand (T)	44.71		Power consumption for existing applications (85.92 TWh) is reduced by 47.96%
Projected Transport Fleet (Scenario 5) (U)			
Electric vehicle fleet	3.59	-	66.6% reduction of short range vehicle transport fleet
Hydrogen production for vehicle fleet	5.17	-	66.6% reduction of truck transport fleet
Hydrogen production for maritime shipping	14.69	-	75% reduction of maritime shipping transport fleet
Biofuel for aviation transport		-	Aviation biofuel capacity not developed, industry shut down
Total	**23.45**	**0.0**	
Projected Heat Genration (Scenario 5)			All new heating heat requirements are CHP biomass sourced
District Heat (18.87 TWh) (Equation 2)		9.44	
Industrial Heat (10.29 TWh) (Half Eqn 1 + Half Eqn 2)		6.87	
Residential Heat (2.6 TWh) (Equation 2)		1.3	
Total		**17.61**	
Net Total [(Demand T+U) - (Production P+Q+R) = New Capacity Required]	**0.00 (TWh)**	**17.61 (Mm^3)**	Net power must be 0 as no new capacity is constructed
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 80.5 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -12.6%	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -27.2 %	

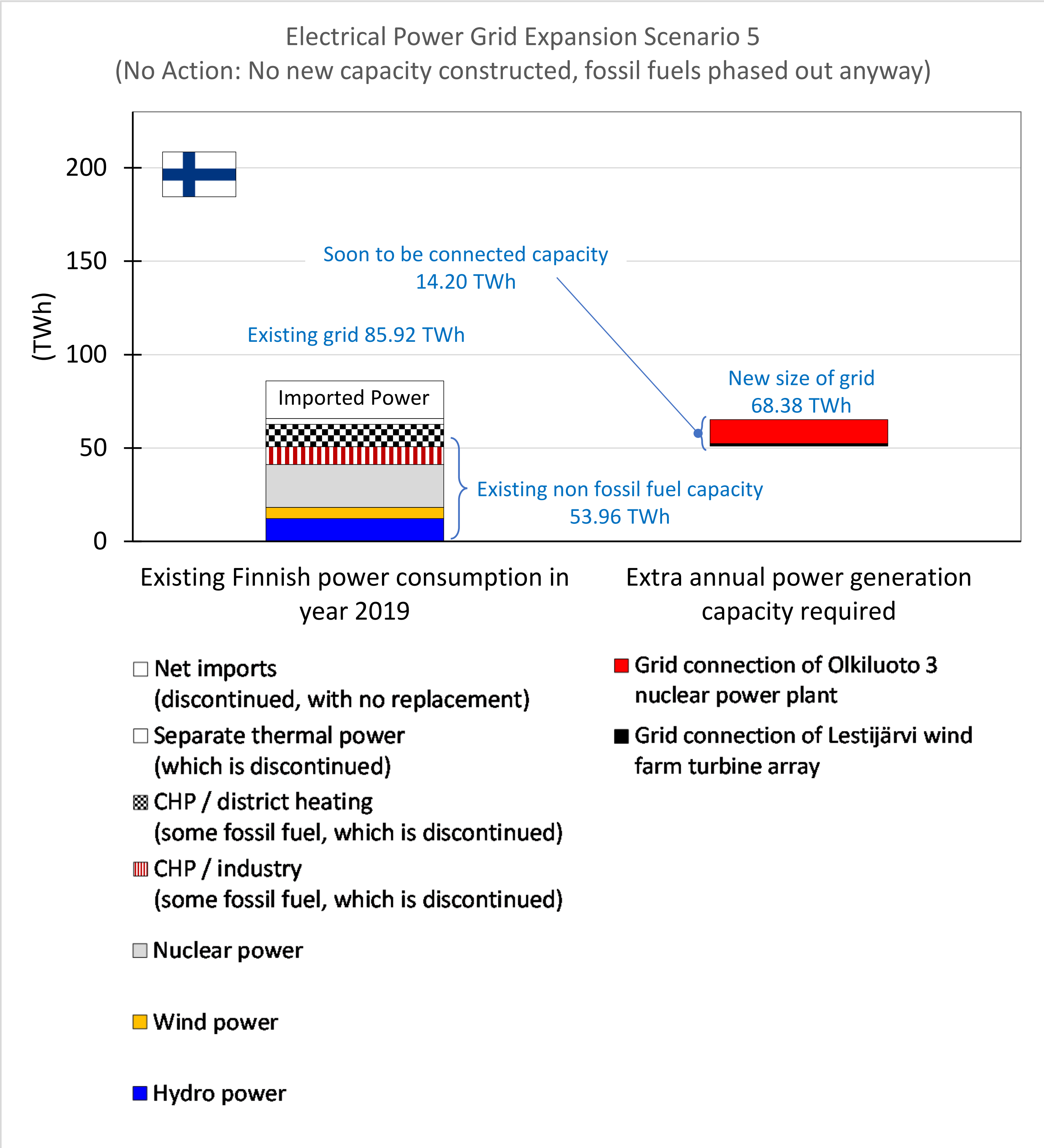

Figure 26. Extra annual electrical energy generation capacity required to phase out fossil fuels for Scenario 5 to phase out fossil fuels, No Action (No new capacity constructed; fossil fuels phased out anyway)

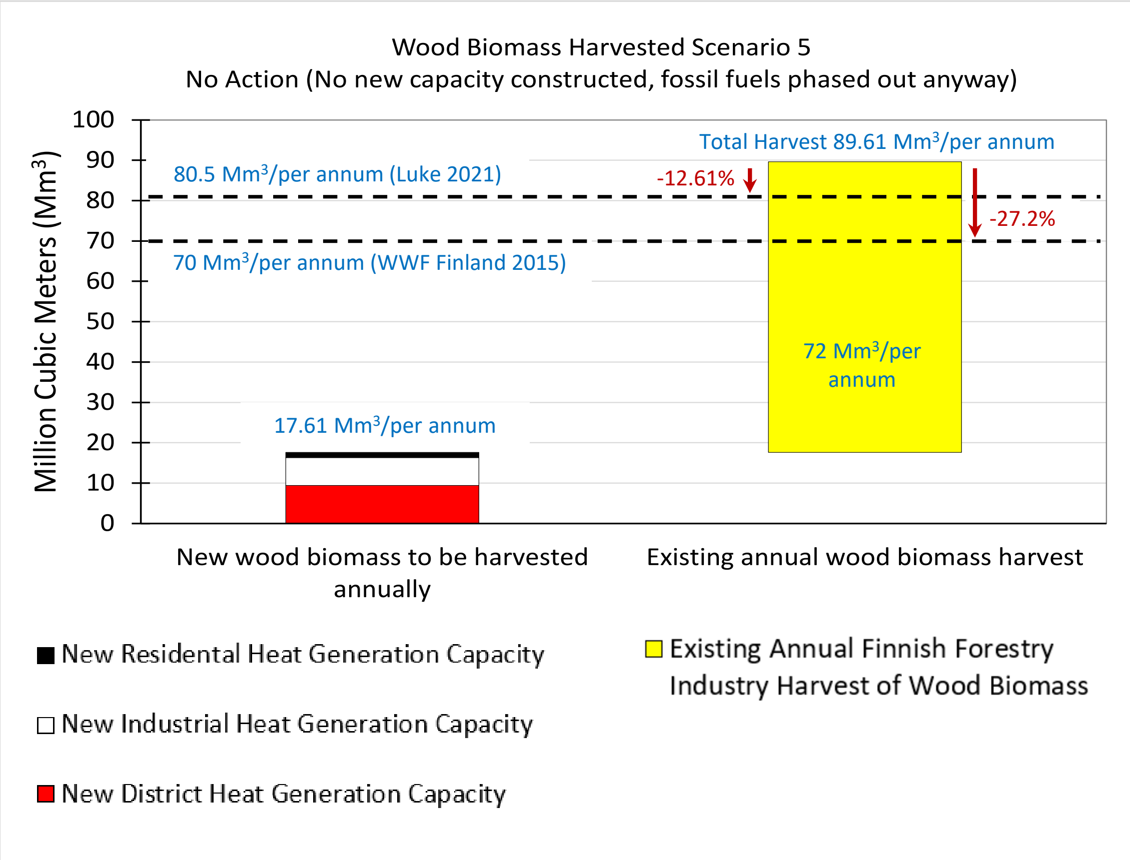

Figure 27. Extra annual wood biomass harvest required to phase out fossil fuels for Scenario 5: No Action (No new capacity constructed; fossil fuels phased out anyway)

Scenario 5 has a dual purpose. The first purpose was to examine what would be the implications to no strategic development to phase out fossil fuels when it may soon be required to do so to mitigate climate change risks. The second purpose was to examine what choices might be made if the required technology units (for example wind turbines or station battery units) were unavailable on the open market.

When planning for industrial power grid expansions, usually the challenges are related to securing capital, or logistical bottlenecks to get infrastructure commissioned. For the last 200 years, the industrial revolution has developed in a context where raw material requirements have been seen merely as a cost, with few examples of mineral shortages. That may not be the case in the short to medium term future. The scale and scope of the global task to phase fossil fuels was examined (Michaux 2021c and Michaux 2022) to determine the quantity of electrical energy needed, the number EV batteries, the number of wind turbines, and the number solar panels. In a global context, 37 670.6 TWh of extra electrical energy will be required. It is appropriate to model the global market, as very few nations manufacture wind turbines, solar panels, and batteries (China, South Korea, and Japan control most of the market share).

Most of the non-fossil fuel system has not yet been constructed. Less than 1% of the global passenger vehicle fleet is electrified, and EV trucks are even rarer. Renewable power supplies approximately 5% of the global primary energy demand. As this system is yet to be constructed, recycling of old components cannot alleviate the demand for virgin materials. Most metals required will have to be sourced from mining of minerals. Figure 28 shows the estimated quantities of metals needed to manufacture just one generation of batteries for the global fleet of EV's and the required stationary energy storage batteries (this figure was developed by taking the outcomes of Michaux 2021c and comparing them to stated global reserves in 2021). Figure 28 also shows the stated global reserves of the same metals. A shortfall can be observed. The same shortfall can be observed for wind turbines and solar panels.

This is a fundamental problem that cannot be resolved easily or quickly. Once the global markets for batteries, wind turbines and solar panels understand this shortfall, they will become inelastic. Procuring these technology units may not be as simple or at the current low prices. It is possible that they may be simply unavailable for some customers. This implies that the non-fossil fuel strategic plan may not develop as hoped.

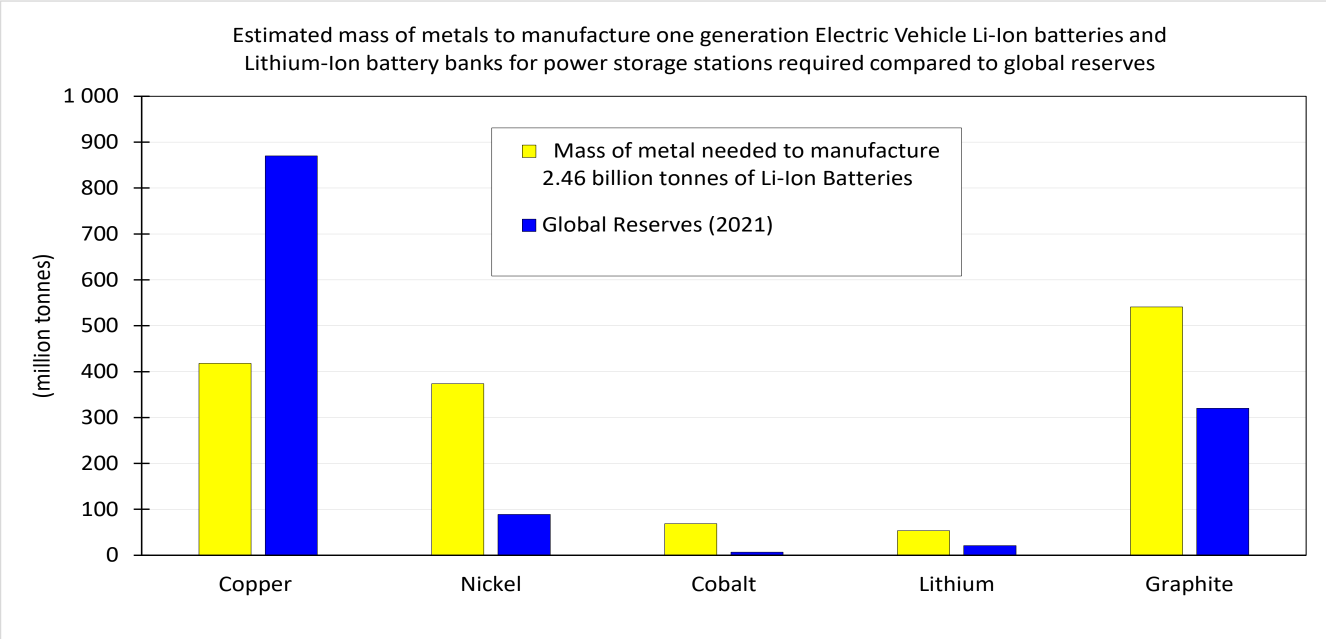

Figure 28. Estimated mass of metals to manufacture one generation Electric Vehicle Li-Ion batteries and Lithium-Ion battery banks for energy storage stations required compared to global reserves (Source: USGS Mineral Statistics for global reserves)

There is now considerable data to show that the supply of oil is becoming unreliable (Michaux 2019). Appendix J shows some of this data. Most oil discoveries happened decades ago, whereas oil demand has been increasing consistently each year for decades. For every 100 barrels of oil society is consuming, only 16 are being replaced with discoveries. At the time of writing this report, the peak of oil production (conventional crude oil) occurred in November 2018, with structural market challenges in the last few years that predate the Covid 19 pandemic. Gas and coal also have structural market challenges. Difficulties in supplying petroleum fueled internal combustion engine technologies are possible. The only viable replacement non-fossil fuel systems to replace ICE technology is Electric Vehicles (EV's), hydrogen fuel cell vehicles and biofuel (including biogas) supported vehicles. These systems in turn will require an electrical power source that does not require oil, gas, or coal fuels. The only viable systems that can do this are wind, solar, hydro, biomass to waste and nuclear. All are examined in this report.

It is conceivable that the transition away from fossil fuels could be forced in the short-term future, in conjunction with non-fossil fuel technology units like wind turbines, batteries and solar panels being either prohibitively expensive, or simply unavailable on the open market. If this unfortunate combination of events come to pass, then the choice presented in Scenario 5 may of practical use for planning. Appendix K shows two time periods in the past (1971 and 2005), when the industrial ecosystem structurally changed. This is in the form of metal price data that the World Bank collects, presented to show eras of stability and volatility. Appendix K is showing that the industrial ecosystem has been transforming for some time now and could be approaching another point of evolution. This suggests that industrial planners have less time to secure milestones than is currently believed.

13.8 Scenario 6: Planned Sustainability (Managed Footprint Contraction 50%)

There is a planned contraction of all sectors by 50% (Table 40 and Figures 29 and 30). Imported electricity energy capacity is replaced. The physical work done (km travelled, freight transported) for EV short range vehicles, H_2-Cell trucks, H_2-Cell shipping, and biofueled aviation was all reduced to half its current footprint.

To meet the challenge, the following adjustments were made. All Finnish electrical energy requirements were reduced by 50%. Thus 42.96 TWh (85.92/2 = 42.96) is now available for other tasks. 50% of existing non-fossil fuel energy production (53.96 TWh) is tasked to new applications. Thus 26.98 TWh (53.96/2 = 26.98) was then available for other tasks. Added to the grid, connection of Olkiluoto 3 nuclear power plant (an extra 12.9 TWh/year) and the Lestijärvi wind farm (an extra 1.3 TWh/year) gives an energy budget of 41.18 TWh (12.9+1.3+26.98 = 41.18) to power the transport fleet.

The main difference between Scenario 5 and Scenario 6 is the electrical energy required to produce hydrogen for maritime shipping. Scenario 5 has a forced reduction of 75% with 13.99 TWh delivered for hydrogen production for the maritime fleet. Scenario 6 has a planned reduction of 50% with 29.39 TWh delivered for hydrogen production for this same task. The maritime shipping industry is consuming a disproportionately large part of the energy budget. It suggests that the maritime industry be examined carefully in context of how necessary it really is.

Industrial activity was kept the same as it is now, as this would secure Finland's future. In Scenario 4, the concept of using shallow geothermal wells for low temperature heating. The study used for Scenario 4, that assessed the potential for shallow geothermal bore holes to be used for building heating in Helsinki (Kallio *et al* 2019), used 300m deep wells in a 20 m spacing (25 wells per hectare), and assumed that all heat from the system is exhausted in 50 years (after which there would be a natural recharging time period and no energy is drawn for the system for heating). This study (Kallio *et al* 2019) is discussed in more detail in Appendix I.

It is recommended for the purpose of Scenario 6 that the well depth be extended to 600 m deep at the same 20 m spacing. This would mean just for the Helsinki city area, approximately 522 000 boreholes 600 m deep would be drilled. This geothermal well heating system would be extended to all the high population density areas in Finland (where the geothermal heating potential is assessed for its usefulness in a local region context). To drill so many holes to that depth would require efficiency performance advancements from drilling technology. If the bore hole grid spacing could be widened, then each well would have a reduced influence on its neighboring wells. The best grid spacing for long term sustainability should be examined in a separate study.

The possible outcome of extending the borehole grid spacing should be examined. This would mean that that much more heating energy could be accessed for longer and make the system more sustainable long term. Also, draw energy for heating only in the coldest part of winter and use the rest of the year to recharge the local reservoir from the regional geothermal heat reservoir. The energy in each 600 m deep borehole would be harvest using a 4th generation heat pump, which would allow more useful heating delivered from lower temperature fluids.

13.8.1 Proposed in Scenario 6

- Demand for electricity consumption for existing applications was reduced by 50% (42.96 TWh).
- Only 50% of existing fossil fuel electrical power generation is replaced (5.96 TWh developed).
- Only 50% of electricity imports were replaced with non-fossil fuel systems (10.02 TWh developed).
- 50% of existing non-fossil fuel electricity production was withheld from existing applications and re-tasked to new applications (26.98 TWh). This permits new applications like the production of hydrogen and the charging of EV batteries.
- The physical work done, and annual distance travelled by short range vehicle transport fleet was reduced by 50%. So, 50% of the existing passenger cars, buses, vans (etc.) are EV and are charged off the grid (5.38 TWh allocated).
- The physical work done, and annual distance travelled by truck transport fleet (heavy vehicles) and long range) was reduced by 50%. So, hydrogen to power 50% of the existing truck fleet was produced (7.75 TWh allocated).
- The physical work done, and annual distance travelled the Finnish maritime shipping transport fleet was reduced by 50%. So, hydrogen to power 50% of the existing shipping fleet was produced (29.39 TWh allocated).
- Aviation biofuel production capability was developed in Finland. Biofuel for only 50% of the existing flights was produced, using wood biomass as a source (4.07 Mm^3 wood biomass allocated).
- All new heating heat requirements kept the same. District and residential building heating was supplied with shallow geothermal wells in the same fashion as Scenario 4 (33.57 TWh sourced from shallow geothermal systems), but with 600m deep holes.
- All remaining heating demand was delivered with wood biomass sourced CHP plants (6.87 Mm^3).
- The extra wood biomass to be annually harvested from Finnish forests would be 10.94 Mm^3.
- To meet the extra wood biomass demand and still maintain sustainability targets, either downgrade the current forestry industry by –3.39% (if sustainable annual harvest is 80.5 Mm^3 [Luke 2021]) or downgrade the current forestry industry by -17.97% (if sustainable annual harvest is 70 Mm^3 [WWF Finland 2015]).
- To supply the required extra 17.32 TWh, 13.3 new Lestijärvi scale wind farms constructed (@ 1.3 TWh annual capacity), or 918 wind turbines (6.6 MW capacity, 6.06 GW installed capacity in total).
- Required stationary energy storage to buffer support new wind generation station fleet @ 4 weeks capacity was 1.33 TWh (Section 5).

In an ideal circumstance, this scenario is the recommended approach. The challenges to phase out fossil fuels are much larger than the current thinking and strategic planning allows for (Michaux 2022 and Michaux

2021c). While Finland may be in a comparatively strong position to phase out fossil fuels, most of the rest of the world is not. Finland is still dependent on imported manufactured goods like computers, automobiles, all of which are produced in nations like China, which may not be able to transition to industrial production post fossil fuels.

The incoming era will require the development of an entirely different industrial ecosystem to what is in place now. This new ecosystem will have different limitations regarding available energy, flexibility, and available raw materials (Michaux 2021b), in comparison to what is considered normal now. It could well be possible that the incoming ecosystem will have to operate on a much lower energy availability than the current ecosystem does (Michaux 2021c).

Scenario 6 could represent the ideal energy profile for Finland. To make this possible though, a new system in how society manages its raw materials would need to be developed. A possible start of that development could be the Resource Balanced Economy (Michaux 2021a), which could be viewed as an evolution of the Circular Economy (European Commission 2019) regarding what the industrial ecosystem could become.

Strategic developments at the industrial scale need to be considered, planned, and implemented. Finland has the capacity to maintain industry on non-fossil fuel systems, which could be one of the few examples in the world at this time. If industrial capability could be maintained, then future trade potential could be much more valuable than it is now. Options for a strategic plan to develop the Finnish battery ecosystem (Tuomela et al 2021) could be a start. This thinking should be extended to all other Finnish industrial sectors.

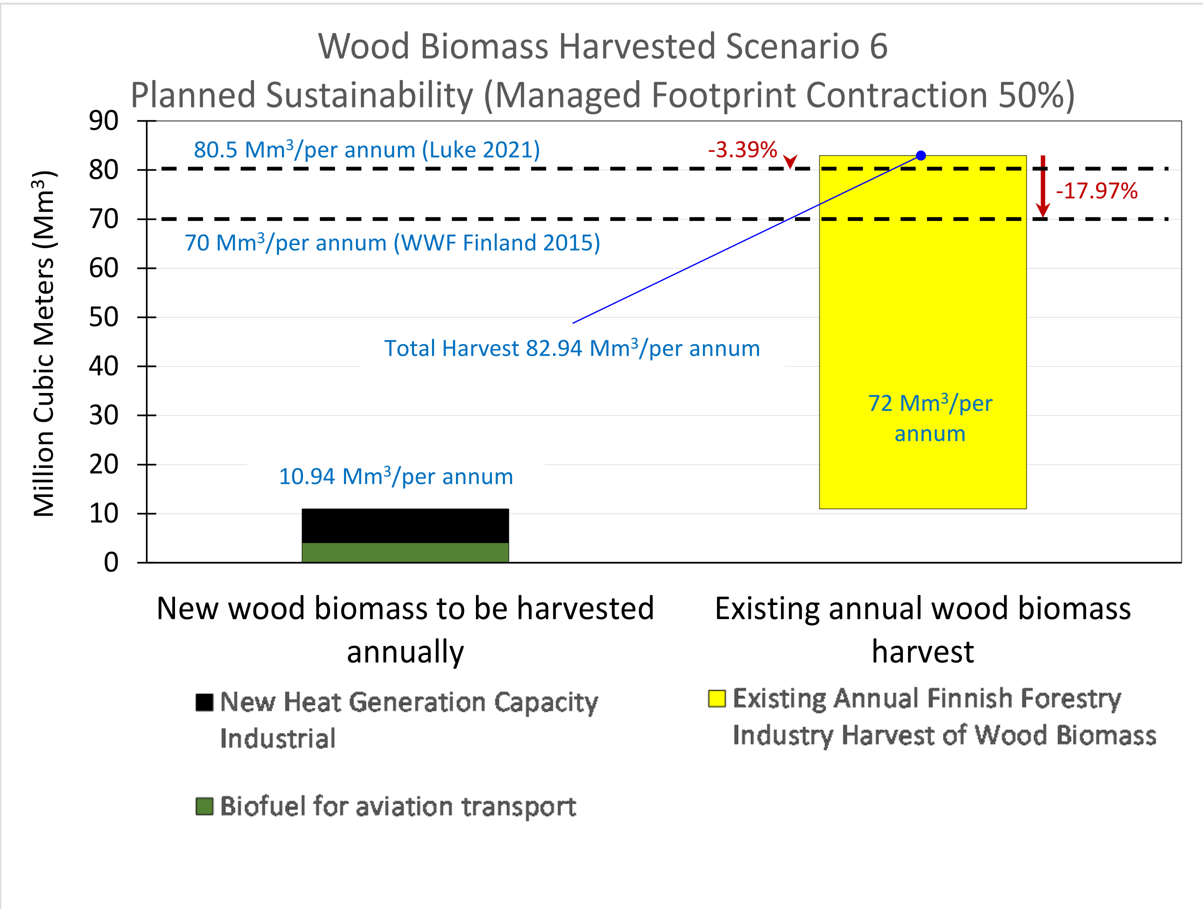

Figure 29. Extra annual wood biomass harvest required to phase out fossil fuels for Scenario 6: Planned Sustainability (Managed Footprint Contraction 50%)

Table 41-1. Scenario 6 to phase out fossil fuels, Planned Sustainability (Managed Footprint Contraction 50%)

Finnish Annual Production and Consumption	Scenario 6 Planned Sustainability (Managed Footprint Contraction 50%)		
	Electricity Capacity (TWh)	Wood Biomass (Mm^3)	Shallow Geothermal wells (TWh)
Existing Finnish electrical power demand	85.92		
Existing electrical non-fossil fuel power production in Finland (A)	53.96		
Existing geothermal heating energy produced by heat pumps in Finland			6.0
Planned Available Electric Power Capacity			
Grid connection of Lestijärvi wind farm turbine array (B)	1.30		
Grid connection of Olkiluoto 3 nuclear power plant (C)	12.90		
Existing power grid tasked to new applications	26.98		
Total	**41.18**		
Projected Electrical Consumption (Scenario 6)			
Electrical power demand for existing tasks (D)	42.96		
New Electric Power Capacity Required (E)			
Replacing fossil fuel power generation	5.96		
Replacing power imports	10.02		
Total	**15.98**		
Transport Fleet Phase out of ICE Technology (F)			
Electric vehicle fleet	5.38		
Hydrogen production for vehicle fleet	7.75		
Hydrogen production for maritime shipping	29.39		
Biofuel for aviation transport		4.07	
Total	**42.52**	**4.07**	
New Heat Generation Capacity (G)			
District Heat (18.87 TWh) (Equation 2)			18.87
Industrial Heat (10.29 TWh) (Half Eqn 1 + Half Eqn 2)		6.87	
Residential Heat			14.7
Total		**6.87**	**33.57**
Net Total [(Demand D+E+F)-(Production A+B+C) = New Capacity Required]	**17.32 (TWh)**	**10.94 (Mm^3)**	**33.57 (TWh)**
Required stationary power storage for new wind generation station fleet @ 4 weeks capacity	**1.33 (TWh)**		
Number Lestijärvi scale wind farms @ 1.3 TWh annual capacity	13.3 Stations		
Number of 6.6 MW capacity wind turbines	918		
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 83 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -3.39%	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3		Downgrade the current forestry industry by -17.97%	
Number of geothermal wells			Approx 522 000 boreholes, 600m deep, just in Helsinki

Table 41-2. Scenario 6 to phase out fossil fuels, Planned Sustainability (Managed Footprint Contraction 50%)

Finnish Annual Production and Consumption 	Comments
Existing Finnish electrical power demand	
Existing electrical non-fossil fuel power production in Finland (A)	
Existing geothermal heating energy produced by heat pumps in Finland	
Planned Available Electric Power Capacity	
Grid connection of Lestijärvi wind farm turbine array (B)	
Grid connection of Olkiluoto 3 nuclear power plant (C)	
Existing power grid tasked to new applications	50% of existing non-fossil fuel power production (53.96/2=26.98 TWh) is tasked to new applications
Total	
Projected Electrical Consumption (Scenario 6)	
Electrical power demand for existing tasks (D)	Power consumption for existing applications is reduced by 50% (85.92/2 = 42.96 TWh)
New Electric Power Capacity Required (E)	
Replacing fossil fuel power generation	Only 50% of existing fossil fuel electrical power generation is replaced (11.92/2 = 5.96 TWh)
Replacing power imports	Only 50% of existing electrical power imports are replaced (20.04/2 = 10.02 TWh)
Total	
Transport Fleet Phase out of ICE Technology (F)	
Electric vehicle fleet	50% reduction of short range vehicle transport fleet (14.7/2 = 7.35 TWh)
Hydrogen production for vehicle fleet	50% reduction of truck transport fleet (15.48/2 = 7.75 TWh)
Hydrogen production for maritime shipping	50% reduction of maritime shipping transport fleet (58.77/2 = 29.39 TWh)
Biofuel for aviation transport	50% reduction of aviation transport fleet (8.14/2 = 4.07 Mm^3)
Total	
New Heat Generation Capacity (G)	
District Heat (18.87 TWh) (Equation 2)	Domestic heat supplied by 4th generation shallow geothermal systems (300m deep)
Industrial Heat (10.29 TWh) (Half Eqn 1 + Half Eqn 2)	
Residential Heat	Industrial heat requirements are CHP biomass sourced
Total	
Net Total [(Demand D+E+F)-(Production A+B+C) = New Capacity Required]	All new electrical power is wind generated
Required stationary power storage for new wind generation station fleet @ 4 weeks capacity	Current thinking suggests this should be battery banks
Number Lestijärvi scale wind farms @ 1.3 TWh annual capacity	Geographical siting not considered
Number of 6.6 MW capacity wind turbines	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 83 Mm^3/per annum (LUKE 2021), and where 2019 forest industry harvest was 72 Mm^3	
If maximum sustainable harvest of wood biomass from Finnish forests is approximately of 70 Mm^3/per annum (WWF Finland 2015), and where 2019 forest industry harvest was 72 Mm^3	
Number of geothermal wells	In a grid 20m apart, 25 boreholes per hectare for populated areas

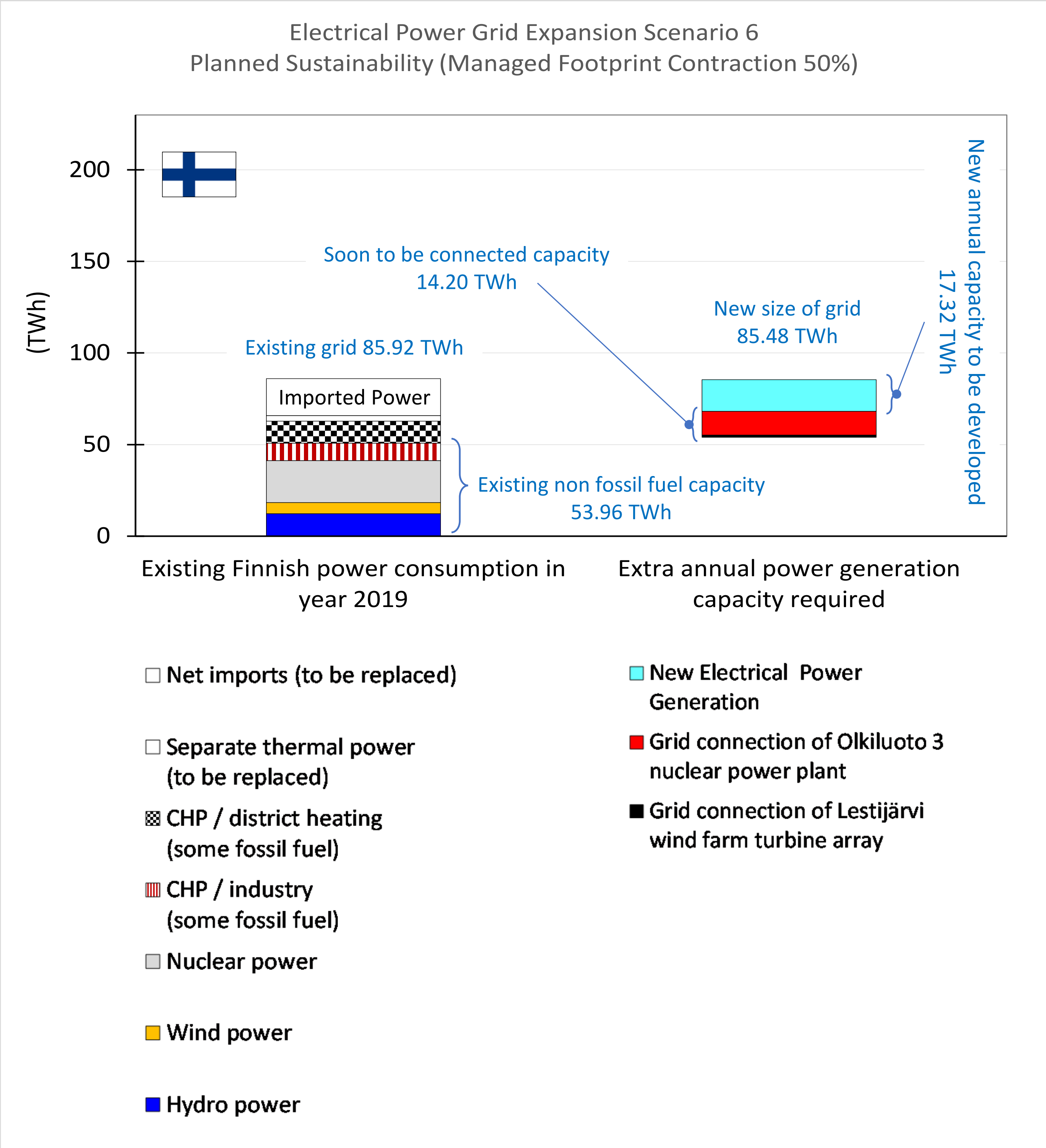

Figure 30. Extra annual electrical energy generation capacity required to phase out fossil fuels for Scenario 6 to phase out fossil fuels, Planned Sustainability (Managed Footprint Contraction 50%)

14 FINLAND'S NET POSITION

The net position for Finland to phase out fossil fuels is much stronger than many other nation states. The tasks before us are much smaller than other nations, due to where electrical power is currently sourced, and strategic industrial development actions taken in the past 10 to 20 years.

At the time of writing this report, very little electrical energy production in Finland is sourced from fossil fuels (13.9 %), where most of electricity generation already comes from nuclear and hydroelectricity. In the next few months, a state-of-the-art nuclear reactor will be added, Olkiluoto plant, with 1600 MW installed capacity (Pukkila 2020). This station has the potential to supply 12.9 TWh annually. This is more than the annual electricity capacity which was produced using fossil fuels in 2019. Finland may be the only nation in the world in this unique position (remembering that the remaining nuclear power plants are due for decommissioning soon).

In addition to this, the world's first deep geological repository for the final disposal of spent nuclear fuel is being built in Olkiluoto (Gil 2020, McEwan & Savage 1996, Deign 2012). This facility (called Onkalo) is near the Olkiluoto Nuclear Power Plant in the municipality of Eurajoki in Finland and is being constructed by Posiva. The facility is expected to be operational in 2023. Finland is the only nation state in the world to develop such a storage facility.

Finland has a large fleet of Combined Heat and Power (CHP) plants. Approximately 75% of the land in Finland is forest. Most of the forests in Finland are managed forests (up to 90 %), and less than 5 % are primary/pristine forest. It is possible that Finnish forests could be managed for long-term broad-spectrum sustainability, where only so much biomass is harvested. How much this should be is currently the subject of debate. One school of thought is that already too much is being harvested. Some of the data assembled in this report suggests more biomass could be harvested above what is taken now to phase out fossil fuels.

Finland has a small but highly educated population. The rail transport network is already 95 % electrified. The industrial sector in Finland, in conjunction with the potential to mine minerals, positions Finland in a capacity to develop an industrial ecosystem that dominates the beginning of the value chain for multiple products like batteries (from mineral exploration to production of chemicals). Government supported investment groups like the Finnish Minerals Group (FMG) have the capacity to ensure that industrial ecosystem remains Finnish, through ownership of strategically important industrial assets. This is relevant to remember, while the future could be more defined by alliances between industrial clusters, than geopolitical agreements.

The main difficulty Finland faces is its dependency on importing energy resources, manufactured goods, and food (mainly in terms of resources needed in food production). While the plan may well be to develop domestic capability on all these sectors, current dependency on imports will continue for many years. Finland's comparative size in the marketplace is very small, thus it cannot dictate terms in the same way that Germany might, for example, if the free market becomes inelastic. If the market does become inelastic, and supply of goods becomes unreliable, Finland may be forced to be become more self-reliant sooner than the larger economies like the United States, China, or Germany.

The task to phase out fossil fuels is perhaps the largest and most significant task the global industrial ecosystem has ever faced. It is required to have tangible physical results in the next years. All nation states, while each in unique circumstances, must meet these same challenges. Finland's net position may be one of the strongest in the world.

15 FINNISH ENERGY SUSTAINABILITY FROM A MORE HOLISTIC PERSPECTIVE

This report has examined what would be required to generate all the energy used in Finland in 2019 using only relatively independent, low greenhouse gas emission energy sources. We have concluded that Finland is in a good position to become even energy independent, if desired. However, the future energy demand and production mix may differ considerably from the figures presented here. Forecasting these demands is a difficult and ultimately subjective exercise which we do not undertake here, although we can note that energy independence is achievable even if energy use increases somewhat from the 2019 levels. Nevertheless, it must be noted that fully *sustainable* energy system will inevitably imply limits to energy and other resource use. Because physical constraints forbid infinite improvements in resource use efficiency, even the use of relatively harmless sources of energy and other resources is ultimately limited. How these limited resources are shared fairly among humanity will be one of the defining questions of this century.

A separate study will be prepared to examine in detail the materials requirements and long-term sustainability of the scenarios presented here. Such studies are required to determine whether even the 2019 energy use can be sustained in the long term, and if not, which technologies in particular need efficiency improvements. We also need to understand whether sustaining 2019 levels of energy use (for example) in Finland is *socially sustainable*, that is, fair to all members of society. Currently, Finnish per capita materials consumption is almost over three times higher than the level sometimes suggested as a sustainable and *fair* share of the Earth's resources (Bringezu 2015, Tukker et al. 2016, Vadén et al. 2020).

Emerging research strongly suggests that high quality of life can, however, be guaranteed even if total energy use is significantly reduced from current levels. For example, Vogel *et al.* (2021) examined the relationships between energy use and six dimensions of human needs satisfaction, concluding that high levels of energy use do not seem either necessary or even particularly beneficial for need satisfaction. According to their estimates, all the assessed needs could be met with as little as 60 GJ (16.7 MWh) of annual final energy use per person, which is approximately 31 % of 2019 Finnish per capita final energy use (54.51 MWh/a). However, this would require changes in the need provisioning factors, such as public service quality, income equality, public health coverage, and trade and transport infrastructure. Nevertheless, even after considering less than optimal policies and Finland's climate and geographical factors, it seems safe to assume that 2019-equivalent levels of well-being could be supported with significantly smaller total final energy use. For example, a reduction of 20 % does seem plausible; alternatively, 2019-level energy supply could be used to provide significantly higher levels of well-being.

16 CONCLUSIONS

The task to phase out fossil fuels in Finland is quite different to many other nations. Due to work done in the past and projects being brought to completion after years of planning, Finland is in a relatively strong net position to undertake these strategic set of tasks. Each of the 6 scenarios presented in this report were designed to answer possible questions about planning options. The outcomes of all 6 should be considered in context of risk mitigation in planning for the future.

To phase out ICE vehicles, a transport fleet that is both EV and H_2-cell powered will be needed, as will the support infrastructure to charge the batteries and produce, store, and transport the hydrogen. The Finnish rail network is 95% electric already and was not considered part of this study. Most studies of this kind do not consider what to do about phasing out the ICE maritime shipping fleet. It is recommended here that the maritime shipping fleet is retooled and refitted to become hydrogen powered. The largest task to undertake to completely phase out fossil fuels is the production of hydrogen to fuel the maritime shipping fleet. A serious question could be how much of that shipping capability is really needed.

Wind may be the most flexible and practical non-fossil fuel electrical energy generation system to be deployed in Finland. One of the challenges to make this possible will be the commissioning of stationary energy storage to act as a buffer for intermittent power supply from the wind turbine arrays. The scale of this task is enormous and will face practical challenges. It may not be physically possible to site so many wind turbines in Finland, either on land or offshore. If so, then the capacity of the wind electrical power generation station fleet will have to be adjusted accordingly.

Of the 6 scenarios presented, 5 of them required the existing forestry industry to contract the amount of biomass wood harvested annually, if fossil fuels were phased out, existing capability was maintained, and sustainability limits were recognized. It is not practical to scale up biofuels to completely replace petroleum products. The environment cannot sustainably deliver the needed biomass quantity. Biofuels could be the most practical way to maintain the aviation industry. Bioplastics from biomass also may be the best way to maintain the plastics industry. A Finnish sustainability audit that examines all environmental limitations is required to determine how large the biofuels, biomass CHP and bioplastics sectors should be. What should also be considered in addition to past studies, is the net position of the forestry industry if petrochemical industrial fertilizers, herbicides, and pesticides were unavailable in the desired quantities.

Geothermal heating systems supported by 4th and 5th generation heat pumps should be installed wherever possible. Sustainable management of the heat reservoir should be assessed and conducted with the long term in mind. This may require the evolution of geothermal systems and drilling technology.

17 RECOMMENDATIONS

Recommendations based on the outcomes of this report are as follows:

1 Comprehensively map the Finnish economy, industrial ecosystem, physical goods moved, where they were moved and to what applications they were they used for. Do this for the year 2019, the last year before the Covid 19 pandemic quarantine lockdowns. Most of this information should be already available. Consolidate it together into one cross referenced data set.

2 Assess what is really needed for Finland to function in context of basic needs for society are being met and continuity of governance is well supported. Quantify how much of this is dependent on imports. Much of what is bought and sold in the current economy could be seen as luxuries and may well be outside Maslow's Hierarchy of Needs (Maslow 1943).

3 Develop a plan for energy contraction. Given that fossil fuels are becoming unreliable now, and the post fossil fuel system has yet to be constructed, the next 10 to 20 years may well be required to function with less energy inputs. Given a predicted a low energy future, develop a hierarchy of priorities. The first priority would be to attend to the basic needs of Finnish society. After that the most important strategic priority could be ensuring the sustainability of the Finnish industrial sector. This will be vitally important to maintain international trade and securing Finland's future long term sovereignty.

4 Make plans to develop capacity for at least an extra 33.29 TWh of electricity generation, from non-fossil fuel systems. This is based on Scenario 6.

5 Assess what will be required to import/construct 4.36 million EV's of various vehicle classes, then assess what support infrastructure will be needed (charging stations for example).

6 Assess what will be required to import/construct 162 186 hydrogen fuel cell trucks, then assess what support infrastructure will be needed (annual production, transport, and storage of 268 028 tonnes of hydrogen).

7 Conduct a comprehensive sustainability audit of Finland's forests and biomass economy in context of its environment, including energy and resource use in forest industry. Include the use of petrochemical sourced fertilizers, herbicides, and pesticides to manage forest plantations.

8 Develop a sustainable biofuels and biomass supported CHP system. Assess what is sustainably possible long term to produce biofuel for aviation, biomass for bioplastics and biomass for heat and power generation.

9 Given above actions, develop an expansion of 29.16 TWh in sustainable heat generation capacity.

10 Develop a post fossil fuel industrial evolution of capability plan. Currently, all parts of the industrial value chain are dependent on fossil fuels in some form. The sudden removal of fossil fuel support systems could disrupt exiting industrial production. This needs to be planned carefully, after a frank discussion around what is possible.

11 Given the implications in this report, consider maintaining capability to use peat as an energy source and as a raw material to facilitate the growing of food as a risk mitigation measure for emergencies.

