Simulation of different scenarios for resource utilization. Uncertainties, availability, and fair distribution of global resources

Erik Dahlquist [a,]*, Stefan Hellstrand [a], Madeleine Martinsen [a]

[a] *Malardalen University, Vasteras, Sweden*
*erik.dahlquist@mdu.se

Abstract

In this paper scenarios are made simulating how demand can be predicted for different materials and resources for the future when we develop new technologies to build the sustainable society for everyone. How does recycling efficiency impact total demand for virgin resources? This also means a fair distribution including all people, but with a bit different demand depending on where people live. In hot countries cooling is important, while heating in cold. But how will global warming affect this? And how can solutions like EV with batteries and H2 with fuel cells (FC), new materials for heat and cold storage etc change the demand for different materials and resources? Different scenarios are simulated, and the results discussed.

Key words: Resources, simulations, scenarios

1. Introduction

Normally we don´t think too much about what resources we have available. Most people want to see that everyone should have access to what we see as a minimum standard, and as this minimum standard is continuously increasing, more resources will be needed. Renewable energy conversion techniques demand a lot of material, as well as all other appliances we demand, like vehicles and communication appliances. When a resource is scarce, we try to find other solutions instead. This makes it very difficult to predict the use of different elements by just extrapolating from the last few years utilization. On the other hand, these types of extrapolations can be very useful to give an insight in what will happen if we don´t take actions.

2. Simulation model

The assumptions now can be to look for what it would mean if all persons globally would have the same usage pattern as EU-27 population today. How would that change the annual demand for materials? At the same time there are strong indications that the world population will increase significantly during the next 50 – 80 years. Especially in Africa south of Sahara the birth rate is very high, although hopefully it will decrease if the population get better living conditions. This has been the case in many parts of Asia during the last 50 years. As no one knows how many we will be year 2100 we calculate for an increase by 1500 million respectively 3000 million, which will cover the predictions made by different organizations and researchers. A second aspect is how much virgin materials are needed respectively how much can be recycled when we have reached steady state at the living standard of the average EU-27 citizen. In table 1 below we see estimates for material use from Eurostat [1] respectively the authors own calculations [2] . As Sweden is a producer of a lot of virgin metals and paper products the energy use is higher than for the average EU citizen but gives a reasonable average if we include that there is a lot of import to EU from other parts of the world. Thus, energy figures for EU may be too low if we don´t include energy for production of the imported materials.

EU-27 had 447 million inhabitants 2019, while the global population was 7 674 million. Of the global population 1 236 million are in high-income countries, 5 769 in middle-income and 668 in low-income countries according to World bank data [3]. The average GDP in US$/capita was 44 618 for high-income, 5573 for middle-income and 810 for low-income 2019.

Table 1.

Per capita use of materials in EU-27 according to Eurostat and energy per capita in Sweden for different uses. Aggregated material groups 2019 in EU-27 with 447 million inhabitants.

	EU-27	Sweden
	kg/c	MWh/c
Agri+food	2235	3
Wood+paper	534	0,89
Metals	1436	2,3
Fossil oil,coke,…..	526	
Chemicals+pharma+rubber	232	1,2
Sand, cement (construction)	4690	
-Electricity		12,7
House hold el ca 1.5-3		
-Heat		13,9
-Transports		9,2
Total counted here	9653	43,19
Total including everything (2019)	14445	
Energy MWh/c (2019)	30,3	43,6
We use 2019 figures as 2020 exeptional due to Covid-19		

Sources: [1],[2] and [4].

EU-27 will represent the high income countries, but we should also be aware of the uneven distribution of wealth inside EU as well as in eg China and India. For the calculations we will use the equations below for material use:

A basic unit is ai = ton/capita,year for component/material i.

If we multiply this with the number of people in a group (Nk) like human population today (7 674 million people), forecasts for the end of this century according to different UN analysis, 9 000 resp 10 500 million people. We also can look at the number of people in low-income, middle-income, or high-income societies according to world bank definitions [3].