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19 APPENDIX A – FINNISH MARKET SHARE OF GLOBAL ENERGY PRODUCTION AND CONSUMPTION

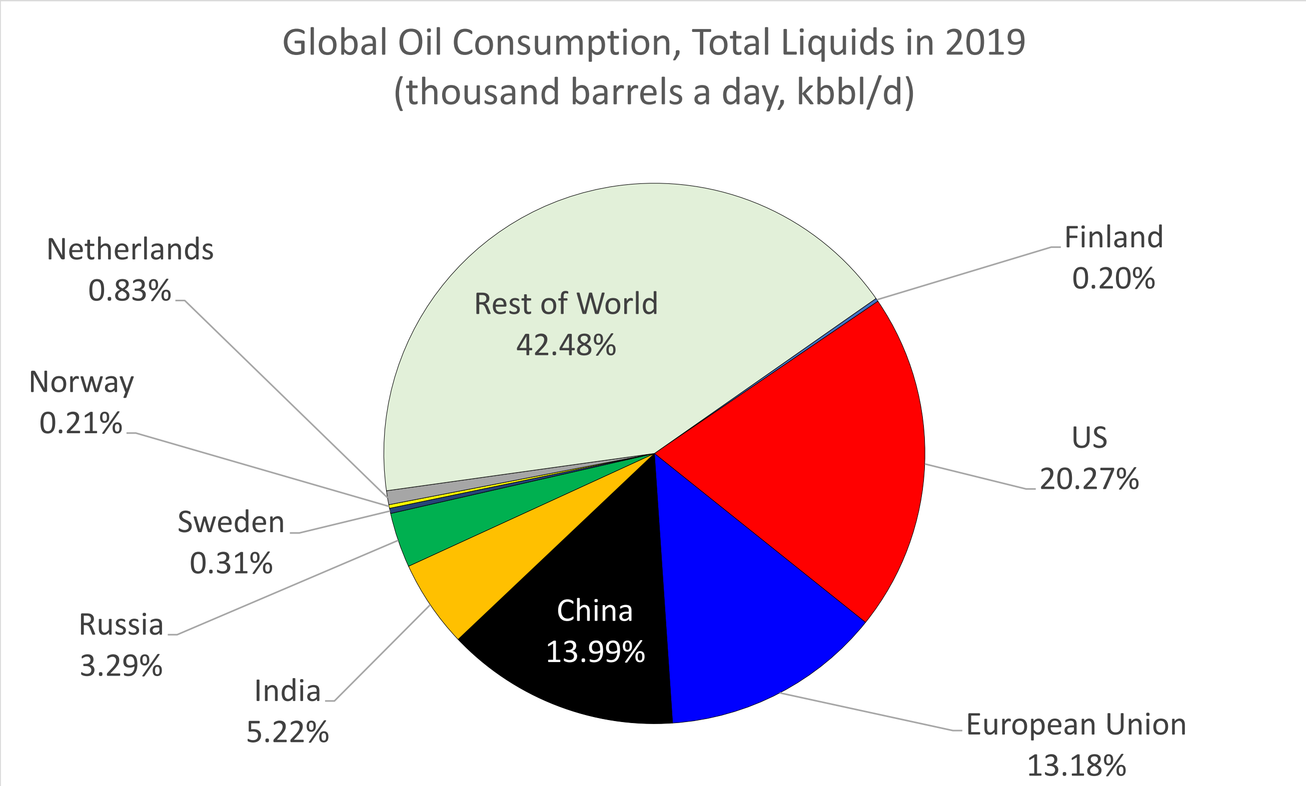

Figure A1. Global total liquids consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A1. Global total liquids consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Oil: Total Liquids consumption	
	(Thousand barrels a day, kbbl/d)	(million Barrels a year, Mbbl/yr)
Finland	201	73
US	20,466	7,470
European Union	13,309	4,858
China	14,127	5,156
India	5,274	1,925
Russia	3,317	1,211
Sweden	317	116
Norway	215	78
Netherlands	843	308
Rest of World	42,890	15,655
World	100,959	36,850

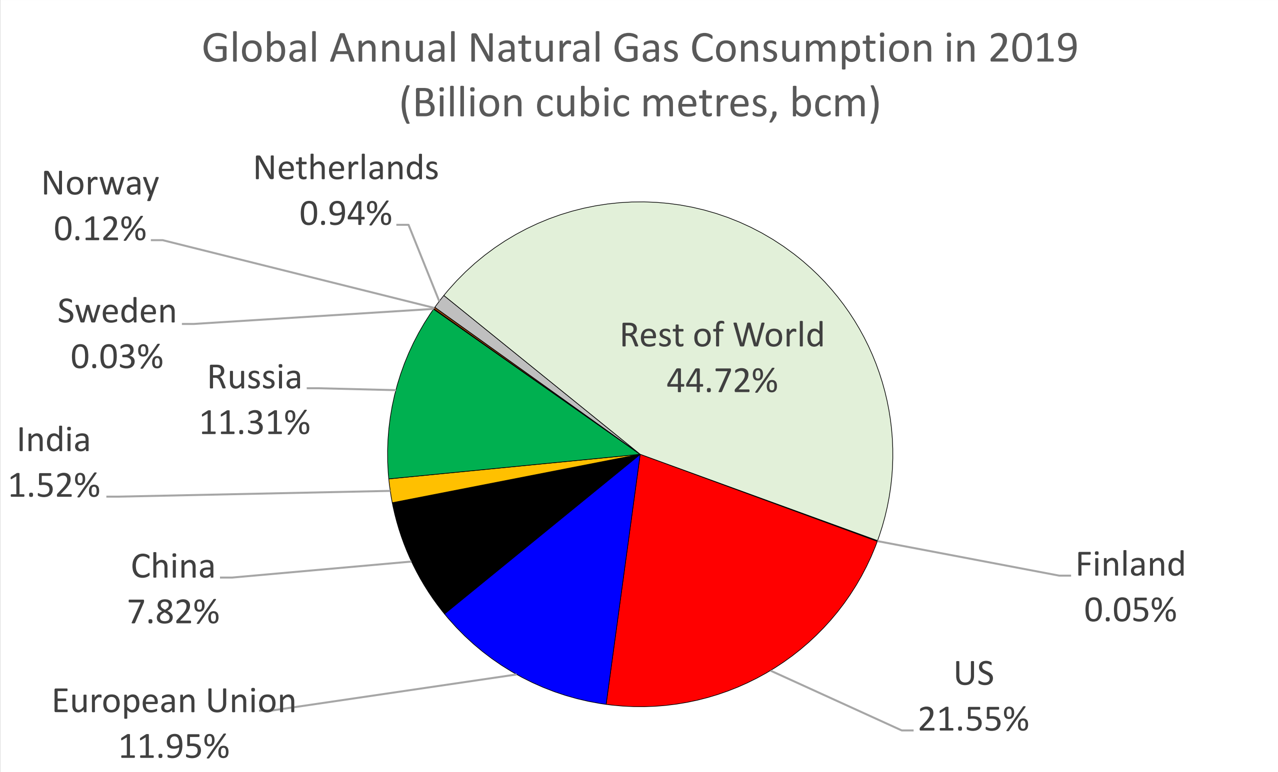

Figure A2. Global natural gas consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A2. Global natural gas consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Natural gas consumption - annual (Billion cubic metres, bm^3)
Finland	2.0
US	846.6
European Union	469.6
China	307.3
India	59.7
Russia	444.3
Sweden	1.0
Norway	4.6
Netherlands	36.8
Rest of World	1757.3
World	3929.2

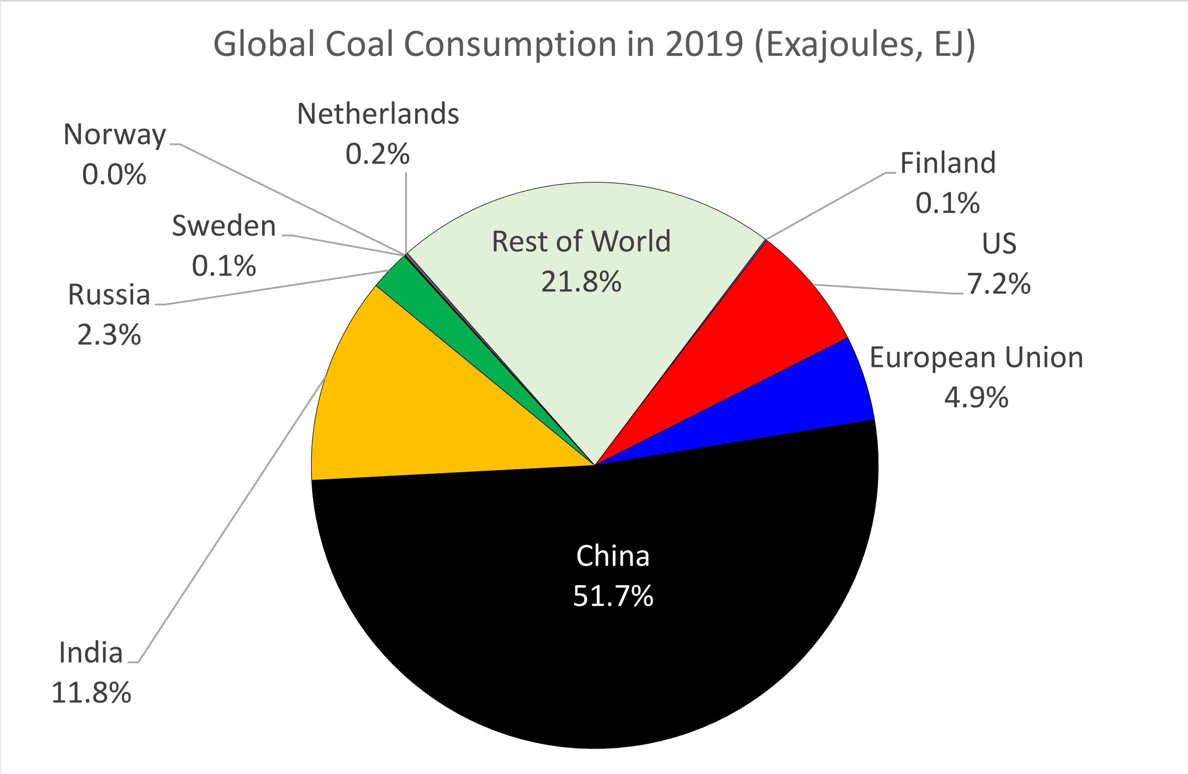

Figure A3. Global coal consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A3. Global coal consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Coal consumption - annual (Exajoules EJ)
Finland	0.15
US	11.34
European Union	7.69
China	81.67
India	18.62
Russia	3.63
Sweden	0.08
Norway	0.03
Netherlands	0.27
Rest of World	34.38
World	157.86

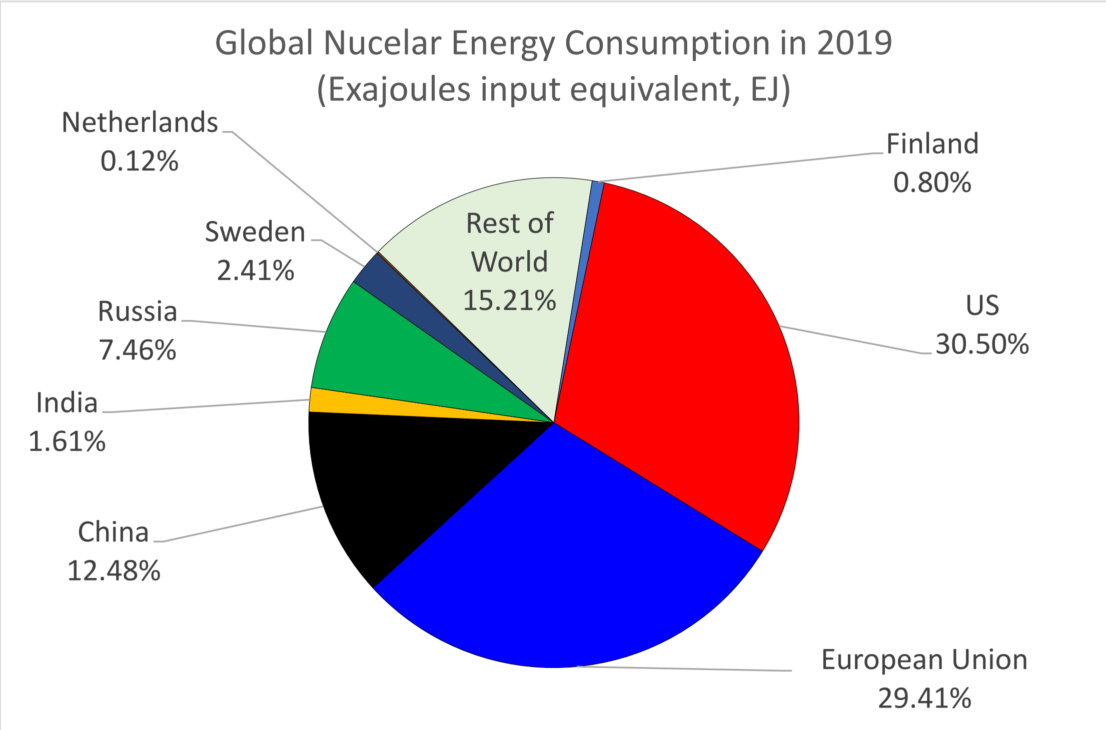

Figure A4. Global nuclear energy consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A4. Global nuclear energy consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Nuclear energy consumption - annual (Exajoules input equivalent EJ)
Finland	0.20
US	7.60
European Union	7.33
China	3.11
India	0.40
Russia	1.86
Sweden	0.60
Netherlands	0.03
Rest of World	3.79
World	24.92

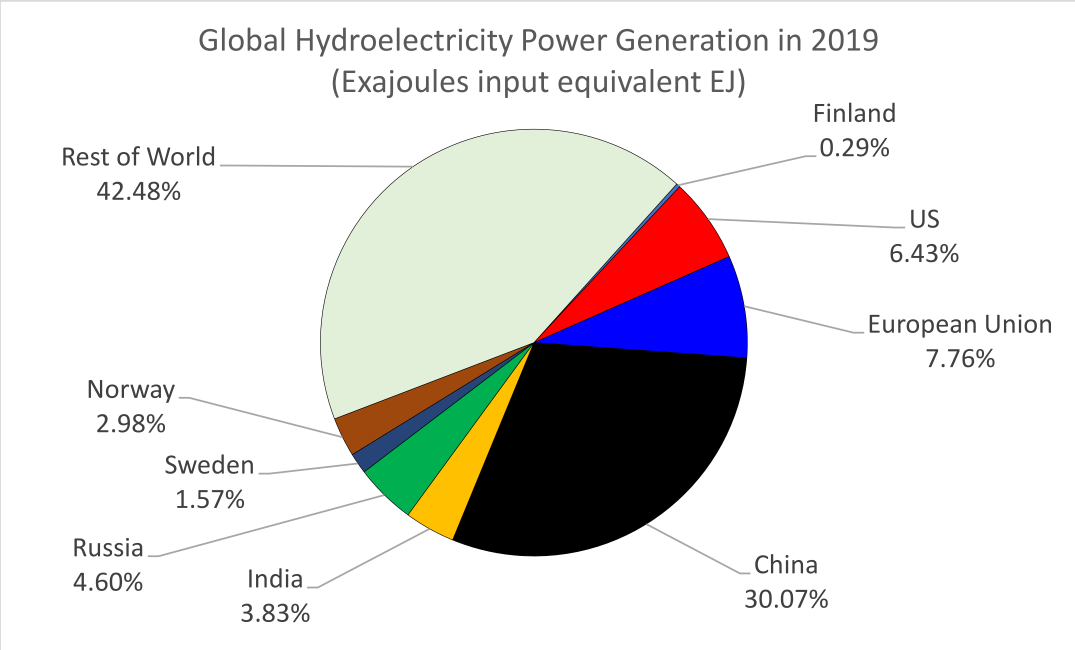

Figure A5. Global hydroelectricity generation (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A5. Global hydroelectricity generation (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Hydroelectricity consumption - annual (Exajoules input equivalent EJ)
Finland	0.11
US	2.42
European Union	2.92
China	11.32
India	1.44
Russia	1.73
Sweden	0.59
Norway	1.12
Rest of World	15.99
World	37.64

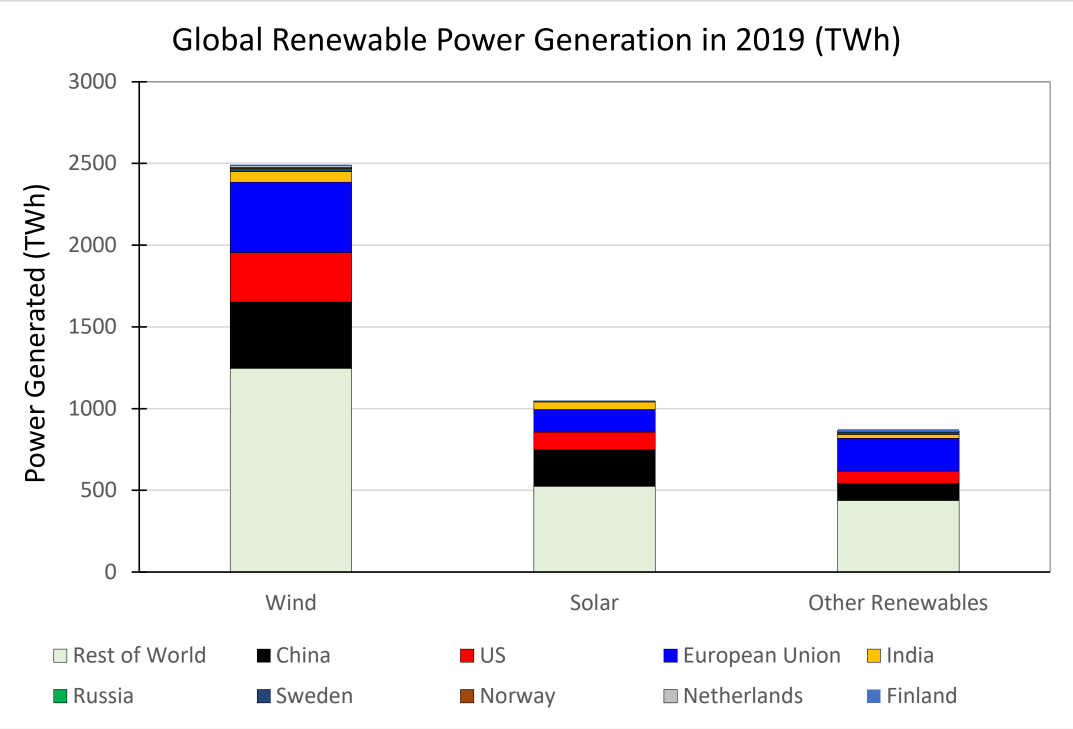

Figure A6. Global renewable power generation (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A6. Global renewable power generation (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Wind (TWh)	Solar (TWh)	Other Renewables (TWh)	Total (TWh)
Finland	6.0	0.2	12.2	18.4
US	303.1	108.4	78.3	489.8
European Union	430.7	138.4	199.1	768.2
China	405.7	223.8	102.8	732.3
India	63.3	46.2	25.4	134.9
Russia	0.3	1.0	0.5	1.8
Sweden	19.9	0.6	13.1	33.6
Norway	5.5	0.1	0.3	5.9
Netherlands	11.5	5.2	5.6	22.3
Rest of World	1246.0	523.9	437.3	2207.2
World	1429.6	724.1	651.8	2805.5

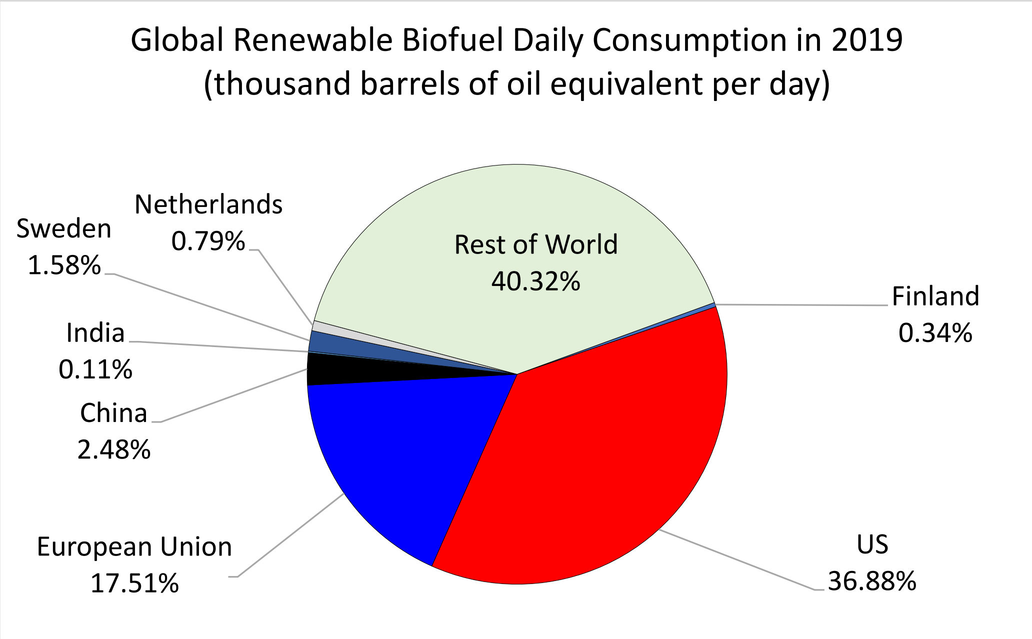

Figure A7. Global renewable biofuel daily consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A7. Global renewable biofuel consumption (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Renewable Biofuel consumption - daily (thousand barrels of oil equivalent per day)	Renewable Biofuel consumption - Annual 2019 (thousand barrels of oil equivalent per day)
Finland	6	2,190
US	655	239,075
European Union	311	113,515
China	44	16,060
India	2	730
Sweden	28	10,220
Netherlands	14	5,110
Rest of World	716	261,340
World	1776	648,240

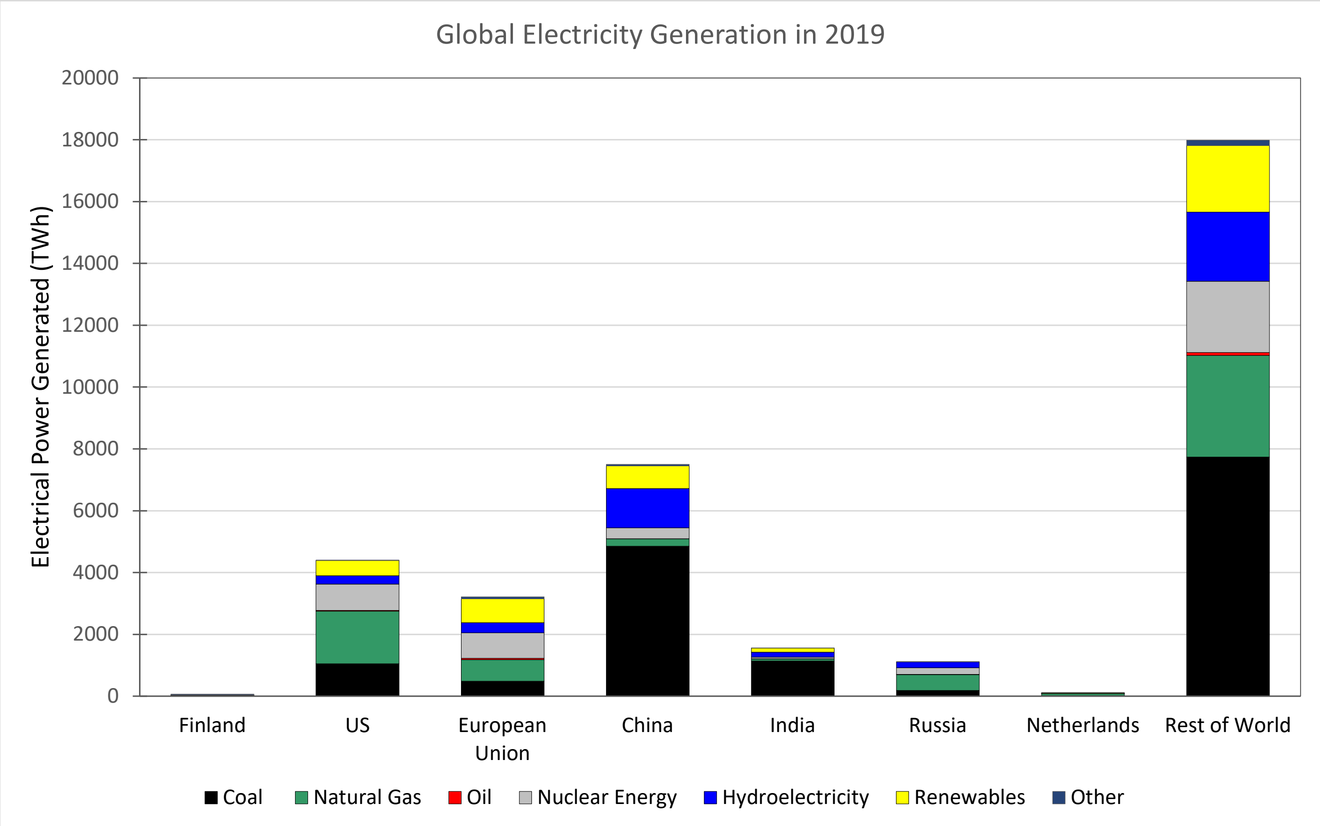

Figure A8. Global electricity generation in 2019 (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Table A8. Global electricity generation (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Country	Oil (TWh)	Natural Gas (TWh)	Coal (TWh)	Nuclear Energy (TWh)	Hydroelectricity (TWh)	Renewables (TWh)	Other (TWh)	Total (TWh)
Finland				22.91	12.25	6.02	27.5	68.7
US	20.0	1,700.9	1,053.9	852.0	271.2	489.8	14.0	4,401.8
European Union	49.1	692.2	488.4	822.4	327.9	768.2	67.2	3,215.4
China	6.0	236.5	4,853.7	348.7	1,269.7	732.3	56.5	7,503.4
India	8.2	71.0	1,137.4	45.2	161.8	134.9	0.2	1,558.7
Russia	6.9	519.5	182.2	209.0	194.4	1.8	4.3	1,118.1
Netherlands	1.4	71.0	17.4	3.9	0.1	22.3	5.0	121.1
World	825.3	6,297.9	9,824.1	2,796.0	4,222.2	2,805.5	233.6	27,004.6

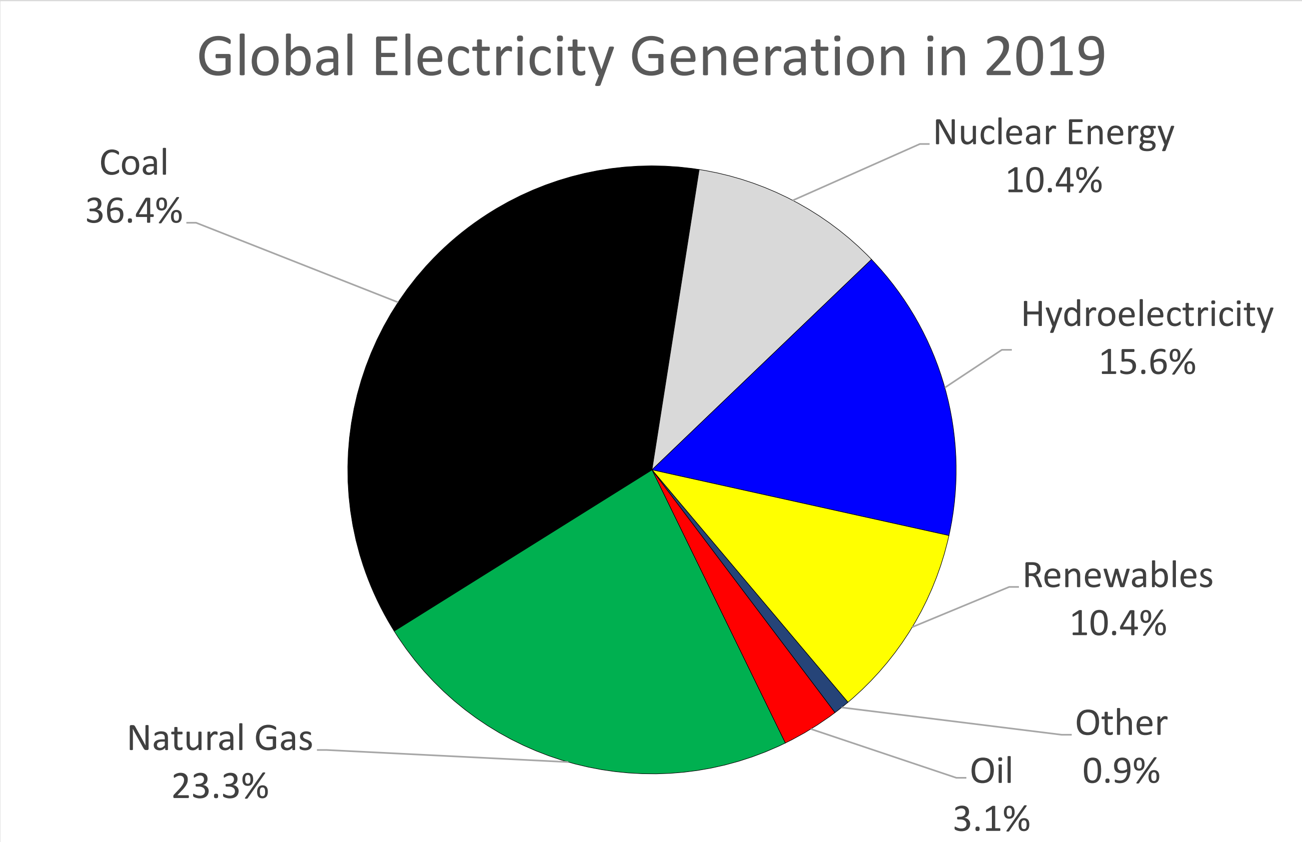

Figure A9. Global electricity generation in 2019 (Source: BP statistical review of world energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)

Globally, 62.8% of electric power generation is fossil fuel dependent

20 APPENDIX B – NUMBER OF ICE VEHICLES IN TRANSPORT FLEET

Table B1 (Part 1 of 3). Number of ICE vehicles in the global fleet.
(This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Refence/Source	Date of Estimate
Global	**205**	**1 416 528 615**		
United States	811	268 913 221	U.S. Dept of Transportation (2017)	2017
European Union	543	261 019 964	ACEA (2018)	2015/2016
China	179	232 312 300	National Bureau of Statistic of China 2019	2018
Japan	615	77 938 515	Japan Dept Transport (2017)	2018
Brazil	350	74 454 951	Balconista (2019)	2019
Russia	373	54 779 626	ЕМИСС (2019)	2018
United Kingdom	579	39 240 439	ACEA (2018)	2016
Mexico	297	37 353 597	The World Bank (2014)	2015
India	22	28 860 000	CEIC (2015)	2015
Canada	650	23 846 147	Statistics Canada (2019)	2017
Indonesia	87	22 512 918	UK Dept of Transport (2015)	2015
South Korea	411	20 989 885	UK Dept of Transport (2015)	2015
Australia	730	19 200 000	Australian Bureau of Statistics (2018)	2018
Thailand	226	15 490 503	UK Dept of Transport (2015)	2015
Turkey	199	16 320 927	ACEA (2018)	2015
Iran	178	14 130 000	UK Dept of Transport (2015)	2015
Argentina	316	13 726 226	UK Dept of Transport (2015)	2015
Malaysia	433	13 308 716	UK Dept of Transport (2015)	2015
Nigeria	64	11 458 370	Nigeria National Bureau of Statistics (2017)	2017
Pakistan	17	10 000 000	UK Dept of Transport (2015)	2015
South Africa	174	9 600 412	UK Dept of Transport (2015)	2015
Ukraine	219	9 290 000	MIUS (2019)	2018
Taiwan	333	7 842 423	Taiwan MTOC (2016)	2016
Syria	368	6 900 000	UK Dept of Transport (2015)	2012
Saudi Arabia	209	6 600 000	UK Dept of Transport (2015)	2015
Colombia	116	5 800 000	ANDEMOS (2018) & Columbian National Census (2018)	2018
Egypt	62	5 733 810	UK Dept of Transport (2015)	2015
Algeria	140	5 570 000	UK Dept of Transport (2015)	2015
Switzerland	539	5 003 551	Switzerland Federal Statistical Office FSO (2018)	2018
Venezuela	145	4 510 000	UK Dept of Transport (2015)	2015
Chile	230	4 444 941	UK Dept of Transport (2015)	2015
Kazakhstan	251	4 397 354	UK Dept of Transport (2015)	2015
New Zealand	860	4 240 000	New Zealand MIA (2018)	2018
Iraq	105	3 900 000	CEIC (2015)	2015
Philippines	38	3 822 544	UK Dept of Transport (2015)	2015
Morocco	103	3 570 000	CEIC (2015)	2015
Belarus	369	3 501 981	UK Dept of Transport (2015)	2015
Israel	384	3 373 139	Israel Central Bureau of Statistics. (2018)	2017
Norway	616	3 236 944	ACEA (2018)	2015
Libya	439	2 740 000	UK Dept of Transport (2011)	2015
Peru	78	2 444 478	UK Dept of Transport (2015)	2015
Ecuador	141	2 267 344	UK Dept of Transport (2015)	2015
Vietnam	23	2 170 000	UK Dept of Transport (2015)	2015
United Arab Emirates	234	2 140 000	UK Dept of Transport (2015)	2015
Serbia	288	2 052 067	Serbian Statistical Office (2016)	2015
Congo, Democratic Republic of the	25	1 900 000	UK Dept of Transport (2015)	2015

Table B1 (Part 2 of 3). Number of ICE vehicles in the global fleet.
(This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Reference/Source	Date of Estimate
Kuwait	477	1 876 188	UK Dept of Transport (2015)	2015
Guatemala	115	1 862 535	UK Dept of Transport (2015)	2015
Dominican Republic	153	1 610 551	UK Dept of Transport (2015)	2015
Afghanistan	47	1 572 663	UK Dept of Transport (2015)	2015
Sri Lanka	70	1 469 821	UK Dept of Transport (2015)	2015
Tunisia	129	1 450 000	UK Dept of Transport (2015)	2015
Kenya	29	1 381 473	UK Dept of Transport (2015)	2015
Kyrgyzstan	223	1 330 000	UK Dept of Transport (2015)	2015
Azerbaijan	135	1 301 926	UK Dept of Transport (2015)	2015
Jordan	123	1 130 000	UK Dept of Transport (2015)	2015
Costa Rica	224	1 076 041	UK Dept of Transport (2015)	2015
Myanmar	20	1 065 897	CEIC (2015)	2017
Georgia	281	1 043 900	UK Dept of Transport (2015)	2015
Qatar	411	1 020 000	UK Dept of Transport (2015)	2015
Yemen	37	1 000 000	UK Dept of Transport (2015)	2015
Oman	233	980 000	UK Dept of Transport (2015)	2015
Uruguay	280	960 000	UK Dept of Transport (2015)	2015
Singapore	170	957 006	Singapore Land Transport Authority (2018)	2018
Zimbabwe	60	940 000	UK Dept of Transport (2015)	2015
Cote d'Ivoire	41	940 000	UK Dept of Transport (2015)	2015
Bosnia and Herzegovina	258	910 969	UK Dept of Transport (2015)	2015
Ghana	32	890 000	UK Dept of Transport (2015)	2015
Angola	32	880 000	UK Dept of Transport (2015)	2015
Ethiopia	9	831 000	2Merkato Business Portal (2017)	2017
Bolivia	72	770 000	UK Dept of Transport (2015)	2015
Moldova	201	715 480	UK Dept of Transport (2015)	2015
Lebanon	117	683 000	Al-akhbar (2019)	2018
Panama	171	677 356	UK Dept of Transport (2015)	2015
Hong Kong	92	674 253	UK Dept of Transport (2015)	2015
Senegal	44	660 000	UK Dept of Transport (2015)	2015
Madagascar	27	660 000	UK Dept of Transport (2015)	2015
Paraguay	98	652 886	CEIC (2015)	2015
Bangladesh	4	620 000	UK Dept of Transport (2015)	2015
Bahrain	422	578 471	UK Dept of Transport (2015)	2015
Uganda	12	490 000	UK Dept of Transport (2015)	2015
Armenia	167	489 346	Armenia vehicle statistics (2018)	2018
Albania	167	481 114	UK Dept of Transport (2015)	2015
Nicaragua	79	480 000	UK Dept of Transport (2015)	2015
Cuba	42	480 000	UK Dept of Transport (2015)	2015
North Macedonia	206	425 764	UK Dept of Transport (2015)	2015
Mozambique	14	400 000	UK Dept of Transport (2015)	2015
Trinidad and Tobago	292	397 000	UK Dept of Transport (2015)	2015
Botswana	177	391 686	UK Dept of Transport (2015)	2015
Tanzania	7	380 000	UK Dept of Transport (2015)	2015
Zambia	23	370 000	UK Dept of Transport (2015)	2015
Cameroon	15	347 000	UK Dept of Transport (2015)	2015
Brunei	721	300 897	UK Dept of Transport (2015)	2015

Table B1 (Part 3 of 3). Number of ICE vehicles in the global fleet.
(This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Reference/Source	Date of Estimate
Burkina Faso	16	297 000	UK Dept of Transport (2015)	2015
Iceland	824	278 924	UK Dept of Transport (2015)	2016
El Salvador	41	260 000	UK Dept of Transport (2015)	2015
Benin	24	252 000	UK Dept of Transport (2015)	2015
Mauritius	192	236 853	UK Dept of Transport (2015)	2015
Mali	12	203 000	UK Dept of Transport (2015)	2015
Montenegro	326	202 322	Montenegrin Statistical Office (2017)	2016
Togo	27	198 000	UK Dept of Transport (2015)	2015
Suriname	349	193 000	UK Dept of Transport (2015)	2015
Jamaica	66	190 000	UK Dept of Transport (2015)	2015
Honduras	18	160 000	CEIC (2015)	2017
Malawi	8	139 000	UK Dept of Transport (2015)	2015
Barbados	387	110 000	UK Dept of Transport (2015)	2015
Haiti	7	80 000	UK Dept of Transport (2015)	2015
Liberia	14	63 000	UK Dept of Transport (2015)	2015
Burundi	6	63 000	UK Dept of Transport (2015)	2015
Belize	139	50 000	UK Dept of Transport (2015)	2015
Mauritania	10	41 000	UK Dept of Transport (2015)	2015

20.1 Chinese Vehicle Fleet in 2018

Table B2. Chinese passenger vehicle class specifications
(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)
(People's Republic of China public safety industry standard
http://www.jxjdcjc.com/ueditor/php/upload/file/20170818/1503017721116112.pdf)

Size	Vehicle Length (mm)	Number of passenger(s) (number)	Other
Large	>= 6000	>=20	
Medium	<6000	10-19	
Small	<6000	=<9 (excluding mini passenger vehicles)	
Mini	=< 3500		Engine capacity =< 1000mL

Table B3. Chinese goods vehicle class specifications
(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)
(People's Republic of China public safety industry standard
http://www.jxjdcjc.com/ueditor/php/upload/file/20170818/1503017721116112.pdf)

Size	**Vehicle Length (mm)**	**Total weight (kg)**
Heavy duty		>= 12000
Medium	>=6000	4500 >= Medium < 12000
Light	< 6000	< 4500
Mini	=< 3500	=< 1800

Table B4. Number of vehicles in the Chinese fleet between years 1978 to 2018, by class (Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)

Year	Total Number of Civilian feelt of cars (10 000)	Passenger Vehicle (10 000)	Large	Medium Size	Small	Mini	Goods Vehicle (10 000)	Heavy Duty	Medium	Light	Mini	Other Vehicle Type (10 000)
1978	135,84	25,90					100,17					
1980	178,29	35,08					129,9					
1985	321,12	79,45					223,2					
1990	551,36	162,19					368,48					
1995	1 040,00	417,90					585,43					
2000	1 608,91	853,73					716,32					
2005	3 159,66	2 132,46	82,13	131,65	1 618,35	300,32	955,55	168,07	236,66	484,51	66,31	71,66
2006	3 697,35	2 619,57	87,34	137,00	2 083,40	311,83	986,30	174,01	235,39	532,13	44,76	91,49
2007	4 358,36	3 195,99	93,82	140,52	2 646,47	315,18	1 054,06	186,74	243,46	587,22	36,63	108,31
2008	5 099,61	3 838,92	100,39	143,19	3 271,14	324,19	1 126,07	200,84	249,73	644,96	30,54	134,62
2009	6 280,61	4 845,09	107,95	145,80	4 246,90	344,44	1 368,60	315,08	262,21	765,33	25,97	66,92
2010	7 801,83	6 124,13	116,44	146,07	5 498,36	363,25	1 597,55	394,80	269,75	911,88	21,12	80,14
2011	9 356,32	7 478,37	126,54	147,41	6 827,54	376,88	1 787,99	460,58	267,80	1 042,07	17,54	89,96
2012	10 933,09	8 943,01	128,13	131,78	8 302,63	380,47	1 894,75	472,51	229,20	1 179,65	13,40	95,33
2013	12 670,14	10 561,78	131,38	117,06	9 951,46	361,87	2 010,62	501,97	196,40	1 300,02	12,23	97,75
2014	14 598,11	12 326,70	139,61	112,06	11 748,19	326,84	2 125,46	533,67	188,09	1 385,77	17,93	145,95
2015	16 284,45	14 095,88	140,07	89,66	13 580,48	285,66	2 065,62	530,05	148,87	1 375,79	10,90	122,95
2016	18 574,54	16 278,24	146,03	83,82	15 813,84	234,55	2 171,89	569,48	138,69	1 455,29	8,43	124,41
2017	20 906,67	18 469,54	152,94	78,95	18 038,69	198,96	2 338,85	635,41	130,68	1 566,30	6,46	98,28
2018	23 231,21	20 555,40	158,33	75,40	20 135,22	186,46	2 567,82	709,53	124,39	1 728,53	5,37	108,00

Table B5. Number of vehicles in the Chinese fleet 2018, by class, and estimated km driven (Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)

Vehicle Class in China	Vehicle Mass According to Chinese Classification	Number of Vehicles in China in 2018 (number)	Vehicle Class in U.S. Dept of Transport Classification System	Proportion of vehicles in Chinese fleet, reclassified with U.S. dept transport Classification System	Average km traveled in 2018 by Vehicle Class in U.S. Dept Transport system (km)	Estimated total km driven by class in 2018 Chinese Fleet (projected from US dept of Transport) (km)
Passenger Vehicle		**205 554 000**	Passenger Car	203 689 500	18 298	3,72716E+12
Large		1 583 300				
Medium Size		754 000				
Small		201 352 200				
Mini		1 864 600	Motorcycle	1 864 600	3 792	7069842142
Goods Vehicle		**25 678 200**				
Heavy Duty	>= 12000 kg	7 095 300	Class 8 Truck	7 095 300	102 077	7,2427E+11
Medium	4500 >= Medium < 12000	1 243 900	Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1 243 900	34 327	42699324241
Light	< 4500 kg	17 285 300	Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	18 419 000	18 908	3,4827E+11
Mini	=< 1800 kg	53 700				
Other Vehicle Type		**1 080 000**				
	Total	232 312 300		232 312 300		4,85E+12
		232.3 Trillion Vehicles		232.3 Trillion Vehicles		4.85 Trillion km

20.2 Global vehicle fleet comparisons

Table B6-1. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
	Gasoline consumption per capita around the world (https://www.globalpetrolprices.com/articles/52/)		(UN World Population Data 2017)	(Consumption per capita times nation population)	(Appendix J, & ACEA 2018 for EU-28)	(annual nation consumption divided by number of vehicles)			
United States of America	4.39	1602.35	319,929,162	5.13E+11	268,913,221	1,906			1
Canada	3.62	1321.30	35,949,709	4.75E+10	23,846,147	1,992			1.04
Kuwait	2.84	1036.60	3,935,794	4.08E+09	1,876,188	2,175			1.14
Saudi Arabia	2.60	949.00	31,557,144	2.99E+10	6,600,000	4,538			2.38
Oman	2.53	923.45	4,199,810	3.88E+09	980,000	3,957			2.08
Qatar	2.48	905.20	2,481,539	2.25E+09	1,020,000	2,202			1.16
Luxembourg	2.43	886.95	566,741	5.03E+08	422,291	1,190	0.62		
Australia	2.40	876.00	23,799,556	2.08E+10	19,200,000	1,086			0.57
Brunei Darussalam	2.36	861.40	417,542	3.60E+08	300,897	1,195			0.63
Libya	2.03	740.95	6,234,955	4.62E+09	2,740,000	1,686			0.88
United Arab Emirates	1.98	722.70	9,154,302	6.62E+09	2,140,000	3,092			1.62
New Zealand	1.91	697.15	4,614,532	3.22E+09	4,240,000	759			0.40
Bahrain	1.86	678.90	1,371,855	9.31E+08	578,471	1,610			0.84
Iceland	1.58	576.70	330,243	1.90E+08	278,924	683			0.36
Bahamas	1.53	558.45	386,838	2.16E+08					
Venezuela (Bolivarian Republic of)	1.45	529.25	31,155,134	1.65E+10	4,510,000	3,656			1.92
Trinidad & Tobago	1.44	525.60	1,360,092	7.15E+08	397,000	1,801			0.94
Lebanon	1.41	514.65	5,851,479	3.01E+09	683,000	4,409			2.31
Switzerland	1.35	492.75	8,319,769	4.10E+09	5,003,551	819			0.43
Israel	1.26	459.90	8,064,547	3.71E+09	3,373,139	1,100			0.58
Japan	1.22	445.30	127,974,958	5.70E+10	77,938,515	731			0.05
Sweden	1.12	408.80	9,763,565	3.99E+09	5,398,128	739	0.39		
Malaysia	1.08	394.20	30,723,155	1.21E+10	13,308,716	910			0.48
Finland	1.07	390.55	5,481,966	2.14E+09	3,048,059	702	0.37		
Mexico	1.01	368.65	125,890,949	4.64E+10	37,353,597	1,242			0.65
Ireland	1.00	365.00	4,700,107	1.72E+09	2,409,983	712	0.37		
Greece	0.97	354.05	11,217,800	3.97E+09	6,235,761	637	0.33		
Denmark	0.94	343.10	5,688,695	1.95E+09	2,936,247	665	0.35		
Slovenia	0.92	335.80	2,074,788	6.97E+08	1,284,382	542	0.28		
Russian Federation	0.91	332.15	143,888,004	4.78E+10	54,779,626	872			0.46
Netherlands	0.91	332.15	16,938,499	5.63E+09	9,528,197	590	0.31		
Germany	0.84	306.60	81,707,789	2.51E+10	49,285,424	508	0.27		
Kazakhstan	0.84	306.60	17,749,648	5.44E+09	4,397,354	1,238			0.65
Turkmenistan	0.83	302.95	5,565,284	1.69E+09					
United Kingdom	0.80	292.00	65,397,080	1.91E+10	39,240,439	487	0.26		
Austria	0.76	277.40	8,678,657	2.41E+09	5,288,596	455	0.24		
Iran (Islamic Republic of)	0.73	266.45	79,360,487	2.11E+10	14,130,000	1,497			0.79
Norway	0.73	266.45	5,199,836	1.39E+09	3,236,944	428			0.22
Iraq	0.72	262.80	36,115,649	9.49E+09	3,900,000	2,434			1.28

Table B6-2. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
Estonia	0.70	255.50	1,315,321	3.36E+08	816,206	412			0.22
Panama	0.67	244.55	3,969,249	9.71E+08	677,356	1,433			0.75
Ecuador	0.67	244.55	16,144,368	3.95E+09	2,267,344	1,741			0.91
Jordan	0.65	237.25	9,159,302	2.17E+09	1,130,000	1,923			1.01
Malta	0.65	237.25	427,616	1.01E+08					
Nambia	0.64	233.60	2,425,561	5.67E+08					
Botswana	0.61	222.65	2,209,197	4.92E+08	391,686	1,256			0.66
Jamaica	0.61	222.65	2,871,934	6.39E+08	190,000	3,365			1.77
South Africa	0.60	219.00	55,291,225	1.21E+10	9,600,412	1,261			0.66
South Korea (Republic of Korea)	0.60	219.00	50,593,662	1.11E+10	20,989,885	528			0.28
Singapore	0.60	219.00	5,535,262	1.21E+09	957,006	1,267			0.66
Costa Rica	0.59	215.35	4,807,852	1.04E+09	1,076,041	962			0.50
Kyrgyzstan	0.59	215.35	5,865,401	1.26E+09	1,330,000	950			0.50
Czech Republic	0.58	211.70	10,603,762	2.24E+09	6,119,478	367	0.19		
Italy	0.58	211.70	59,504,212	1.26E+10	42,862,046	294	0.15		
Chile	0.57	208.05	17,762,681	3.70E+09	4,444,941	831			0.44
Uruguay	0.52	189.80	3,431,552	6.51E+08	960,000	678			0.36
Mongolia	0.51	186.15	2,976,877	5.54E+08					
Coatia	0.51	186.15	4,236,016	7.89E+08	1,724,267	457	0.24		
Azerbaijan	0.50	182.50	9,617,484	1.76E+09	1,301,926	1,348			0.71
Argentina	0.50	182.50	43,417,765	7.92E+09	13,726,226	577			0.30
Hungary	0.47	171.55	9,783,925	1.68E+09	3,821,432	439	0.23		
Belize	0.47	171.55	359,288	6.16E+07	50,000	1,233			0.65
France	0.44	160.60	64,457,201	1.04E+10	38,651,953	268	0.14		
Belarus	0.43	156.95	9,485,772	1.49E+09	3,501,981	425			0.22
Dominican Republic	0.42	153.30	10,528,394	1.61E+09	1,610,551	1,002			0.53
Brazil	0.42	153.30	205,962,108	3.16E+10	74,454,951	424			0.22
Belgium	0.40	146.00	11,287,940	1.65E+09	6,538,095	252	0.13		
Latvia	0.40	146.00	1,992,663	2.91E+08	753,373	386	0.20		
Portugal	0.39	142.35	10,418,473	1.48E+09	5,824,700	255	0.13		
Slovakia	0.39	142.35	5,439,318	7.74E+08	2,461,598	315	0.17		
Spain	0.39	142.35	46,397,664	6.60E+09	28,026,696	236	0.12		
Poland	0.37	135.05	38,265,226	5.17E+09	25,329,863	204	0.11		
Georgia	0.35	127.75	3,951,524	5.05E+08	1,043,900	484			0.25
Algeria	0.35	127.75	39,871,528	5.09E+09	5,570,000	914			0.48
Indonesia	0.34	124.10	258,162,113	3.20E+10	22,512,918	1,423			0.75
Bolivia (Plurinational State of)	0.31	113.15	10,724,705	1.21E+09	770,000	1,576			0.83
Thailand	0.29	105.85	68,657,600	7.27E+09	15,490,503	469			0.25
Colombia	0.28	102.20	48,228,697	4.93E+09	5,800,000	850			0.45
El Salvador	0.27	98.55	6,312,478	6.22E+08	260,000	2,393			1.26

Table B6-3. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
Maldives	0.27	98.55	418,403	4.12E+07					
Ukraine	0.26	94.90	44,657,704	4.24E+09	12,834,673	330			0.17
Bulgaria	0.26	94.90	7,177,396	6.81E+08					
Romania	0.25	91.25	19,876,621	1.81E+09	6,408,904	283	0.15		
Syrian Arab Republic	0.25	91.25	18,734,987	1.71E+09	6,900,000	248			0.13
Honduras	0.24	87.60	8,960,829	7.85E+08					
Egypt	0.23	83.95	93,778,172	7.87E+09	5,733,810	1,373			0.72
China	0.22	80.30	1,397,028,553	1.12E+11	232,312,300	483		0.25	
Guatemala	0.22	80.30	16,252,429	1.31E+09	1,862,535	701			0.37
Serbia	0.21	76.65	8,851,280	6.78E+08	2,052,067	331			0.17
Yemen	0.21	76.65	26,916,207	2.06E+09	1,000,000	2,063			1.08
Paraguay	0.21	76.65	6,639,119	5.09E+08	652,886	779			0.41
Viet Nam	0.21	76.65	93,571,567	7.17E+09	2,170,000	3,305			1.73
China, Hong Kong SAR	0.21	76.65	7,245,701	5.55E+08	674,253	824			0.43
Macedonia TFYR	0.20	73.00	2,079,308	1.52E+08	425,764	357			0.19
Peru	0.19	69.35	31,376,671	2.18E+09	2,444,478	890			0.47
Fiji	0.18	65.70	892,149	5.86E+07					
Angola	0.18	65.70	27,859,305	1.83E+09	880,000	2,080			1.09
Republic of Moldova	0.18	65.70	4,065,980	2.67E+08	715,480	373			0.20
Lithuania	0.17	62.05	2,931,926	1.82E+08	1,295,630	140			0.07
Tunisia	0.17	62.05	11,273,661	7.00E+08	1,450,000	482			0.25
Armenia	0.17	62.05	2,916,950	1.81E+08	489,346	370			0.19
Nigeria	0.17	62.05	181,181,744	1.12E+10	11,458,370	981			0.51
Nicaragua	0.15	54.75	6,082,035	3.33E+08	480,000	694			0.36
Ghana	0.15	54.75	27,582,821	1.51E+09	890,000	1,697			0.89
Uzbekistan	0.15	54.75	30,976,021	1.70E+09					
Cuba	0.14	51.10	11,461,432	5.86E+08	480,000	1,220			0.64
Gambia	0.14	51.10	1,977,590	1.01E+08					
Sri Lanka	0.14	51.10	20,714,040	1.06E+09	1,469,821	720			0.38
Afghanistan	0.14	51.10	33,736,494	1.72E+09	1,572,663	1,096			0.58
Albania	0.13	47.45	2,923,352	1.39E+08	481,114	288			0.15
Gabon	0.13	47.45	1,930,175	9.16E+07					
Philippines	0.11	40.15	101,716,359	4.08E+09	3,822,544	1,068			0.56
Solomon Islands	0.11	40.15	587,482	2.36E+07					
State of Palestine	0.11	40.15	4,662,884	1.87E+08					
Turkey	0.09	32.85	78,271,472	2.57E+09	16,320,927	158			0.08
Sudan	0.09	32.85	38,647,803	1.27E+09					
Togo	0.08	29.20	7,416,802	2.17E+08	198,000	1,094			0.57
Pakistan	0.07	25.55	189,380,513	4.84E+09	10,000,000	484			0.25
Morocco	0.06	21.90	34,803,322	7.62E+08	3,570,000	213			0.11

Table B6-4. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
Cameroon	0.06	21.90	22,834,522	5.00E+08	347,000	1,441			0.76
Cape Verde	0.06	21.90	532,913	1.17E+07					
Zambia	0.06	21.90	16,100,587	3.53E+08	370,000	953			0.50
Kenya	0.05	18.25	47,236,259	8.62E+08	1,381,473	624			0.33
Liberia	0.05	18.25	4,499,621	8.21E+07	63,000	1,303			0.68
Haiti	0.05	18.25	10,711,061	1.95E+08	80,000	2,443			1.28
India	0.05	18.25	1,309,053,980	2.39E+10	28,860,000	828			0.43
Zimbabwe	0.04	14.60	15,777,451	2.30E+08	940,000	245			0.13
Senegal	0.03	10.95	14,976,994	1.64E+08	660,000	248			0.13
Papua New Ginea	0.03	10.95	7,919,825	8.67E+07					
Burkina Faso	0.03	10.95	18,110,624	1.98E+08	297,000	668			0.35
Uganda	0.03	10.95	40,144,870	4.40E+08	490,000	897			0.47
North Korea (Dem. People's Republic of Korea)	0.03	10.95	25,243,917	2.76E+08					
Guinea	0.03	10.95	12,091,533	1.32E+08					
Mozambique	0.03	10.95	28,010,691	3.07E+08	400,000	767			0.40
Ivory Coast (Côte d'Ivoire)	0.03	10.95	23,108,472	2.53E+08	940,000	269			0.14
United Republic of Tanzania	0.02	7.30	53,879,957	3.93E+08	380,000	1,035			0.54
Mauritania	0.02	7.30	4,182,341	3.05E+07	41,000	745			0.39
Malawi	0.02	7.30	17,573,607	1.28E+08	139,000	923			0.48
Rwanda	0.02	7.30	11,629,553	8.49E+07					
Mali	0.02	7.30	17,467,905	1.28E+08	203,000	628			0.33
Nepal	0.02	7.30	28,656,282	2.09E+08					
Niger	0.02	7.30	19,896,965	1.45E+08					
Lao People's Democratic Republic	0.01	3.65	6,663,967	2.43E+07					
Ethiopia	0.01	3.65	99,873,033	3.65E+08	831,000	439			0.23
Bangladesh	0.01	3.65	161,200,886	5.88E+08	620,000	949			0.50
						1	0.210	0.253	0.622
						USA	EU-28	China	RoW

21 APPENDIX C: COMPARISON BETWEEN THE ELECTRIC EV SOLUTION AND THE HYDROGEN ECONOMY SOLUTION TO SUBSTITUTE FOR PETROLEUM FUELED ICE

This section directly compares the full electric vehicle for the global fleet to a fully hydrogen powered H_2 fuel cell vehicle global fleet. Table C1 compares the quantity of electricity required to charge the batteries of an entirely EV global fleet of vehicles (Scenario A in Michaux 2021) compared to the electricity required to produce the required annual mass of hydrogen needed to fuel an entirely H_2 fuel cell global fleet of vehicles (Scenario C in Michaux 2021). As can be observed, the hydrogen solution requires between 2 and 4 times the electricity for it to be implemented. This has important implications. To deliver this extra electricity, 2 to 4 times the installed capacity in power (Table C1) generation needs to be constructed. This is not a trivial matter.

Figure C1 shows a required electrical power direct comparison between the EV Scenario A and the fuel cell Scenario C against what electric power was generated in the year 2018.

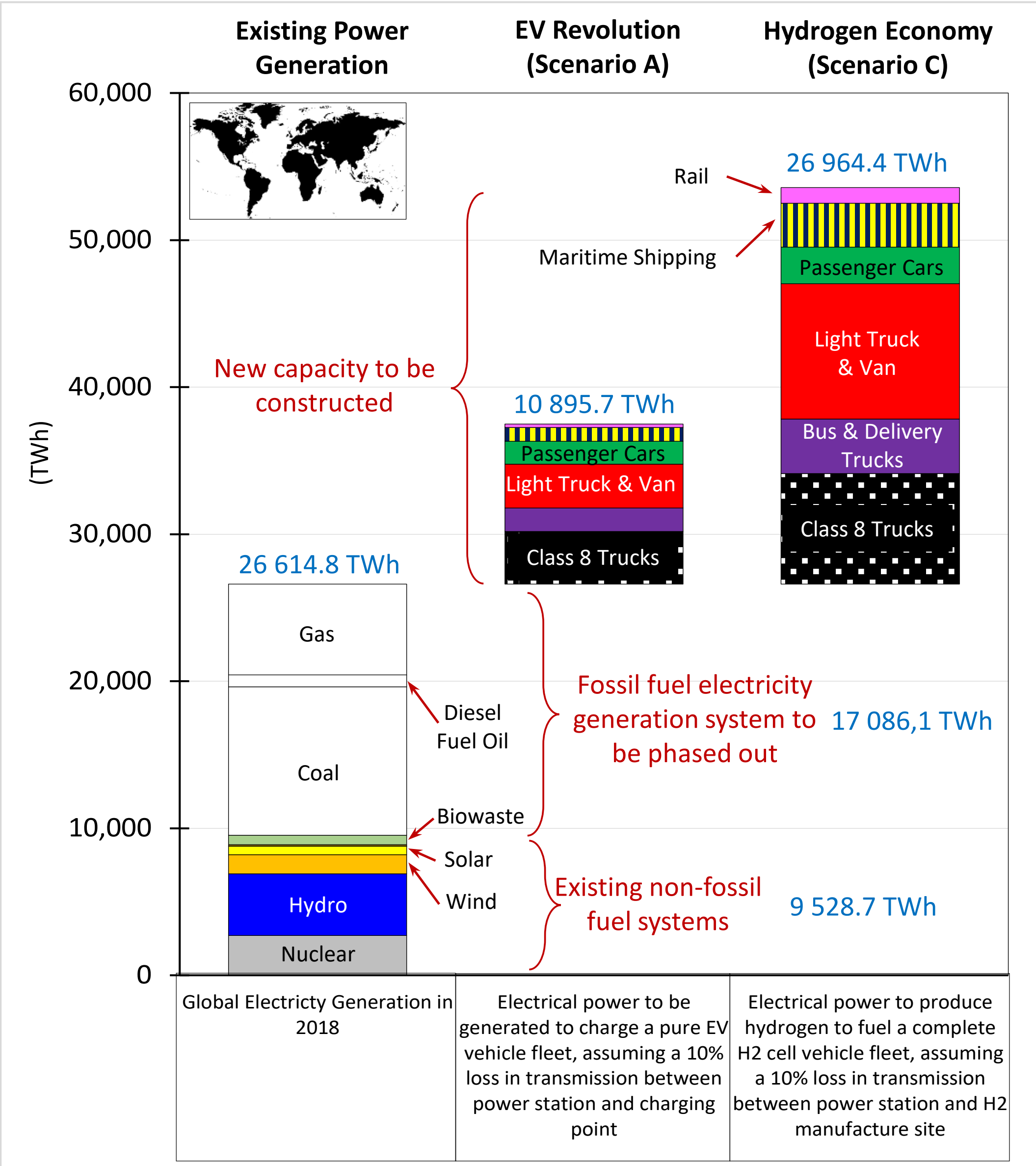

Figure C1. Comparison of the global size of the hydrogen economy power requirements (Scenario C) to the complete global electric vehicle fleet power requirements (Scenario A), and power production in 2018 (Michaux 2021) (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

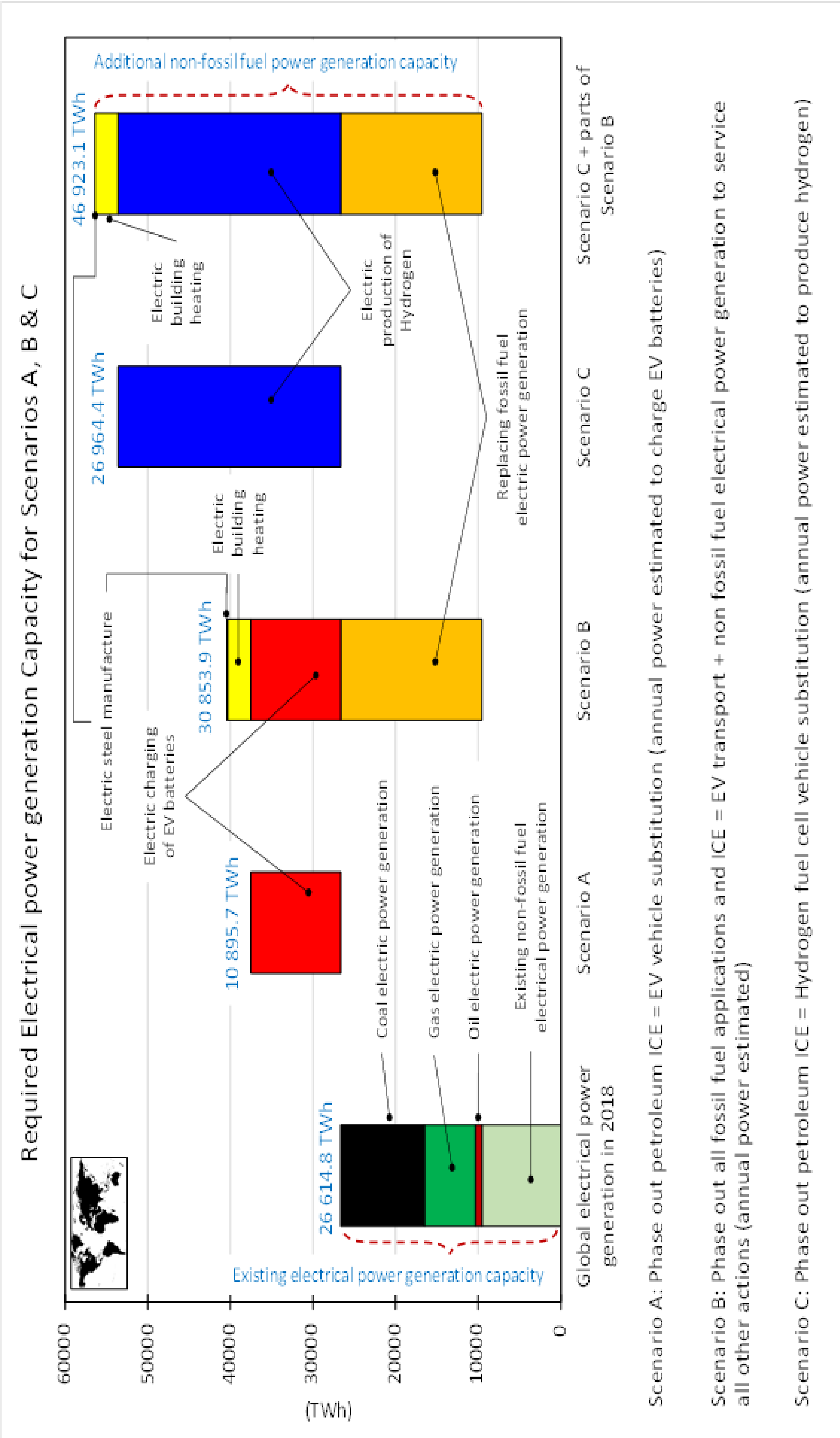

Figure C2. Extra non-fossil fuel electrical power to be constructed for Scenarios A, B and C (Michaux 2021) (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Figure C2 expands upon Figure C1 where the extra power required to charge a fully EV vehicle fleet (Scenario A in Michaux 2021) is compared against the extra power needed to charge the EV fleet but also phase out fossil fuel power generation entirely and substitute with non-fossil fuel power (17 086.1 TWh from Scenario B in Michaux 2021). If gas for heating (2816 TWh) and coal for steel production (56.5 TWh) was included, then the total non-transport contribution from Scenario B would be 19 958.7 TWh. Both of these were then compared to the hydrogen economy of fuel cell vehicles (Scenario C in Michaux 2021), and then against a hydrogen fuel cell vehicle fleet with a fully non-fossil fuel power generation system. Of the power generated in 2018, only 9 528.7 TWh was non-fossil fuels, which means that all other capacity has to be built from that base level.

Table C1. Comparison the annual electrical power to be generated to charge a global fleet of pure EV vehicles to the electrical power to produce the annual mass of hydrogen to fuel a global complete H_2 cell vehicle fleet (Michaux 2021)

Vehicle	Required annual electrical power to be generated to charge a global fleet of pure EV vehicles, assuming a 10% loss in transmission between power station and charging point (TWh)	Electrical power to produce the annual required mass of hydrogen to fuel a global complete H_2 cell vehicle fleet, assuming a 10% loss in transmission between power station and H_2 manufacture site (TWh)	Ratio of electric power needed to charge a global fleet of pure EV vechicles to the electric power needed to produce enough of H_2 to power a global fleet of Fuel Cell vehicles
Class 8 Truck	3,564.3	7,503.7	2.1
Bus & Delivery Truck	1,597.5	3,710.4	2.3
Light Truck & Van	2,988.6	9,203.9	3.1
Passenger Car	1,545.9	2,494.5	1.6
Motor Cycle	26.5		N/A
Maritime Shipping	945.9	2,983.4	3.2
Rail Transport	226.6	1,066.5	4.7
Sum Total	10,895.2	26,962.4	2.5
			Average Ratio

Table C2 shows the mass of energy storage required to be on board the vehicle while operating. The mass of the battery needed to power the EV vehicle was compared against the mass of the H_2 fuel tank needed to power the fuel cell vehicle, for each vehicle class. The mass of the needed hydrogen tank was assumed to have a storage density for 700 bar compressed hydrogen to be 5.7 wt% (similar to the Toyota Mirai passenger car). It is clear that the hydrogen fuel cell solution has a much lighter mass energy storage than the EV solution, by an average multiplier of 3.2.

Table C2. Comparison the estimated mass of energy storage of an EV vehicle (a Lithium-Ion Battery) to the estimated mass of the energy storage of a fuel cell vehicle (compressed H_2 tank at 700 bar pressure) of the same class doing a similar task (Michaux 2021)

Vehicle	Scenario A - EV Vehicles		Scenario C - Hydrogen Fuel Cell Vehicles	Ratio between mass of EV battery and mass of H_2 tank
	Estimated needed capacity of the EV battery in the vehicle (kWh)	Estimated mass of lithium ion battery in vehicle, @230 Wh/kg (kg)	Estimated weight of 700 bar pressure compressed hydrogen storage tank @ 5.7 wt% storage density (kg)	
Class 8 Truck	450.0	1,957	563	3.5
Bus & Delivery Truck	227.5	896	474	1.9
Light Truck & Van	42.1	183	123	1.5
Passenger Car	46.8	203	70	2.9
Motor Cycle	21.5	80	N/A	N/A
Rail Freight Locomotive	65,000	282,609	75,789	3.7
Maritime Shipping				
Small Vessel	14,269.5	62,041	16,689	3.7
Medium Vessel	358,397.3	1,558,249	419,178	3.7
Large Vessel	4,977,739.7	21,642,347	5,821,918	3.7
Very Large Vessel	11,614,726.0	50,498,809	13,584,475	3.7
			Average:	3.2

Table C3 shows the same comparison as Table C2, but instead of compressed hydrogen gas, storage is in the form of liquid hydrogen in cryogenic tanks. This has been presented as liquid hydrogen has a much smaller mass and volume of storage system for the same unit of mass of hydrogen fuel. The EV storage system mass ratio to liquid hydrogen storage system is approximately 9:1. This would be important for the large long range vehicles like very large ships. The engineering and logistics of liquid hydrogen are much more complex than compressed hydrogen gas. The viability of the system should consider all of these things.

Table C3. Comparison the size of energy storage of an EV vehicle (a Lithium-Ion Battery) to the size of the energy storage of a fuel cell vehicle (cryogenic liquid H2 tank) of the same class doing a similar task (Michaux 2021)

Vehicle	Estimated needed capacity of the EV battery in the vehicle (kWh)	Estimated mass of lithium ion battery in vehicle, @230 Wh/kg (kg)	Estimated mass of cryogenic liquid hydrogen storage tank @14 wt% storage density (kg)	Ratio between mass of EV battery and mass of cryogenic liquid H_2 tank
Rail Freight Locomotive	65,000	282,609	30,857	9.2
Maritime Shipping				
Small Vessel	14,269.5	62,041	6,795	9.1
Medium Vessel	358,397.3	1,558,249	170,665	9.1
Large Vessel	4,977,739.7	21,642,347	2,370,352	9.1
Very Large Vessel	11,614,726.0	50,498,809	5,530,822	9.1

This has clear implications. A fuel cell vehicle will be able to have a much greater range and capacity to carry cargo and passengers than an EV. So, the fuel cell is more appropriate for long range and cargo transport applications.

22 APPENDIX D - BIOPLASTICS AND PLASTICS MANUFACTURED FROM BIOMASS

There is no accepted economically viable substitution for plastics in current technology nor the non-fossil fuel feedstocks to make them in the volumes the global industrial ecosystem currently demands. Petrochemicals are economically cheaper to produce and often have better material performance properties.

However, it is now required to examine the phasing out of fossil fuels like oil, gas, and coal, all of which are used as feedstocks to plastics manufacture. There are a number of alternative process paths, but they are logistically impractical, currently difficult to scale and/or the resulting products have performance issues. The most promising is the bioplastics industry.

Bioplastics are plastic materials that have been manufactured from renewable biomass sources and raw materials. Not all sources are as effective in the production of a bioplastic, and it is appropriate to optimize the raw material of the bio plastic product to the final application. Examples of source materials include vegetable fats and oils, corn starch, straw, woodchips, sawdust, recycled food waste, etc. Bioplastic can be made from agricultural by-products and also from used plastics (i.e. plastic bottles and other containers) by using microorganisms. Bioplastics are usually derived from sugar derivatives, including starch, cellulose, and lactic acid.

The IEA (2018b) estimates that to produce just chemicals with biomass as feedstock and process energy (including the refining sector), rather than with natural gas, coal, or oil, would require half of the world's sustainable renewable biomass production by 2030 (Friedemann 2021). That much biomass would be about 2 385 million metric tons of oil equivalent (Mtoe) equal to 102 ExaJoules (EJ) each year. So, there are significant challenges with a direct substitution of bioplastics to replace petrochemical plastics.

A clear advantage of bioplastics is that they are designed to be at least partially biodegradable. Figure E1 shows a matrix of bioplastics in context of the source raw material and their approximate biodegradability.

Bioplastics are sustainable, largely biodegradable, and biocompatible. Today, bioplastics have become a necessity in many industrial applications such as food packaging, agriculture and horticulture, composting bags, and hygiene (Ashter 2016). Bioplastics have also found their use in biomedical, structural, electrical, and other consumer products. There are three fundamental methods to produce bioplastics.

1. To make use of natural polymers which may be modified but remain mostly intact. For example, starch plastics.
2. To produce bio-based monomers by fermentation or conventional chemistry and to polymerize these monomers in a 2nd step. For example, polylactic acid.
3. To produce bio-based polymers directly in microorganisms or in genetically modified crops.

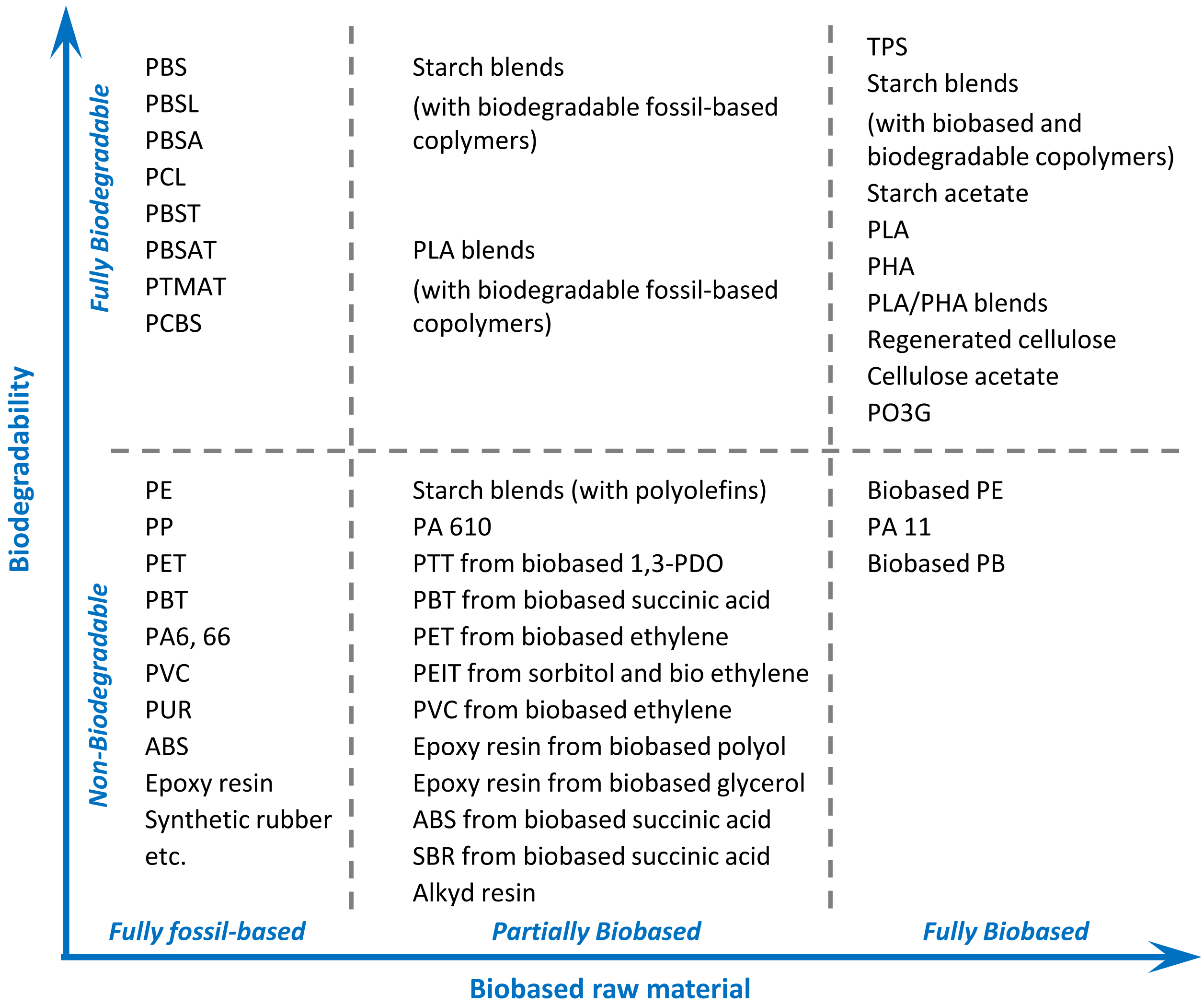

Figure D1. Bio-based plastics and their biodegradability (Shen *et al* 2009)

There are twelve building block chemicals that can be produced from sugars via biological or chemical conversions (Table D1) (U.S. DoE 2004). The twelve building blocks can be subsequently converted to several high-value bio-based chemicals or materials. Building block chemicals, as considered for this analysis, are molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules. The twelve sugar-based building blocks are 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, sorbitol, and xylitol/arabinitol (U.S. DoE 2004).

Table D1. The twelve building block chemicals that can be produced from sugars via biological or chemical conversions (Source: U.S. Dept of Energy 2004)

Building Blocks
1,4 succinic, fumaric and malic acids
2,5 furan dicarboxylic acid
3 hydroxy propionic acid
aspartic acid
glucaric acid
glutamic acid
itaconic acid
levulinic acid
3-hydroxybutyrolactone
glycerol
sorbitol
xylitol/arabinitol

Below is a list of the approximate groupings of bioplastic products (also shown in Table 10.2).

- Cellulose polymers
- PLA (polylactic acid)
- PTT (polytrimethylene)
- PA (polyamides or nylon)
- PHA (polyhdroxyalkanoates)
- PE (polyethylene)
- PVC (polyvinylchloride)
- PBS (polybutylene succiniate)
- PET (polyethylene terephthalate)
- PEIT (polyehthylene-co-isosorbite terephthalate)
- PUR (polyurethane)
- Thermosets (e.g. epoxy resins)

While it is clear that bioplastics are not as sophisticated in material properties performance compared to petrochemical plastics, bioplastics may be the solution to phase out the use of petrochemicals. Bioplastics could be used in applications that do not need high performance material properties. A small number of plastic applications that do require high performance material properties could continue to be petrochemical based. This hybrid solution would phase out the majority of oil, gas and coal consumption currently tasked to plastics manufacture, but would also maintain industrial requirements.

Table D2. Overview of most important groups and types of bioplastics (Source: Shen *et al* 2009)

Group	Bio-based plastics (group)	Type of polymer	Types/Structure/Production Method
1	Starch Plastics	Polysaccharides	Partially fermented starch; Thermoplastic starch (TPS); Chemically modified starch; Starch blends; Starch composites
2	Cellulose polymers	Polysaccharides	Organic cellulose esters; Regenerated cellulose
3	Polylactide (PLA)	Polyester	Bio-based monomer (lactide) by fermentation, followed by polymerisation
4	Polytrimethylene terephthalate (PTT)	Polyester	Bio-based 1,3-propanediol (1,3-PDO) by fermentation plus petrochemical terephthalic acid (or DMT)
5	Polyamides	Polyamide	
	a. PA11		Bio-based monomer 11-aminoundecanoic acid from castor oil
	b. PA610		Monomer sebacic acid from castor oil
	c. PA6		Bio-based monomer caprolactam by fermentation of sugar
	d. PA66		Bio-based adipic acid by fermentation
	e. PA69		Bio-based monomer obtained from oleic acid via azelaic (di)acid
6	Polyhdroxyalkanoates (PHA)	Polyester	Direct production of PHA by fermentation
7	Polyethylene (PE)	Polyolefin	Bio-based monomer ethylene obtained from ethanol; ethanol is produced by fermentation of sugar.
8	Polyvinylchloride (PVC)	Polyvinyls	Monomer vinyl chloride can be obtained from bio-based ethylene (from ethanol)
9	Other Thermoplastics *		
	a. Other polyesters (PBT, PBS, PBSL, PBSA, PBST, PBAT, PET, PEIT PVAc, Polyacrylates, PTN, PTI, thermoplastic elastomoers)	Polyester	Variou carboxylic acids, various alcohols
	b. Other ethylene-based compounds (e.g. polystyrene and EPDM rubber)	Various	Ethylene by dehydration of bio-ethanol, reacted with other compounds
	c. Methanol-based compounds (e.g. phenolic resins, urea formaldehyde resins, melamine formaldehyde resins)	Various	Syngas by gasification of biomass, and synthesis of methanol, reacted with other compounds
	d. Propylene-based compounds (e.g. PP, polyacrylates, PUR, PA)	Various	Thermochemical propylene production via bionaphtha plus steamcracking or via biomethanol, followed by Lurgi's methanol-to-propylene (MTP) process or UOP's methanol-to-olefins process.
10	Polyurethanes (PUR)	Polyurethanes	React polyol with isocyanate. Bio-based polyol can be prodcued from vegetable oils.
11	Thermosets	Cross-linked polymers	
	a. Epoxy resins	Epoxy resins	Diglycidyl ether of bisphenol A (DGEBA) derived from bisphenol A and epichlorohydrin (ECH). ECH can be produced by glycerine-to-epichlorohydrin (GTE) process; glycerine is a byproduct of bio-diesel production.
	b. Epoxidised vegetable oils	Epoxide	Addition of oxygen to alkenes
	c. Thermosets based on 1,2-PDO and 1,3-PDO	Unsaturated polyester	Polycondensation of unsaturated and saturated dicarboxylic acids with diols.
	d. Alkyd resins	Alkyd resin	Condensation polymerization of polyols, organic acids and fatty acids or triglyceride oils

* Abbreviations: PBT=polybutylene terephthalate; PBS=polybutylene succinate; PBSL=polybutylene succinate-co-lactate; PBAT=polybutylene adipate-co-butylene terephthalate; PET=polyethylene terephthalate; PEIT=polyethylene-co-isosorbite terephthalate; PVAc=polyvinyl acetate; PTN=polytrimethylene naphthalate; PTI=polytrimethylene isophthalate; EPDM=ethylene propylene diene M-class rubber; PP=polypropylene; UOP=Universal oil Products LLC.

22.1 Starch Plastics

Table D3 Overview of starch use for food and non-food purposes in Europe in 2007 (Shen et al 2009)

Sector	Consumption		
	10^6 tonnes	(%) total	% (of non-food, non-fuel)
Food/Feed, Total *	5.6	50%	-
Confectionary & drinks	2.9	26%	-
Processed food	2.6	23%	-
feed	0.1	1%	-
Non-food (without starch for ethanol used as fuel, Total *	3.7	33%	100%
Corrugating & paper making	2.6	23%	70%
Pharmacutical & chemcials	0.7	6%	19%
Other non-food	0.4	4%	11%
Fuel ethanol **	1.9	17%	-
Total	11.2	100%	-

* Data source AFF (2009)

** Estimate done in (Shen et al 2009)

Table D4. Properties and uses of various chemical modified corn starch (Shen et al 2009)

Type	Distinguished properties	Common commercial non-food use
Acid-modified	Decreased hot-paste viscosity compared to unmodifed starches	Textile sizing agents; as binding materials in cardboard making
Cross-linkeded	Reduced peak viscosity, increased paste stability	Ingredients in antiperspirants and textile printing paste; as oil-well drilling muds, printing ink, charcoal briquette binders, fiberglass sizing, and textile sizing.
Acetylated (ester)	Excellent paste clarity and stability, good freeze - thaw stability; hydrophobic for high degree of substitution starch acetate	Low degree of substitution:Warp sizing in textile; forming sizes, and surface sizes in paper making. High degree of subsitution: thermoplastic molding and in films as plasticizer.
Phosphate, monoesters (ester)	Reduced gelatinization temperature, reduced retrogradation	Wet-end additives in paper making; sizes in textile (polyester) and thickeners in textile printing inks.
Hydroxypropyl (ester)	Increased paste clarity, reduced retrogradation, good freeze - thaw stability	Surface sizing and wet ends in paper making; low DS starch ethers are used as warp sizing in textiles.

Table D5. Properties of selected starch plastics (Source: Shen et al 2009)

Type of Plastics	Partially fermented starch	TPS	Starch Blends						For Comparison
Product name and type	Solanyl ® BP [1]	Bioplast TPS® [1]	Mater-Bi ® Y101U [2]	Mater-Bi ® ZF03U/A [2]	Bioplast GF106 [1]	Bioplast GF105/30 [3]	BIOPAR ® [1, 4]	Cereplast Hybrid resin [5]	
Polymer	Starch	Starch	Starch - cellulose acetate	Starch - PCL	Starch - copolymer	Starch - copolymer	Starch - copolymer	Starch - PP	LDPE [6]
Resin grade	Injection moulding		Injection moulding	Film	Film	Film	Film	Injection moulding - PP	Film
Melt flow rate (g / 10 min)			8	4.7	1 - 6	5 - 9	2 - 7	3 - 6	
Density (g/cm^3)	1.29	1.3 - 1.5	1.34	1.23	1.2 - 1.3	1.21	1.26 - 1.29	1.04	0.92
Tensile strength at yield (MPa)	24		26	31	20 - 35	38 (TD) 44 (MD)	20 - 30	16.6	20 - 25
Elongation at yield (%)			27	900	500 - 900	400 - 500	300 - 1200	9.5	400 - 700
Flexural Modulus (MPa)	1730		1700	185			25 - 600	965	
HDT (^{0}C)								60	
VICAT Softening point (^{0}C)	52.9								
Melting Point (^{0}C)				64					110
Biodegradable (Yes/No)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Bio-ba/Partially/Fully)	Fully	Fully	Fully	Partially	Partially	Partially	Partially	No	No

[1] Widdecke et al 2008, [2] Degli Innocenti 2008, [3] Biotec 2003, [4] BIOP 2008, [5] Cereplast 2008, [6] Schmitz & Janocha 2002

22.2 Cellulosic Polymers

Table D6. Major areas of applications in which the individual product groups of cellulose ethers are used (Shen et al 2009, Theilking & Schmidt 2006)

Carboxymethyl cellulose (CMC)	Methyl cellulose (MC), hydroxyalkyl methyl cellulose (HMC)	Hydroxyethyl cellulose (HEC)	Hydroxypropyl cellulose (HPC)
Paper	Tile adhesives	Latex paints	Adhesives
Detergents	Plaster/renders	Adhesives	Ceramics
Drilling for oil and gas	Pharma/cosmetics	Buildings materials	Cosmetics
Pharma	Joint compounds	Cosmetics	Encapsulation
Cosmetics	Wallpaper paste	Drilling for oil and gas	Food
Textile industry	Polymerisation	Agriculture	Household goods
Food	Food	paper	Printing inks
Coatings	Latex paints	Synthetic resins	Polymerisation
Encapsulation	Cement extrusion	Textile industry	Films

Table D7. Mechanical, thermal and water retention of selected staple fibres (Shen et al 2009)

Fibre name	Trade name	Density (g/cm^3)	Tenacity [a] (wet) (cN/tex)	Tenacity [a] (dry) (cN/tex)	Water retention (%)	Melting poin (°C)
Cotton		1.5 - 1.54 [1)]	26 - 40 [2)]	24 - 36	38 - 45 [3)]	n/a
Viscose	Lenzing Viscose	1.52 - 1.54 [1)]	10 - 13 [2)]	24 - 26	90 - 100 [3)]	n/a
Modal	Lenzing Modal	1.52 - 1.54 [1)]	19 -21 [2)]	34 - 36	60 - 65 [3)]	n/a
Lyocell	Tencel	1.50 [1)]	34 - 36 [2)]	40 - 42	60 - 70 [3)]	n/a [b]
Cellulose acetate	Arnel, Celco, Dicel	1.29 - 1.32 [1)]	10 -15 [1)]	20 - 30 [1)]	n/a	255 [1)]
PET [1)]	Dacron	1.36 - 1.41	30 - 55	28 - 55	03-May	250 - 260
PP [1)]	Herculon	0.9 - 0.92	25 - 60	25 - 60	0	160 - 175
PLA [4)]	Ingeo	1.25	n/a [b]	32 - 36	n/a [b]	170

Notes: 1) Schultze-Gebhardt & Herlinger 2002, 2) Abu-Rous & Schuster 2006, 3) Lenzing AG 2006, 4) NatureWorks LLC 2006

[a] Tenacity is expressed realtive to the fineness (1 tex = 1 gram per 1000 metres). Numbers for tenacity are based on both fiber fineness (tex) and cross-sectional area of the sample.

[b] n/a = data not available or not applicable

Table D8. Mechanical, thermal, and permeability properties of selected films (Schmitz & Janocha 2002)

Property	Units	Cellulose (uncoated)	Cellulose acetate [a]	LDPE [c]	HDPE [c]	OPP [c]
Thickness	µm	12 - 45	12 - 350	25 - 200	50 - 1000	4 - 80
Density	g/cm^3	1.45	1.3	0.92	0.95	0.91
Modulus of elasticity						
logitudinal	N/mm^2	5 300	1 500	170	900	2 000
lateral	N/mm^2	2 800	1 500	170	900	4 000
Melting point	°C	n/a[b]	n/a[b]	110	130	165
Permeability						
water vapour	g/m^2/d	very high	350	2.5	1	1.5
oxygen [d]	cm^3/m^2/d/bar	10	1 500	4 000	1 600	600
CO_2 [d]	cm^3/m^2/d/bar	100	10 000	16 000	7 000	1 800
nitrogen [e]	cm^3/m^2/d/bar	12	300	1 300	400	140

[a] cellulose acetate film containing plasticiser
[b] n/a = not applicable
[c] LDPE = low density polyethylene; HDPE = high density polyethylene; OPP = oriented polypropylene
[d] Film thickness = 40 µm, 23 °C
[e] Film thickness = 200 µm

22.3 Polylactic acid (PLA)

Table D9. Properties of NatureWorks® PLA polymers (NatureWorks LLC, 2008)

Used in the Application	Sheet Extrusion	Injecton Moulding	Oriented Film		Blow Moulded Bottles	
Polymer type	2002D polymer	3015D resin	4032D film	4042D film	7000D Bottle	7032D Bottle
Density (g/cm^3)	1.24 [b]	1.25 [b]	1.24 [c]	1.24 [c]	1.24 [b]	1.24 [b]
Melt flow rate, (g/10 min) (210 ^{0}C/2.16 kg) [d]	5 - 7	10 - 25	- [m]	-	5 - 15	5 - 15
Colour	Transp.	Transp.	-	-	-	-
Haze [e]	-	-	2.1%	2.1%	-	-
Gloss, 20^0 [e]	-	-	90	90	-	-
T_g (^{0}C)	-	55 - 65 [f]	-	135 [g]	55 - 60 [f]	55 - 60 [f]
T_m (^{0}C)	Amorphous no T_m	150 - 165 [g]	160 [e]	150 [e]	145 - 155 [g]	160 [g]
Tensile strength @ break (Mpa)	53 [h]	48 [i]	103 (MD) [h] 144 (TD) [h]	110 (MD) [h] 144 (TD) [h]	-	-
Tensile Modulus (GPa)	3.5 [h]	-	3.4 (MD) [h] 3.8 (TD) [h]	3.3 (MD) [h] 3.9 (TD) [h]	-	-
Tensile Elongation (%)	6.0 [h]	2.5 [i]	180 (MD) [h] 100 (TD) [h]	160 (MD) [h] 100 (TD) [h]	-	-
Flexural Strength (Mpa)	-	83 [j]	-	-	-	-
Flexural Modulus (Mpa)	-	3828 [j]	-	-	-	-
Transmission Rates	-					
O_2 (cc-mil/m^2 /24h atm)	-	-	550 [k]	550 [k]	-	550 [k]
CO_2 (cc-mil/m^2 /24h atm)	-	-	3000 [k]	3000 [k]	-	3000 [k]
Water vapour (g-mil/m^2/24h atm)	-	-	325 [k]	325 [k]	-	325 [k]

[a] Refer to NatureWorks® PLA processing guide (sheet extrusion, injection moulding, oriented film extrusion & blow moulding); [b] Testing method: ASTM D792; [c] Testing method: ASTM1505; [d] Testing method: ASTM D1238; [e] Testing method: ASTM 1003; [f] Testing method: ASTM D3417; [g] Testing method: ASTM D3418; [h] Testing method: ASTM D882; **MD** means polymer orientation in machine direction; **TD** means polymer orientation in transverse direction; [i] Testing method: ASTM D638; [j] Testing method: ASTM D790; [k] Testing method: ASTM D1434; [l] Testing method: ASTM E96; [m] data not available, not reported or not applicable.

Table D10. Thermal properties of amorphous versus crystalline and stereocomplex PLA (with courtesy to PURAC 2008)

Property	Amorphous PLA	Crystalline PLA	Stereocomplex PLA (50/50)
T_g (^{0}C)	55 - 60	55 - 60	60 - 70
T_m (^{0}C)	-	160 - 170	200 - 240
HDT (@0.45 MPa, ^{0}C)	55 - 60	100 - 150	160 - 200

23 APPENDIX E - HEAT AND ENERGY REQUIREMENTS FOR MANUFACTURE

Finland has a strong industrial sector. There are world class sites for refining of chemicals, recycling and metal production. The technology that supports the industrial ecosystem is global in nature, where feed stock raw materials, refined chemicals, manufactured components and manufactured technological units are transported across the globe. The value chain for most technology is spread across multiple time zones.

It is appropriate to understand the relationship between the industrial value chain throughout the ecosystem, energy, and heat requirements. In doing so, the replacement of fossil fuel feedstocks and energy sources is possible. If Finland is to become genuinely fossil free and maintain its industrial capability, then it is required to go through this process.

Manufacturing consumes 54 % of primary energy supply in the global industrial ecosystem (EIA 2019b). Moreover, manufacturing requires large quantities of energy in concentrated in individual industrial sites. This energy is also often required to be consistently and reliably supplied, often over a continuous time period measured in years. Industrial annual consumption of energy in the global market by raw material in 2018 was (EIA 2019):

- 73% of coal
- 37% of natural gas
- 7.2% of oil
- 42% of electricity generated

Understanding the challenges of replacing fossil fuel heating applications for manufacture is a relatively unknown task. While very few researchers have recognized this challenge, there is good data available for examination.

For instance, the Finnish Climate Change Panel has collected a report on possibilities for electrification in industry (Jegoroff, Arasto & Tsupari, 2021). The report concentrates on electrification in the production of steel and iron, concrete, minerals and bricks, pulp and paper industry, chemical industry and water treatment. However, it does not present quantitative information on energy needs or replacement possibulities, other than noting that typically in EU28-countries, about half of the heat used by industry is high-grade (over 400 °C) (Jegoroff, Arasto & Tsupari, 2021, 10).

The use of energy in industrial applications is very process requirement specific. That being stated, there are patterns. Heat is often required, where the steady temperature consistently maintained is critical to the manufacturing process. Industrial sites will draw large quantities of electric off the power grid, but most of the energy is generated directly with the combustion of fossil fuels (coal, gas, and oil) in furnaces, boilers, or kilns. Sometimes thermal heat is used directly, sometimes it is used to generate electricity on site, and sometimes it is used to make steam, which drives turbines. Examples of this are steel and cement production. In the United States, 75% of industrial energy use is to generate heat, with 83% generated from fossil fuels (Friedemann 2021, U.S. DoE 2014).

Fossil fuels has been the most efficient and effective method of generating large quantities of thermal heat that can be used industrially (Friedemann 2021). It has been the industrial application of thermal that has allowed the mass production of materials like steel or concrete (cement). It has been the underlying parameter that has allowed such high purity materials to be produced in any quantity (especially metals with very high melting temperatures), for which current engineering standards depend upon. Many renewable power technologies require high heat capability. For example, solar panels require 1 500 – 2 000 °C of heat to transform silicon dioxide into metallurgical grade silicon metal (Honsberg & Bowden 2019, Friedemann 2021). Thermal heat has been required to manufacture products such as fertilizers, glass, plastics, rubber, ceramics, computers, chemicals, and tools (Table E1).

Table E1 Manufacturing temperatures, energy proportion, operations and applications
(Source: U.S. DoE 2015, Friedemann 2021, Sandalow et al 2019, McMillan et al 2016)

Temperature (^{0}C)	Proportion of total US manufacturing energy consumption (%)	Manufacturing Operation	Application Examples
932 - 1 649	3.7	Nonmetal melting	Plastics, rubber, food prepartion, softening
721 - 1 649	17.8	Ore smelting and metal melting	Steelmaking and other metal production, glass, ceramics
621 - 1 449	7.3	Cement	Calcining 900 ^{0}C, Sintering 1 449 ^{0}C
721 - 1 649	3.7	Metal heat treating and reheating	Hardening; annealing; tempering; forging; rolling
377 - 1 099	1.7	Coking	Ironmaking and other metal production
160 -549	21.6	Drying	Water and organic compound removal
138 -649	2	Curing and forming	Coating; polymers; enameling; moulding; extrusion
110 - 460	29.3	Fluid heating	Food preparation: chemicals; ditsillation; cracking
850	-	Combustion gases/primary steam reforming	Nitrogenous fertilizer manufacturing
99 - 1 649	12.8	Other	Incineration; preheating; catalysis

To date, most of the tasks shown in Table E1 have been met with the use of fossil fuels (coal, gas and oil). To replace fossil fuels, non-fossil fuel power sources are required that are capable of consistently and reliably producing quantities of heat over 1 200 ^{0}C, for sustained time periods.

Most iron and steel are made in large scale blast furnaces that take time to be brought to a stable temperature high enough to produce metal products. Some of these industrial sites optimally run continuously for up to 20 years, without shutting down. Unexpected power outages or disruptions of fuel supply can damage the brickwork lining. Complex fabrication assembly lines like those that produce computer chip need to run continuously for weeks to accomplish the thousands of steps needed to make microchips. Even a short disruption can be very costly. For example, a half-hour power outage at Samsung's Pyeongtaek chip plant caused losses of over $43 million dollars (Reuters 2019). For some products, it may be possible to run in batches as opposed to a continuous process. If this were possible, it would be less energy efficient (otherwise it would be done now), cost more, and produce less product (Heinberg and Fridley 2016). Complex electronics (e.g. microchips), some chemicals, and other products might not be possible to produce in batch mode.

Unexpected outages can leave materials cooling in tanks and pipes, causing them to crystallize or harden, clogging the pipes (Friedemann 2021). Many processes need an exact continuous temperature and pressure because variations can cause metal fatigue and wear and tear. Even facilities that do not run continuously need to be up 60–95% of the time to repay their high capital investment (Friedemann 2021).

Currently, there are no means to store hours of high heat (Friedemann 2021). As many industrial processes need continuous heat a high temperature, either manufacturing plants are required to relocate to a continuous heat source like a nuclear power plant, or a completely new kind renewable power source has to be developed. Solar applications can only produce heat for a few hours at a time, then the sun sets. Wind is highly intermittent, as previously discussed, and is not suitable. For renewable power sources to truly substitute fossil fuels they must not only deliver enough electricity to replace fossil fuel applications in transport, but also must reach a "thermal parity" by powering industrial manufacturing processes that use high levels of heat in excess of 1 500 ^{0}C (Friedemann 2021). Table F2 shows non-fossil fuel heat sources.

Table E2. Maximum heat generated by non-fossil energy sources
(Source: U.S. DoE 2015, Friedemann 2021, Sandalow et al 2019)

Heat Source	Maximum Temperature Generated (⁰C)	Comment	Feasible heat supply for smelting, metal forming & cement manfucature applications?
Biomass (Fuel)	2204	Biodiesel, ethanol	**Yes**
Hydrogen (H_2 gas)	2093	Made from natural gas or electrolysis	**Yes**
Electric: Resistance	1802	Indirect heat	**Yes**
Solar: Parabolic dish	1204	Small surface area heated, only for a few hours at a time	No
Biomass: Charcoal	1099	From forests, agriculture, waste	No
Concentrated Solar Power (CSP)	982	Small surface area heated, only for a few hours at a time	No
CSP oven	982	Small surface area heated, only for a few hours at a time, not commerical	No
Nuclear: Advanced	850	Not commercial	No
Biomass: Birch wood	950	Depends on the tree, i.e., rewood is 364 ⁰C	No
Molten Salt	560	Thermal energy storage	No
Solar: Parabolic trough	400	Small surface area heated, only for a few hours at a time	No
Nuclear: Conventional	300	Generation III+ reactors	No
Geothermal	193		No
Electric: Microwave direct heat		Temperature depends on material	

Due to the size and operational footprint of each industrial asset, the manufacturing sector is global in nature. The feedstocks for one industrial plant are often sourced from a very geographically different region. This means that manufacturing is intimately linked with global transport logistics. The United States is a remarkable case study, where much of the needed logistics exist inside just one national economy. For the last century, it has been the dominant economy, and holds the international reserve currency. Historically, the United States has an unusual signature in that it is very large, has a large consumer base, is a globally significant supplier of raw materials, and has globally significant industrial capacity. China may well be evolving into this profile. The United States manufactures 18% of the world goods (West & Lansang 2018), which makes it an excellent case study to quantify how industrialization consumes energy. Figures E1 and E2 compilation of the energy consumption requirements for the United States manufacturing sector. These flowsheets were released by the U.S. Department of Energy in 2014 (U.S. Department of Energy 2014). Figure E1 provides a high-level view of supply and end use (primary energy use). Figure E2 shows details of how energy is distributed to onsite industrial end uses.