The amount consumed per year $X_{i,k}$ then will be for component or material i for the population-group k:

$$X_{i,k} = N_k * a_i \quad \text{(in ton/y)} \qquad (1)$$

We identify the known or estimated sources of component or material i to be zi million tons. The amount of years Yi the known resources will last then will be calculated by

$$Y_i = z_i/x_{i,k} \qquad (2)$$

For many important materials we will recycle a large portion of the material. The recycling rate is R %. The consumed amount $X_{i,k,V}$ of virgin material i then will be:

$$X_{i,k,V} = x_{i,k}\,(100\text{-}R) \qquad (3)$$

and the number of remaining years $Y_{i,k,R}$ of nown resources will be

$$Y_{i,k,V} = z_i/\ X_{i,k,V} \qquad (4)$$

If we want to study how much would be consumed of material i if all countries had the same use level as EU-27 we calculate this for the world (G i,EUlevel) from per capita figures for EU-27 for eg the global population (N_k)

$$G_{i,EUlevel} = a_{i,EU27level} * N_k \qquad (5)$$

Sometimes it is interesting also to look for usage of several different materials and we then can summarize G_i for M components or materials i:

$$G_{tot} = \sum_{i=1}^{M} Gi \qquad (6)$$

Concerning energy, we have a slightly different procedure as the usage is split at different applications like transport, residential, industry and others.

The total energy E_i used for material i will be the sum of mass in kg times energy per kg for virgin material $E_{pkgV,i}$ respectively recycled material $E_{pkgR,i}$:

$$E_i = (100\text{-}R)/100 * X_{i,k,V} * E_{pkgV,i} + R/100 * X_{i,k,R} * E_{pkgR,i} \qquad (7)$$

When it comes to replace fossil fuels by renewables, we will have three main cases. The first will be just to replace fossil fuel with a biofuel. Then we will have the energy per kg for fossil fuel x, $E_{x,i,}$ with efficiency for conversion $\eta_{x,i}$ for eg reduction of metal oxide MeO to metal Me and the corresponding energy per kg for biomass, $E_{bio,i}$, and conversion efficiency $\eta_{bio,i}$. The correlation between the two will be

$$E_{bio,i,} = E_{x,i,} * (\eta_{bio,*i} / \eta_{x,i}) \qquad (8)$$

For some specific reaction and processes we can also add several conversion steps with separate conversion efficiencies. If we take the case with using H_2 instead of C we will first have the actual chemical reactions to consider:

2MeO + 1 C ------- 2Me + 1 CO2

2 MeO + 2 H2 ------ 2 Me + 2 H_2O

What we can see here is that we need twice as many moles to convert 1 MeO with H_2 compared to C, assuming the same conversion efficiency ηc for both cases. If we then look at the losses on the way, we will have small extra losses for the C case while the production of H_2 from water using an electrolyzer will have efficiency ηelectrolyser and compression of the H_2 gas will have efficiency ηcompression . If the gas is to be used for EVs (Electric vehicles) using Fuel Cells (FC) we will need to add the fuel cell efficiency ηFC.

The total efficiency (ηtot,H2) for the H2 compared to C then would be:

$$\eta_{tot,H2} = ½ \text{ (Cmol)} * \eta_{electrolyser} * \eta_{compression} * \eta_{FC} \qquad (9)$$

where η_{FC} =1.0 if no Fuel Cell in the system. Normally we can assume approximately the following efficiencies today: $\eta_{electrolyser}$ = 0.5-0.7 ; $\eta_{compression}$ = 0.9 if 250 bar ; η_{FC} = 0.5-0.7. If we multiply this assuming reasonable figures of today we get $\eta_{tot,H2} = \eta_{electrolyser} * \eta_{compression} * \eta_{FC} = 0.6 * 0.9 * 0.6 = 0.32$ or 32 %. To this we have twice as many moles of H_2 compared to C.

For a conversion of a vehicle with ICE (internal combustion engine) using fossil fuel to an EV we have the conversion efficiency $\eta_{c,ICE}$ in the ICE engine at approximately 0.30-0.45 depending on driving in the city or at the highway. This means that we normally need some 0.5-0.7 liter/10 km or some 5-7 kWh/10 km with the internal combustion engine. If we drive an EV with battery the corresponding calculation $\eta_{battery}$ including both charging and discharging is 0.9-0.95. The electric engine efficiency ηeleng will be very high; 0.95-0.97 is realistic. This gives a total efficiency $\eta_{tot,el}$ around 0.86-0.92.

$$\eta_{tot,el} = \eta_{battery} * \eta_{eleng} \qquad (10)$$

For the case with H_2 we can use the equation from earlier and then get approximately ηtot,FC = 0.32. This shows that from an energy perspective it is much more efficient to use battery electric solutions compared to H_2/FC. On the other hand – H_2 can be stored easier at a large scale than electricity in batteries, which can still give advantages with H_2 from a storage perspective, at least for more long-term storages. Hydrogen also can be stored in chemicals like NH_3.