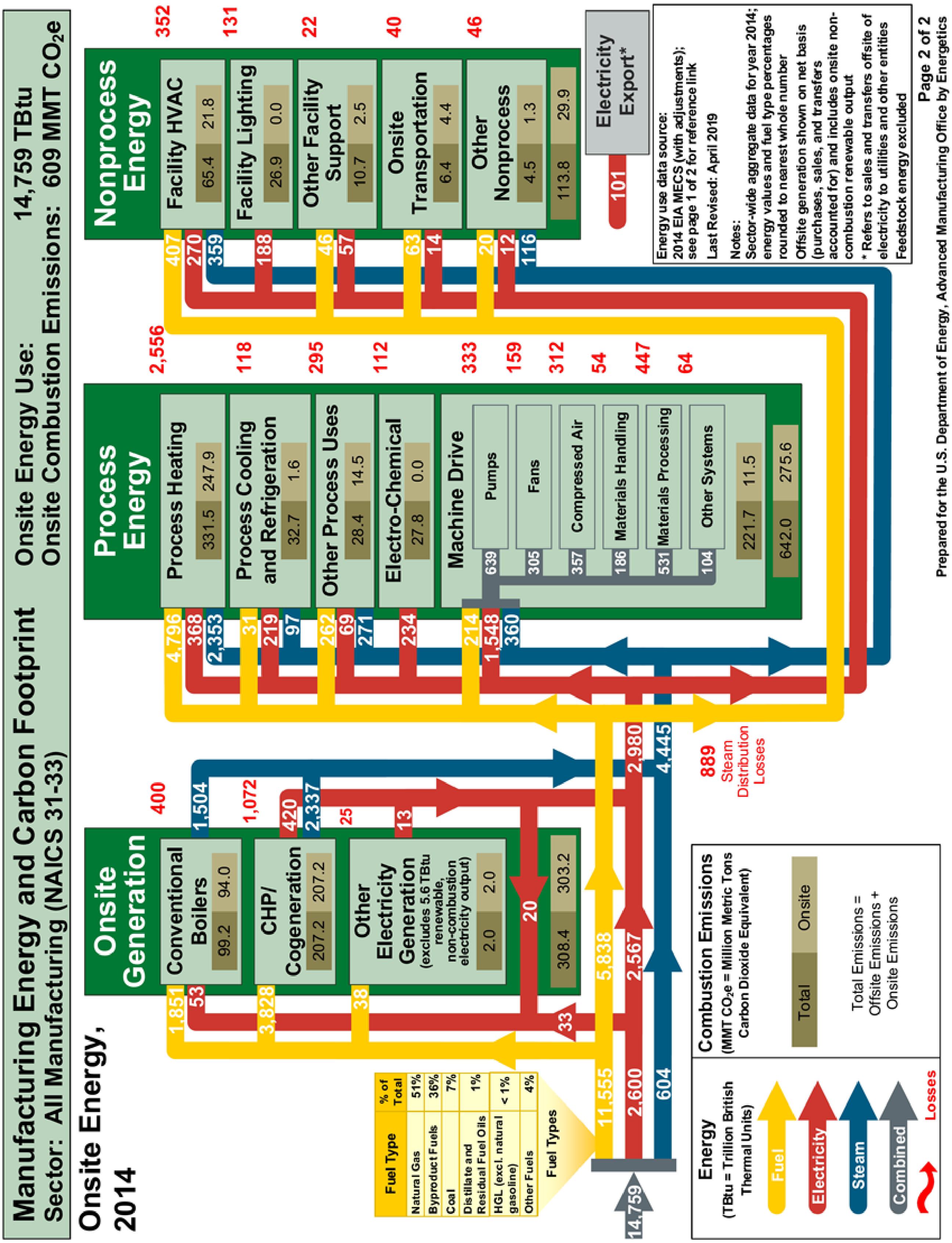

Figure E1. Manufacturing energy Onsite energy use of all manufacturing in the US, combines the footprints of 94% of manufacturing energy used for: Alumina and aluminum, cement, chemicals, computers, electronics, electrical equipment, fabricated metals, food and beverage, forest products, foundries, glass, iron and steel, machinery, petroleum refining, plastics, textiles, transportation equipment. Part 1 (US DoE 2014)
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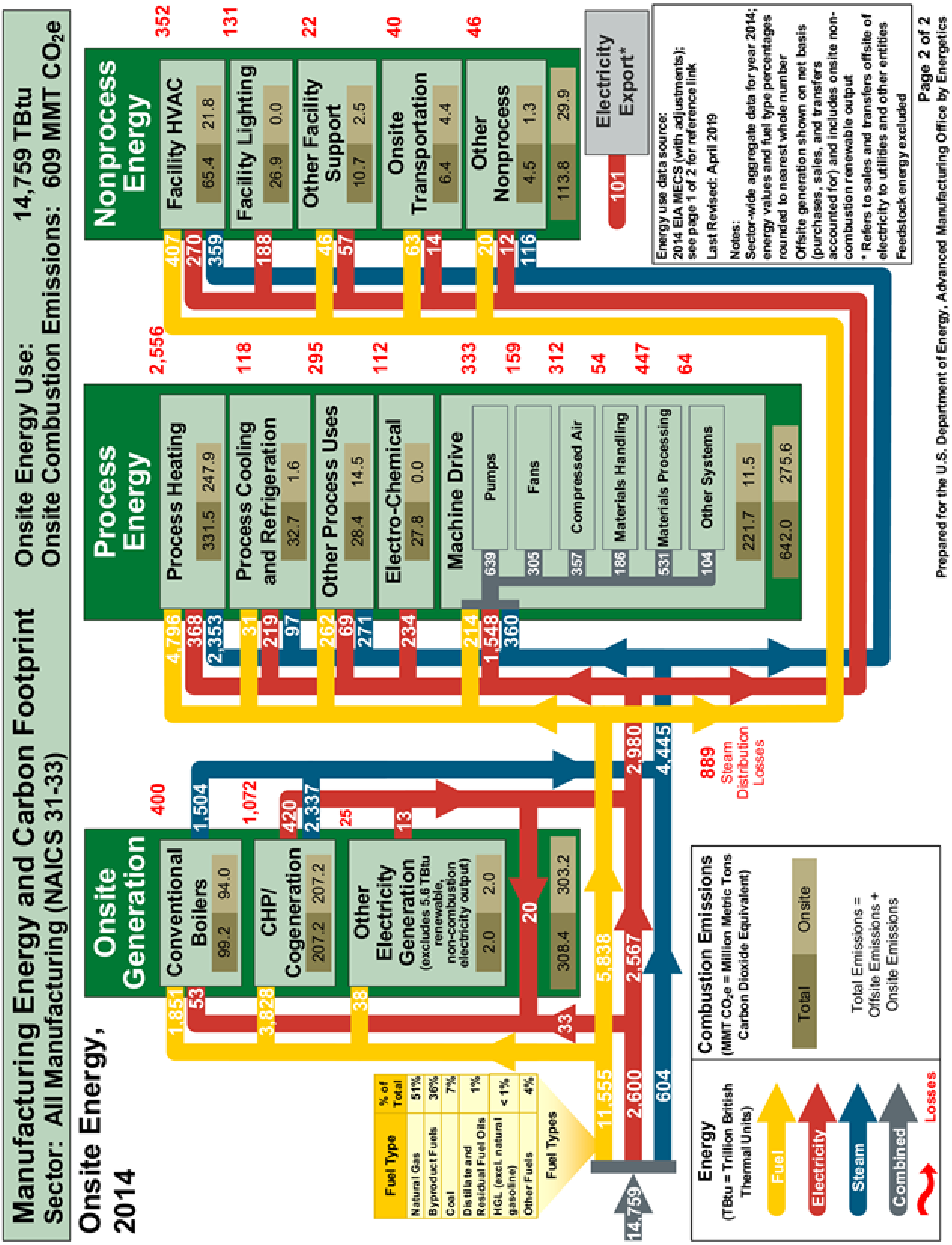

Figure E2. Manufacturing energy Onsite energy use of all manufacturing in the US, combines the footprints of 94% of manufacturing energy used for: Alumina and aluminum, cement, chemicals, computers, electronics, electrical equipment, fabricated metals, food and beverage, forest products, foundries, glass, iron and steel, machinery, petroleum refining, plastics, textiles, transportation equipment. Part 2 (US DoE 2014)
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Figures E1 and E2 represents a summary of all United States manufacturing (in 2014). Energy losses and inefficiencies are visible in these flow charts. Before fossil fuel energy is delivered to an industrial site, 27 % is lost in processes offsite (off site energy input of 20 008 TBtu into the energy generation system with an actual delivery of 14,759 TBtu to site) (Figure E1) (Friedemann 2021). A further 50 % of energy is lost in internal industrial site processes like electricity generation and steam production (7427/14,759) (14 759 TBtu delivered to site and 2 980 TBtu electricity and 4 445 TBtu of steam directly applied to engineering processes, with a net loss of 7 334 TBtu of energy in process) (Figure E2) (Friedemann 2021). The mechanics of these flowsheets are discussed in Brueske *et al.* (2012). With 77 % of energy losses, only 23% of that energy is converted into usable work.

To manufacture these products requires industrial conditions like stable high-volume supply of electrical power, fuels, and feedstocks. Most products have no known way of being made with electricity or renewables (Friedemann 2021). Most of the manufacturing value chain will have to be re-designed and re-tooled. Possibly new equipment and processes need to be developed to replace fossil fuel supported systems, for nearly all kinds of industry (Sandalow et al 2019).

This requirement to completely reinvent the manufacturing sector also impacts the current capability to produce engineering units for non-fossil fuel energy generation systems. Consider for example, what is required to construct a wind turbine array with 30 turbines connected to the electric power grid, or even a single solar panel. Most past developments of engineering have evolved with the assumption of easy access to concentrated electrical power, and concentrated thermal heat, both of which are consistently delivered for long periods of time. Rebuilding the manufacturing value chain to meet sustainable requirements of zero carbon emissions will be a challenge.

It is recommended that the United States Manufacturing sector case study is examined in full, then compared against manufacturing output for the relevant year. In doing so, the heat and energy needs of all the industrial sectors that are currently dependent on fossil fuels as feedstock or energy sources can be genuinely understood. Finland could then conduct its own planning for the future to phase out fossil fuels and retain its industrial capability.

24 APPENDIX F - MARITIME AND AVIATION TRANSPORT

Data gathered from Official Statistics Finland: http://www.stat.fi/til/uvliik/ and Salanne et. al. (2021).

Maritime transport data 2019

Cargo - 111,4 million tons, including

- 48 million tons exports
- 53,3 million tons imports

- 404 000 000 000 ton-kilometers
- 296 000 000 000 ton-kilometers exports
- 105 000 000 000 ton-kilometers imports
- 200 000 000 ton-kilometers internal, domestic

Fuel (both light and heavy fuel oil)

- 2 300 000 tons
    - 1 800 000 tons foreign, out-of-borders
    - 500 000 tons indirect foreign
    - 20 000 tons domestic, internal

Aviation transport data 2019

Fuel

• Kerosene	1 435 GWh
• Aviation gasoline ("lentobensiini")	10 GWh

Passengers and freight

• Passengers	26 267 299
• Freight Cargo	225 856 tons

25 APPENDIX G - BIOETHANOL FUEL USE IN AIRCRAFT

It is possible to produce jet fuel from biomass, in a fashion where jet aircraft can perform to specification. Conventional jet fuel is produced by refining petroleum crude. Its composition depends on the raw crude oil, but is typically around 20% paraffins, 40% isoparaffins, 20% naphthenes and 20% aromatics (Blakey, Rye & Wilson, 2011). Each of these components plays a critical role in providing specific fuel characteristics.

For example, the high hydrogen-to-carbon ratio of paraffins and isoparaffins enhances the heat density per unit mass of fuel; naphthenes help to reduce the freeze point, which is critical at high altitudes; and aromatics contribute to material compatibility and prevent leaks in the seals of some aircraft (Liu, Yan & Chen 2013, Blakey, Rye & Wilson 2011, Bauen *et al* 2009). For biofuel to be viable as jet fuel, all of these material specifications would be required to be met (Mawhood *et al* 2014).

The biomass to liquids (BTL) process involves the gasification of biomass feedstocks (after pre-treatment), followed by Fischer-Tropsch synthesis of the resulting syngas (also termed as gasification/Fischer-Tropsch synthesis or GFT). The ASTM-certified fuel produced by this pathway is called Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK).

The pretreated feedstock is gasified at high temperatures and pressures with a controlled volume of oxygen to generate synthesis gas (syngas), a mixture mostly composed of carbon monoxide and hydrogen. The syngas is then conditioned to remove CO_2 and impurities such as tar, H_2S, COS, HCN, NH_3 and HCl. This can involve a combination of physical and chemical process such as thermal or catalytic cracking, scrubbing, filters, and cyclones (Liu, Yan & Chen 2013, Güell *et al* 2012).

The clean syngas is subjected to Fischer-Tropsch synthesis, during which it reacts with hydrogen in the presence of a metallic catalyst (commonly iron, cobalt, or nickel). The reactions are usually conducted at temperatures of 150°C to 300°C and pressures of 10 to 40 bars (Maniatis, Weitz & Zschocke, 2013, Bauen et al., 2009). The resulting product is a mix of saturated hydrocarbons, ranging from gases to waxes. The mixture is upgraded to liquid fuels using methods common in conventional petroleum refineries, for example hydrocracking and distillation, or oligomerisation (Blakey, Rye & Wilson 2011).

Alcohol to jet (ATJ) refers to the conversion pathway that produces jet fuel from biomass via an alcohol intermediate (ethanol). A wide range of processes can be used to synthesise alcohols, depending on the characteristics of the feedstock. Sugars can be directly converted to alcohols though fermentation with yeasts or microbe, whilst starches are converted via acidic or enzymatic hydrolyzation (to release sugars), followed by fermentation. Conversion of lignocellulosic feedstocks is more complex, involving either aggressive hydrolyzation followed by fermentation, or thermochemical conversion (gasification to produce a syngas) followed by fermentation or catalytic hydrogenation to synthesize alcohols (Teelucksingh 2013, Güell *et al* 2012, Rosillo-Calle *et al* 2012).

The alcohols produced undergo a four-step upgrading process to create hydrocarbons in the jet fuel range (Teelucksingh 2013, Güell *et al* 2012):

1. Alcohols are catalytically dehydrated to generate olefins,
2. Olefins are oligomerised, typically in the presence of catalysts, to produce a middle distillate containing diesel and kerosene fractions.
3. The middle distillates are hydrogenated
4. Distillation

A wide range of biomass feedstocks are suitable for ATJ, including forestry and agricultural residues, corn starches and sugars, as well as municipal solid waste (Güell et al., 2012). Ideal biomass feedstocks are highly porous, contain low levels of highly soluble lignin and have low ash and acetyl content (as this can inhibit fermentation).

Jet fuel has a calorific density of 43.0 MJ/kg. This high value allows heavy aircraft like the A350-900 Airbus to fly 15 000 km by carrying only 141 000 liters of fuel. If this power system was phased out, then its replacement would have to do something similar (ideally). An electric powered system that could make such a large aircraft fly any practically useful distance would require a very heavy battery bank. A hydrogen fuel cell would require the storage of hydrogen fuel under pressure. The size and geometry (a reinforced cylinder) of this tank and the amount of hydrogen that could be stored would also mean the aircraft would have a short range or could not carry very much cargo.

A viable technology solution to phase out jet fuel was not able to be found in a useful from for this report. That is, clearly presented data in the widespread application at an industrial scale, at a cheap enough cost for society to access and use the outcome. The closest possible technology that could do this is the use of biofuels as an aviation tool (to be discussed in Section 22, Scenario D). More work needs to be done before this solution can be directly implemented though.

Since 2008, more than 150,000 flights have used biofuels. Only five airports have regular biofuel distribution in 2019 (Bergen, Brisbane, Los Angeles, Oslo, and Stockholm), with others offering occasional supply (Le Feuvre 2019). Trials of using algae as biofuel were carried out by Lufthansa, and Virgin Atlantic as early as 2008, although there is little evidence that using algae is a reasonable source for jet biofuels (Reddy & O'Neil 2015). By 2015, cultivation of fatty acid methyl esters and alkenones from the algae, isochrysis, was under research as a possible jet biofuel feedstock.

As of 2017, there was little progress in producing jet fuel from algae, with a forecast that only 3 to 5% of fuel needs could be provided from algae by 2050. Further, algae companies that formed in the early 21st century as a base for an algae biofuel industry have either closed or changed their business development toward other commodities, such as cosmetics, animal feed, or specialty oil products.

Current biojet volumes are on practice based on HVO product derived from fats. This is considered as the easiest and most potentially viable route to industrial scale biojet production in the short run. By 2030, it may be possible for biojet volumes to be produced by a gasification- Fischer-Tropsch pathway (J. Lehtonen personal communication).

This biofuel technology solution could make jet aviation viable after fossil fuels are phased out. However, in its current state of readiness, it is not viable to consider this as a full replacement of petroleum-based aviation jet fuel as a fuel. Global consumption of jet fuel in 2018 by volume was 2 260 million barrels. To produce this volume of fuel that is viable for aviation from biofuels at the required rate is not practical at this time. The ERoEI ratio for biofuels is between 0.8:1 to 1.6:1, with rare examples of 10:1 (Michaux 2021). This implies that this process will be difficult to apply on a large scale. Also, biofuels are in direct competition with the production of food, at a time when food shortages are observed around the world (Michaux 2021).

Batteries are too heavy in mass to be practical in developing a commercial sized Electric Vehicle jet aircraft. Biofuel could be a technology that is possible in a small-scale conceptual fashion, where biofuel is blended with petroleum derived jet fuel. Aviation biofuel is a biofuel used for aircraft. Sustainable Alternative Jet Fuel (SAJF): a general term used to describe the class of non-petroleum-based jet fuels (or blended components) that are being pursued by the aviation industry. It is considered by some to be the primary Figure G1 shows a summary of the biofuel to jet fuel applications conversion pathways.

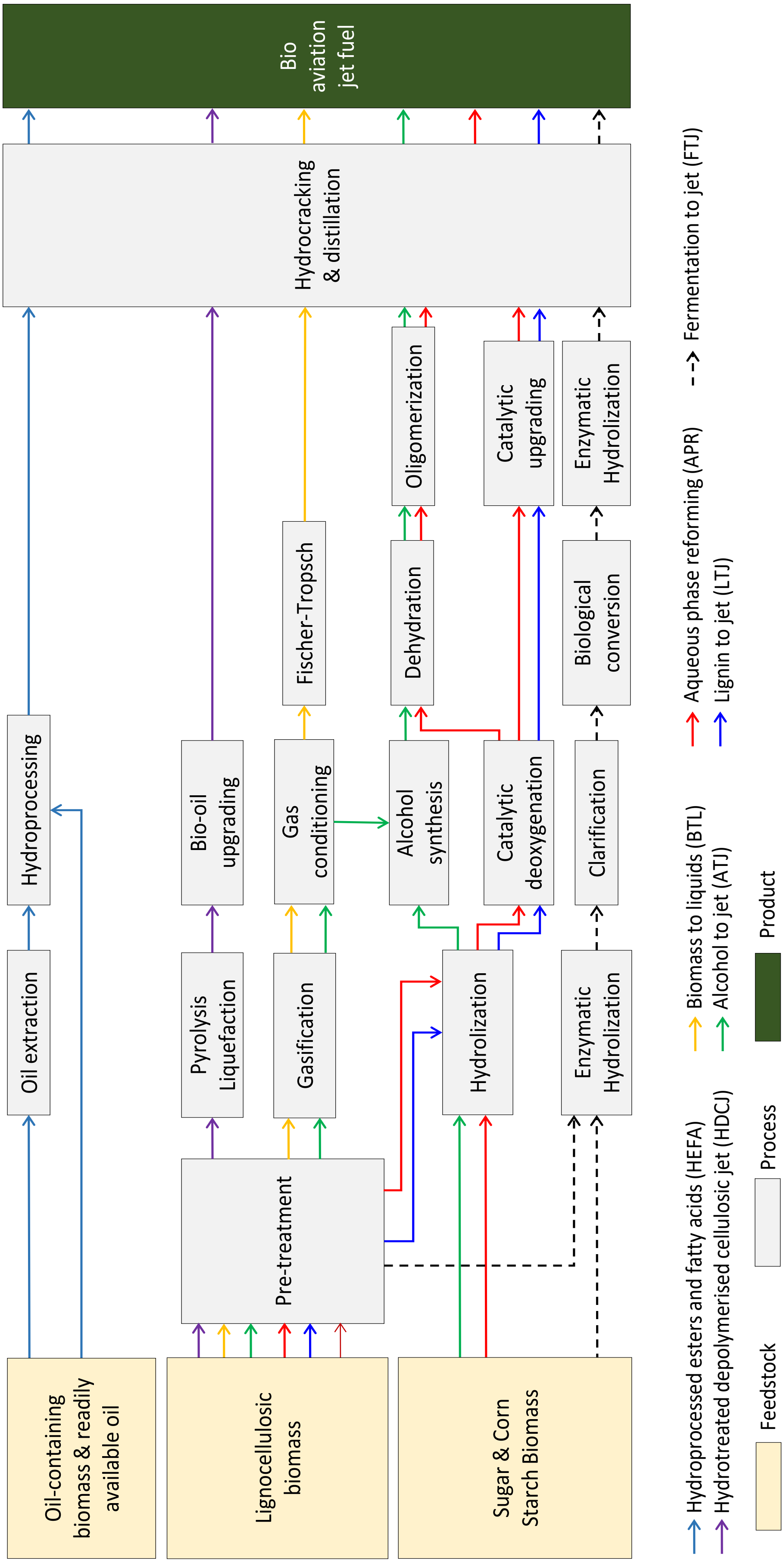

Figure G1. Biojet conversion pathways: feedstocks and processes
(Source: Redrawn from Mawhood *et al* 2014)

means by which the aviation industry can replace conventional petroleum derived jet fuel (General Aviation Manufacturers Association *et al* 2018). The first flight using blended biofuel took place in 2008 (Downing 2011).

Since then, aircraft makers, engine manufacturers and oil companies have developed this technology in sophistication and reliability. Biofuels were approved for commercial use to be blended with jet fuel in July 2011 (General Aviation Manufacturers Association *et al* 2018). Since then, some airlines have experimented with using biofuels on commercial flights. The focus of the industry has now turned to second generation sustainable biofuels (sustainable aviation fuels) that do not compete with food supplies nor are major consumers of prime agricultural land or fresh water. NASA has determined that 50% aviation biofuel mixture can cut air pollution caused by air traffic by 50–70% (Elliot 2017). The relevant industry standards for fuel classification are ASTM D1655 and ASTM D7566 (General Aviation Manufacturers Association *et al* 2018)

25.1 ASTM D1655 (Standard Specification for Aviation Turbine Fuel)

Defines specific types of aviation turbine fuel for civil use in the operation and certification of aircraft, and describes fuel found satisfactory by the Original Equipment Manufacturers (OEMs) and regulatory authorities for the operation of aircraft and engines. The specification can be used as a standard in describing the quality of aviation turbine fuel from the refinery to the aircraft and covers the use of purchasing agencies in formulating specifications for purchases of aviation turbine fuel under contract. The specification covers two types (or grades) of commonly used jet fuel that differ in freeze point:

- Jet A: commercial jet fuel grade commonly used in North America (-40ºC freeze point).
- Jet A-1: jet fuel grade commonly used outside of North America (-47ºC freeze point).

25.2 ASTM D7566 (Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons)

Defines aviation turbine fuel (jet fuel) produced with synthesized components derived from non-petroleum, non-shale, and non-oil sand origin. This can include jet fuel produced from coal, natural gas, landfill recovery gas, biomass (lignocellulose, sugars, fats, oils, and greases), waste streams, syngas, etc.

Table G1. ASTM certified technology platforms for sustainable aviation fleet production (ATAG 2017; Clean Skies for Tomorrow 2020, 15-16; SkyNRG 2021; Sustainable Aviation Fuel: Technical Certification 2021, 1-3)

Technology Platform	Date of Approval	Maximum Blend Ratio	Feedstock
Fischer-Tropsch (FT-SPK)	2009	50 %	Biomass such as forestry residues, grasses and municipal solid waste
Fischer-Tropsch (FT-SAK)	2015	50 %	Biomass such as agricultural and forestry residues, municipal solid waste, wood and energy crops
Hydrotreated Esters and Fatty Acids (HEFA-SPK)	2011	50 %	Oil containing biomass such as palm, algae, jatropha, camelina, carinata and used cooking oil
Synthetized Iso-paraffins (SIP)	2014	10 %	Sugars such as sugarcane and sugar beet
Alcohol to Jet (AtJ)	2016	50 %	Agricultural wastes such as grasses, forestry slash, crop straws, sawdust, lignocellulostic sugarcane and sugar beet
Catalytic Hydrothermolysis Sythetized Kerosene (CH-SK)	2020	50 %	Waste and energy oils such as soybean oil and other organic oils
Hydrocarbon - HEFA (HC-HEFA)	2020	10 %	Algae

26 APPENDIX H – ENERGY CONTENT OF FUELS AND EFFICIENCIES OF POWER GENERATION SYSTEMS

Table H.1. Higher and Lower Calorific Values of fuels (Source: Redrawn from The Engineering Toolbox https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html)

Fuel	Density at temperature 0°C/32°F, 1 bar		Higher Heating Value (HHV) (Gross Calorific Value - GCV)					Lower Heating Value (LHV) (Net Calorific Value - NCV)				
Gaseous fuels	**(kg/m³)**	**(g/ft³)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/m³)**	**(Btu/ft³)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/m³)**	**(Btu/ft³)**
at tempertaure of 0°C/32°F, and 1 bar of atmospheric pressure												
Acetylene	1.10	31.1	13.9	49.9	21,453	54.7	1,468					
Ammonia				22.5	9,690							
Hydrogen	0.09	2.6	39.4	141.7	60,920	12.7	341	33.3	120.0	51,591.0	10.8	290.0
Methane	0.72	20.3	15.4	55.5	23,874	39.8	1,069	13.9	50.0	21,496.0	35.8	964.0
Natural gas (US market)*	0.78	22.0	14.5	52.2	22,446	40.6	1,090	13.1	47.1	20,262.0	36.6	983.0
Town gas						18	483					
Liquid fuels	**(kg/l)**	**(kg/gal)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/l)**	**(Btu/gal)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/l)**	**(Btu/gal)**
at tempertaure of 15°C/60°F, and 1 bar of atmospheric pressure												
Acetone	0.79	2.98	8.83	31.8	13,671	25	89,792	8.22	29.6	12,726	23.3	83,580
Butane	0.60	3.07	13.64	49.1	21,109	29.5	105,875	12.58	45.3	19,475	27.2	97,681
Butanol	0.81		10.36	37.3	16,036	30.2	108,359	9.56	34.4	14,789	27.9	99,934
Diesel fuel*	0.85	3.20	12.67	45.6	19,604	38.6	138,412	11.83	42.6	18,315	36.0	129,306
Dimethyl ether (DME)	0.67	2.52	8.81	31.7	13,629	21.1	75,655	8.03	28.9	12,425	19.2	68,973
Ethane	0.57	2.17	14.42	51.9	22,313	29.7	106,513	13.28	47.8	20,550	27.3	98,098
Ethanol (100%)	0.79	2.99	8.25	29.7	12,769	23.4	84,076	7.42		11,479	21.1	75,583
Diethyl ether (ether)	0.72	2.71	11.94	43	18,487	30.8	110,464					
Gasoline (petrol)*	0.74	2.79	12.89	46.4	19,948	34.2	122,694	12.06	43.4	18,659	32.0	114,761
Gas oil (heating oil)*	0.84	3.18	11.95	43	18,495	36.1	129,654	11.89	42.8	18,401	36.0	128,991
Glycerin	1.26	4.78	5.28	19	8,169	24	86,098					
Heavy fuel oil*	0.98	3.71	11.61	41.8	17,971	41	146,974	10.83	39.0	16,767	38.2	137,129
Kerosene*	0.82	3.11	12.83	46.2	19,862	37.9	126,663	11.94	43.0	18,487	35.3	126,663
Light fuel oil*	0.96	3.63	12.22	44	18,917	42.2	151,552	11.28	40.6	17,455	39.0	139,841
LNG*	0.43	1.62	15.33	55.2	23,732	23.6	84,810	13.50	48.6	20,894	20.8	74,670
LPG*	0.54	2.03	13.69	49.3	21,195	26.5	94,986	12.64	45.5	19,561	24.4	87,664
Marine gas oil*	0.86	3.24	12.75	45.9	19,733	39.2	140,804	11.89	42.8	18,401	36.6	131,295
Methanol	0.79	2.99	6.39	23	9,888	18.2	65,274	5.54		8,568	15.8	56,562
Methyl ester (biodiesel)	0.89	3.36	11.17	40.2	17,283	35.7	128,062	10.42	37.5	16,122	33.3	119,460
MTBE	0.74	2.81	10.56	38	16,337	41.4	101,244	9.75	35.1	15,090	26.1	93,517
Oils vegetable (biodiesel)*	0.92	3.48	11.25	40.5	17,412	37.3	133,684	10.50	37.8	16,251	34.8	124,772
Paraffin (wax)*	0.90	3.41	12.78	46	19,776	41.4	148,538	11.53	41.5	17,842	37.4	134,007
Pentane	0.63	2.39	13.50	48.6	20,894	30.6	109,854	12.60	45.4	19,497	28.6	102,507
Petroleum naphtha*	0.73	2.75	13.36	48.1	20,679	34.9	125,145	12.47	44.9	19,303	32.6	116,819
Propane	0.50	1.89	13.99	50.4	21,647	25.1	89,963	12.88	46.4	19,927	23.1	82,816
Residual oil*	0.99	3.75				41.8	150,072	10.97	39.5	16,982	39.2	140,470
Tar*			10.00	36	15,477							
Turpentine	0.87	3.27	12.22	44	18,917	38.1	136,555					
Solid fuels*	**(kWh/kg)**		**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**			**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**		
Anthracite coal			9.06	32.6	14,015							
Bituminous coal			8.39	30.2	12,984			8.06	29.0	12,468		
Carbon			9.11	32.8	14,101							
Charcoal			8.22	29.6	12,726			7.89	28.4	12,210		
Coke			7.22	26.0	11,178							
Lignite (brown coal)			3.89	14.0	6,019							
Peat			4.72	17.0	7,309							
Petroleum coke			8.69	31.3	13,457			8.19	29.5	12,683		
Semi anthracite			8.19	29.5	12,683							
Sub-Bituminous coal			6.78	24.4	10,490							
Sulfur (s)			2.56	9.2	3,955			2.55	9.2	3,939		
Wood (dry)	0.701		4.50	16.2	6,965			4.28	15.4	6,621		

* Fuels which consist of a mixture of several different compounds may vary in quality between seasons and markets. The given values are for fuels with the given density. The variation in quality may give heating values within a range 5 -10% higher and lower than the given value. Also the solid fuels will have a similar quality variation for the different classes of fuel.

Below is a list of common units used in thermodynamics and conversion formulae between them (Moran *et al* 2014).

- 1 Btu(IT)/lb = 2.3278 MJ/t = 2327.8 J/kg = 0.55598 kcal/kg = 0.000646 kWh/kg
- 1 kcal/kg = 1 cal/g = 4.1868 MJ/t = 4186.8 J/kg = 1.8 Btu(IT)/lb = 0.001162 kWh/kg
- 1 MJ/kg = 1000 J/g = 1 GJ/t = 238.85 kcal/kg = 429.9 Btu(IT)/lb = 0.2778 kWh/kg
- 1 kWh/kg = 1547.7 Btu(IT)/lb = 3.597 GJ/t = 3597.1 kJ/kg = 860.421 kcal/kg
- 1 Btu(IT)/ft^3 = 0.1337 Btu(IT)/gal(US liq) = 0.03531 Btu(IT)/l = 8.89915 kcal/m^3 = 3.7259x10^4 J/m^3
- 1 Btu(IT)/gal(US liq) = 0.2642 Btu(IT)/l = 7.4805 Btu(IT)/ft^3 = 66.6148 kcal/m^3 = 2.7872x10^5 J/m^3
- 1 MJ/m^3 = 26.839 Btu(IT)/ft^3 = 3.5879 Btu(IT)/gal(US liq) = 0.94782 Btu(IT)/l = 239.01 kcal/m^3
- 1 kcal/m^3 = 0.11237 Btu(IT)/ft^3 = 0.01501 Btu(IT)/gal(US liq) = 0.003966 Btu(IT)/l = 4186.8 J/m^3

26.1 The Efficiency of Power Plants of Different Types

Each of the methods used to industrially generate power in the quantities needed all have a range of advantages and disadvantages (Moran *et al* 2014). The fuel used has a range of calorific density values. Then there are the relative efficiencies of generating power.

Table H.2. Efficiency of electric power generation by fuel source

Power Generation System	Fuel	Global Consumption in 2018 (Appendix C, D, E, F, G, H, I)	Energy Content of Fuel (Table 4.3)	Efficiency of Power Generation from Fuel (Section 8.6)	Installed Global Capacity (Section 8.6 & Global Energy Observatory)	Global Electricity Production in 2018 (Appendix B, G, H, I & Agora Energiewende and Sandbag 2019)
Coal	Coal	3772.1 Mtoe	30.2 MJ/kg	32-42%	1237.7 GW	10100.5 TWh
Gas	Gas	3309.4 Mtoe	40.6 MJ/m^3	32-38%	1207.5 GW	6182.8 TWh
Nuclear	Enriched Uranium	611.3 Mtoe	2000 MJ/Kg	0.27%	431.8 GW	2701.4 TWh
Hydroelectric	Moving water	948.8 Mtoe	-	85-90%	712.9 GW	4193.1 TWh
Wind	Moving air	-	-	35-45%	597 GW	1303.8 TWh
Solar PV	Sunlight	-	-	15-20%	580.14 GW	579.1 TWh
Solar Thermal	Sunlight	-	-	20%	5.5 GW	5.5 TWh
Geothermal	Geological heat	-	-	10-35%	14.6 GW	93 TWh
Biowaste to energy	Biowaste	-	12-35 MJ/kg	13%	55 GW	60 TWh
Fuel Oil Diesel	Crude Oil	4662.1 Mtoe	45.6 MJ/kg	38%	225.8 GW	802.8 TWh

Table H.3. Refined Petroleum Products (Source: OECD Data Statistics Database, EIA, IEA)

Fuel	Energy Content of Fuel	ICE Technology	Energy Efficiency of ICE Technology	Reference
Crude Oil	41.87 MJ/kg	N/A		
Diesel Fuel Oil	45.6 MJ/kg	Diesel Engine	35-42%	Kiameh 2013
Heavy Fuel Oil	41.8 MJ/kg	Diesel Engine	35-42%	Kiameh 2013
Petrol (Gasoline)	46.4 MJ/kg	Petrol Engine	25-50%	Kiameh 2013
Jet Fuel	43.0 MJ/kg	Jet Turbine	36-48%	Griggs et al 2014

27 APPENDIX I - HELSINKI'S GEO-ENERGY POTENTIAL SUMMARY

The following is an extract summary from: Helsinki's geo-energy potential (Kallio *et al* 2019). This text has been taken directly from the report and translated into English.

Geothermal energy is thermal energy stored in the earth's crust and generated in it. The geoenergy of the surface parts of the Earth's crust (0–1 km) is the geothermal energy of low temperatures. The geoenergy of the surface parts of the earth's crust is utilized for heat production by means of geothermal pumps. Although the temperature levels of the earth's surface are low compared to the depths in the deeper part of the earth's crust, the geoenergy reserve of the surface is so large that it could theoretically cover Helsinki's heating needs (about 7 TWh /year) for several decades. However, this would require that the entire land area of Helsinki be drilled full of geothermal wells deeper than 300 meters every 20 meters.

The utilization of geoenergy from the bedrock takes place by means of rock heating systems. They consist of a ground source heat pump, heat wells and an internal building system. The rock heating system draws heat from the rock using a heat well. This poses challenges to the efficient exploitation of geoenergy resources. The heat well is a hole drilled vertically in the rock and it absorbs heat only through the wall of the borehole, which is why the heat reserve of the bedrock can be utilized most efficiently from the immediate vicinity of the well.

Thus, a single heat well is the least efficient way of extracting heat if the geoenergy reserve of the bedrock is to be maximized. In contrast, a heat well field with evenly spaced wells is a much more efficient method because the well field absorbs heat more evenly from the volume of heat resource to be utilized (Fig. I1). However, the geoenergy per meter from a single heat well is about three times higher than the geoenergy from a single well in a wellfield.

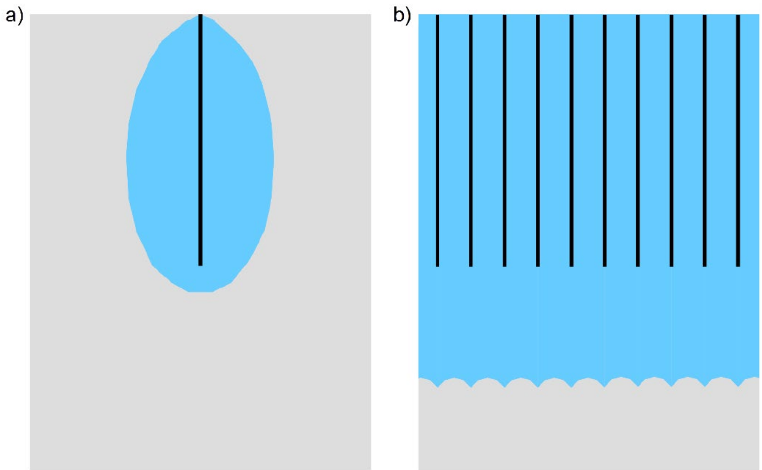

Figure I1. Extent of heat uptake in the case of a single heat well and heat well field. The figure shows by way of example how wide a (a) a single heat well and (b) a large heat well field absorb heat. Black lines represent heat wells. The color blue represents the part of the rock from which heat has been taken and whose temperature has therefore fallen. The gray color shows the part of the rock where the heat has not been taken and the temperature has not dropped as a result.

Proper sizing of heat wells and heat well fields require knowledge of local thermogeology and climate. Necessary data include ground temperature, rock thermal conductivity, rock heat capacity, and geothermal heat flux density. Based on the results of the first part of this report and the existing data, map data were prepared that describe the parameters affecting the dimensioning in the Helsinki area. In addition, a map was prepared on the thickness of the land cover, as it affects the buildability and construction costs of heat wells.

The prepared data provide a basis for the current dimensioning of rock heating systems based on the researched data.

The purpose of the report was to assess the geoenergy potential of the Helsinki area. Based on the dimensioning parameter maps, two sets of maps were created that describe the geoenergy potential from two different perspectives. The maps of the theoretical geoenergy potential illustrate how much of the thermal energy bound to the top 150, 300 and 1000 meters of each hectare in Helsinki could be taken annually for 50 years. Maps of the technical geoenergy potential illustrate how much pure geoenergy could be taken from each hectare of Helsinki in 50 years if Helsinki were one large thermal well field with a distance of 20 meters and wells of 150, 300 or 1000 meters. Thus, the technical implementation of heat abstraction in heat wells has not been considered in the calculations of the theoretical geoenergy potential, while it has been taken into account in a simplified way in the calculations of the technical geoenergy potential.

Table I1 Summary of the geoenergy potential maps

Depth Spacing [m]	Thermal energy bound to the bedrock	Geoenergy for use in heat wells	Heating energy from heat pumps
0-150	128 MWh/year/hectare (2.65 TWh/year)	122 MWh/year/hectare (2.57 TWh/year)	183 MWh/year/hectare (3.86 TWh/year)
0-300	292 MWh/year/hectare (5.98 TWh/year)	234 MWh/year/hectare (4.76 TWh/year)	351 MWh/year/hectare (7.14 TWh/year)
0-1000	1518 MWh/year/hectare (30.71 TWh/year)	765 MWh/year/hectare (15.91 TWh/year)	1148 MWh/year/hectare (23.87 TWh/year)

Table I1 shows the amounts of thermal energy bound to the three different depth ranges, as well as the amounts of geoenergy available from them in the heat wells and the amounts of heating energies obtained from the heat pumps. Based on the results, so much thermal energy has been bound to the bedrock of the Helsinki area that Helsinki's annual heating demand could be covered for 50 years if a thermal well field covering the land with a depth of 300 or 1000 meters was built in Helsinki. The figures shown are the most common values for the maps (mode). The heating energies from the heat pumps are calculated on the assumption that the heat factor of the heat pump is 3. The figures in parentheses indicate the total amounts of energy (sums of all cells in the maps).

When evaluating the results, it should be considered that the calculations were made using simplified theoretical models. However, modeling is the only approach that can estimate geoenergy potential on such a large scale. The main uncertainty in the calculations is that the bedrock temperature profile of the islands and coastal areas is unknown. As a result, the results in these areas are the most unreliable. The calculations for the maps also did not consider the horizontal heat transfer between the well plots, which may play a significant role particularly in the islands and coastal areas. Due to these factors, the unreliability of the results is greatest in these areas. The calculations also did not consider climate change or urban heat. Rising atmospheric temperatures, asphalted urban areas and heat flowing from buildings to the ground raise the temperature of the earth's crust. Elevated crustal temperature has the effect of increasing geo-energy potential (e.g., Rivera et al. 2017). However, the results give an estimate of the minimum geoenergy potential.

In addition, the heat extraction from the heat well field was compared to the heat extraction from a single heat well. A single heat well here refers to a well that does not have other wells in the vicinity that would consume the same geoenergy resource. Based on the results, about three times the amount of heat from a single well in a thermal well field can be taken from a single well 150, 300, or 1000 meters deep. However, individual wells are an inefficient way to exploit geoenergy resources. The distance between unaffected wells

150 meters deep should be at least 162 meters. Similarly, unaffected wells at a depth of 300 or 1000 meters should be at least 176 meters apart. Thus, Helsinki would only hold about 7,000 unaffected wells 150 meters deep or about 8,000 unaffected wells 300 or 1000 meters deep. Thus, non-interacting wells could cover a maximum of only about 3–11 per cent of Helsinki's annual heating energy needs.

Finally, it was examined how taking cooling into account would affect the operation of the rock heating system. When cooling the room air with a rock heating system, the waste heat collected from the room air is loaded into the rock, ie the rock is heated. Based on the results, an amount of thermal energy proportional to the amount of cooling is available for heating at a later time, i.e. the rock heating system can thus cover a higher heating demand in this case. On the other hand, if the heat uptake is not increased by the amount of cooling energy, cooling can extend the life cycle of the rock heating system. If the annual amount of cooling energy is 25% of the annual heating demand, the life cycle of the rock heating system can be extended by about 17–24 years.The following figures and tables have been taken from the report and presented here for context.

Table I2. Derived quantities calculated for field samples. The table shows the rock type-specific averages for volumetric heat capacity (C) and thermal diffusivity (α)

Rock Type	C [MJ/m³·K]	α [mm²/s]
Amphibolite	2,106	1,19
Gabro	1,996	1,628
Granite	1,905	1,682
Granite and Quartzite	1,952	1,612
Mica Gneiss	1,967	1,442
Quartz-Feldspar-Gneiss	2,021	1,551

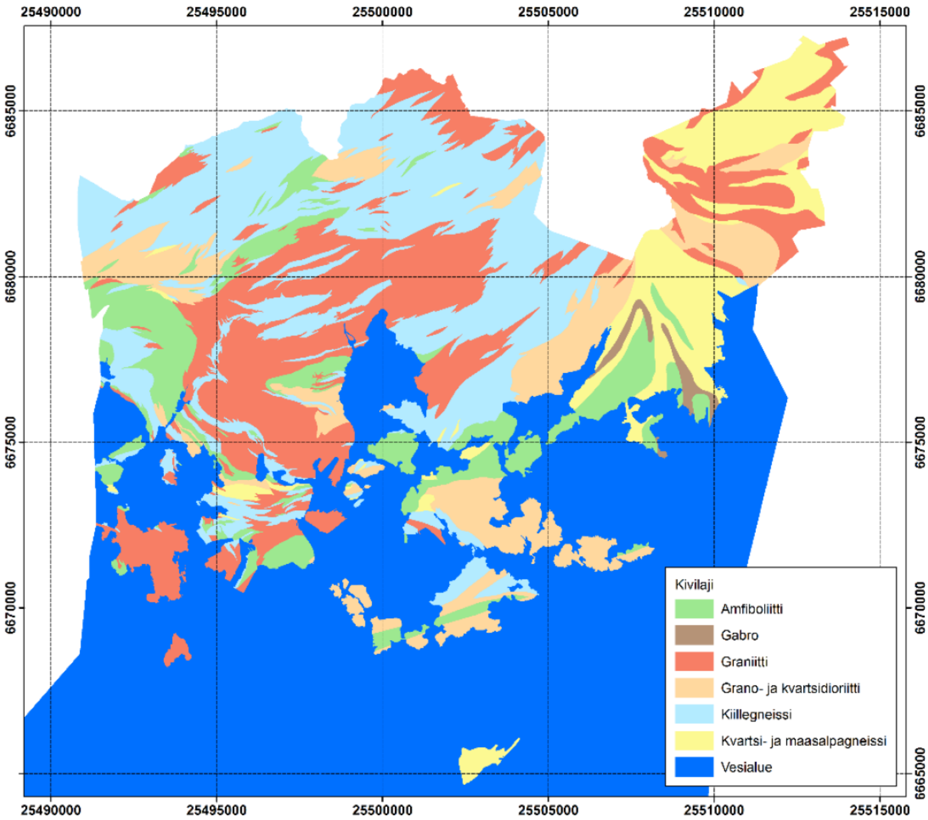

Figure I2. Simplified rock type map of Helsinki. The coordinate system is ETRS-GK25FIN. © City of Helsinki.

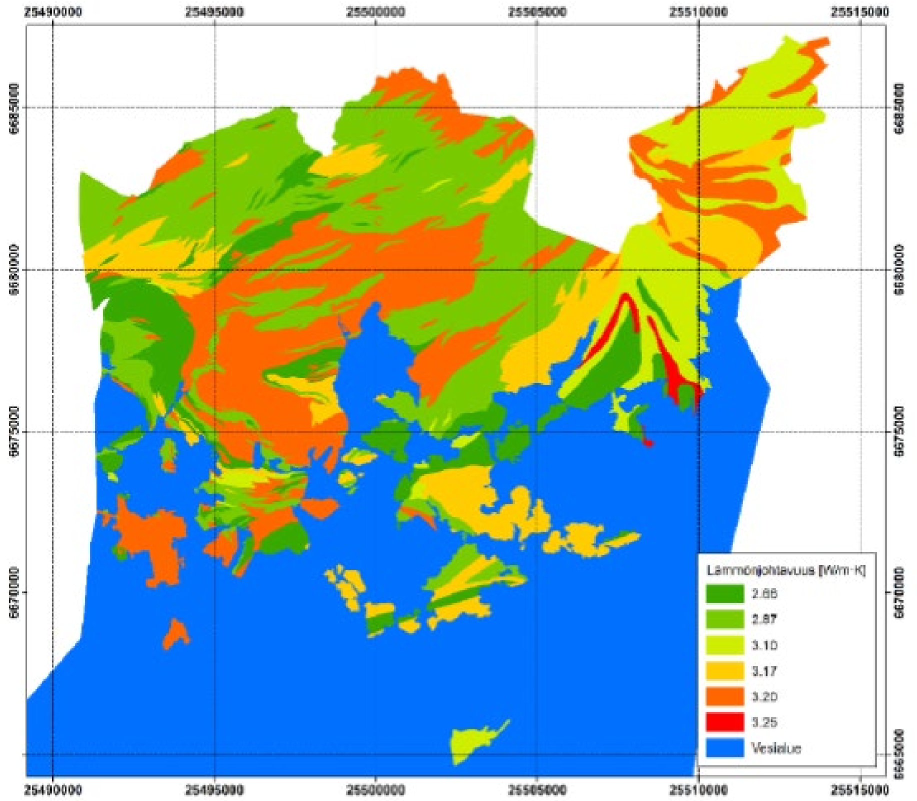

Figure I2. Thermal conductivity of the Helsinki bedrock. On the map, the highest thermal conductivities are for gabbro and granite. The thermal conductivity of Gabro is based on only one measurement and does not represent the typical thermal conductivity value of Gabro but is exceptionally high. The coordinate system is ETRS-GK25FIN.

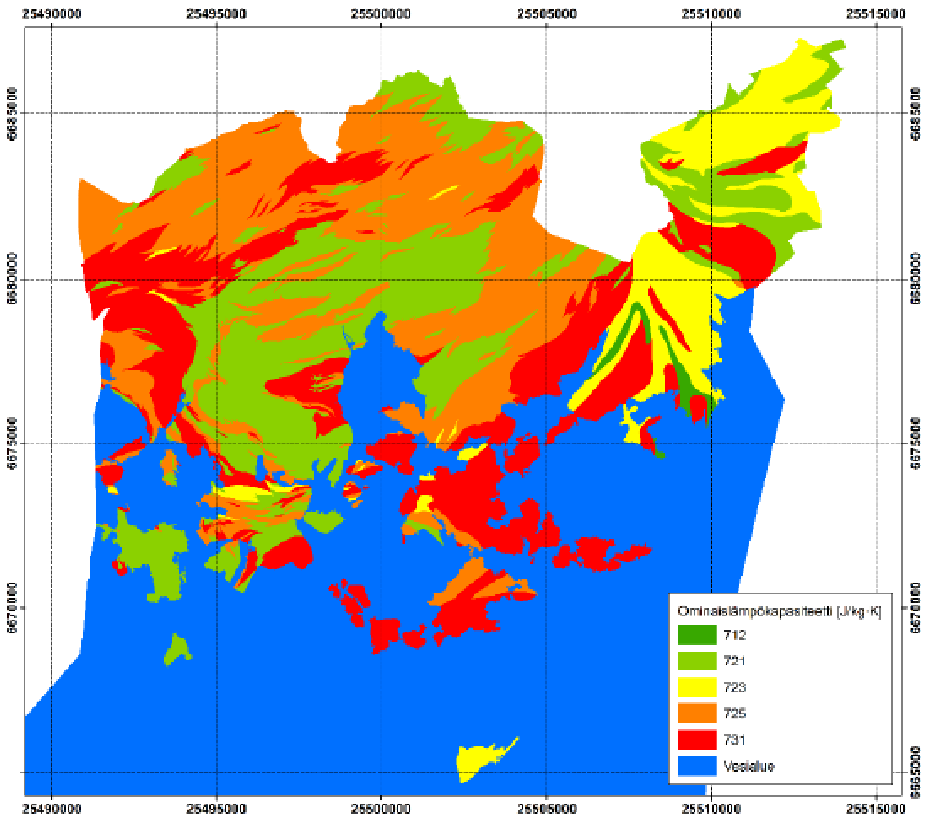

Figure I3. Specific heat capacity of the Helsinki bedrock. The coordinate system is ETRS-GK25FIN.

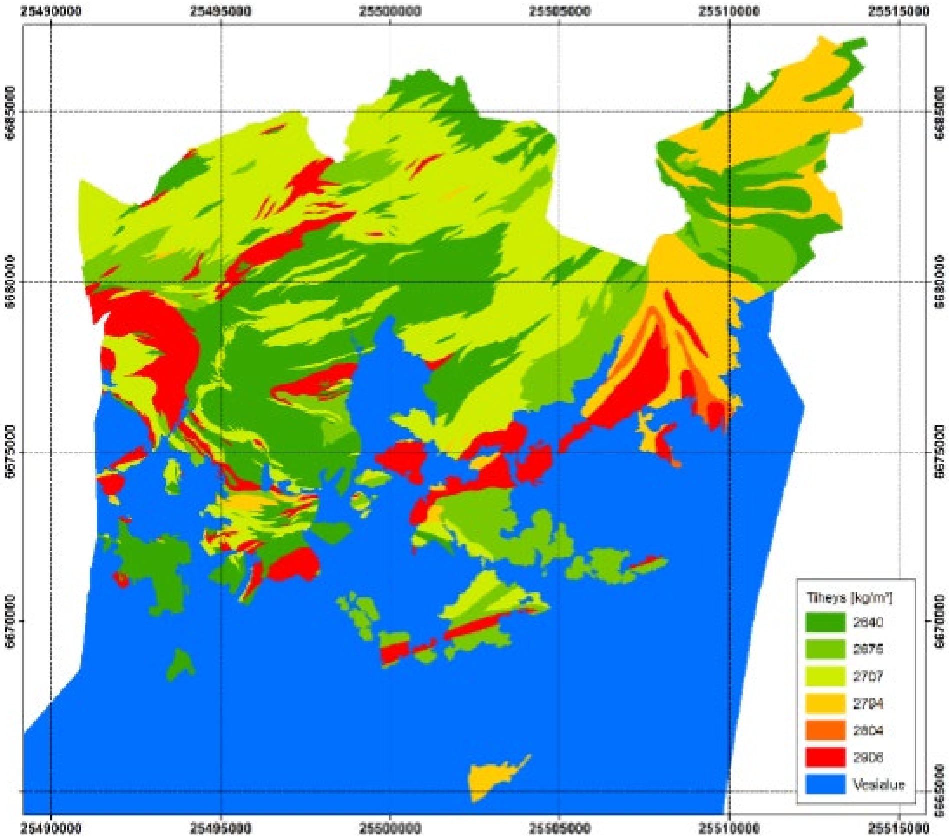

Figure I4. Density of the Helsinki bedrock. The coordinate system is ETRS-GK25FIN.

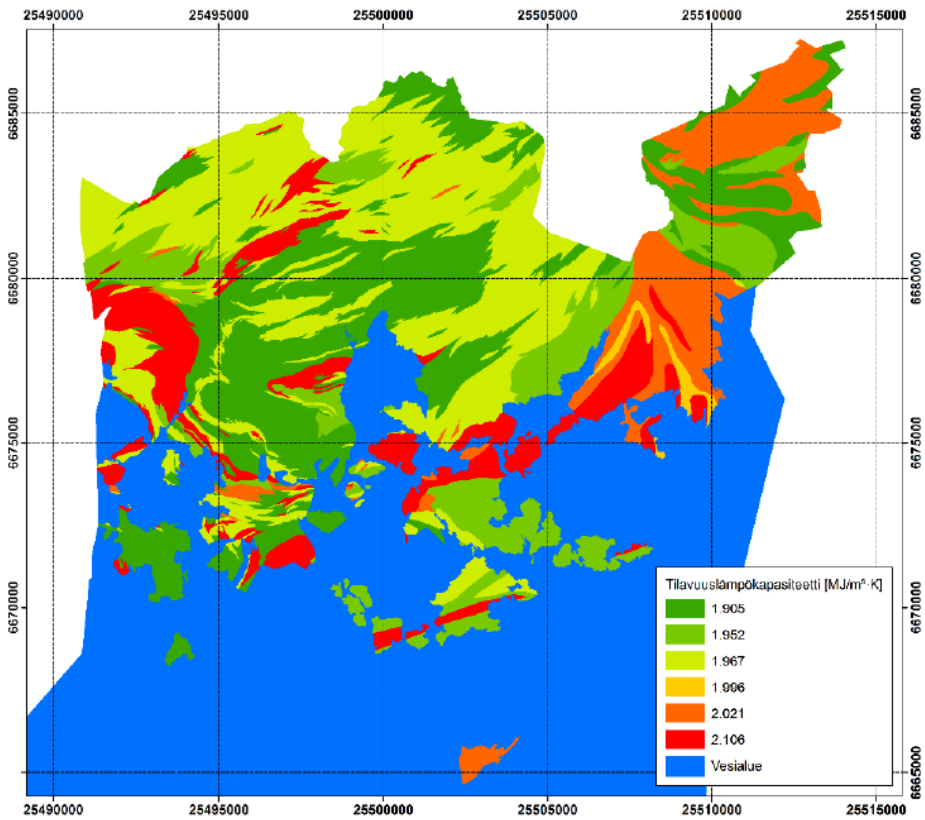

Figure I5. Volumetric heat capacity of the Helsinki bedrock. The coordinate system is ETRS-GK25FIN.

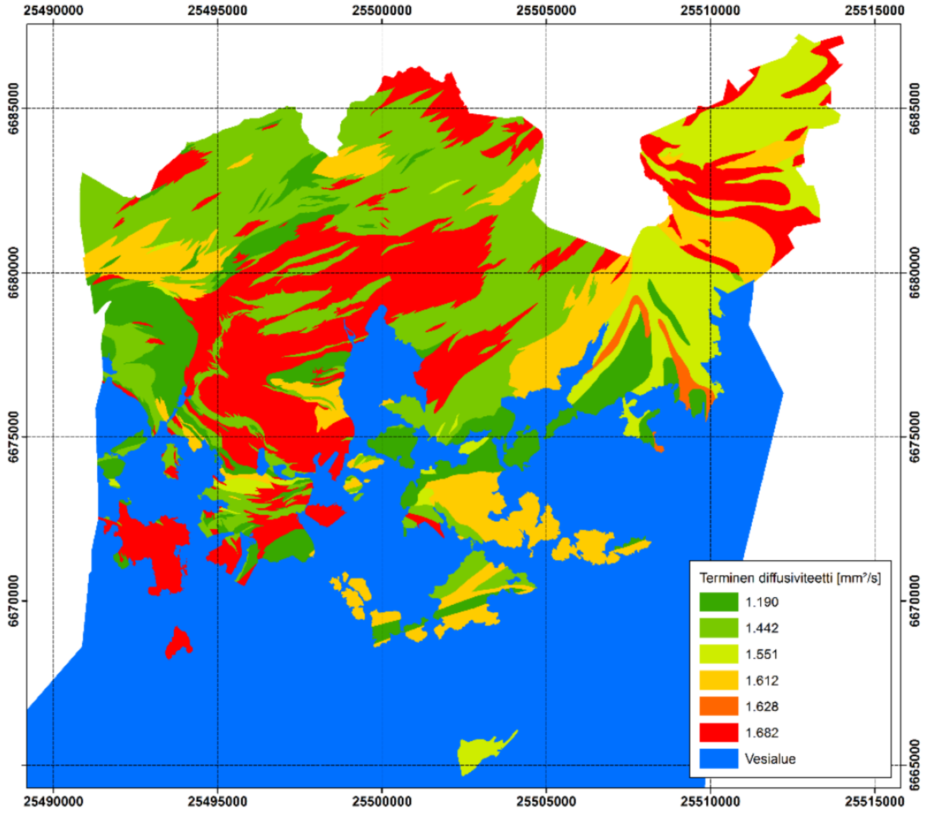

Figure I6. Thermal diffusivity of the Helsinki bedrock. The coordinate system is ETRS-GK25FIN.

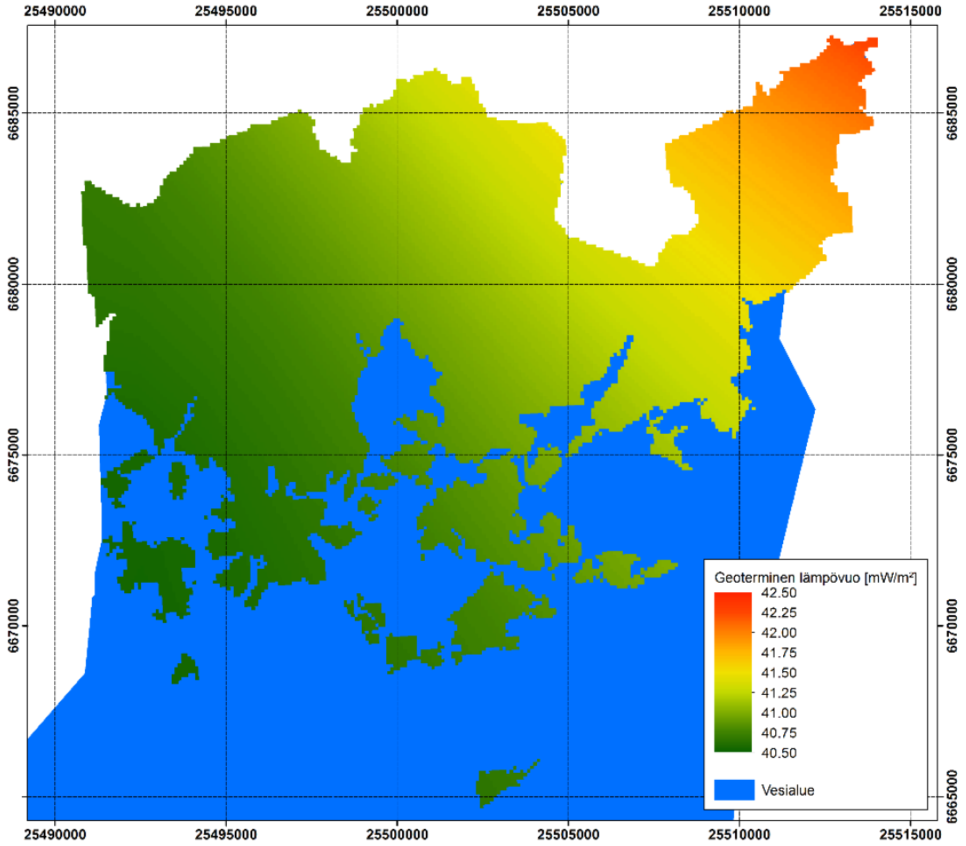

Figure I7. Geothermal heat flux on the ground in Helsinki. The coordinate system is ETRS-GK25FIN.

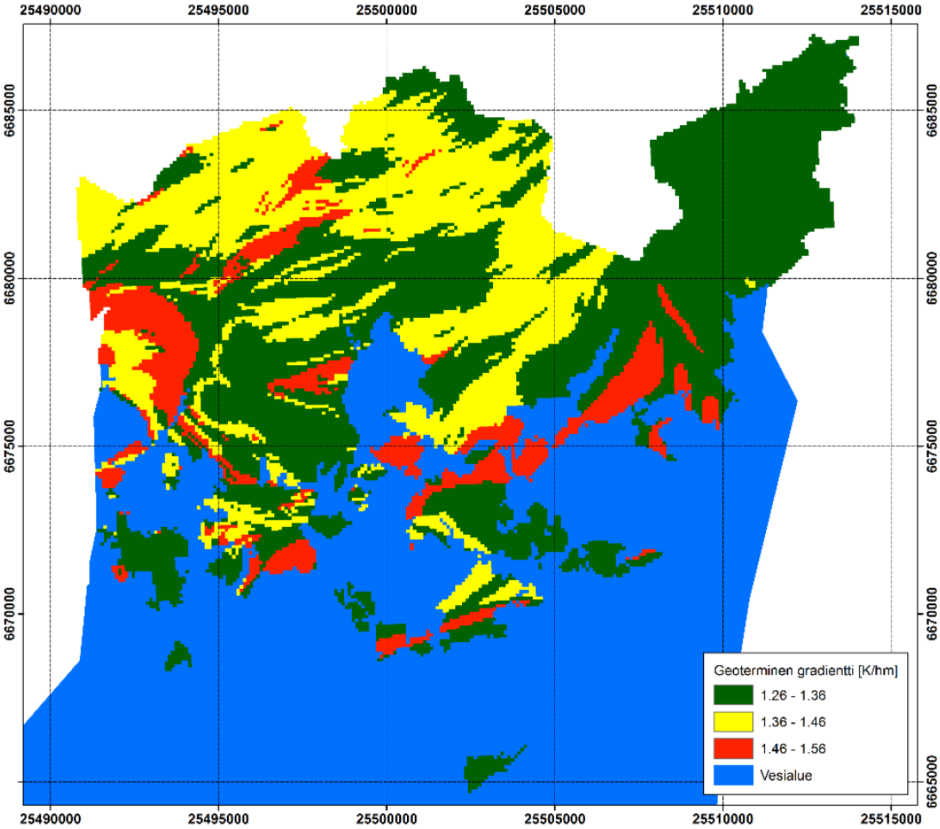

Figure I8. Geothermal gradient of the Helsinki bedrock. The coordinate system is ETRS-GK25FIN.

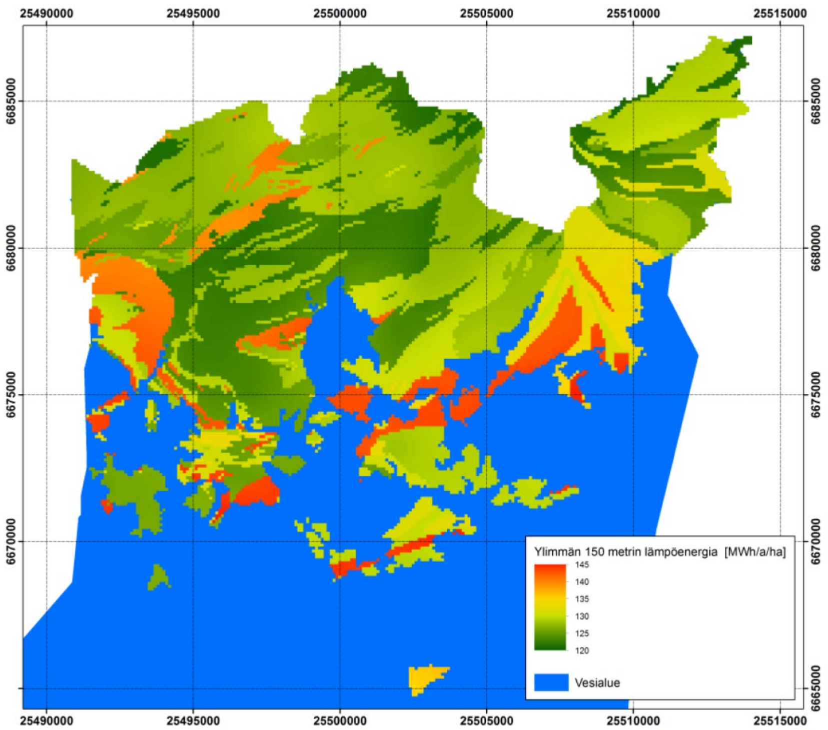

Figure I9. Theoretical geoenergy potential of the top 150 m of the Helsinki bedrock. The map shows how much geoenergy could be obtained from one hectare if the temperature of the top 150 meters were reduced to zero degrees Celsius in 50 years. The sum of all cells is 2.65 TWh / a. The coordinate system is ETRS-GK25FIN.

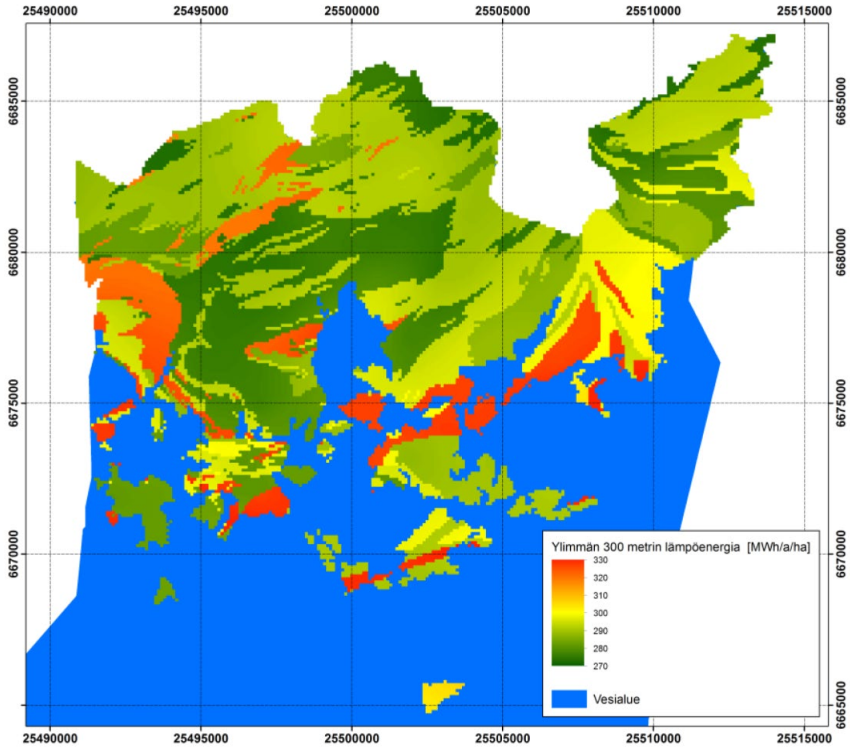

Figure I10. Theoretical geoenergy potential of the top 300 m of the Helsinki bedrock. The map shows how much geoenergy could be obtained from one hectare if the temperature of the top 300 meters were reduced to zero degrees Celsius in 50 years. The sum of all cells is 5.98 TWh / a. The coordinate system is ETRS-GK25FIN

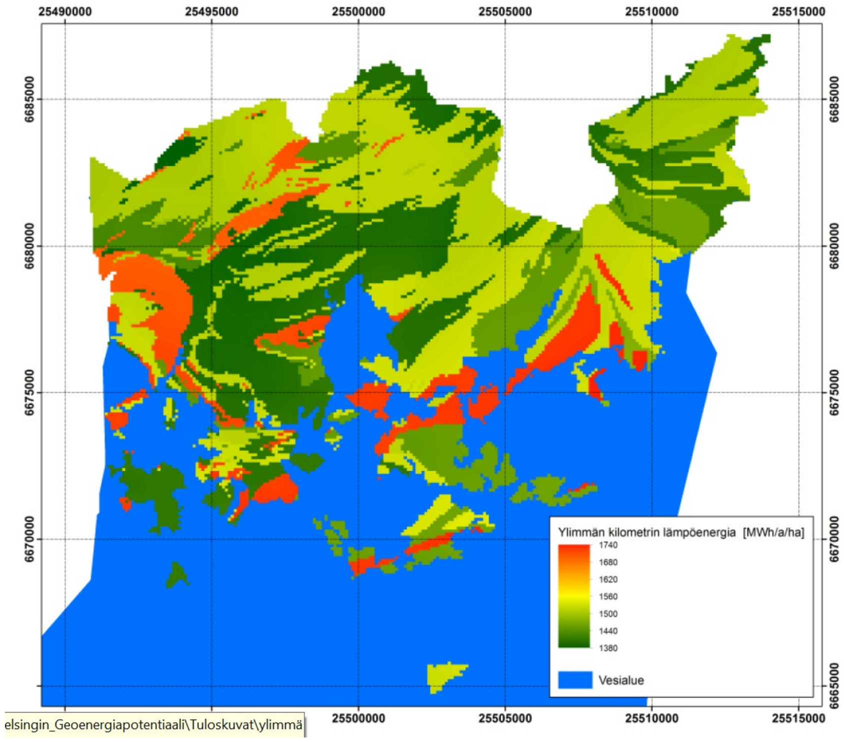

Figure I11. Theoretical geoenergy potential for the top kilometer of the Helsinki bedrock. The map shows how much geoenergy could be obtained from one hectare if the temperature of the top 1000 meters were reduced to zero degrees Celsius in 50 years. The sum of all cells is 30.71 TWh / a. The coordinate system is ETRS-GK25FIN.

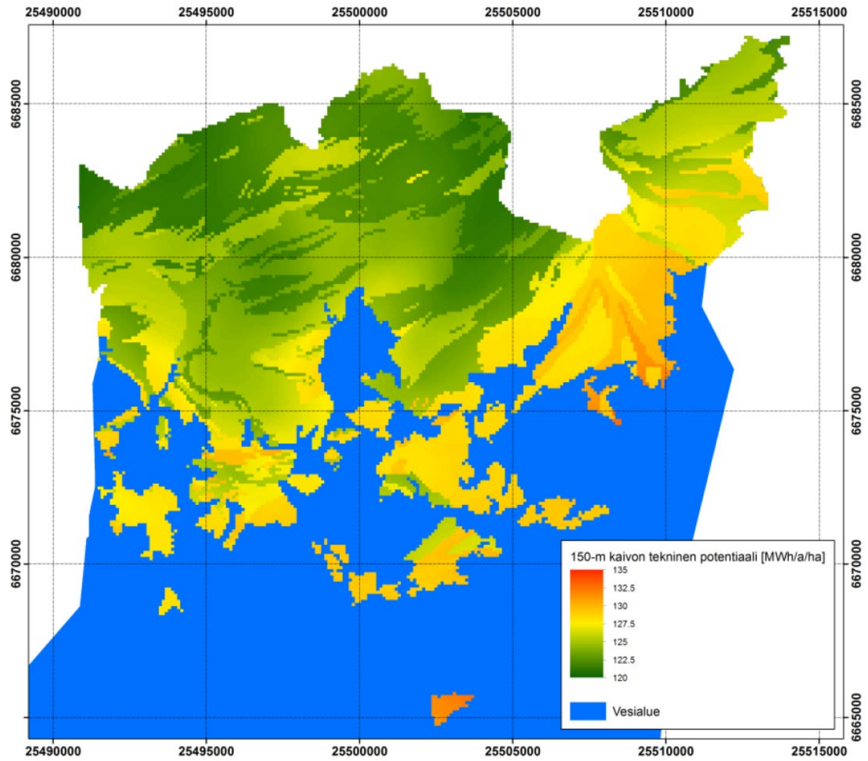

Figure I12. Technical geoenergy potential for 150-meter-deep heat wells. The map describes how much geoenergy from Helsinki could be obtained from a maximum of one hectare for 50 years without freezing the rock if Helsinki were one large thermal well field. The sum of all cells is about 2.57 TWh / a. The coordinate system is ETRS-GK25FIN.

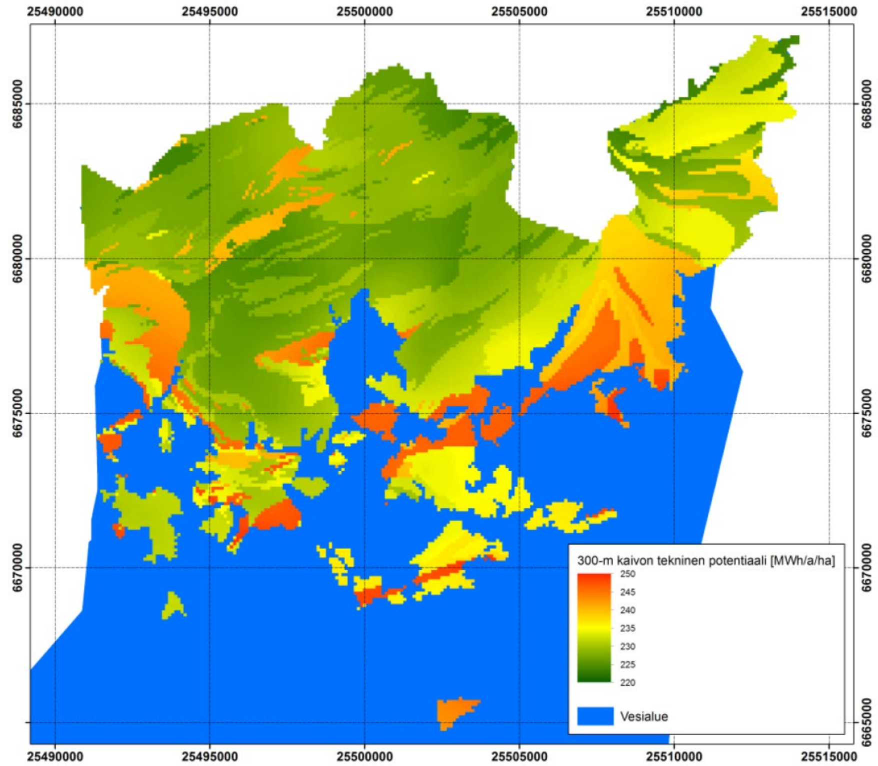

Figure I13. Technical geoenergy potential for 300 m deep heat wells. The map describes how much geoenergy from Helsinki could be obtained from a maximum of one hectare for 50 years without freezing the rock if Helsinki were one large thermal well field. The sum of all cells is about 4.76 TWh / a. The coordinate system is ETRS-GK25FIN.

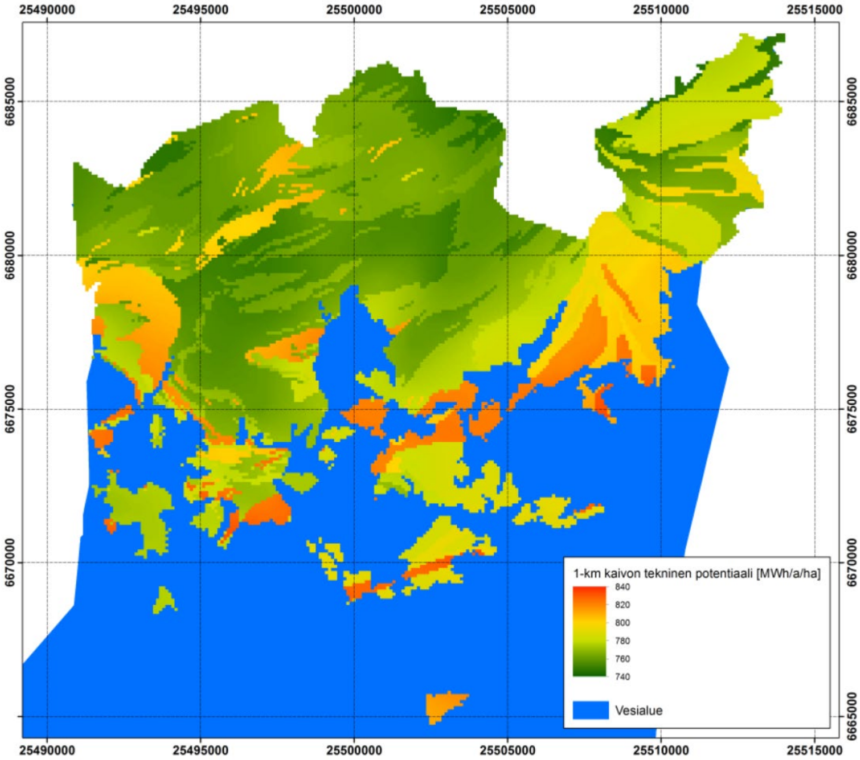

Figure I14. Technical geoenergy potential for 1000-meter-deep heat wells. The map describes how much geoenergy from Helsinki could be obtained from a maximum of one hectare for 50 years without freezing the rock if Helsinki were one large thermal well field. The sum of all cells is about 15.91 TWh / a. The coordinate system is ETRS-GK25FIN.

28 APPENDIX J: FOSSIL FUELS OUTLOOK

Energy is the master resource. It allows and facilitates all physical work done, the development of technology and allows human population to live in such high-density settlements like modern cities. Energy consumption correlates directly with the real economy (Bradley and Fulmer 2008). The real economy, the part of the economy that is concerned with actually producing goods and services, as opposed to the part of the economy that is concerned with buying and selling on the financial markets.

Future projections of global energy demand are usually developed on past behavior, with no understanding of finite limits or depleting resources. Generally, reserves have been projected on by past production and demand has been defined by population growth and economic GDP.

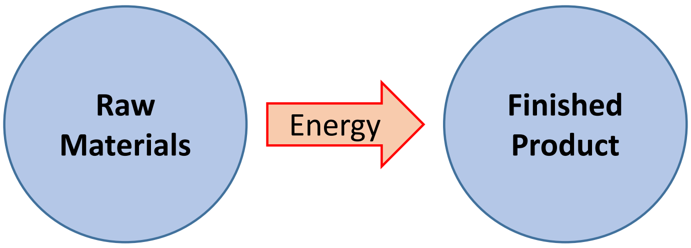

Figure. J1 Relationship between raw materials and finished manufactured goods

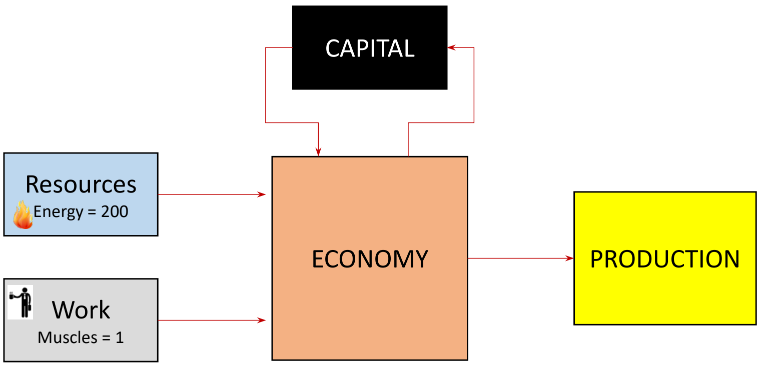

Figure J2. A simplified flow physical flows that sustain our productive system (Source: Jancovici 2011)

The modern world is heavily interdependent. Many of the structures and institutions we now depend upon function in a global context. Energy as a fundamental resource underpins the global industrial system (Fizaine & Court 2016, Meadow *et al.* 1972, Hall *et al.* 2009, Heinberg 2011, Martenson 2011, Morse 2001, Ruppert 2004 and Tverberg 2014).

Population growth is another fundamental driver to this current set of circumstances. Consumption is a function of the number of people who consume (Figure J3). An increase in production or an achieved efficiency must be put in context of the population growth across that time frame. Population has grown in a manner that strongly correlates with the increase in energy consumption once all sources have been summed together (Bartlett 1994). Since the start of the industrial revolution, population has been empowered by technology coupled with increased energy density (coal vs biomass wood, followed by the introduction of oil). Note in Figure J3 how the middle chart has Per Capita Consumption for energy. This highlights how increasing complexity of technology has resulted in an increase per person in terms of energy requirements (the same can be shown for all natural resources).

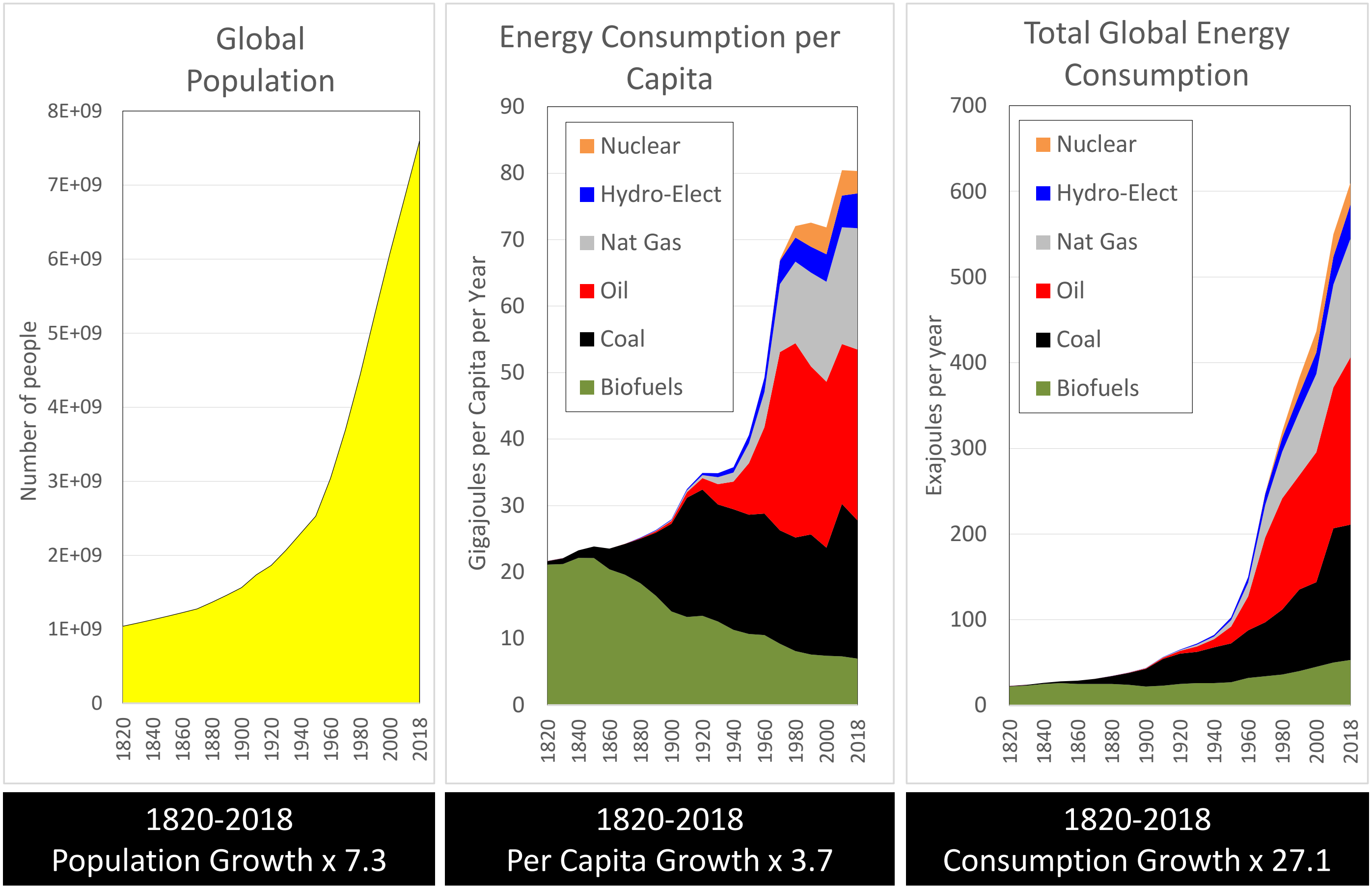

Figure J3. World population, per capita-, and total energy consumption, 1820-2018
(Source: Data from Tverberg, G. https://ourfiniteworld.com/, and BP Statistical Review of the World Energy 2019, US Census Bureau)

28.1 Oil Outlook

Today approximately 90% of all industrially manufactured products depend on the availability of oil. Oil is not only the source material for producing fuels and lubricants but is also used as hydrocarbon for most organic polymers (plastic materials). It is therefore one of the most important raw materials in the production of many different products such as pharmaceuticals, dyes, and textiles (Michaux 2019).

As the source material for various types of fuels, oil is a basic prerequisite for the transportation of large quantities of goods over long distances. Oil, alongside information technology, container ships, trucks and aircraft form the backbone of globalization and our current industrial ecosystem.

Most of energy generated is supported by a nonrenewable natural resource as a fuel. Currently we are a petroleum dominated society (Martenson 2011, Ruppert 2004, Tainter 1988), with a heavily dependency on other fossil fuels like gas and coal.

The situation for oil is particularly critical, especially given that it is by far the world's major source of liquid fuel, powering 95% of all transport. Currently, approximately 60–80% of conventional oil fields are in terminal decline (Fustier *et al.* 2016). It is estimated that to maintain current supply rates of oil by 2040 the world would need to find four Saudi Arabia Ghawar elephant fields (the largest to date single producing oil field) worth of additional oil just to maintain current rates of supply. If the projected demand in 2040 is to be met, eight Saudi Arabia Ghawar elephant fields would need to be found and operating by that date.

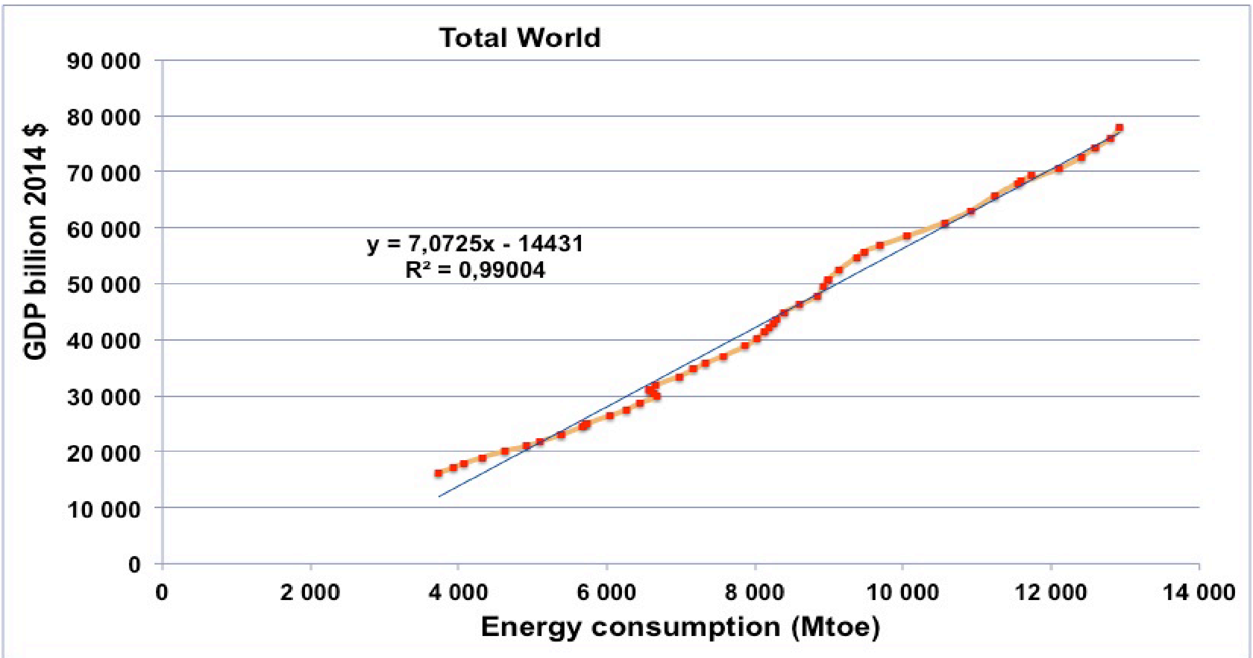

Figure J4. World GDP in constant dollars (vertical axis) plotted against the world energy consumption in million tonnes oil equivalent (horizontal axis), from 1965 to 2014.
(Source: BP Statistical Review, 2015, and World Bank 2015 (GDP), Jancovici 2011)

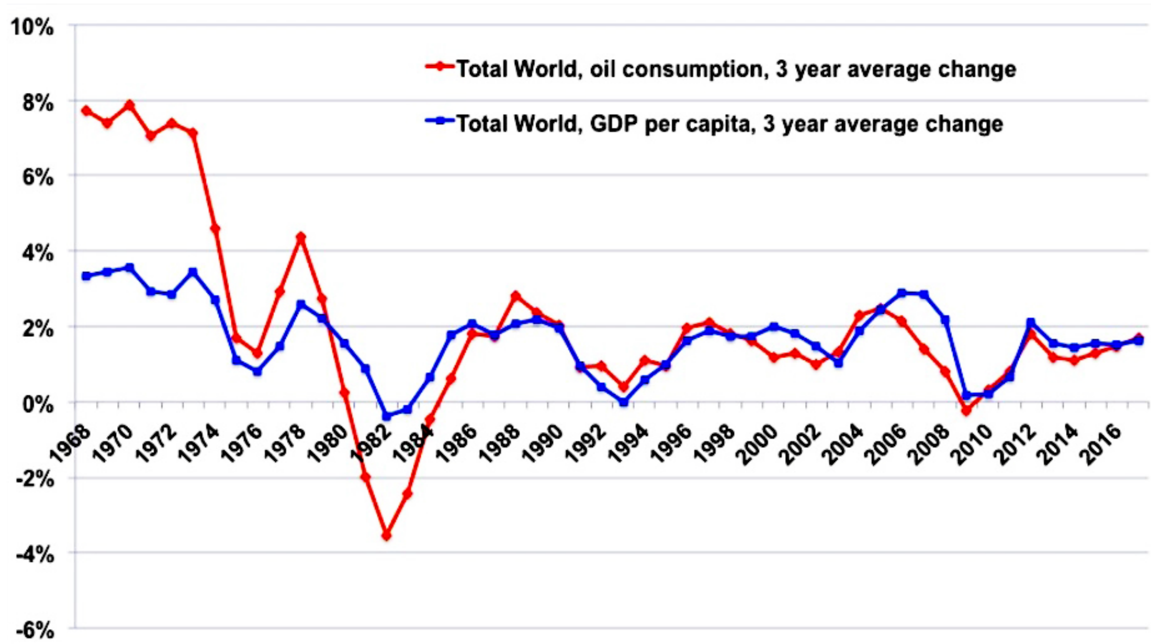

Figure J5. Correlation between the annual relative change in world oil consumption and GDP per capita averaged over three years (Source: Data from BP Statistical Review 2018, World Bank)

Figure J4 and J5 shows the strong correlation between the economic activity index global GDP, global energy consumption and global oil consumption. The importance of this cannot be understated. In our current form, industrial society correlates directly with our ability to consume energy. Oil in particular is important to understand. As can be seen, oil consumption correlates with both GDP and energy consumption. This is because modern society is a petroleum driven economy (Heinberg 2011, Martenson 2011, Morse 2001, Ruppert 2004, Tverberg 2014 and Wiedenhofer 2013).

Figure J6 shows the correlation relationship between the change in Chinese industrial output (Year on Year % change) and a change in Brent oil price on the international market (Year on Year % change).

Industrial activity represents real physical work, and the YOY % Industrial output is a measured index of physical work done and goods manufactured by Chinese heavy industry. China dominates the industrial activity in the global market, controlling the majority of mining, refining recycling and manufacture (Wübbeke *et al* 2016). This means that a change in Chinese industrial activity is a useful proxy for global industrial activity. Energy is the ability to do work, and the YOY % change in the price of oil is a proxy for the stability of the energy system. A correlation between the two strongly supports

As can be observed there is a correlation. It can also be noted in Figure J6 that there are three different time periods that have different signatures.

During the crash of 2008 (Global Financial Crisis), there is a strong correlation as both indexes dip sharply followed by temporary recovery (this signature is the most prominent in the whole data set from 1991 to 2018), followed by a steady decrease. Prior to the GFC crash in 2008, there is a second time period where the two indexes correlate (but not as strongly). The relation between the two proxies is clearly involving multiple parameters. After the GFC is a third time period where the two indexes do not correlate at all. The change in Chinese industrial output decreases steadily, where the change in oil price does not. This is another signature of the contraction of the real economy.

On August 11, 2015, the People's Bank of China (PBOC) conducted three consecutive devaluations of the yuan renminbi or yuan (CNY), removing over 3% off its value. Between 2005 and 2015, China's currency had appreciated 33% against the U.S. dollar, and the first devaluation marked the most significant single drop in 20 years (Investopedia 2019).

This is significant as in Figure J6, there is a crash in the YOY % change in the average monthly Brent oil spot price in 2015. This crash is of similar size to the Global Financial Crisis (GFC). At a similar time, the industrial Baltic Dry Index (The Baltic Dry Index measures how much it costs to ship "dry" commodities around the world — raw materials like grain and steel) crashed to an all-time low of 291 on February 12th, 2016 (Bloomberg BDIY Quote 2019). So Chinese industrial output, the price of oil, and the global maritime trade of dry goods all had a signature in 2015 as significant as the GFC in 2008. This happened just as the U.S. Federal Reserve 3rd Quantitative Easing program (QE3) ended. The Baltic Dry Index has been used as a leading indicator for an economic slowdown (Martin 2016).

This suggests a structural move happened in the global economy in 2015 that significantly affected the real economy (the production of physical goods and services as opposed to financial products like derivatives).

In addition to the correlation between industrial output and oil production (energy), there is also a correlation between oil price and geopolitical events (Table J1 and Figures J7 and J8).