Concerning emission of CO_2 equivalents from power production we have principally the conversion relation that 1 C consumes 1 O_2 to produce 1 CO_2. If we know the fuel composition $CxH_yO_vN_zS_p$ we thus can easily calculate the emissions, if we know the amount of fuel being used. Unfortunately, the composition can vary a lot for coal, oil and biomass, which can give high uncertainties. In table 2 we have the total global figures for energy "consumption" respectively "production" in ton per capita in ton oil equivalent per year.

Table 2. ‘

Global use in ton per capita for different usage areas and different energy sources [5]

Globally ton/capita	NG	oil	coal	electricity	"Total"	% of con
Total Mtoe final consumption	0,20993	0,527886	0,129528	0,250065	1,295022	(excl bio
Total Mtoe production	0,441723	0,578447	0,482799	0	1,861089	of all
Industry	0,077912	0,038168	0,100514	0,105027	0,321622	24,8356
Residential	0,062744	0,028506	0,009715	0,067268	0,168232	12,9909
Transport	0,015272	0,344182	0	0,004251	0,363705	28,0853
Commercial &public service	0,027	0	0	0,053764	0,080764	6,23662
Non-energy use	0,025192	0,088157	0,006735	0	0,120084	9,272
other	0,001889	0,029034	0,012564	0,019755	0,063243	4,88359
Total exclud bio+waste+other					1,11765	86,3050

Unfortunately collected data is primarily distributed on NG, oil, coal, and electricity as the values for biomass and waste are so uncertain. Thus, the sum of use here is only giving 86.3% of the estimated total energy use. In the last column thus % of what is measured is given as well. What we can see is that Industry and Transport sectors are dominating. Another interesting variable is how much CO2 equivalents that is emitted in the different applications as well. In table 3 we see the energy utilization annually as well as estimated emission of CO2 equivalents for three of the major emitters.

Table 3.

Global use of energy and emission of CO_2 eq 2018. Data for energy use [6]

Global use 2018			
TWh/y and Gton CO_{2eq}/y	TWh/y	$Gton_{CO2eq}$/	Mtoe/y
Industry	43 610	8,5	3180-3677
Transport	30479	7,3	2783
Agriculture&forestry (non-ener	5800	9,3	922
Buildings	34881	10	2981- 3478
Total use	116269	36	9938

The high and low figures for buildings and industry is if construction industry should be included in one or the other post. The total emission globally is approximately 36 GtonCO2eq/y, where most of the rest is for energy use (electricity and heat/cooling). When we summarize these components, we reach 35.1 GtCO2eq/y. Especially battery or fuel cell/Hydrogen vehicles or industrial processes as replacement of fossil fuels can be studied as described earlier. If we assume EVs with battery the global energy use can be reduced as batteries with electric motors are much more efficient than ICE internal combustion engines. Assuming that the electricity is made from renewables or nuclear the CO_2,eq emissions will be dramatically reduced, but also the total energy reduced to roughly 1/3 of the demand today [7]. For production of Hydrogen by electrolysis, storage and then combustion in a fuel cell gives an increased energy demand by approximately 2.5-2.7 times compared to what is used with coal or other fossil fuel [8]. On the other hand, also here the CO_2 emissions can be reduced in the same way as with batteries.

So, what would it mean in material use to produce the electricity with wind, PV, hydropower or biomass-CHP? In table 4 below approximate figures for how much material is needed per MW installed capacity. The electricity production still will depend on the capacity factor Cp. Eurostat gives the average figure Cp for EU 2019 to be 26%, with 24% on-shore and 38% off-shore. For PV cells it is lower but depend a lot on the geographic site. For CHP and hydropower with reservoir for storage the Cp can be varied intentionally, which is an advantage compared to wind and PV.