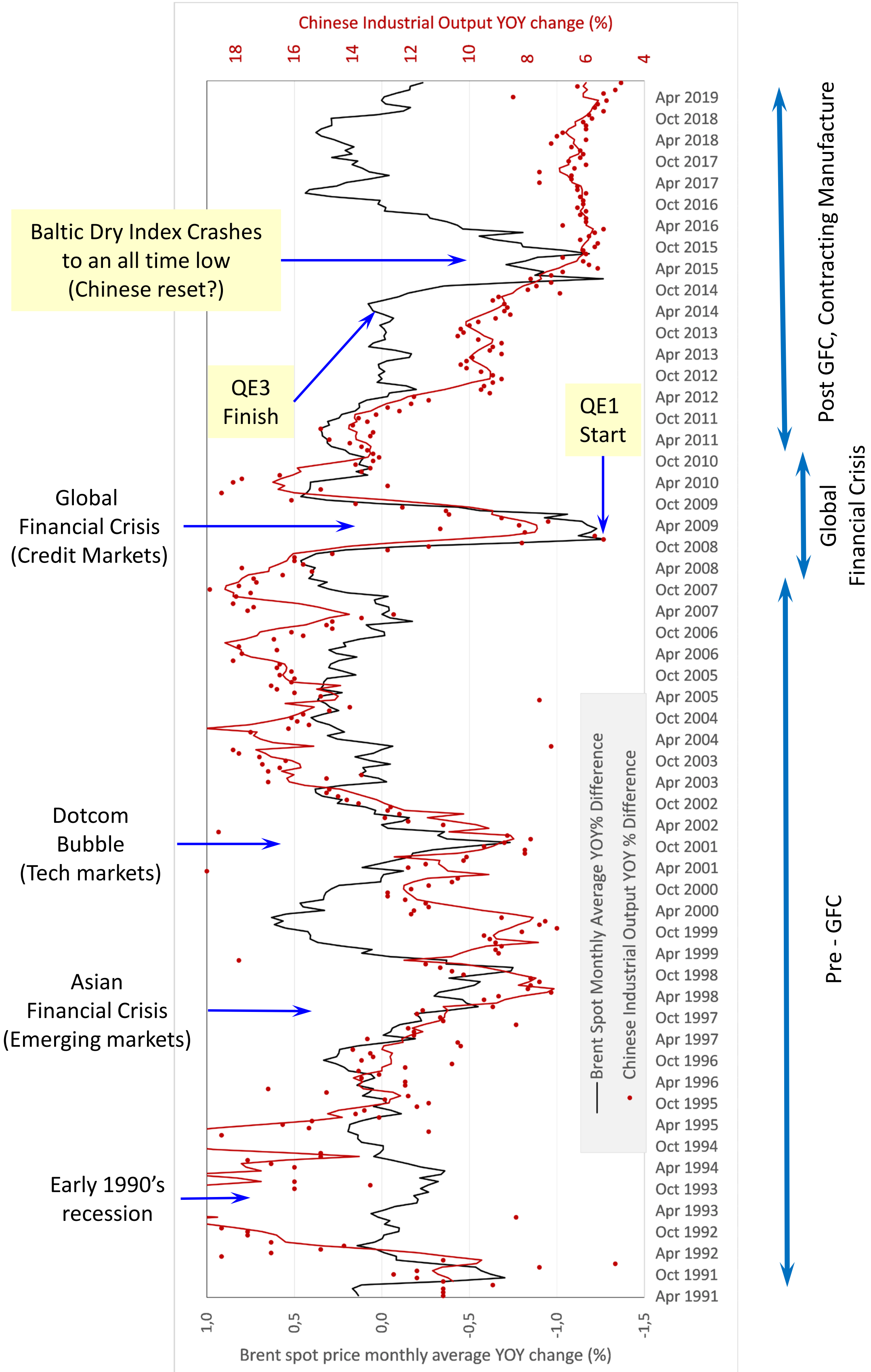

Figure J6. Chinese Industrial output and the price of oil, 1991 - 2018
(Source: National Bureau of Statistics of China, Nasdaq Stock Exchange, https://www.nasdaq.com/markets/crude-oil-brent.aspx)

Table J1. Insights on the causes of key oil-economy events from different research communities (Source: Kallis et al 2016)

Event	Oil economics	Macro economics	Political economy	Ecological economics
Oil and economic crises 1973 & 1979	Growth and rising demand from developed economies (Kilian) vs. supply interruptions from events in Middle East (Hamilton).	Wrong policy response by the Fed which fearing inflation by oil prices precipitated recession by raising interest rates (Bernanke et al). US inflation and depreciation of the dollar to which OPEC responded by restricting production (Frankel).	End of Bretton Woods, US unable to finance Vietnam war un-pegged from gold and became a global importer of surpluses, "recycling" petrodollars (Varoufakis, Spiro). U.S. supported higher prices given dollar devaluation to back up Shah's regime in Iran (Anderson, Engler).	Resource limits to growth.
Low oil prices – low growth 1985–89 High oil prices – high growth 2002–2007	Tax reform and low investment in US oil industry (Edelstein & Kilian). Effect of oil prices on expenditures is cumulative and until 2007 hadn't passed the threshold where households change consumption patterns, hence no effect on growth (Hamilton). Prices increased because of economic growth and industrial demand from Asia, which more than compensated for negative effects of high oil prices – the effects of a demand-driven rise of oil price take time to show (Kilian).	– Independent monetary authorities responding to core inflation did not repeat mistakes of the 1970s (Blanchard & Gali, Nordhaus). Growth in oil-producing countries and in countries exporting to them overcompensated for negative effects from high oil prices (Rasmusen & Roitman). Asian savings and petrodollars flooding US, pushing interest rates down, keeping growth high and creating housing and commodity asset bubbles (Caballero et al)	U.S. worked with Saudis to increase oil production and damage Soviet Union (Gaidar, Schweizer) Strategic underinvestment by major producers in order to maintain high prices (Smith). Petrodollars channeled from US consumers and developing countries to oil producing nations, and from them back to US Treasury and global banks and corporations (Spiro, Sager).	Prices did not reflect real scarcity of oil. (No explanation about low growth) Resource limitations – major producers could not increase production even if they wanted Over-borrowing and credit/housing bubbles sustained household consumption and growth despite rising oil prices (Martinez-Alier)
Oil shock 2008 – Financial crisis	Rising demand from the East facing. stagnating oil production (Kilian, Hamilton). Reduced expenditures, esp. for cars and houses, from US households tilting economy to recession (Hamilton). Foreclosures in suburbs facing high commuting costs (Cortright, Kaufman et al).	With the subprime mortgage and housing bubble broken, Asian savings and petrodollars shifted to oil. Oil prices appreciated, while the economy collapsed because of the collapse of the housing bubble (Caballero et al).		Peak oil increased oil prices to unsustainable levels causing recession, which in turn led to the collapse of the credit/housing bubbles. (Daly, Martinez-Alier)
Slump of oil prices 2014c, limited recovery	Expectations for a growth slow-down and to a lesser extent higher global oil production (Baumeister & Kilian).	Negative economic effect from low oil prices on domestic US (shale) oil industry (Krugman). Expectations for tightened US interest rates in the near future (Frankel). Appreciation of the dollar (Tokic).	Saudi Arabia increasing production to drive US competitors out of the market.	Low EROI of the new supplies of unconventional oil? (Kerschner and Capellán-Pérez)

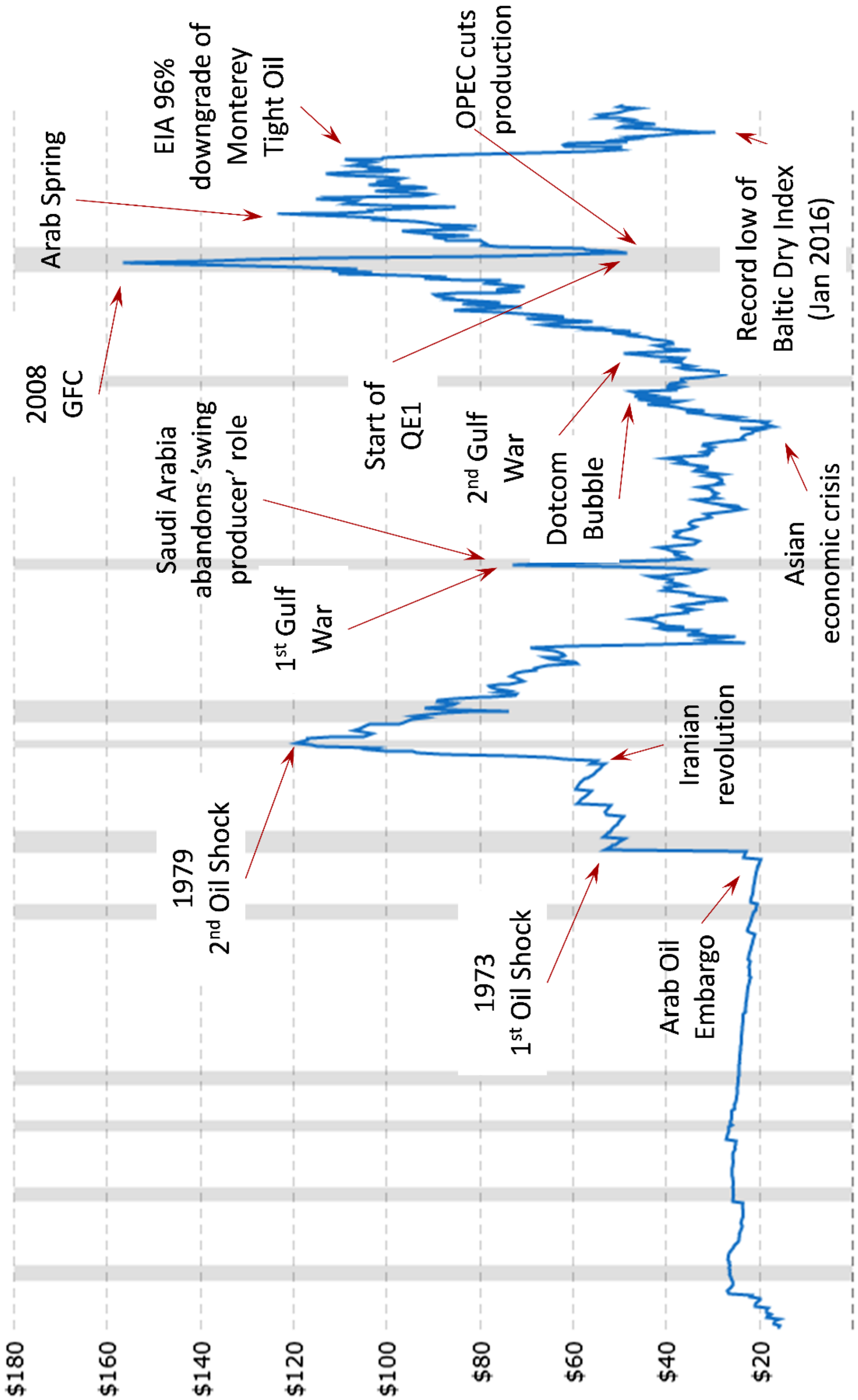

Figure J7. Crude Oil Prices - 70 Year Historical Chart 1946 - 2017
(Source: Data from Interactive charts of West Texas Intermediate (WTI or NYMEX) crude oil prices per barrel back to 1946. The price of oil shown is adjusted for inflation using the headline CPI and is shown by default on a logarithmic scale. The current price of WTI crude oil as of August 03, 2017 is $49.20 per barrel.)

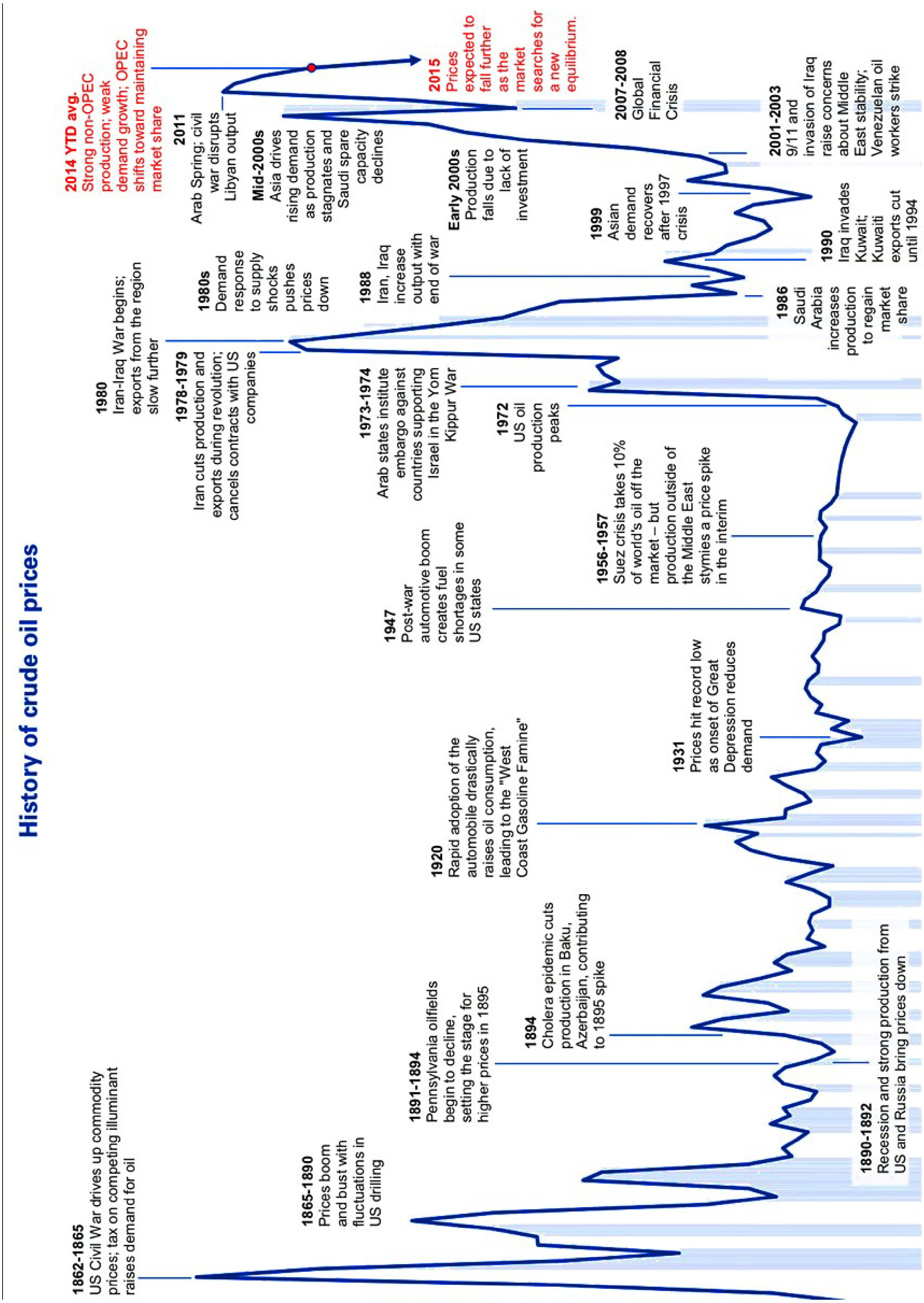

Figure J8. Oil market price (West Texas Intermediate WTI or NYMEX) in context geopolitical events, 1863 to 2014 (Source: data from Business Insider, BP Statistics, Goldman Sachs Global Investment Research, Money Morning Staff Research)

Of the 193 countries in the United Nations assembly (all of which consume oil as a critical necessity), only 6 of them have the capacity to grow oil production capacity while all other producing nations are declining. If the United States and Iraq were removed, then peak oil happened in 2016. However, this statistic is by nation state. If one was to consider each crude oil producing operation, it is estimated that 81% of world liquids production is already in decline (excluding future redevelopments) (Ahmed 2017).

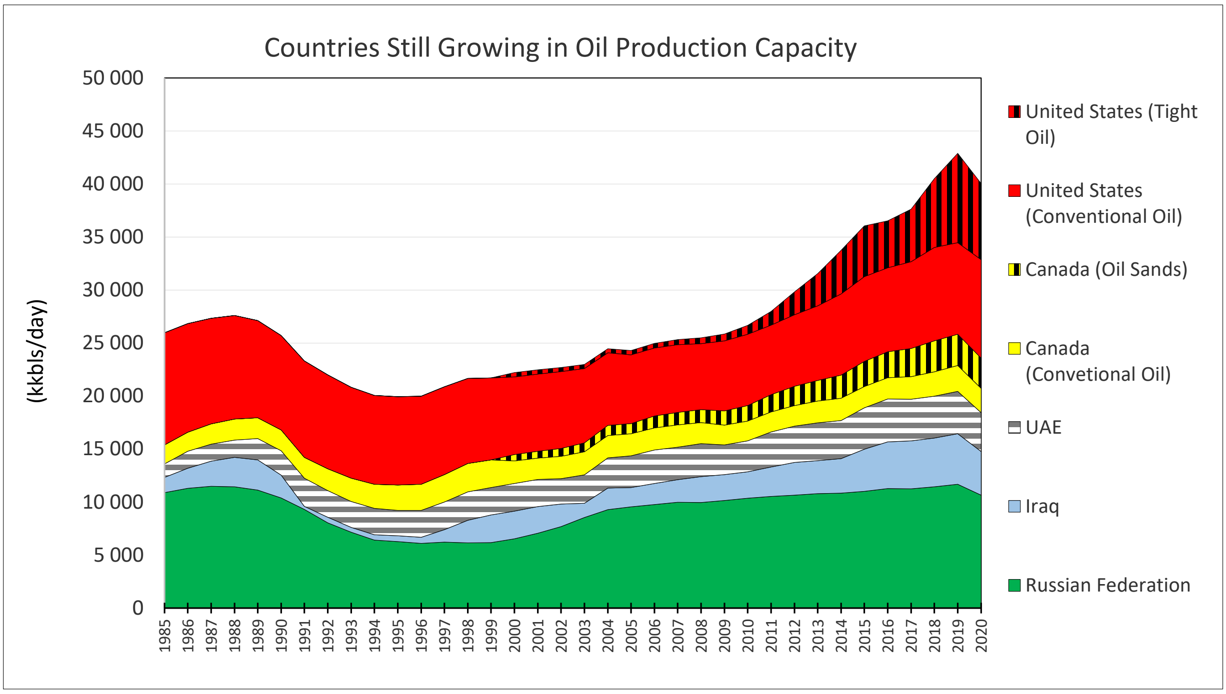

Figure J9. Oil producing countries still growing capacity
(Source: BP Statistical World Energy Review 2019)

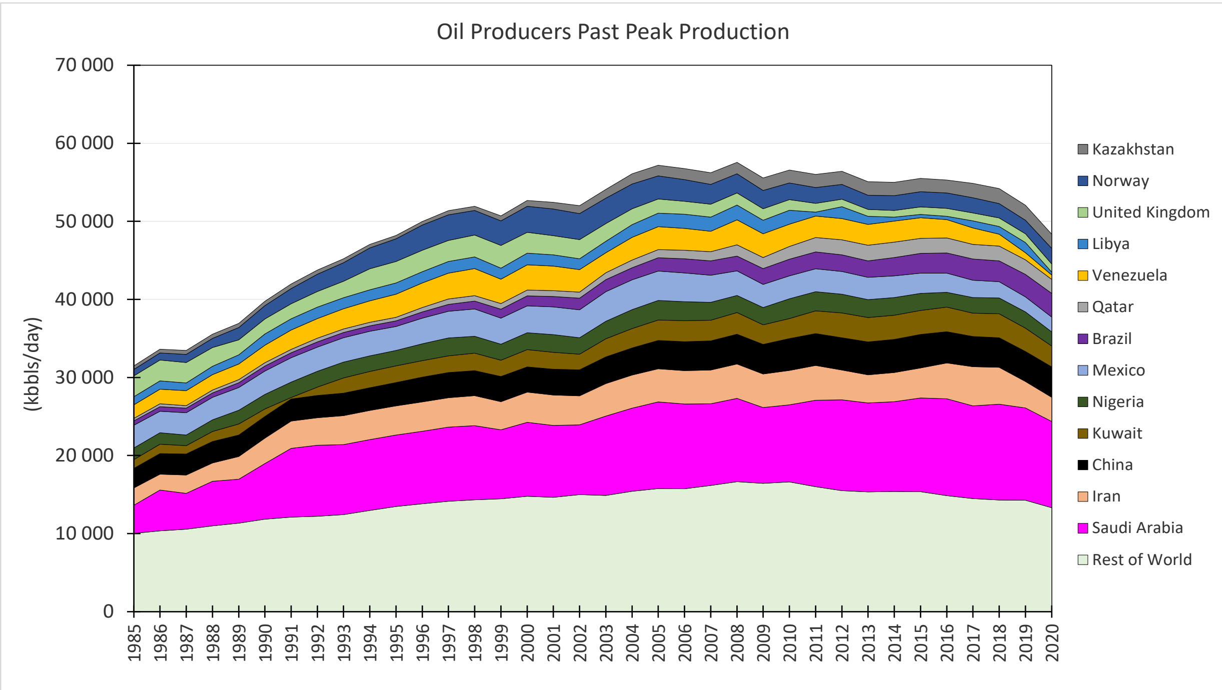

Figure J10. Oil producing countries that have peaked production
(Source: BP Statistical World Energy Review 2019)

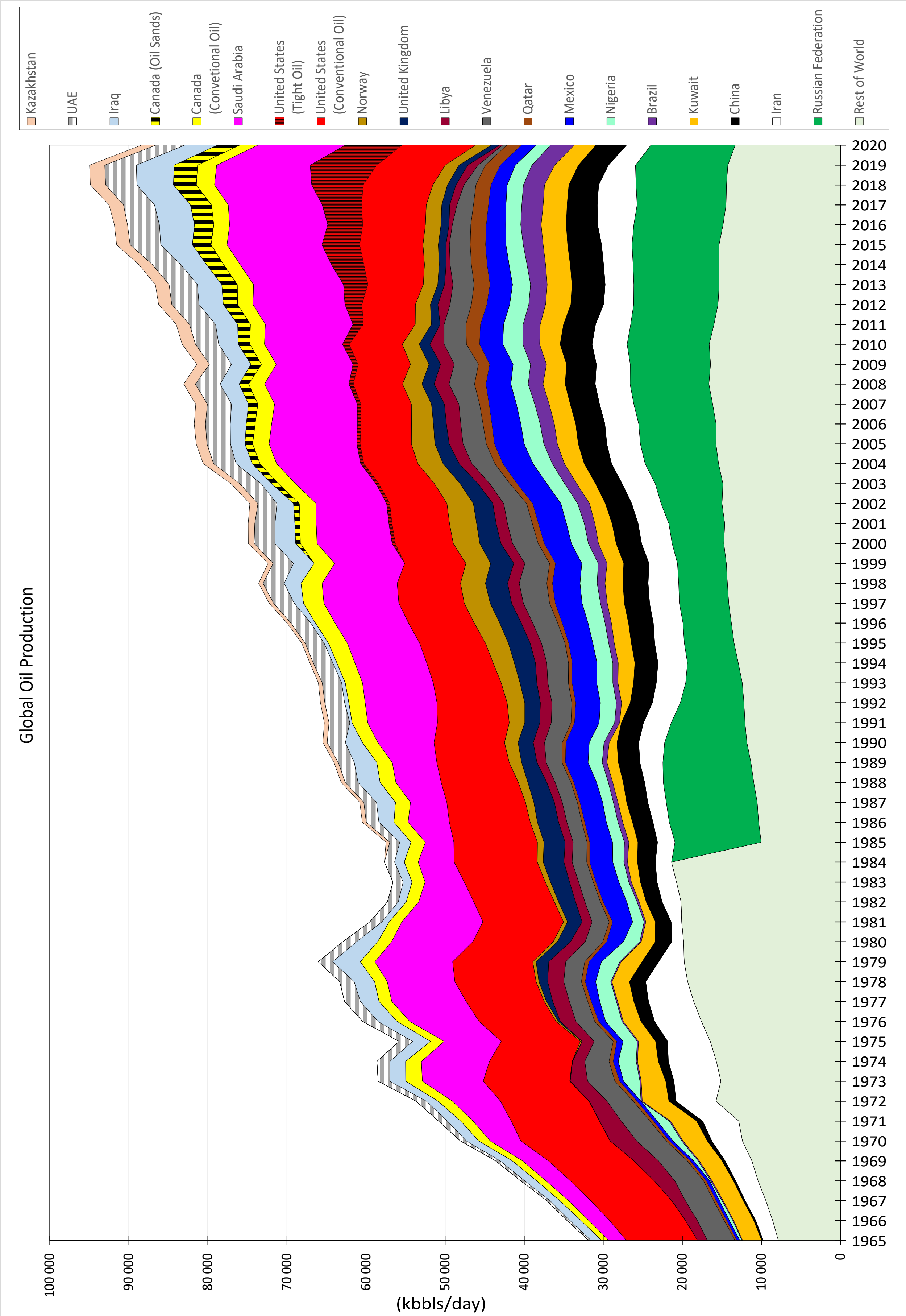

Figure J11. Global oil production 1965 - 2020
(Source: BP Statistical World Energy Review 2019)

The HSBC study (Fustier *et al.* 2016) quoted a projected probable range for average decline rate on post-peak production is 5-7%, equivalent to around 3-4.5mb/d of lost production every year from 2016 forward (Figure J12). Small oilfields typically decline twice as fast as large fields.

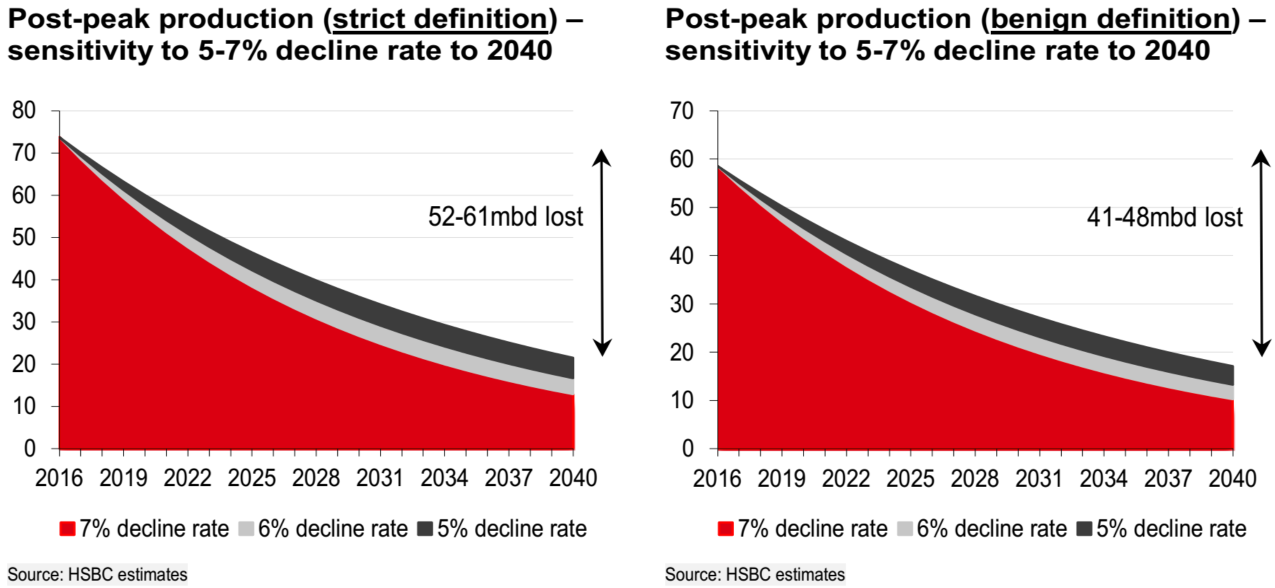

Figure J12. Post peak oil production decline rates
(Source: HSBC Global Research, Fustier et al. 2016)

- 81% of existing producing fields are in decline at an average rate of 5-7% p.a. (HSBC 2016)
- Of the largest 10 modern producing fields, the youngest was discovered in 1976 (Hirsch 2010)
- Record low discoveries in 2020 (Rystad 2021)
- Once energy becomes much more expensive, the economics of all other raw materials will change
- All raw materials will have this profile eventually

Figure J13 shows historical oil discovery. Most oil was discovered in the 1960's with a persistent decline since a peak in 1962. The largest producing field in the world, Ghawar, Saudi Arabia, was discovered in 1948 (Michaux 2019). Figure J14 shows the global oil and gas deposit discovery between 2013 and 2018, which fits inside the red box in Figure J13.

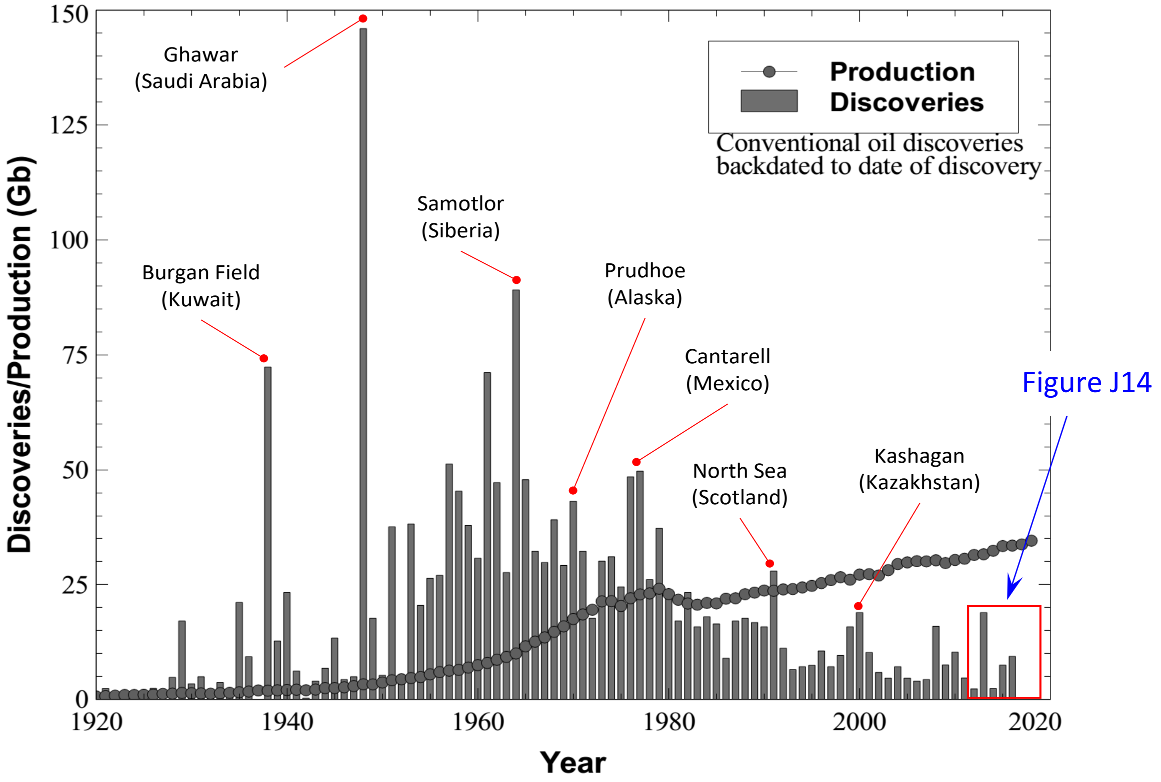

Figure J13. Conventional oil resource discovery 1920-2018
(Source: Analyst – John Peach, data from ASPO 2019, Wood and Mackenzie, Oil Price 2017, Rsytad Energy 2018, Our World in Data 2019, BP Energy Statistics 2019 CNBC 2017)

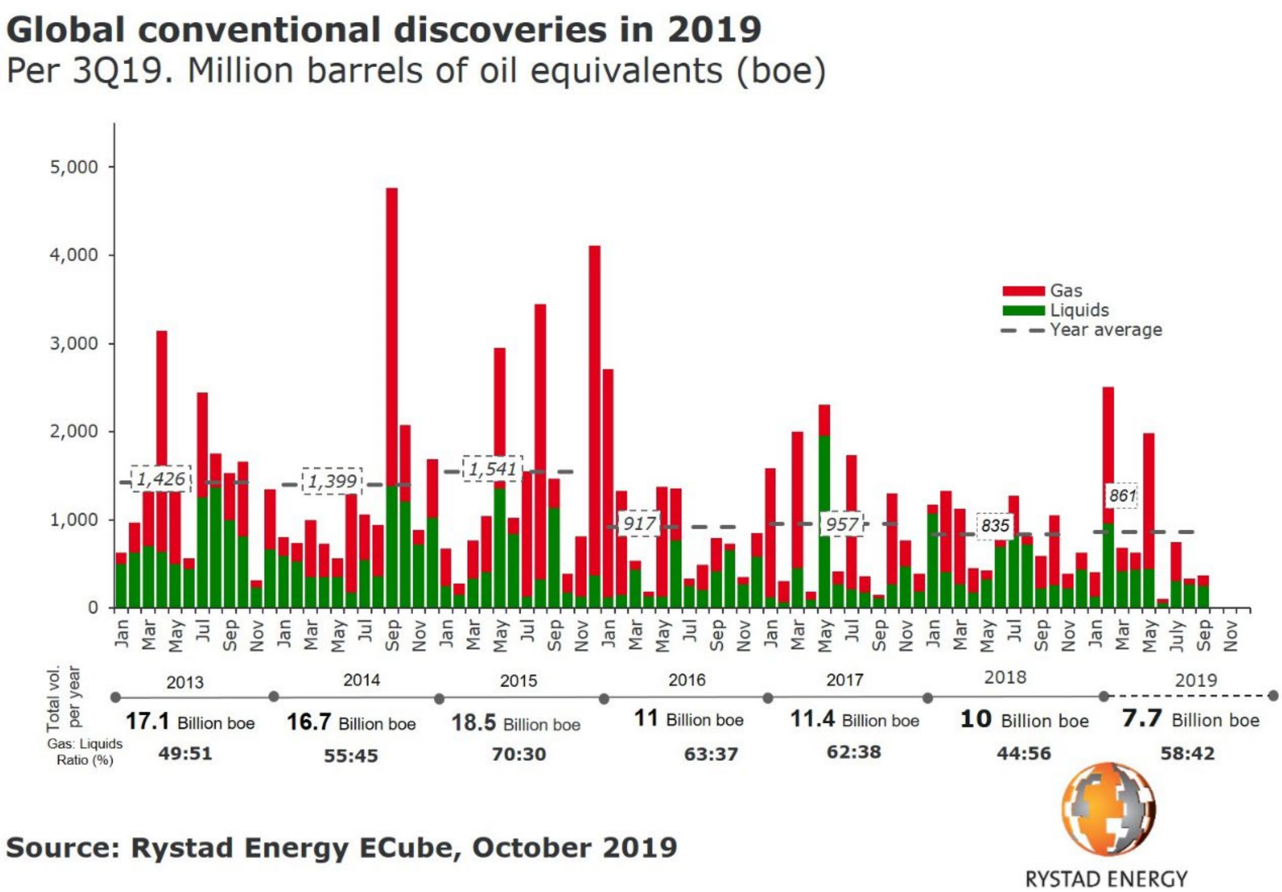

Figure J14. Global resource discoveries for conventional oil and gas in 2019 (Source: Rsytad Energy ECube Oct 2019)

New oil deposit discoveries in 2017 were at the lowest since 1947. Explorers replaced just 6% of resources that were consumed in the same year (Rystad 2018, Davis 2017). Explorers in 2015 discovered only about a tenth as much oil as they did annually on average since 1960 (Davis 2017).

It is to be remembered that this is new volumes discovered. This does not mean that these deposits are extractable with current technology, or economically viable to be exploited commercially. No, this cannot be extrapolated to the whole world, but suggests that commercial discoveries are somewhat less than total discoveries (Likvern 2019).

The Hirsch report (Hirsch 2005 & 2010) showed, new oil discoveries have been in long term decline — lately reaching record lows notwithstanding record investments between 2001–2014. New discoveries are invariably smaller fields with more rapid peak and decline rates.

If the 2018 stated global reserves of oil is 1730 billion barrels (BP Statistics 2019), and the 2018 global consumption of oil was 36.4 billion barrels (99 843 kbbls/day) (BP Statistics 2019), **then current reserve will last just 47.5 years before complete depletion**.

This number assumes that all of that oil is extractable. Also, the rate of global oil production will peak and decline well before 47 years, creating a demand to supply gap. At which point the current economic industrial system will not be able to depend on oil as a primary fuel.

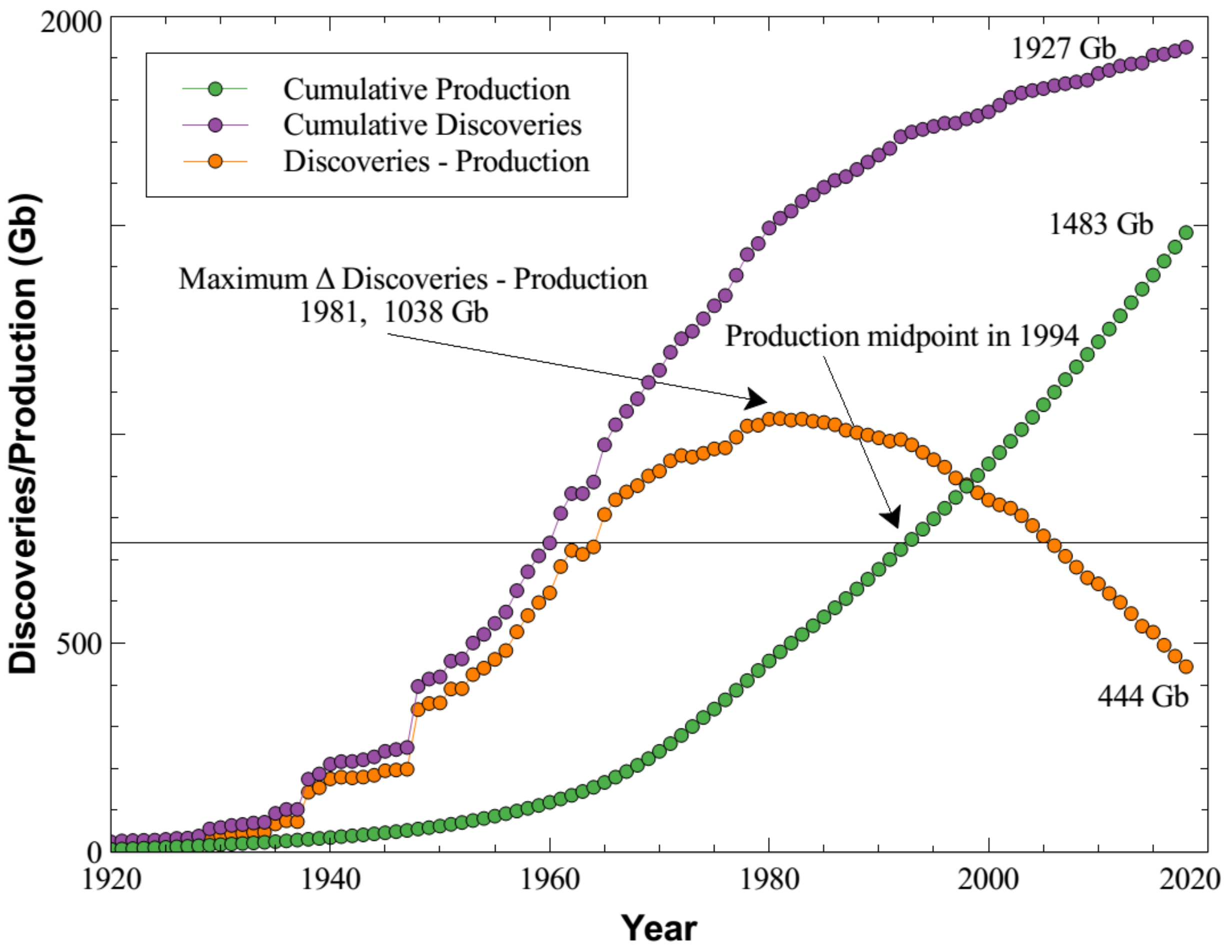

Figure J15. Cumulative global oil resource discoveries and global oil production, and net difference (Source: Analyst – John Peach, data from ASPO 2019, Wood and Mackenzie, Oil Price 2017, Rsytad Energy 2018, Our World in Data 2019, BP Energy Statistics 2019 CNBC 2017)

Figure J15 shows the cumulative global oil discovery and global oil production, and the difference between the two. The midpoint of production occurred in 1994, meaning the global industrial system has consumed 50% of all oil produced in the last 25 years (Peach 2019). The peak of net contribution of oil discovery was in 1981. That is, since 1981, production outpaced discovery additions to the global oil deposit inventory. Figure J16 shows the net contribution to annual world oil reserves. Again, since 1981, net contribution has declined.

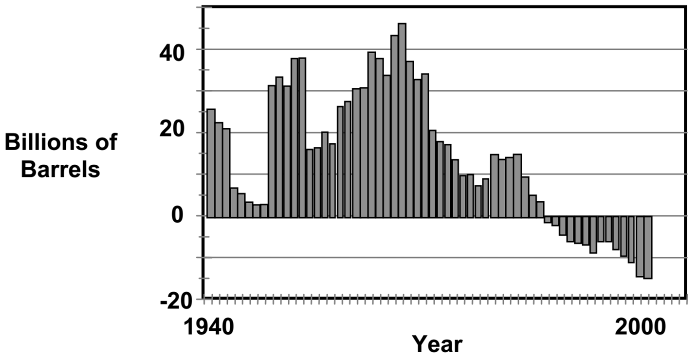

Figure J16. Net difference between annual world oil reserves additions and annual consumption (Source: Hirsch *et al.* 2005 report commissioned by US DOE)

Figure J17 is a chart of oil price (inflation adjusted), and it shows that the window of oil market viability is closing, which suggests the temporary measures (also termed 'a band-aid on a bullet wound') are being overrun with the underlying issues that have yet to be resolved. If this is correct, then we will soon observe a resumption of the 2008 economic correction, but QE measures will no longer be sufficient.

Figure J17. West Texas Intermediate (WTI or NYMEX) crude oil prices per barrel October 1999 to October 2019, Inflation adjusted (Source: MacroTrends) (Copyright: https://www.macrotrends.net/terms)

Predicting the time and date this market window will completely close, is not appropriate as this is a nonlinear system with unknown influences. It could be postulated though that the window of viable operation could close between now and 2025.

At the time of writing this report, global peak oil production was in November 2018 at 102.24 million barrels a day. Just after November 2018, it has been shown that the oil industry, tight oil had its challenges, with 9 out of 10 operators having a negative cash flow. IEEFA, (Institute for Energy Economics and Financial Analysis), in partnership with the Sightline Institute published a market report (Williams-Derry *et al.* 2019) examining the viability of the U.S. fracking industry. This is relevant as the U.S. tight oil sector was now the global swing producer for crude oil (Michaux 2019). The situation was that investor returns were not very good, but by the second quarter in 2019, capital investment had returned to the oil industry and roughly half of the oil producing companies had positive cash flow (Berman 2022). By June 2021, the U.S. Tight Oil sector had fully recovered and U.S. crude + condensate had recovered to 11.8 mmb/d at the time this report was written, but still remained more than 1 mmb/d less than the November 2019 level.

> *"The key to maintaining a stable and slightly increasing production volume and keeping cash flow positive has been completing previously drilled but uncompleted wells (DUCs) rather than drilling new wells. Most of those DUCs do not perform as well as new wells but they have been adequate. Companies are now drilling more new wells as the DUC inventory falls and oil prices increase. Companies, however, remain steadfast in their stated commitment to cash flow and dividends as they try to lure investors back.*
>
> *The larger question is whether or not outside capital will become available to support the needed drilling beyond cash flow—not just in the US but globally. The effect of investor focus on returns will make that uncertain because high volatility markets mean that investors will expect unrealistically high margins."*

-Art Berman April 2022 (Berman 2022)

The use of DUC inventory does suggest that short term production gains were prioritized over long term oil field stewardship. A new model for peak oil has been proposed (Michaux 2019), where the world runs out of money before it runs out of oil (or gas). The oil price must be high enough for producers to be economically viable. That same price must be low enough for the market consumers to access that oil in large enough volumes to allow for economic growth. Oil will peak in production, not because there is not enough reserves in the ground to meet demand, but because consumers cannot support the oil price at a level that allows oil producers to remain economically viable. This pattern will be seen as a cumulative build up over many years, not an overnight crash.

> *"The capital deficit in this market is extreme. And now it's kicking off this volatility trap where the underinvestment leads to declining inventories to raise cash, liquidation of financial positions to raise cash. All of that accentuates the volatility and then scares off further investment. So, you now are entering this volatility trap. You know, we've made the point and I've testified in Congress on this point before, is the only way out of this is you need somebody to stop that vicious cycle and create some type of stability. The saying I like to say is spot prices solve surpluses, long-term contracts solve shortages."*

-Jeff Currie, Global director of commodity research at Goldman Sachs (Bloomberg 2022)

Figure J18 shows oil production (total liquids) may have peaked in November 2018. For the validity of this data pattern to be accepted, the peak date of November 2018 would have to remain the record for at least a period of 5 years following recording. Remember, 81% of existing fields are declining at a rate of 5-7% for each passing year. Due to depleting reserves (Figures J13 & J14), with each passing month, that peak record would be more difficult to surpass (Simmons 2005). So, if this record of crude oil production is maintained till November 2023 (18 months from the time of writing this report), then the date of peak oil production could be declared.

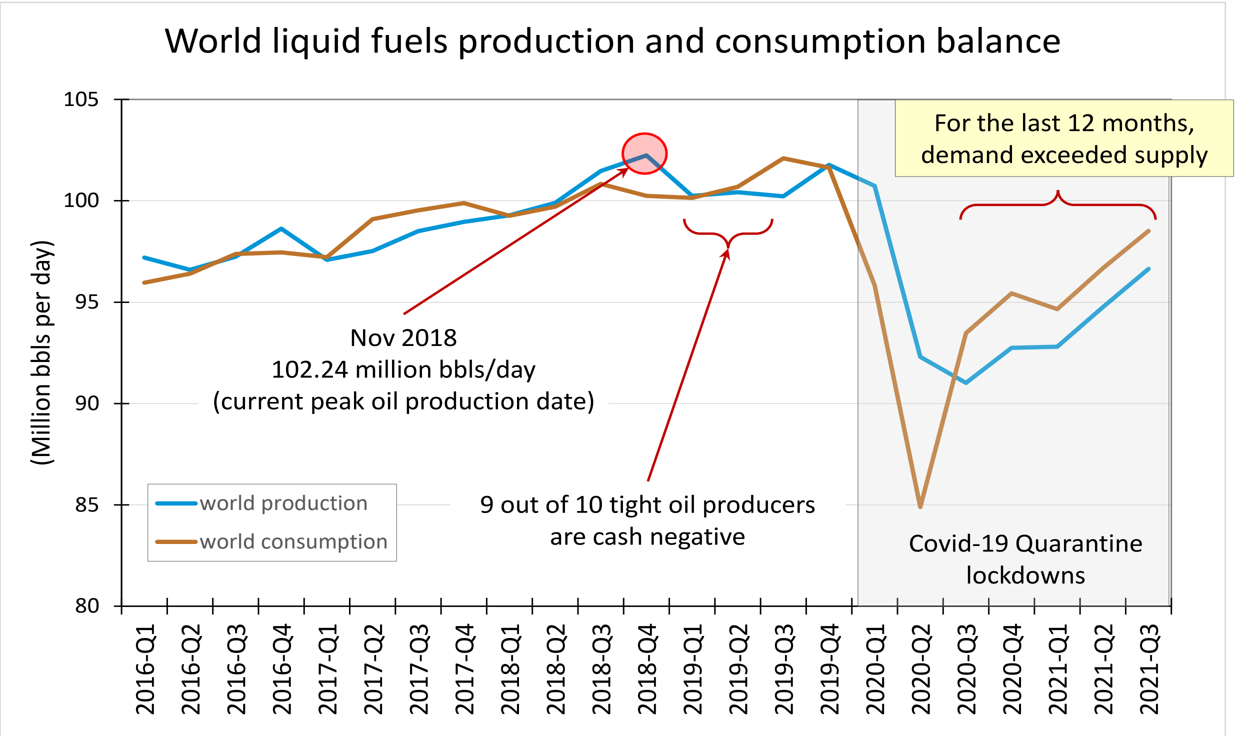

Figure J18. Global oil consumption and production
(Source: U.S. Energy Information Administration, Short-Term Energy Outlook, October 2021)

Oil will peak in production, not because there are not enough reserves in the ground to meet demand, but because consumers cannot support the oil price at a level that allows oil producers to remain economically viable. Figure J17 shows how this interaction may happen. Figure J18 shows this may already have happened in October 2018. This may or may not be peak oil, depending on whether more investment is put into the oil industry. The longer the peak persists though, the harder it is to overcome with a new record due to the depletion of conventional oil reserves.

In 2020, the Corona virus appeared and the pandemic quarantines resulted in oil demand dropping significantly. So, are the current economic stresses simply a data artifact of the Covid-19 pandemic? Figures J17 & J18 suggest it is not as these patterns' pre-date the pandemic.

The implications of this suggest that with the depletion and unreliability in supply of oil, our industrial ecosystem would be required to evolve into a lower energy consumption profile with less complexity. As there is no real replacement for oil in terms of what it contributes, this necessitates a complete restructure of the demand side of energy requirements. This has far reaching implications in the structure of the industrial ecosystem. Due to the widespread environmental impact of the current system, this would be required for long term stability of any modern industrial society (like Europe and Finland) in a sustainable fashion.

28.2 Gas Outlook

Gobal natural gas production in 2020 was dominated by just four nations: United States (23.7%), Russian Federation (16.6%), Iran (6.5%) and China (5.0%). It is possible that global peak gas production was in 2019 (Table J3 and Figure J19), but this could be an artefact of the Covid-19 Pandemic disruptions to the global supply chains. We will not really know when peak gas is until 5 years have passed the record production. So, if that production record is still observed in 2024, then the global peak gas production date can be declared. When peak gas is apparent, then the gas reserves that are left will become much more valuable and all producers may require a renegotiation of all supply contracts.

Consumption of natural gas was dominated by 4 nations: United States, Russian Federation, China, and Iran. As these nations are also the largest producers, the natural gas market can only be understood by examining the net import/export balance for each nation (Table J5). The two regions were net negative in the consumption of gas, Europe (with an annual shortfall of 322.5 bcm in 2020) and Asia Pacific (with an annual shortfall of 209.5 bcm in 2020). In Europe the largest net consumers were Germany (-82.0 bcm), Italy (-63.8 bcm), Turkey (-46.6 bcm) and France (-40.7 bcm). In Asia Pacific, China (-136.6 bcm) and Japan (-104.4 bcm) were the largest net consumers.

The net export balance for the United States was 82.6 bcm in 2020. In the same year, The European Union had a net import shortfall -332.1 bcm (Table J4). It is not clear if the United States can deliver enough gas to Europe if Russia leaves the international market.

Reported national reserves of natural gas peaked in 2018 at 196.9 trillion cubic meters. Only two nations, United States (6.7%) and China (4.5%) reported the potential to expand gas reserves in 2020. 88.8% of global gas reserves were in decline in 2020.

The United States gas production industry is heavily dependent on the Tight Oil sector (or fracking). The question becomes, can the U.S. Tight Oil sector continue to deliver such large quantities of gas to the global market?

28.2.1 Natural Gas Production

Global natural gas production peaked in 2019. This could be a data artefact of the Covid-19 pandemic, and production may recover when the global supply chain difficulties created by the pandemic are resolved. Global natural gas production in 2020 was dominated by just four nations: United States (23.7%), Russian Federation (16.6%), Iran (6.5%) and China (5.0%).

- 18.1% of global natural gas production continued to expand in 2020 and have yet to reach peak production. The nations were Iran (6.5%), China (5.0%), Saudi Arabia (2.9%), Nigeria (1.3%), Oman (1.0%), Azerbaijan (0.7%), Bahrain (0.4%) and Colombia (0.3%).

- 46.2% of global natural gas production peaked production in 2019. The nations were The United States (23.7%), Russian Federation (16.6%), Australia (3.7%), Malaysia (2.1%), Egypt (1.7%), Kuwait (0.5%) and Iraq (0.3%). It is possible that some of this production will recover.

- 32.4% of global natural gas production has peaked in production before 2019

- United States + Canada + Australia + Saudi Arabia = 34.6% of global gas production

- Russian Federation + China + Iran = 28.1% of global gas production

Table J2. Global gas production (Source: BP Statistical review of World Energy 2021)

Natural Gas Production by Geographic Region	Annual Production in 2020 (billion cubic metres)	Production Market Share in 2020 (%)	Annual Production in 2019 (billion cubic metres)	Annual Production in 2000 (billion cubic metres)
Global	**3853,7**		**3976,2**	**2427**
Total North America	1 109,9	28,8 %	1130,3	761,6
Total Central & South America	152,9	4,0 %	172,3	99,2
Total Europe	218,6	5,7 %	235,2	
Commonwealth of Independant States	802,4	20,8 %	858,2	
Middle East	686,6	17,8 %	678,2	206,8
Total Africa	231,3	6,0 %	243,8	126,8
Total Asia Pacific	652,1	16,9 %	658,2	274,1
Nations				
United States	914,6	23,7 %	930	543,2
China	194	5,0 %	177,6	27,2
India	23,8	0,6 %	26,9	26,4
European Union	47,8	1,2 %	61,1	231,2
Russian Federation	638,5	16,6 %	679	545

Table J3-1. Global gas production (Source: BP Statistical review of World Energy 2021, 2020, 2019, 2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006, 2005 and 2004)

Production of Natural Gas (billion cubic metres)	1997 (bcm)	1998 (bcm)	1999 (bcm)	2000 (bcm)	2001 (bcm)	2002 (bcm)	2003 (bcm)	2004 (bcm)	2005 (bcm)	2006 (bcm)	2007 (bcm)	2008 (bcm)	2009 (bcm)
Canada	535,3	538,7	533,3	543,2	555,5	536	540,8	526,4	511,1	523,2	545,9	570,8	584
Mexico	168,6	173,4	176,8	182,2	186,5	187,9	184,7	183,7	187,4	188,4	183,7	176,6	164
United States	31,7	34,8	36,7	36,1	34,9	35,4	36,2	37,7	38,9	42,8	46,2	53,9	54,6
Total North America	735,5	747,0	746,8	761,6	776,8	759,2	761,7	747,9	737,4	754,4	775,8	801,3	802,6
Argentina	27,4	29,6	34,6	37,4	37,1	36,1	41,0	44,9	45,6	46,1	44,8	44,1	41,4
Bolivia	2,7	2,8	2,3	3,2	4,7	4,9	6,4	9,8	11,9	12,7	13,5	14,3	12,3
Brazil	6,0	6,3	6,7	7,2	7,6	9,2	10,0	11,0	11,0	11,3	11,3	13,7	11,7
Colombia	5,9	6,3	5,2	5,9	6,1	6,2	6,1	6,4	6,8	7,3	7,7	9,1	10,5
Peru					0,4	0,4	0,5	0,9	1,5	1,8	2,7	3,4	3,5
Trinidad	7,4	8,6	11,7	14,1	15,2	17,3	24,7	27,3	30,3	36,4	39,0	39,3	40,6
Venezuela	30,8	32,3	27,4	27,9	29,6	28,4	25,2	28,4	28,1	27,9	28,5	30,0	28,7
Other S. & Cent. America	2,6	2,7	3,3	3,5	3,7	3,7	3,4	3,9	4,8	5,3	6,1	3,7	3,2
Total S. & Cent. America	82,8	88,6	91,1	99,2	104,0	105,8	116,9	131,7	138,6	147,2	150,8	157,8	151,9
Denmark	7,9	7,6	7,8	8,1	8,4	8,4	8,0	9,4	10,4	10,4	9,2	10,1	8,4
Germany	17,1	16,7	17,8	16,9	17,0	17,0	17,7	16,4	15,8	15,6	14,3	13,0	12,2
Italy	17,7	17,4	16,0	15,2	14,0	13,4	12,7	11,9	11,1	10,1	8,9	8,5	7,3
Netherlands	67,7	63,6	59,3	57,3	61,9	59,9	58,4	68,8	62,9	62,3	64,5	66,6	62,7
Norway	43,0	44,2	48,5	49,7	53,9	65,5	73,1	78,5	85,0	87,6	89,7	99,3	103,7
Poland	3,6	3,6	3,4	3,7	3,9	4,0	4,0	4,4	4,3	4,3	4,3	4,1	4,1
Romania	15,0	14,0	14,0	13,8	13,5	13,2	13,0	12,8	12,4	11,9	11,6	11,4	11,3
Ukraine	17,4	16,8	16,9	16,7	17,1	17,4	18,0	19,1	19,4	19,1	19,0	19,0	19,2
United Kingdom	85,9	90,2	99,1	108,4	105,8	103,6	102,9	96,4	88,2	80,0	72,4	69,6	59,7
Other Europe													
Total Europe													
Azerbaijan	5,6	5,2	5,6	5,3	5,2	4,8	4,8	4,7	5,3	6,3	10,3	14,8	14,8
Kazakhstan	7,6	7,4	9,3	10,8	10,8	10,6	12,9	20,6	23,3	24,6	27,3	18,7	17,8
Russian	532,6	551,3	551,0	545,0	542,4	555,4	578,6	591,0	598,0	612,1	607,4	601,7	527,7
Turkmenistan	16,1	12,4	21,3	43,8	47,9	49,9	55,1	54,4	58,8	62,2	67,4	66,1	36,4
Uzbekistan	47,8	51,1	51,8	52,6	53,6	53,5	53,6	55,8	55,0	55,4	58,5	62,2	60,0
Other CIS													
Total CIS													
Bahrain	8,0	8,4	8,7	8,8	9,1	9,5	9,6	9,8	10,7	11,1	11,5	12,7	12,8
Iran	47,0	50,0	50,4	60,2	66,0	75,0	81,5	91,8	100,9	108,6	111,9	116,3	131,2
Iraq					2,8	2,4	1,6	1,0	1,5	1,5	1,5	1,9	1,2
Kuwait	9,3	9,5	8,6	9,6	8,5	8,0	9,1	11,0	12,3	12,9	12,6	12,8	11,2
Oman	5,0	5,2	5,5	8,7	14,0	15,0	16,5	18,5	19,8	23,7	24,1	24,1	24,8
Qatar	17,4	19,6	22,1	23,7	27,0	29,5	31,4	39,2	45,8	50,7	59,8	77,0	89,3
Saudi Arabia	45,3	46,8	46,2	49,8	53,7	56,7	60,1	65,7	71,2	73,5	75,9	80,4	78,5
Syria	3,8	4,3	4,5	4,2	4,1	5,0	5,2	5,3	5,4	5,5	5,6	5,3	5,6
United Arab Emirates	36,3	37,1	38,5	38,4	39,4	43,4	44,8	46,3	47,0	47,4	49,2	50,2	48,8
Yemen													0,8
Other Middle East													
Total Middle East													
Algeria	71,8	76,6	86	84,4	78,2	80,4	82,8	82	88,2	84,5	83,0	85,8	79,6
Egypt	11,6	12,2	14,7	18,3	21,5	22,7	25	26,9	34,6	44,7	46,5	59	62,7
Libya	6,0	5,8	4,7	5,3	5,6	5,6	5,8	6,2	11,3	14,8	15,2	15,9	15,9
Nigeria	5,1	5,1	6	12,5	14,9	14,2	19,2	22,8	22,4	28,4	35,0	35	24,8
Other Africa	4,9	5,0	5,7	6,2	6,7	7,4	7,1	7,9	9,0	9,2	10,7	15,8	16,3
Total Africa	99,4	104,8	117,1	126,8	126,9	130,3	139,9	145,8	165,5	181,6	190,4	211,5	199,2
Australia	29,8	30,4	30,8	31,2	32,5	32,6	33,2	35,3	37,1	38,9	40,0	38,3	42,3
Bangladesh	7,6	7,8	8,3	10	10,7	11,4	12,3	13,2	14,5	15,3	16,3	17	18,5
Brunei	11,7	10,8	11,2	11,3	11,4	11,5	12,4	12,2	12	12,6	12,3	12,2	11,4
China	22,7	23,3	25,2	27,2	30,3	32,7	35	41,5	49,3	58,6	69,3	80,3	85,3
India	22,3	24,5	25,1	26,4	26,4	27,6	29,5	29,2	29,6	29,3	30,2	30,5	39,2
Indonesia	65,7	64,5	70	65,7	64,5	70,6	72,7	72,8	68,7	69,3	66,7	69,7	71,9
Malaysia	38,6	38,5	40,8	45,3	46,9	48,3	51,8	53,9	59,9	60,2	60,5	64,7	64,1
Myanmar	1,5	1,8	1,7	3,4	7,2	8,4	9,6	10,2	13	13,4	14,7	12,4	11,5
Pakistan	19,8	20,1	22,2	22,8	23,4	22,9	25,2	27,4	30,2	30,5	30,8	37,5	38,4
Thailand	16,2	17,5	19,2	20,2	19,6	20,5	21,8	22,4	23,7	24,4	25,9	28,8	30,9
Vietnam	0,5	0,9	1,3	1,6	2	2,4	2,4	4,2	6,9	7	7,7	7,5	8
Other Asia Pacific	3,4	3,5	3,5	3,6	3,8	5,4	6,6	6,4	7,2	10,7	13,1	18,3	18,6
Total Asia Pacific	245	248,1	264,7	274,1	284,7	300	316,8	332,5	355,8	373,7	391,5	417,1	440,3
Total World	**2235,7**	**2286,2**	**2346,8**	**2427**	**2483,8**	**2527,9**	**2618,8**	**2703,7**	**2775,5**	**2872,2**	**2940**	**3047,2**	**2955,9**
of which:													
OECD	1025,5	1037,1	1045,9	1068,5	1090,7	1079,7	1086,5	1083,5	1066,4	1080,6	1093,3	1130,9	1121,9
Non-OECD													
Former Soviet Union	627,4	644,5	656,2	674,5	677,3	691,3	723,5	745,8	760	780	790,2	782,7	676
European Union	224,5	222,2	225,7	231,2	232,4	227,4	223,9	227,8	212,3	204,9	191,9	189,4	171,5

* Excludes gas flared or recycled. Includes natural gas produced for gas-to-liquids transformation.
◆ Less than 0.05%.
n/a not available.
Notes: As far as possible, the data above represents standard cubic metres (measured at 15°C and 1013 mbar); as they are derived directly from measures of energy content using an average conversion factor and have been standardized using a gross calorific value (GCV) of 40 MJ/m3, they do not necessarily equate with gas volumes expressed in specific national terms.
Annual changes and shares of total are calculated using billion cubic metres figures.

Table J3-2. Global gas production (Source: BP Statistical review of World Energy 2021, 2020, 2019, 2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006, 2005 and 2004)

Production of Natural Gas (billion cubic metres)	2010 (bcm)	2011 (bcm)	2012 (bcm)	2013 (bcm)	2014 (bcm)	2015 (bcm)	2016 (bcm)	2017 (bcm)	2018 (bcm)	2019 (bcm)	2020 (bcm)
Canada	149,6	151,1	150,3	151,9	159	160,8	172	173,9	176,8	169	165,2
Mexico	51,2	52,1	50,9	52,5	51,3	47,9	43,7	38,3	35,2	31,3	30,1
United States	575,2	617,4	649,1	655,7	704,7	740,3	727,4	746,2	840,9	930,0	914,6
Total North America	775,9	820,5	850,3	860,1	915,0	949,0	943,0	958,3	1 052,9	1 130,3	1 109,9
Argentina	39,0	37,7	36,7	34,6	34,5	35,5	37,3	37,1	39,4	41,6	38,3
Bolivia	13,7	15,0	17,1	19,6	20,3	19,6	18,8	18,2	17	15	14,4
Brazil	15,0	17,2	19,8	21,9	23,3	23,8	24,1	27,2	25,2	25,7	23,9
Colombia	10,8	10,5	11,5	13,2	12,3	11,6	12,0	12,3	12,9	13,2	13,3
Peru	7,3	11,5	12,0	12,4	13,1	12,7	14,0	13,0	12,8	13,5	12,1
Trinidad	40,3	38,7	38,5	38,7	38,1	36,0	31,3	31,9	34	34,6	29,5
Venezuela	30,5	30,2	31,9	30,6	31,8	36,1	37,2	38,6	31,6	25,6	18,8
Other S. & Cent. America	3,8	3,2	3,0	2,7	2,6	2,9	3,1	3,1	3	3,2	2,7
Total S. & Cent. America	160,4	164,1	170,6	173,8	176	178	177,9	181,4	175,9	172,3	152,9
Denmark	8,5	6,9	6	5	4,8	4,8	4,7	5,1	4,3	3,2	1,4
Germany	11,1	10,5	9,5	8,6	8,1	7,5	6,9	6,4	5,5	5,3	4,5
Italy	8,0	8,0	8,2	7,4	6,8	6,4	5,5	5,3	5,2	4,6	3,9
Netherlands	75,3	69,5	68,4	72,4	60,4	45,9	44,3	37,9	32,3	27,8	20
Norway	106,2	100,5	113,9	107,9	107,5	116,1	115,9	123,7	121,3	114,3	111,5
Poland	4,3	4,5	4,5	4,4	4,3	4,3	4,1	4	4	4	3,9
Romania	10,0	10,1	10,1	10	10,2	10,2	9,1	10	10	9,6	8,7
Ukraine	19,4	19,5	19,4	20,2	20,2	18,8	19	19,4	19,7	19,4	19
United Kingdom	57,9	46,1	39,2	37,0	37,4	40,7	41,7	41,9	40,7	39,5	39,5
Other Europe	9,3	9,2	8,4	7,2	6,3	6,1	8,7	9,0	8,4	7,4	6,3
Total Europe	310,1	284,8	287,5	280,0	266,1	260,8	259,9	262,7	251,4	235,2	218,6
Azerbaijan	16,3	16,0	16,8	17,4	18,4	18,8	18,3	17,8	19	24,3	25,8
Kazakhstan	27,8	29,3	29,7	31,1	31,7	31,9	32,1	34,5	34,1	34	31,7
Russian	598,4	616,8	601,9	614,5	591,2	584,4	589,3	635,6	669,1	679,0	638,5
Turkmenistan	40,1	56,3	59,0	59,0	63,5	65,9	63,2	58,7	61,5	63,2	59,0
Uzbekistan	57,1	56,6	56,5	55,9	56,3	53,6	53,1	53,4	57,2	57,3	47,1
Other CIS	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Total CIS	740,0	775,4	764,2	778,3	761,4	754,9	756,3	800,2	841,3	858,2	802,4
Bahrain	12,4	12,6	13,1	14,0	14,7	14,6	14,4	14,5	14,6	16,3	16,4
Iran	143,9	151,0	156,9	157,5	175,5	183,5	199,3	213,8	232,0	241,4	250,8
Iraq	7,1	6,3	6,3	7,1	7,5	7,3	9,9	10,1	10,6	11,0	10,5
Kuwait	11,1	12,9	14,7	15,5	14,3	16,1	16,4	16,2	16,9	17,9	15,0
Oman	25,7	27,1	28,3	30,8	29,3	30,7	31,5	32,3	36,3	36,7	36,9
Qatar	123,1	150,4	162,5	167,9	169,4	175,8	174,5	170,5	169,1	172,1	171,3
Saudi Arabia	83,3	87,6	94,4	95,0	97,3	99,2	105,3	109,3	112,1	111,2	112,1
Syria	8,4	7,4	6,1	5,0	4,6	4,1	3,5	3,5	3,5	3,3	3,0
United Arab Emirates	50,0	51,0	52,9	53,2	52,9	58,6	59,5	59,5	58,0	58,0	55,4
Yemen	6,3	9,4	7,6	10,4	9,8	2,9	0,5	0,3	0,1	0,1	0,1
Other Middle East	3,3	4,2	2,5	6,3	7,3	8,1	9,0	9,5	10,1	10,2	15,0
Total Middle East	474,6	520,0	545,5	562,6	582,6	600,8	624,1	639,5	663,3	678,2	686,6
Algeria	77,4	79,6	78,4	79,3	80,2	81,4	91,4	93	93,8	87	81,5
Egypt	59	59,1	58,6	54	47	42,6	40,3	48,8	58,6	64,9	58,5
Libya	16	7,5	11,6	12,2	15,7	14,7	14,8	13,6	13,2	14,5	13,3
Nigeria	30,9	36,4	39,2	33,1	40	47,6	42,6	47,2	48,3	49,3	49,4
Other Africa	18,2	18,0	18,9	20,5	20,7	21,7	22,8	26,9	27,6	28,1	28,6
Total Africa	201,5	200,6	206,7	199,1	203,5	208,0	211,9	229,5	241,4	243,8	231,3
Australia	52,6	54,2	58,0	60,3	64,9	74,1	94,0	110,1	126,0	143,1	142,5
Bangladesh	19,3	19,6	21,3	22	23	25,9	26,5	26,6	26,6	25,3	24,7
Brunei	12	12,5	12,3	11,9	12,7	13,3	12,9	12,9	12,6	13	12,6
China	96,5	106,2	111,5	121,8	131,2	135,7	137,9	149,2	161,4	177,6	194,0
India	47,4	42,9	37,3	31,1	29,4	28,1	26,6	27,7	27,5	26,9	23,8
Indonesia	87	82,7	78,3	77,6	76,4	76,2	75,1	72,7	72,8	67,6	63,2
Malaysia	65,1	67	69,3	72,6	72,2	76,8	76,7	78,5	77,2	79,3	73,2
Myanmar	12,2	12,6	12,5	12,9	16,5	19,2	18,3	17,8	17	18,5	17,7
Pakistan	35,3	35,3	36,6	35,6	35	35	34,7	34,7	34,2	32,7	30,6
Thailand	33,7	33,8	38,4	38,9	39,1	37,5	37,3	35,9	34,7	35,8	32,7
Vietnam	9,1	8,2	9	9,4	9,9	10,3	10,2	9,5	9,7	9,9	8,7
Other Asia Pacific	17,9	17,7	17,7	18,2	23	27,9	28,9	29,1	27	28,7	28,4
Total Asia Pacific	488,1	492,6	502,1	512,2	533,3	560	579	604,6	626,6	658,2	652,1
Total World	**3150,8**	**3258**	**3326,8**	**3366,1**	**3437,9**	**3511,7**	**3552,1**	**3676,2**	**3852,9**	**3976,2**	**3 853,7**
of which:											
OECD	1130,9	1151	1187	1196,4	1242,1	1281	1296,7	1331,1	1430,9	1 510,8	1 478,5
Non-OECD	2019,9	2107	2139,8	2169,6	2195,8	2230,6	2255,4	2345,1	2422	2 465,4	2 375,2
European Union	125,6	117,5	113,9	113,9	99,9	84,3	82,3	76,8	68,8	61,1	47,8

* Excludes gas flared or recycled. Includes natural gas produced for gas-to-liquids transformation.
◆ Less than 0.05%.
n/a not available.
Notes: As far as possible, the data above represents standard cubic metres (measured at 15°C and 1013 mbar); as they are derived directly from measures of energy content using an average conversion factor and have been standardized using a gross calorific value (GCV) of 40 MJ/m3, they do not necessarily equate with gas volumes expressed in specific national terms.
Annual changes and shares of total are calculated using billion cubic metres figures.
Natural gas production data expressed in billion cubic feet per day is available at bp.com/statisticalreview.

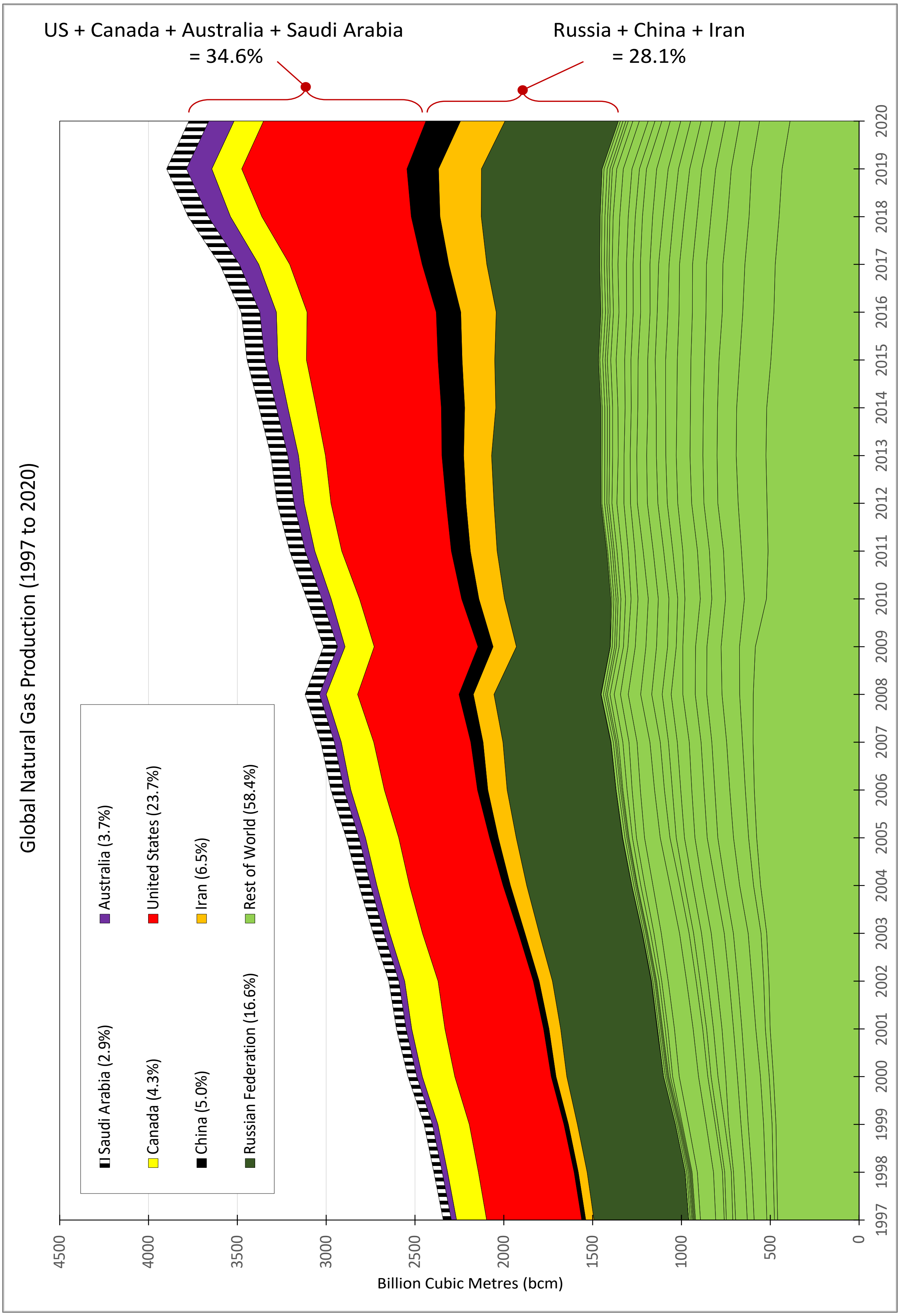

Figure J19. Global natural gas production
(Source: BP Energy Statistics 2021, 2015, 2012 and 2008)

28.2.2 Natural Gas Consumption

Table J4. Global gas consumption (Source: BP Statistical review of World Energy 2021)

Natural Gas Consumption by Geographic Region	Annual Consumption in 2020 (billion cubic metres)	Consumption Market Share in 2020 (%)	Annual Consumption in 2019 (billion cubic metres)	Annual Consumption in 2000 (billion cubic metres)
Global	**3 822,8**		**3 903,9**	**2 437,3**
Total North America	1 030,9	27,0 %	1 055,1	791,8
Total Central & South America	145,6	3,8 %	163,3	95,1
Total Europe	541,1	14,2 %	553,5	
Commonwealth of Independant States	538,2	14,1 %	574,2	
Middle East	552,3	14,4 %	544,5	185,4
Total Africa	153,0	4,0 %	155,3	55,5
Total Asia Pacific	861,6	22,5 %	858,1	296,1
Nations				
United States	832,0	21,8 %	849,2	660,7
China	330,6	8,6 %	308,4	24,5
India	59,6	1,6 %	59,3	26,4
European Union	379,9	9,9 %	391,2	440,4
Russian Federation	411,4	10,8 %	444,3	377,2

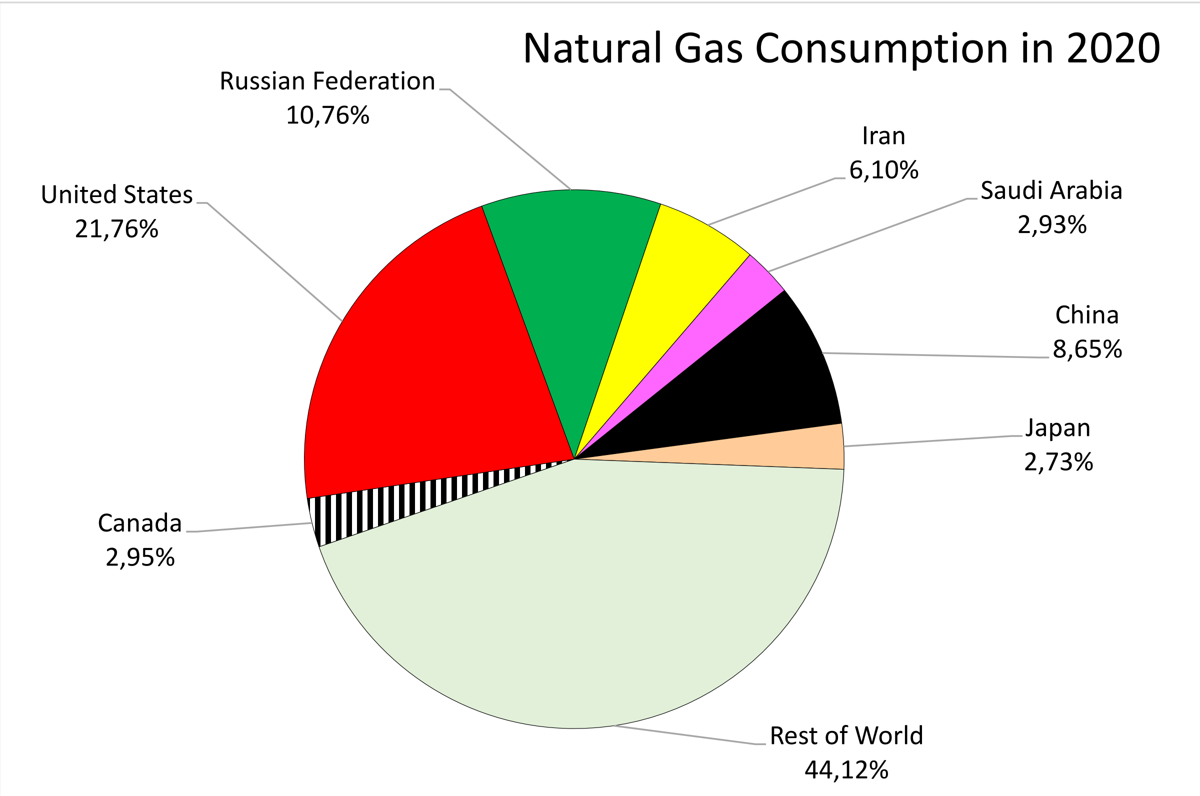

Figure J20. Global gas consumption (Source: BP Statistical review of World Energy 2021)

The largest consumers are also the largest producers. It is appropriate to look at the net production vs. consumption balance (Table J5 parts 1 & 2).

Table J5-1. Global natural gas production to consumption balance (Source: BP Statistical review of World Energy 2021)

Production to Consumption Balance (billion cubic metres)	Production (bcm)	Consumption (bcm)		Net Import/Export (bcm)
Canada	165,2	112,6		52,6
Mexico	30,1	86,3		-56,2
US	914,6	832,0		82,6
Total North America	**1109,9**	**1030,9**		**79,0**
Argentina	38,3	43,9		-5,6
Bolivia	14,4			14,4
Brazil	23,9	32,1		-8,2
Colombia	13,3	13,9		-0,6
Peru	12,1	7,1		5,0
Trinidad	29,5	15,1		14,4
Venezuela	18,8	18,8		0,0
Other S. & Cent. America	2,7	8,1		-5,4
Total S. & Cent. America	**152,9**	**145,6**		**7,3**
Austria		8,5		-8,5
Belgium		17,0		-17,0
Czech Republic		8,5		-8,5
Denmark	1,4			1,4
Finland		2,0		-2,0
France		40,7		-40,7
Germany	4,5	86,5		-82,0
Greece		5,7		-5,7
Hungary		10,2		-10,2
Italy	3,9	67,7		-63,8
Netherlands	20,0	36,6		-16,6
Norway	111,5	4,4		107,1
Poland	3,9	21,6		-17,7
Portugal		6,0		-6,0
Romania	8,7	11,3		-2,6
Spain		32,4		-32,4
Sweden		1,1		-1,1
Switzerland		3,2		-3,2
Turkey		46,4		-46,4
Ukraine	19,0	29,3		-10,3
United Kingdom	39,5	72,5		-33,0
Other Europe	6,3	29,6		-23,3
Total Europe	**218,6**	**541,1**		**-322,5**
Azerbaijan	25,8	11,9		13,9
Belarus		17,9		-17,9
Kazakhstan	31,7	16,6		15,1
Russian Federation	638,5	411,4		227,1
Turkmenistan	59,0	31,3		27,7
Uzbekistan	47,1	43,0		4,1
Other CIS	0,3	6,1		-5,8
Total CIS	**802,4**	**538,1**		**264,3**

Table J5-2. Global natural gas production to consumption balance (Source: BP Statistical review of World Energy 2021)

Production to Consumption Balance (billion cubic metres)	Production (bcm)	Consumption (bcm)		Net Import/Export (bcm)
Bahrain	16,4			16,4
Iran	250,8	233,1		17,7
Iraq	10,5	20,8		-10,3
Israel		11,3		-11,3
Kuwait	15,0	20,6		-5,6
Oman	36,9	25,9		11,0
Qatar	171,3	35,0		136,3
Saudi Arabia	112,1	112,1		0,0
Syria	3,0			3,0
United Arab Emirates	55,4	69,6		-14,2
Yemen	0,1			0,1
Other Middle East	15,0	23,9		-8,9
Total Middle East	**686,6**	**552,3**		**134,3**
Algeria	81,5	43,1		38,4
Egypt	58,5	57,8		0,7
Libya	13,3			13,3
Nigeria	49,4			49,4
Morocco		0,8		-0,8
South Africa		4,1		-4,1
Other Africa	28,6	47,3		-18,7
Total Africa	**231,3**	**153,0**		**78,3**
Australia	142,5	40,9		101,6
Bangladesh	24,7	30,4		-5,7
Brunei	12,6			12,6
China	194,0	330,6		-136,6
China Hing Kong SAR		4,9		-4,9
India	23,8	59,6		-35,8
Indonesia	63,2	41,5		21,7
Japan		104,4		-104,4
Malaysia	73,2	38,2		35,0
Myanmar	17,7			17,7
New Zealand		4,6		-4,6
Pakistan	30,6	41,2		-10,6
Phillipines		3,8		-3,8
Singapore		12,6		-12,6
South Korea		56,6		-56,6
Taiwan		24,9		-24,9
Thailand	32,7	46,9		-14,2
Vietnam	8,7	8,7		0,0
Other Asia Pacific	28,4	11,7		16,7
Total Asia Pacific	652,1	861,6		-209,5
Total World	3853,7	3822,8		30,9
of which:				
OECD	1478,5	1757,7		-279,2
Non-OECD	2375,2	2065,1		310,1
European Union	47,8	379,9		-332,1

28.2.3 Natural Gas Reserves

- Reported national reserves of natural gas peaked in 2018 at 196.9 trillion cubic meters.
- Only two nations, United States (6.7%) and China (4.5%) reported the potential to expand gas reserves in 2020.
- 88.8% of global gas reserves were in decline in 2020
- The natural gas reserves are dominated by 3 major players, Russian Federation (19.79%), Iran (16.98%), Qatar (13.07%), and 3 minor producers, Turkmenistan (7.2%), United States (6.67%) and China (4.44%).

Table J6. Global gas reserves (Source: BP Statistical review of World Energy 2021, 2020, 2019, 2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006, 2005 and 2004)

National Gas Reserves	1997 (tcm)	1998 (tcm)	1999 (tcm)	2000 (tcm)	2001 (tcm)	2002 (tcm)	2003 (tcm)	2004 (tcm)	2005 (tcm)	2006 (tcm)	2007 (tcm)	2008 (tcm)	2009 (tcm)	2010 (tcm)
Russian Federation	45,2	33,4	44,4	33,2	42,4	29,8	30,4	31,1	31,2	44,6	44,7	43,3	44,4	34,1
Iran	23,0	22,8	25,0	25,4	26,1	26,7	27,6	27,5	27,6	27,6	27,8	29,6	29,6	32,3
Qatar	8,5	11,3	11,2	14,9	25,8	25,8	25,3	25,4	25,6	25,6	25,6	25,4	25,4	25,9
Turkmenistan	2,7	2,5	2,6	1,8	2,6	2,3	2,3	2,3	2,3	2,7	2,7	8,1	8,1	13,6
United States	4,7	4,4	4,7	4,8	5,2	5,3	5,4	5,5	5,8	6,0	6,0	6,9	6,9	8,3
China	1,2	1,4	1,4	1,4	1,4	1,3	1,3	1,5	1,6	1,7	1,9	2,5	2,5	2,9
Saudi Arabia	5,9	5,8	6,2	6,0	6,5	6,6	6,8	6,8	6,8	7,1	7,2	7,6	7,9	7,5
Australia	1,5	1,6	2,0	1,7	2,7	2,5	2,4	2,3	2,2	2,5	2,5	3,1	3,1	2,9
India	0,7	0,6	0,7	0,7	0,8	0,8	0,9	0,9	1,1	1,1	1,1	1,1	1,1	1,1
Malaysia	2,5	2,4	2,5	1,1	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,4	2,4	1,0
European Union	3,9	3,5	4,0	2,5	3,6	1,8	3,2	2,8	3,0	2,9	2,8	2,5	2,4	1,6
Rest of World	49,3	43,5	46,5	45,6	51,4	52,0	50,1	50,4	50,1	54,5	55,2	55,3	56,1	49,7
Global	**146,5**	**130,8**	**148,6**	**138,0**	**168,5**	**154,9**	**155,7**	**156,5**	**157,3**	**176,2**	**177,4**	**185,3**	**187,5**	**179,9**

National Gas Reserves	2011 (tcm)	2012 (tcm)	2013 (tcm)	2014 (tcm)	2015 (tcm)	2016 (tcm)	2017 (tcm)	2018 (tcm)	2019 (tcm)	2020 (tcm)	Year of Peak Capacity	Proportion of Global Reserves in 2020 (%)
Russian Federation	32,9	32,9	32,3	32,6	32,3	35,0	38,9	38,9	37,6	37,4	1997	19,9 %
Iran	33,6	33,6	34,0	34,0	34,0	33,2	31,9	31,9	32,1	32,1	2015	17,1 %
Qatar	25,0	25,1	24,7	24,5	24,5	24,9	24,7	24,7	24,7	24,7	2002	13,1 %
Turkmenistan	17,5	17,5	17,5	17,5	17,5	19,5	19,5	19,5	13,6	13,6	2018	7,2 %
United States	8,8	8,5	9,6	9,8	10,4	8,7	11,9	11,9	12,6	12,6	2020	6,7 %
China	3,1	3,1	3,5	3,5	3,8	5,5	6,1	6,1	8,4	8,4	2020	4,5 %
Saudi Arabia	8,2	8,2	8,2	8,2	8,3	8,0	5,7	5,9	6,0	6,0	2015	3,2 %
Australia	3,8	3,8	3,7	3,7	3,5	3,6	2,4	2,4	2,4	2,4	2011	1,3 %
India	1,3	1,3	1,4	1,4	1,5	1,2	1,2	1,3	1,3	1,3	2015	0,7 %
Malaysia	1,2	1,3	1,1	1,1	1,2	2,7	2,4	2,4	0,9	0,9	2016	0,5 %
European Union	1,8	1,7	1,5	1,5	1,3	1,2	1,1	1,1	0,4	0,4	1999	0,2 %
Rest of World	51,8	51,6	50,1	50,4	49,8	52,7	52,7	53,2	51,2	49,2	2009	26,2 %
Global	**187,8**	**187,3**	**186,5**	**187,1**	**186,9**	**193,5**	**196,1**	**196,9**	**190,3**	**188,1**	**2018**	

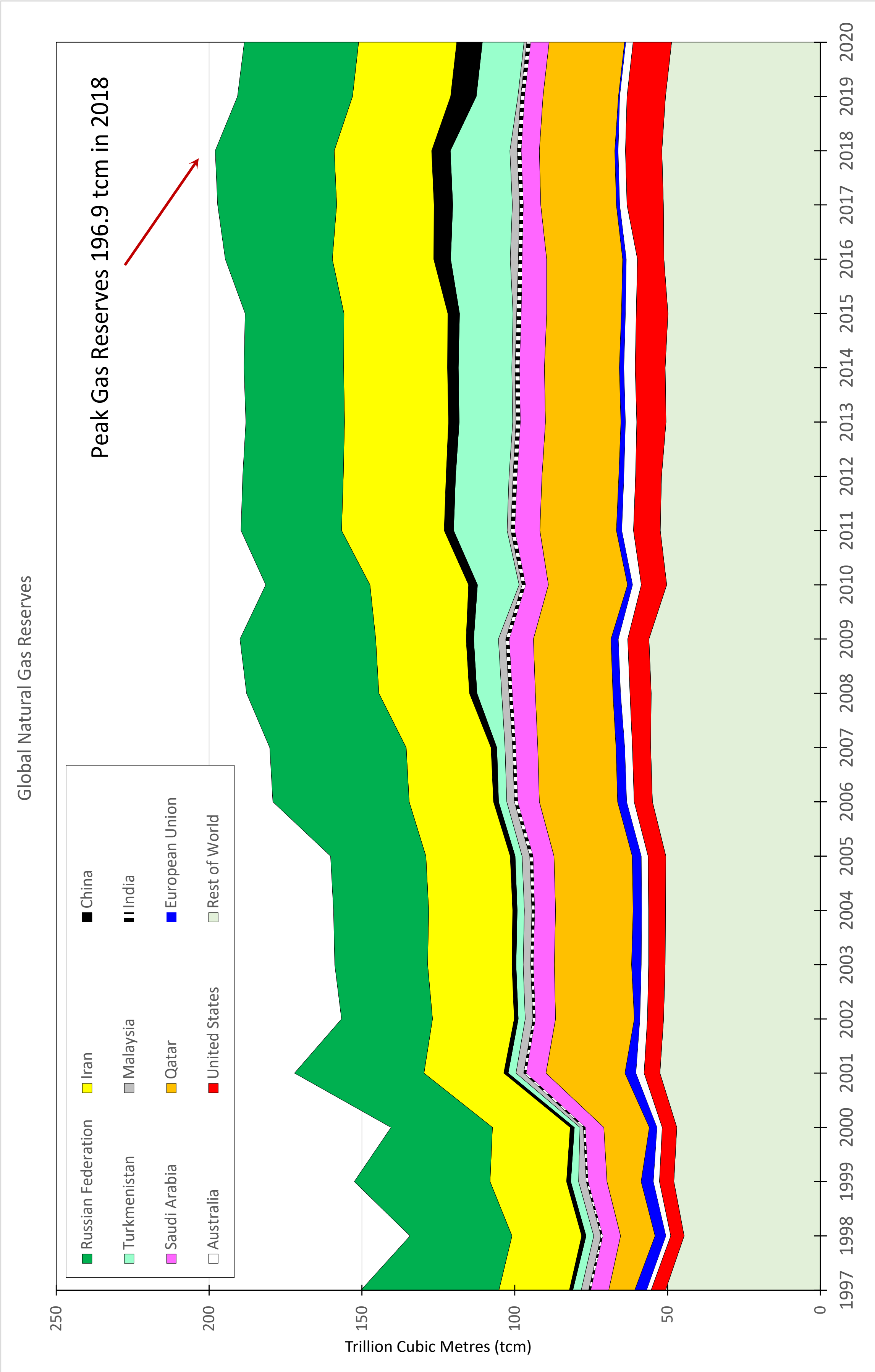

Figure J21. Global natural gas reserves (Source: BP Energy Statistics 2021, 2020, 2019, 2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006, 2005 and 2004)

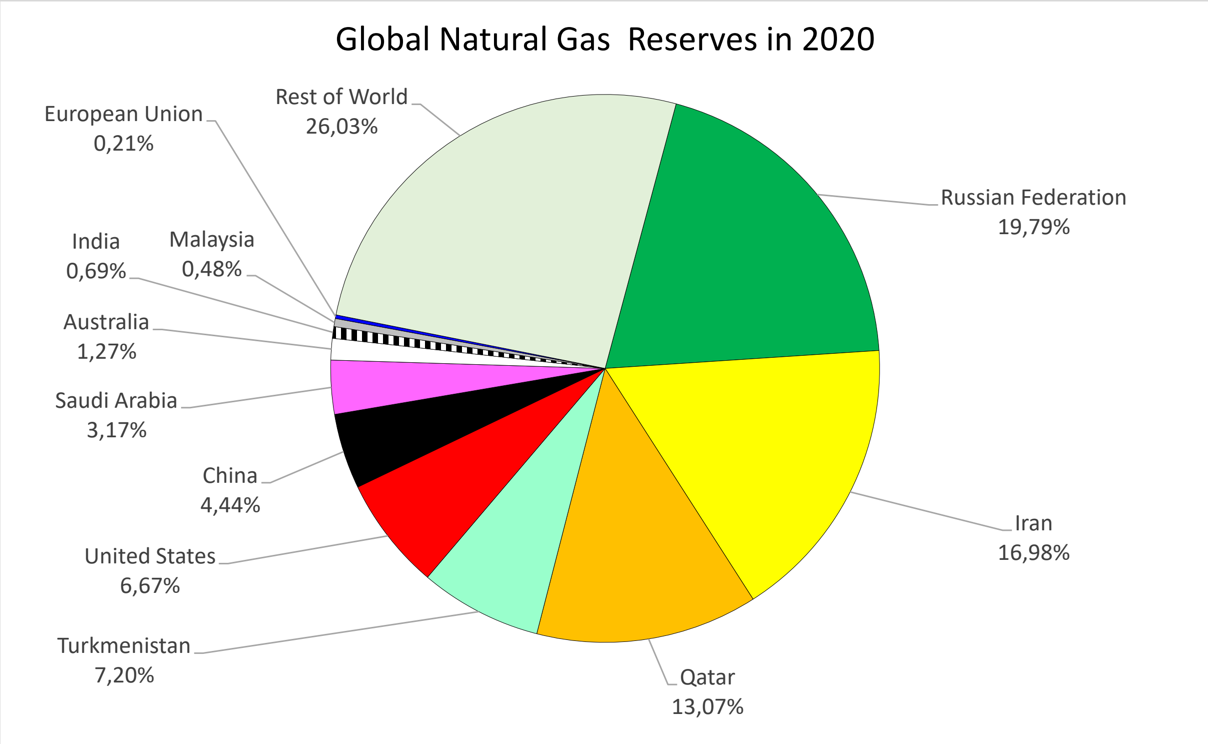

Figure J22. Global natural gas reserves in 2020
(Source: BP Energy Statistics 2021)

Figure J23 shows a world gas production projection that was published in 2013 (Zittel *et al.* 2013). It shows a peak of gas production around 2018 to 2020. It would be interesting to review the assumptions behind this study in context of production values being reported.