Table 4.

How much material is needed per MW installed capacity and how much of first year electricity production is needed to compensate for energy input in building plants. [9], [10], [11], [12] and [13]

		PVcells	Wind	CHP or CC
Concrete		0	73%	75.8%
Steel		0	25%	24%
Glass		76%		
Aluminium		8%	0	0.2%
Copper				0.16%
Plastic		10%	1.7%	
Oil/lubricant 20y			0.1%	
Total ton/MW		840	515	129
Energy input as % of one year production		39%	4-18%	8%

To operate the transport fleet with EVs we would need some 15 000 TWh/y of electricity. From Table 4 we can see that the amount of materials in ton per MW is 129-840 ton/MW. In table 5 we have how many GWh/GW we get according to statistics on installed capacity and production per year. If we assume a mix with 1/3 of each Wind, PV and Thermal power we get 5000 000 GWh/2197 = 2275 GW wind, 5 000 000 GWh/1145 = 4366 GW solar power and 5 000 000 GWh/4366 = 1145 GW thermal, assuming same efficiency for coal fired and biomass fired CHP plants.

Table 5.

Energy as TWh/y, GW installed capacity 2019 and GWh/GW

Type	TWh/y	GW install	GWh/GW
	2019	2019	
PV	720	629	1145
Wind	1430	651	2197
Coal	9168	2100	4366
NG	6250	1812	3449
Nuclear	2500	390	6410

From table 4 we have 840 ton/MW for PV cell system, meaning 840 ton/MW* 4 366 000 MW= 3,67 Gton. For wind power we get 515 ton/MW* 2 275 000 MW= 1.17 Gton and for thermal power 129 ton/MW* 1 145 000 MW= 0.148 Gton materials. For wind and thermal power, we will put in approximately 10 % of first year production into the manufacturing, while approximately 4 times as much for PV cells with today´s technology [9]. From this we see that CHP demands least materials for construction but on the other hand demand fuels for operation.

3. Results – Scenarios

There are two major challenges for the human population. The first is the issue with fair distribution of resources. What would it mean if everyone would have the same living standard as the average EU-27 person, for world resource utilization? The second big challenge is what it will mean if world population proceed to increase significantly. In table 6 we see how demand for resources would be impacted under these conditions.

Table 6.

Scenarios for demand for resources if everyone globally should use same amount of resources as an average EU-27 citizen respectively how much will be needed if population increase to 9000 respectively 10500 million inhabitants.

			Population	Assuming EU-27 level		Total toda	Diff today	Diff today	Diff today
Population in millions	447		7674	9000	10500	Today	- to EU-27	- to 9000	- to 10500
	EU-27	Sweden	Mton/y	Mton/y	Mton/y	Mton/y	Mton/y	Mton/y	Mton/y
	ton/c	MWh/c	Wrld if Eulev			Global			
Agri+food	2,235	3	17151	20115	23468	8000	9151	12115	15468
Food including stalks etc			17151	20115	23468	16000	1151	4115	7468
Wood+paper	0,534	0,89	4098	4806	5607	600	3498	4206	5007
Forest products totally			4098	4806	5607	2999	1099	1807	2608
Metals	1,436	2,3	11020	12924	15078	2000	9020	10924	13078
Fossil oil,coal, NG	2,35	10,9	18034	21150	24675				
Plastics, Chemicals+pharma+ru	0,232	1,2	1780	2088	2436	300	1480	1788	2136
Cement	0,317		2433	2853	3329	4100	-1667	-1247	-772
Sand, cement (construction)	4,69		35991	42210	49245				

What we can see here is that food and agriculture is of highest importance. The total production and use today are approximately 8 000 million tons/y but would be more than double this if we extrapolate EU-27 figures to all people globally. Roughly twice as much biomass is produced including stalks and leaves giving approximately 16000 Mton/y. Approximately 30% of what we produce is wasted due to different reasons like poor storage, food getting to old and thus thrown away etc. In figure 1 we see annual consumption today compared to if all at EU-27 level, and if we become 9000 or 10500 million inhabitants at EU-27 level.