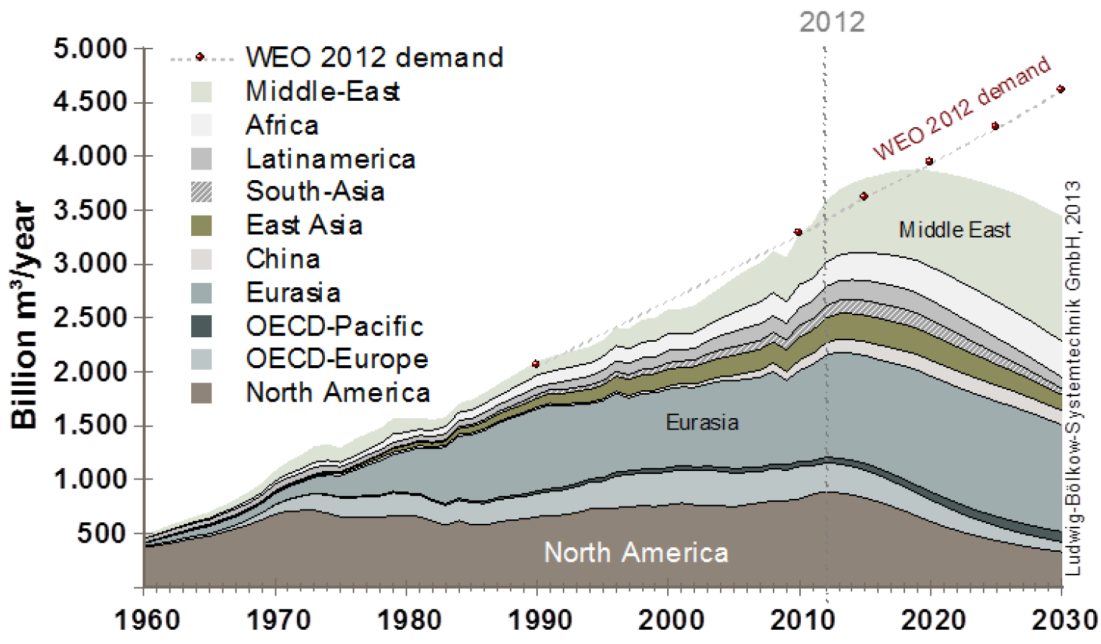

Figure J23. World supply of natural gas, the projection of the WEO 2012 by the International Energy Agency is also shown
(Source: Zittel et al. 2013)

29 APPENDIX K: INDUSTRIAL ECOSYSTEM EVOLUTION IN 1971 AND IN 2005

The industrial ecosystem is evolving into something else. This appendix shows that in 1971 and in 2005, the global industrial ecosystem and its economy had a structural blowout. Mining of metal as shown by market price is the transfer point between metal mining, heavy industry and manufacturing industry. Conventionally, the industrial society sources its raw materials from mining. How this happens is an underlying foundation of the industrial society. Figures K1 to K3 show the metal price for 13 commonly traded commodities that the World Bank uses to track the performance of the global economy and the global industrial ecosystem.

The data trend lines were overlaid by indexing the real price to the date January 1970 to the number 100 for Figures K2 and K3, and to the date of December 2001 to the number 100 for Figure K1. This is the price of metals market. These dates were picked based on patterns seen elsewhere in this report, where the reference point is about 20 months before the significant change date.

The purpose of indexing the price data is to overlay the price curves, which shows time periods of relative stability and time periods of volatility. The data selected is the following commodity groups used by the World Bank to map the performance of the global industrial economy:

Energy Resources

- Oil
- Gas
- Coal

Precious Metals

- Gold
- Silver
- Platinum

Industrial Metals

- Aluminum
- Copper
- Tin
- Zinc
- Iron ore
- Lead
- Nickel

By examining this combination of commodities in context of monthly sell price, a good summary of the global industrial ecosystem. The metal sell price is the transfer point between raw material extraction and the manufacturing sector to use the metals to make products.

Figures K1 to K3 show a series of interesting patterns. There are five clear time periods of significance shown in these Figures and seen elsewhere in this report. They are:

- 1960 to August 1971
- August 1971 to January 2005
- January 2005 to June 2008
- June 2008 to November 2011
- November 2011 to 2019

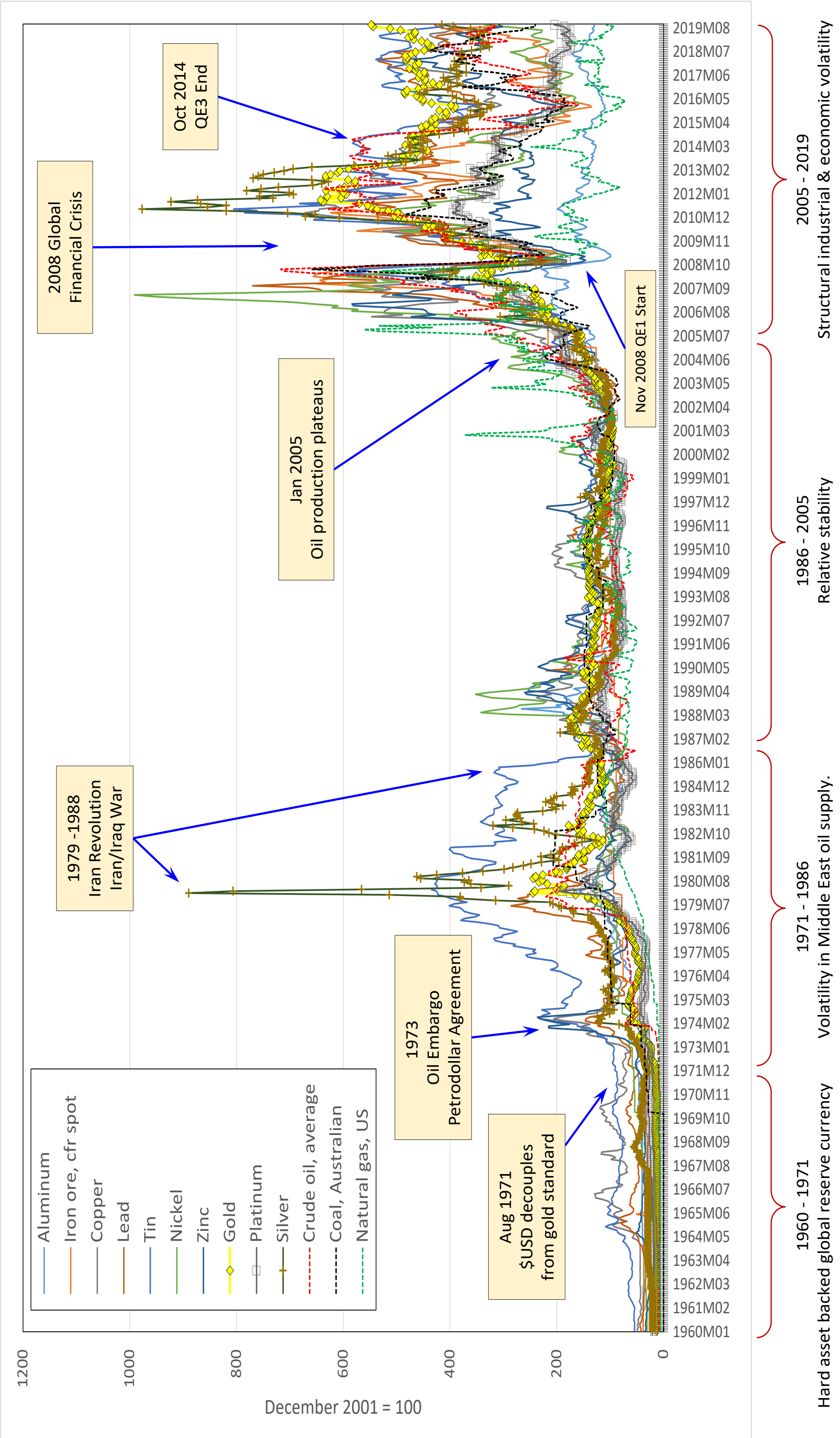

Figure K1. The price of industrial metals, precious metals and energy resources, January 1960 to September 2019, The price of metals Indexed to the year December 2001 = number 100
(Source: World Bank Commodity Price Data used to calculate Indices, monthly data updated Oct 2019)

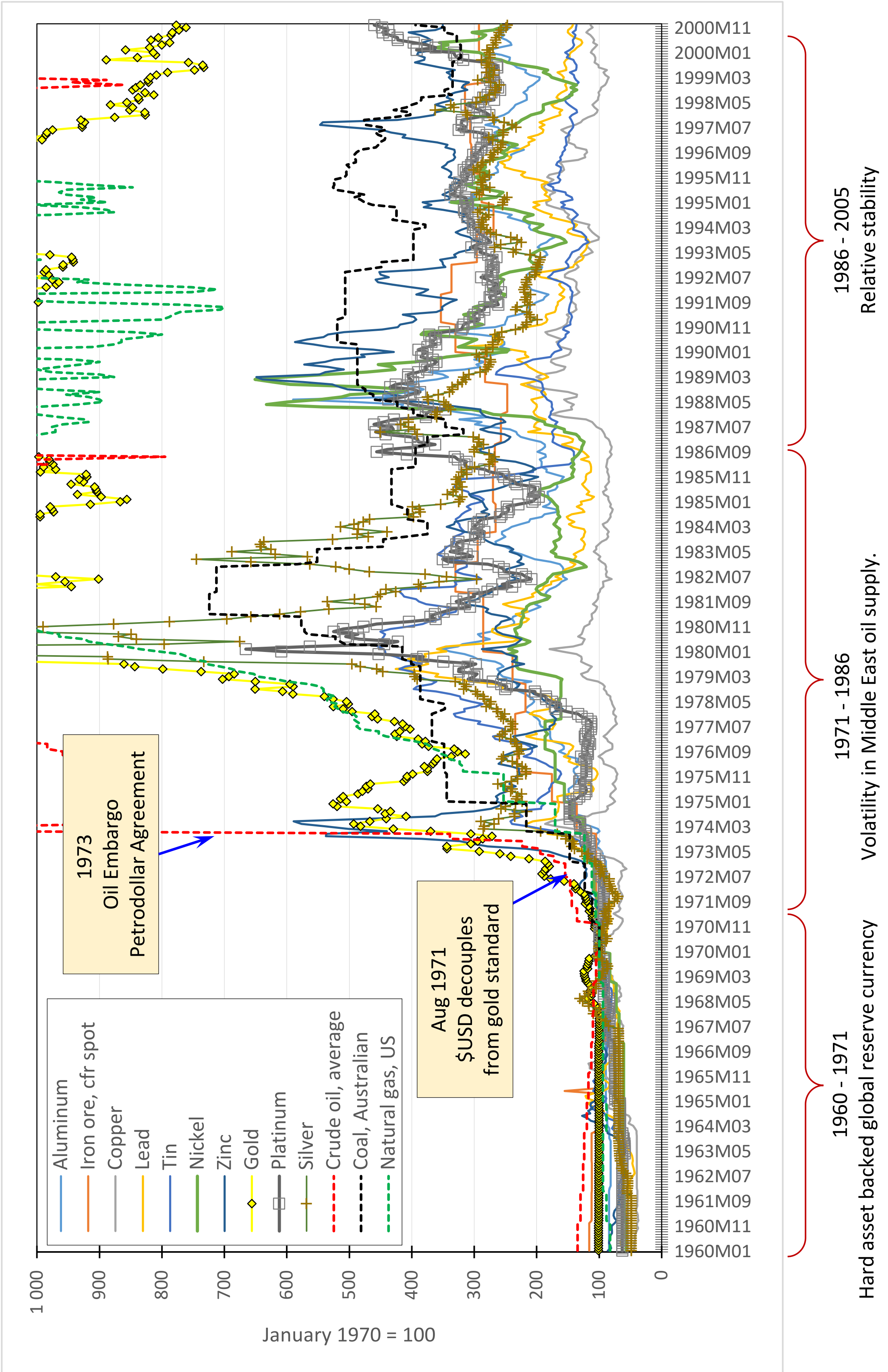

Figure K2. The price of industrial metals, precious metals and energy resources, January 1960 to December 2000, Indexed to the year January 1970 = number 100
(Source: World Bank Commodity Price Data used to calculate Indices, monthly data updated Oct 2019)

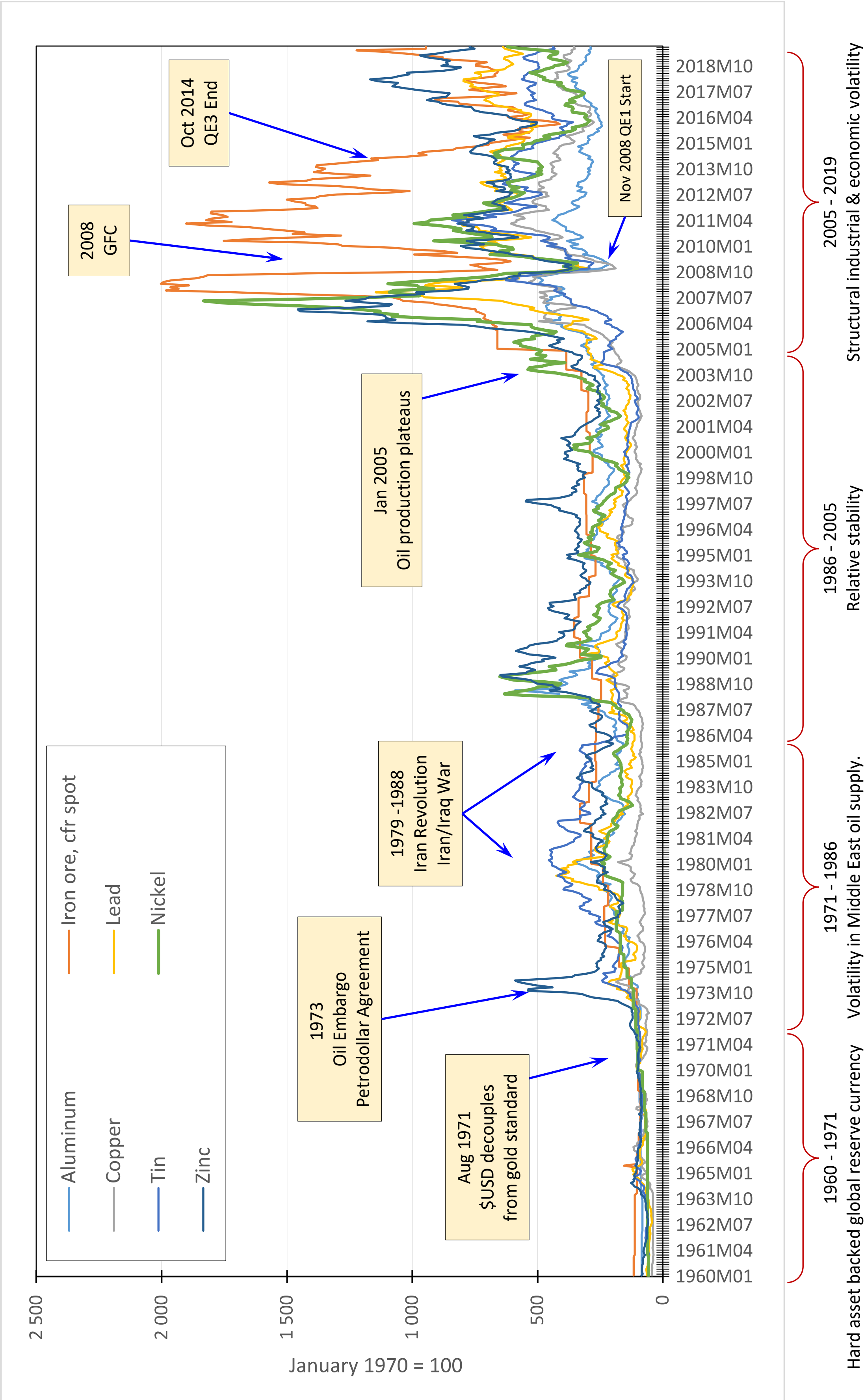

Figure K3. The price of industrial metals January 1960 to September 2019, Indexed to the year January 1970 = 100 (Source: World Bank Commodity Price Data used to calculate Indices, monthly data updated Oct 2019)

29.1 Divergence of the fiat economy and the physical goods economy

Prior to 1971, oil production and GDP overlaid each other and correlated very strongly. That is an increase in GDP had a very similar increase in the production of oil. Energy and economic activity directly correlated. This is still the case (see Figure J5) only now the relationship is quite different. After 1971, changes in GDP start to separate from oil production. An increasing gap progressed and does so for as long as there is data available. There are two events of significance that could be relevant in explaining this:

- In August 15th 1971, the U.S. dollar (the global reserve currency) was decoupled from the international gold standard, and existing Bretton Woods currency agreement was suspended. The U.S. dollar became a fully-fledged *fiat* currency (Rickards 2014 and Patel 2009).

- In 1973, a deal was struck between Saudi Arabia and the United States in which every barrel of oil purchased from the Saudis would be denominated in U.S. dollars. Under this new arrangement, any country that sought to purchase oil from Saudi Arabia would be required to first exchange their own national currency for U.S. dollars. In exchange for Saudi Arabia's willingness to denominate their oil sales exclusively in U.S. dollars, the United States offered weapons and protection of their oil fields from neighboring nations (Emerson 1985 and Simmons 2005).

This allowed the U.S. government to balance the federal budget with the printing of money. Due to the authority projected by the U.S. dollar, the rest of the world was forced to engage in the dollar system by virtue of Saudi Arabia being the dominant world supplier of oil (once the U.S. oil production started to decline in 1970). Oil has been demonstrated as a critical master resource that underpins the global industrial system. So, the global financial currency systems were not only tied directly to oil production but were subject currency debasement through expansion of supply of U.S. dollars. GDP became inflated in comparison to the real economy of physical goods and services.

Also, of note in Figure K4 is a change in gradient around the year 2001. From that point, GDP increased at a greater rate than ever before. A change in the United States law could explain this:

- The financial derivatives market was deregulated. The Commodity Futures Modernization Act, (CFMA) signed into law on December 21, 2000 updates commodity trading regulations. The most notable change was in addressing newer types of financial contracts such as over-the-counter derivatives. This was just after the Dotcom Bubble had burst (1994-2000).

When credit markets froze up in the fall of 2008, many economists pronounced the crisis both inexplicable and unforeseeable. This could be because the roots of the catastrophe lay not in changes in the markets, but changes in the law (Stout 2009). The Commodity Futures Modernization Act was signed into law as a consequence of lobbying from the private finance sector, in response to the DotCom financial bubble busting. The logic being that the money that could be made by the financial industry could stabilize the rest of the economy by forming a buffer. Clearly, they were wrong.

The printing of money (which was done consistently since 1971) became directly linked to the creation of financial derivatives and credit default swaps, creating the largest bubble ever observed.

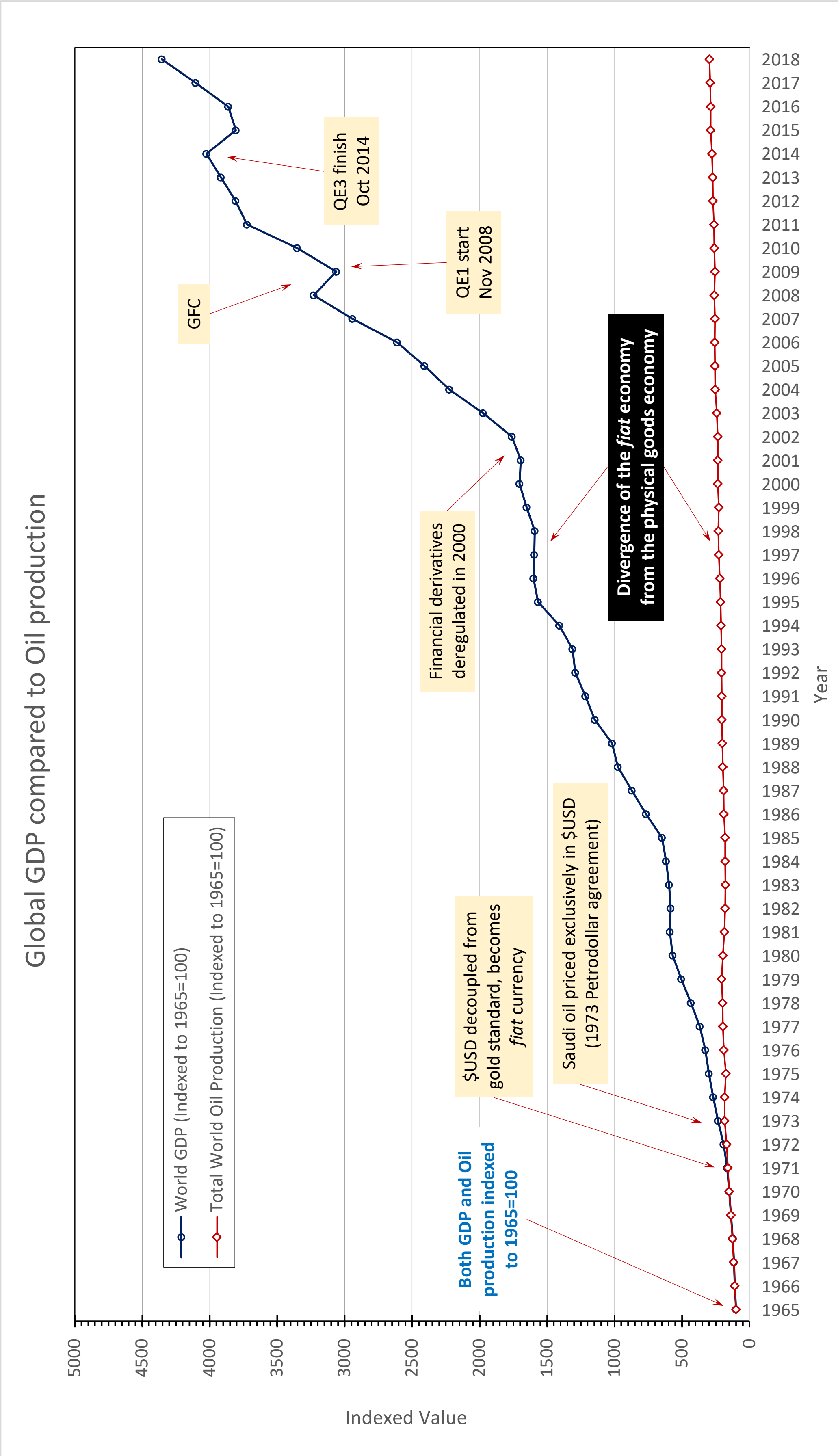

Figure K4. Global GDP and Crude Oil Production
(Source: BP Statistical Review of World Energy 2019, BP Statistical Review of World Energy 2011, World Bank Data)

As Figure K4 shows, the real economy has diverged from the fiat economy for some years. Between 1965 and 2018, oil production has increased 298%. Alternatively, GDP has been growing steadily (through quantitative easing) and has increased in the same time span, 4 355%.

For the last 40 years, US government debt creation has been approximately twice the rated economic growth (Rickards 2014). This spiraling volume of debt since the 1970's has been historically unprecedented. What has facilitated this to continue working is the Saudi Arabian commitment to price all of their oil contracts in $USD. For the last 20 years, the increase in debt can be related to the higher cost of energy (the 1973 Petrodollar agreement). As the cost of energy went up, there was a need to increase the volume of debt to the system to maintain growth. Most nation state economies (all fiat currency based) now have debt to GDP ratio that exceeds 90% (US Debt Clock). This means that each of those economies that have such high debt/GDP ratios have to go further into debt to maintain their economies and maintain debt repayments (Rickards 2014).

Figure K4 in conjunction with Figure J4 shows that growth in GDP is a debt fueled mirage. If debt is a promised claim on the future, the total amount of goods and services has been growing, while debt levels and other kinds of promises have been growing more rapidly than their physical collateral. Figure K5 shows how this may have happened.

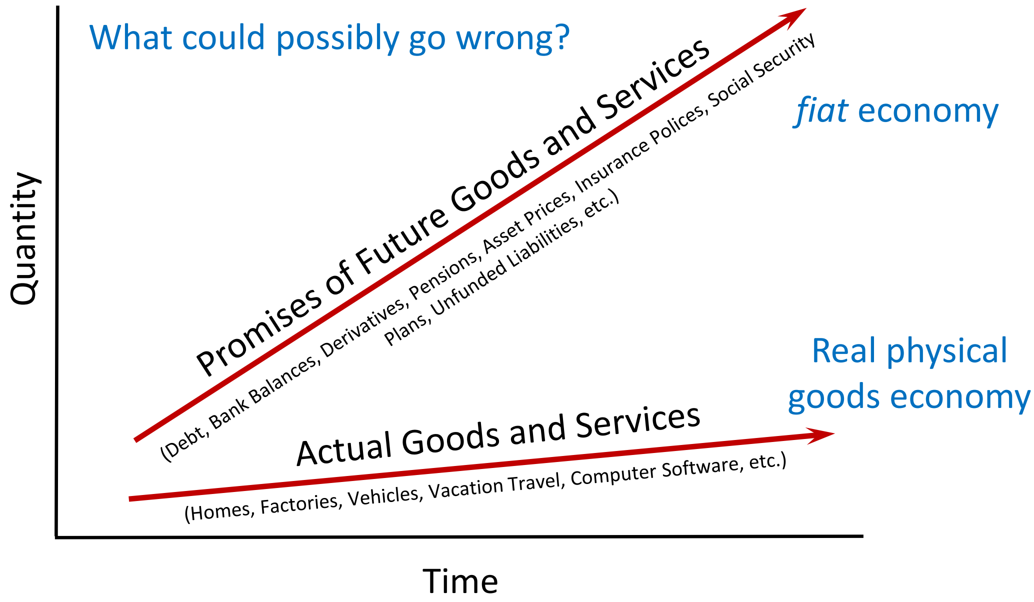

Figure K5. Promises of future goods and services tend to rise much more rapidly than actual goods and services. (Source: Figure recreated from Tverberg 2019).

> "Many things can go wrong with this system. If the growth in added debt slows too much, we can expect to start seeing financial problems like those we saw in 2008. Also, if the level of debt (such as student debt) gets too high, its payback interferes with the purchase of other needed goods, such as a home. If energy providers decide prices are too low and stop producing, then promised Future Goods and Services can't really appear. Huge defaults on promises of all kinds can be expected. This happens because the laws of physics require the dissipation of energy for physical processes underlying GDP growth."

Gail Tverberg – Retired Financial Actuary (Tverberg 2019)

29.2 How Commodity Groups Interrelate

Figures K1 to K4 show an interesting pattern of significance. The purpose of indexing all the commodity price curves to a single point (August 1971=100) is to show relative patterns with each other. Previous parts of this chapter have shown that there are time periods of structural change, where the point January 2005 was very significant. Not all commodities blow out at the same time. There is a very interesting pattern that shows a sequence of commodities that blow out around 2005.

Figure K1 shows that the energy resources of gas and oil proportionally increase in price compared to all other commodities. Compared to the August 1971=100 reference point, oil and gas have the value of around 900 in the years 1985 to 2003 and spike up to the 4000 to 6000 after around 2003. In the same time frames, precious metals have the values around 300 to 500 from 1985 to 2003, and spike to 1000 to 2000 after 2003. Industrial metals (and coal) have in the same time frames, values of around 180 to 400 from 1985 to 2005, spike to 1500 in 2007, and settle into a bandwidth of 300 to 700 after 2010.

In summary:

- Gas and Oil (gas leads) price blows out to a proportionally much larger value set than precious metals, starting around 2002

- Precious metals price blows out to a proportionally much larger value set than industrial base metals. This precious metals blow out signature starts in approximately 2003, after oil and gas, before base metals.

- Base metals price blows out in 2005. Coal (an industrial energy resource) behaves more like an industrial base metal, than like oil or gas.

These signatures are still visible when the reference point of December 2001=100 is used but they are not as clear (see Figure K1). This suggests that the structural problems facing the current industrial ecosystem started with a blowout in the real cost of energy, which had a ripple effect, which took time to be felt in the base industrial metal markets. As it requires energy to mine minerals and more energy to refine them into metals, it is appropriate that the price blowout of the metals market (which are the fundamental lifeblood of the industrial ecosystem) is triggered by a signature in the energy market (oil production plateaus in January 2005).

It all starts with energy, and it all ends with what we use it for. Money is just the language of exchange.

29.3 1960 to August 1971

Prior to August 1971, the U.S. dollar was a hard asset backed currency. The 1944 Bretton Woods agreement established a new global monetary system. It replaced the international gold standard with the U.S. dollar as the global currency. By so doing, it established America as the dominant power in the world economy. After the agreement was signed, America was the only country with the ability to print dollars. The agreement created the World Bank and the International Monetary Fund. These U.S.-backed organizations would monitor the new system.

Before Bretton Woods, most countries followed the gold standard. That meant each country guaranteed that it would redeem its currency for its value in gold. After Bretton Woods, each nation member agreed to redeem its currency for U.S. dollars, not gold. At the time, the United States held three-fourths of the world's supply of gold. At the time of the Bretton Woods agreement, no other currency had enough gold to back it as a replacement. The dollar's value was 1/35th of an ounce of gold. Bretton Woods allowed the world to slowly transition from a gold standard to a U.S. dollar standard. This meant that commodity prices (and everything else) were subject to classical economic theory that enforced economic corrections in a fashion that supported foundational market value.

The dollar had now become a substitute for gold. As a result, the value of the dollar began to increase relative to other currencies. There was more demand for it, even though its worth in gold remained the same.

29.4 August 1971 to January 2005

On the 15th of August 1971, the United States government decoupled the U.S. dollar from its gold standard. The U.S. dollar decoupling from the gold standard ended the Bretton Woods system agreement. Two years later, the 1973 Petrodollar agreement secured the U.S. as the world reserve currency with the use of $USD to purchase oil from Saudi Arabia. This meant that prior to 1971, the $USD was backed with gold and post 1973, the $USD was backed with oil, but was still a fiat currency, where extra money supply could be created any time by the U.S. Federal Reserve bank (Krause 1999, Rickards 2014).

The date January 1970 was chosen to be one of the index points for Figures K2 and K3 due to the signatures seen in Figure K4, where relative GDP and oil production diverged on this date. This decision would prove strategically significant. A case can be made where the implications of the 1971 decoupling could have laid part of the foundation of the ultimate trivialization of the U.S. dollar as a viable currency. The only other decision that has similar structural implications was the formation of the U.S. Federal Reserve Bank in 1913, and the implementation of fractional reserve banking practices (Krause 1999, Rickards 2014).

When the $USD became a fiat currency, its value became the collective perception of the world market and it trust in the United States. The relative relationship between all curves prior to August 1971 was quite stable and clustered in a small bandwidth. The relative relationship of the same curves post to August 1971 was comparatively blown out. Each metal price curve was 150-400% higher in direct comparison to prior to August 1971, moving in a bandwidth between 150 and 400 compared to the 100 reference point.

Figure K3 shows the period between August 1971 and January 2005 has the same consistent signature, different to time periods before 1971 and after 2005.

The implication of this time period is that anytime a geopolitical issue arose, that issue could be resolved taking on debt (Actually printing money). Prices did not blow out immediately. The first instance of this was shown in the 1973 Oil Embargo two years later.

In Figures K2 and K3, an era of volatility can be seen in years between 1973 to 1986. This could be seen as geopolitical instability in the Middle East, affecting the oil production supply to the international markets. This ear is dominated by:

- Iranian Revolution 1979
- Iran/Iraq war 1980 to 1988
- The Saudi Arabian cut in production in response to the oil glut in the market at the time

29.5 January 2005 to June 2008

Figure K1 shows the same data as the previous figures, but this time, the commodity prices where indexed to December 2001 = 100. The purpose of this was to highlight the relative change that happened 36 months later in January 2005.

Compared to the January 2005 reference point (100), the time period after this point varies between 150 and 500, with two spikes up to 1000. Comparing this January 2005 reference point of 100 to the August 1971 reference point, commodities would range from 30 to 80.

This date is seen as a fundamental turning point in the evolution of the industrial ecosystem, where a case could be made that it will later be shown, that it was this date was when permanent structural change happened (Figure K1). Something fundamental changed on this date, something that had the rippled effect to be felt throughout the entire global system. It can be seen as one of the major turning points in the operation of the industrial economy and can be referred to the Third Oil Shock (Michaux 2019). This temporal signature significantly affected the industrial ecosystem.

The data shown in K6 and K7 suggests that the genesis cause of this major turning point is related to the oil market. The economic signatures are lagging indicators, not leading indicators. Figure K6 shows the answer. This plateau of production is postulated to be caused by the inability of Saudi Arabia to increase its production as shown in Figure K7.

29.6 The 2008 GFC was caused by a chain reaction with its genesis in the oil industry

In the year 2008, the most serious economic correction since the 1929 Great Depression was initiated (later called the GFC or the Global Financial Crisis). Since then, industrial stagnation has persisted on a global scale (Mathiason 2008 and Kingsley 2012). A case can be made that the GFC was a financial blowout, that was caused by a chain reaction in the industrial markets, oil in particular. This chain reaction had its visible starting point in early 2005, possibly in the month of January, and can be seen in the oil markets data.

As a direct consequence of the GFC, quantitative easing (QE1, QE2 and QE3 programs) were deployed by the U.S. Federal Reserve Bank (Yellen 2017). This unprecedented measure was shown to be very effective. The GFC crash was reversed, and markets started to recover. Since 2008, central banks around the world have been engaging in Quantitative Easing (colloquially referred to as the printing of money). This is dangerous as it deteriorates the integrity of the monetary system. The volumes of money being created through QE is historically unprecedented. The United States is not the only nation to engage in printing money to keep economic growth positive. The European Union, Japan, China, and the United Kingdom all have engaged in unprecedented quantitative easing to prop up growth in the global economy (Nelson 2018 and Guardian 2015).

Preceding the GFC was a spike in the oil price. This is relevant as the starting point for the GFC was marked by an unprecedented crash in the oil price (Figure K8). Just one of the outcomes was a large correction in the U.S. housing market. The panic to sell spread to all sectors and markets all over the world. The New York stock exchange crashed, and trading was stopped on several occasions. The whole finance system was with a few hours from complete paralysis (Mathiason 2008). As oil is a vital part of our industrial society (Michaux 2019), *a sustained rise in oil price over a few years (2004-2008) will put pressure on the entire system*. As such, there will come a point where that system will be under such strain that something would blow out.

So, what happened to cause this serious economic correction in 2008? Something significant did happen on the date of January 2005. The global supply of crude oil plateaued in January 2005 (Figure K6). The production of oil plateaued in January 2005, and the supply market became inelastic. Unconventional oil production capacity would later make up extra global supply to meet demand, but not in meaningful quantities until 2009.

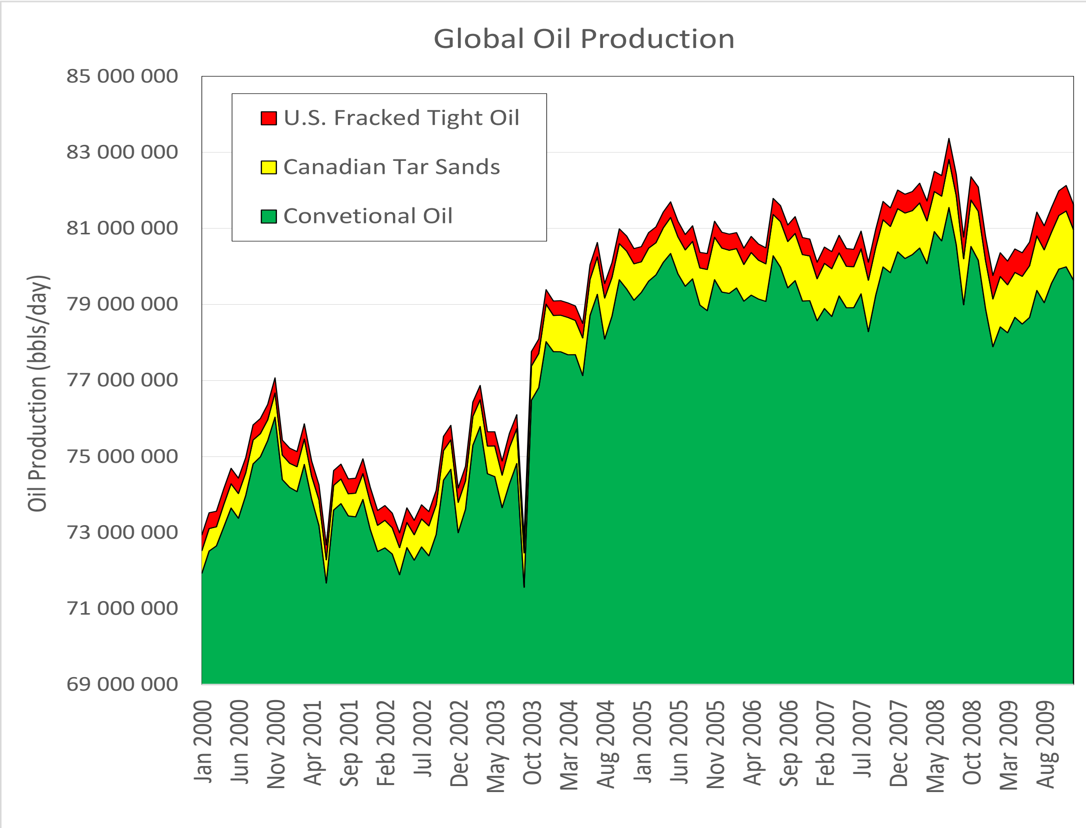

Figure K6. Global oil production 2000 to 2009
(Source: data from BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Demand for oil would have increased with each passing year as it always has (Figure J3). For the last few decades, Saudi Arabia has been the swing producer in the global oil market, where it had the capacity to raise or lower production to regulate the oil price. In January 2005, Saudi Arabia was not able to raise production of crude oil for the first time. This can be seen in Figure K7 showing the number of Baker Hughes drill rigs brought online and oil production in Saudi Arabia from January 2000 to December 2009.

Saudi Arabia expanded its rig count from 31.35 (average from October 2000 to October 2004) to 76.52 (average from September 2006 to September 2008), or a 144% increase. In the same time frames, Saudi Arabian oil production went from 8.41 million barrels a day to 8.99 barrels a day (or a 6.5% increase). *In that time when profit presumably was at an all-time high, Saudi Arabia brought on line 144% extra capacity of operating drill rigs to produce oil, yet oil production in that time increased comparatively little.* Remember, during the years 2004 to 2008, the price of oil spiked from $USD50/bbl to $USD147/bbl. This could mean that Saudi Arabia is very close to peak production of crude oil.

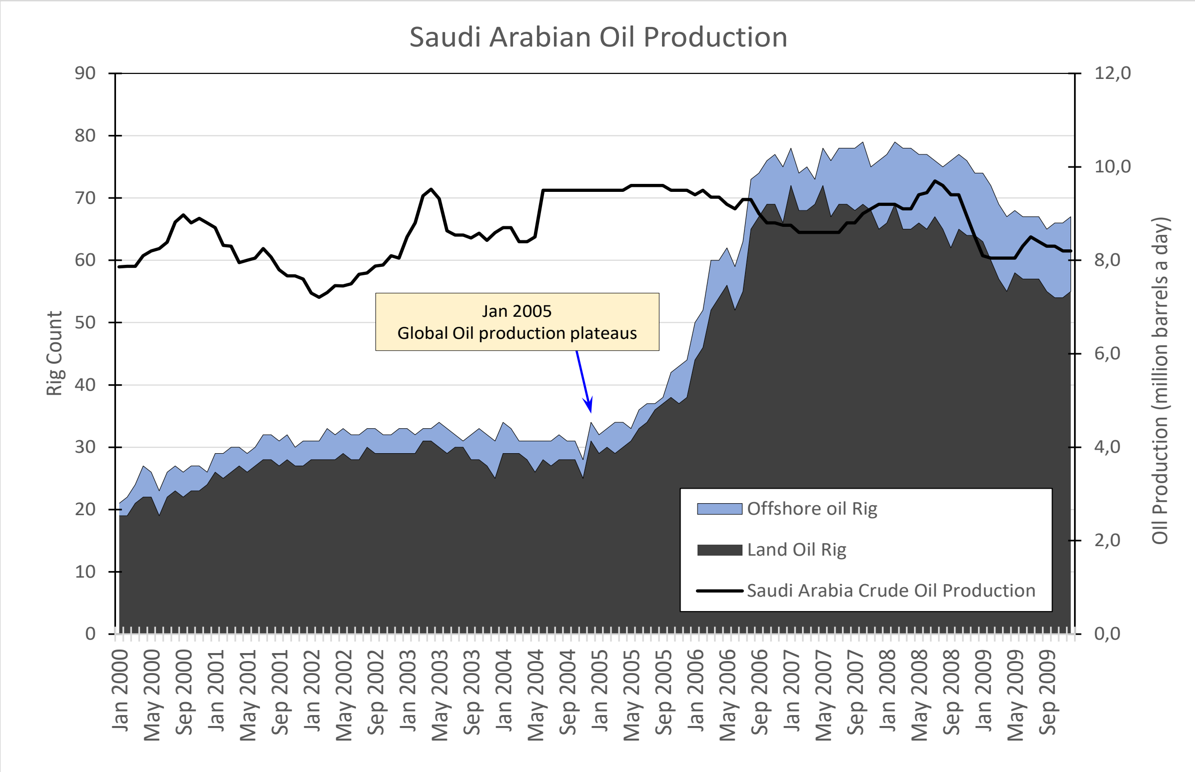

Figure K7. Saudi Arabian rig count and crude oil production, January 2000 to December 2009 (Source. Baker Hughes Rig Count data, EIA monthly production data)

Between 2005 and 2008, global oil demand did outstrip global oil supply (Figure K8). This supply gap happened when oil production plateaued in 2005, while demand continued to grow in line with GDP and population (Figure J3). This was resolved with an increase in oil production, in particular the addition of the tight oil fields of the United States started producing, using fracking technology.

So, an oil price rise between 2005 and 2008 was appropriate, but what was observed was overridden by a speculative bubble. This leaves the industry set up for a major price bust, as the speculators dump oil as desired commodity and a price undershoot is observed. This crippled investment for future development, which became increasingly expensive (Michaux 2019). Without sufficient future capital investment, the current oil production value chain is set up for a reduction in production due to old fields depleting (Figure J8); this happens much more quickly for fracked tight oil plays (Michaux 2019).

So, oil production plateaued between January 2005 and October 2009, and for a short time (August 2008 to September 2008), supply and demand separated. The oil market became inelastic, and the price increased, accelerated by a speculative bubble. The market could not sustain high oil prices as it is a vital commodity that empowers most economic activity. The whole system was put under strain between January 2005 and July 2008, and the weakest link broke, triggering a systemic market crash. The weakest link was the sub-prime mortgage market in the United States. This was not the cause, so much as the first think to break. The situation was resolved with an unprecedented application of Quantitative Easing (also known as printing of money), which will have long term implications on the structural integrity of all *fiat* currencies.

The second important development was that the global supply of oil was able to be increased, talking pressure off the markets. A technological breakthrough in horizontal drilling made the tight oil sector (fracking) viable. The United States had become the new global swing producer from 2009 onwards, with the majority of oil production growth coming from the U.S tight oil sector (Michaux 2019).

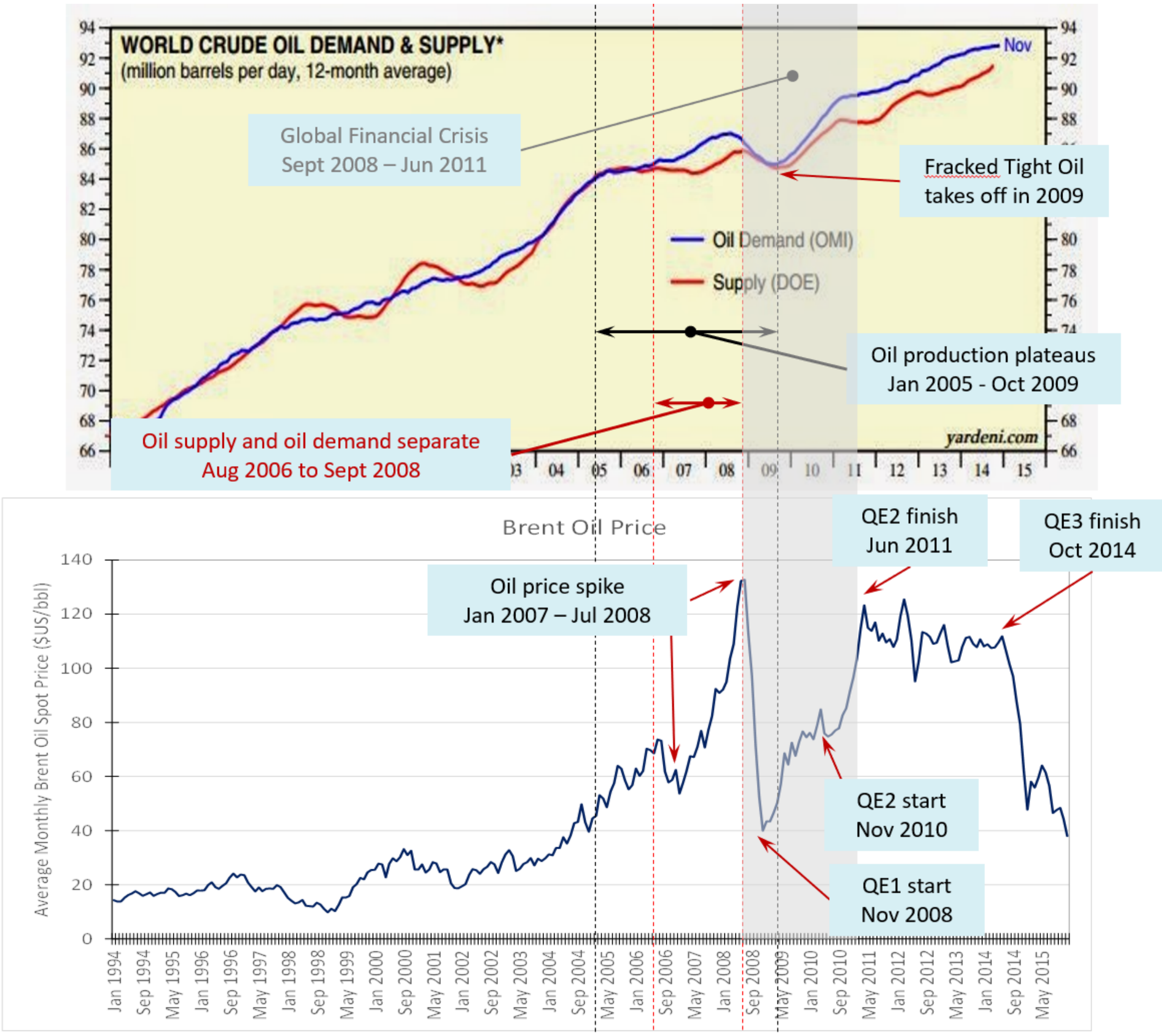

Figure K8. The sequence of events that led to the Global Financial Crisis

A simplified sequence of events:

1. Global oil production plateaued in early 2005 (see Figure K6). The market becomes inelastic in oil supply (Figure K8). Global oil consumption continues to expand at the same rate.
2. The oil price rises between years 2005 to 2008 unusually quickly. Speculation on oil price clearly had a role in pushing the price up to $147USD/barrel. There is also a supply gap between supply and demand for a short time.
3. In 2008, the largest economic correction since the 1929 Great Depression started (The GFC). The GFC began in 2007 with a crisis in the subprime mortgage market in the United States and developed into a full-blown international banking crisis with the collapse of the investment bank Lehman Brothers on September 15, 2008 (Mathiason 2008 and Kingsley 2012).
4. The United States Federal Reserve Bank intervenes into the finance markets with the first program of Quantitative Easing (QE1) in November 2008. A historically unprecedented volume of debt is applied and added to the U.S Federal Reserve Bank ledger (Yellen 2017). From that date, a new kind of economics underpinned the global economy.
5. A new technology in oil extraction (horizontal drilling of fracking wells) was developed in the United States, opening up the tight oil field plays (Rapier 2018). This allows global oil production to expand again at the same rate as consumption demand. The oil supply gap is resolved.

Compare the blow out in metal prices (Figure K8) align with the plateauing of oil production (Figure K1). The 2008 GFC was triggered by a chain reaction initiated 3 years earlier in 2005. The point of genesis was the plateauing of global production of crude oil in January 2005. This signature can be most clearly seen in the global market metal prices for all major metals and energy resources. Commodity price (and metal price) is the transfer point between those operators who produce the commodities and metals, and those operators who use those products to manufacture physical goods and engage in physical activities. This is the heartbeat of the industrial ecosystem. The GFC can now be seen as the point where the industrial ecosystem and the global economy fundamentally changed. That continued change was arrested and reversed by intervention actions that have the capacity to make the current financial system irrelevant. These issues have not been resolved, and still require structural change on a global scale. The relationship between oil and the economy needs to be changed and decoupled.

"We should leave oil before it leaves us."

Dr Fatih Birol, chief economist of the IEA, 2008

In the GFC case study, most of the global markets at all scales (National governments, corporations and individual citizens) are now heavily loaded with debt of all kinds. This means that the real economy cannot really recover until that debt level is reduced (Figures K4 & K5). Economic growth is now very difficult, and in some cases not really possible. This implies structural change in the finance and energy markets is coming.

All Critical Raw Materials (CRM) could be modelled in this fashion as it goes through a scarcity vs. relevance cycle. All CRM's as defined by the European Union (European Commission 2017) could be examined in this context.