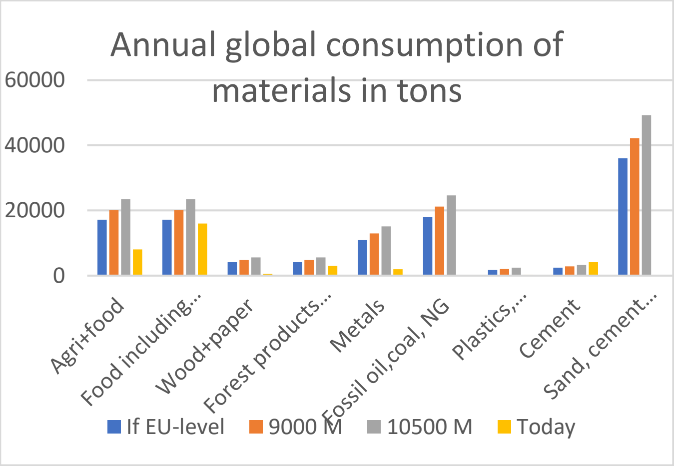

Figure 1. Annual consumption in million tons for different world populations – A. As reference we have the total global use today, 7 674 million 2021 (today). B. same assuming same level as EU-27 and scenarios with C. 9 000 respectively D. 10 500 million inhabitants.

For wood and paper products we have a similar discussion. If we use EU-27 average per capita we get 4098 Mton/y globally while official figures on global level says 2999 Mton forest products/y. If we then take the production of pulp + paper this is 600 Mton/y. A significant amount of the rest is for direct use of wood for constructions but also as biomass fuel. Still, we have a difference between the average global use per capita and the EU-27 level. As internet trading is increasing, we see more packages and boxes, but less printing and journal paper demanded. Tissue like toilet paper is increasing where it has not been used so much before. But also, we see a new demand for replacement of oil and plastic by wood fibers.

For metals it is complex to take averages as in some countries we have a very high recycling rate of metals in relation to virgin materials compared to others. Even if you use the same amount as kg/capita it can still be very big differences with respect to amount of virgin material. This gives a very high amount if we multiply average use in kg/c,y in EU-27 with number of people in the world, as a lot of the EU-27 use is recycled metals. For Iron for instance, recycling rate is in the range of 88%. Thus, it may be more interesting to look at the total metal production which is 2000 Mton/y. A fact is that if everyone should have their own Electric vehicle the amount of metal will increase a lot, as many of the existing population still hasn´t any car. If we then add 1500 million or 3000 million people, we can see that the demand increases dramatically (see figure 1). From weight perspective cars are very important, but also armament in concrete buildings or metal as construction material. Batteries and wind power plants as well as power transmission and distribution will affect the total use a lot next 20 years for transfer into non-fossil energy, but also even more if the world population increases even further. This will include also more demand for cement and other bulk materials like sand and gravel.

Energy is another aspect of resources. In table 2 we see how energy is used per capita in Sweden, which is one of the EU-27 countries with a high energy demand per capita. The total use is 43 MWh/c,y from which 10.9 MWh/c,y from fossil sources. Approximately 3 MWh/c,y is for food and food production while 0.89 MWh/c,y for wood and paper. 2.3 MWh/c,y is for metals and metal production while 1.2 MWh/c,y for plastics and chemicals. This is for a country with relatively high amount of virgin wood fibers and metals, so average EU-27 will be significantly less if the share of recycled materials is high, as the case with pulp and paper and metals generally. We still can see that the amount of energy for materials (7.4 MWh/c,y) is significantly less than the amount used for transport (9.2 MWh/c,y), heating (13.9 MWh/c,y) and electricity (12.7 MWh/c,y). The total use varies between countries and especially the national power mix varies a lot. In Sweden more than 90% of electric power is from renewables or nuclear and most of the fossil CO2 emissions comes from other countries through different products, fuel for transportation or for industry use. As at average 23 TWh out of 158 TWh produced is exported annually, the “net” electricity production is close to 100% non-fossil. In a country like Poland with large amount of coal the situation is the opposite, although also Poland is driving renewable energy a lot, and the same goes for Germany, Denmark and Finland, although with different mix of technologies.

Without going too deep into the relation between energy and materials, we can see that the average energy input per kg for several products was presented in table 1. When recycling e.g. iron the kWh/kg decreases by 75%, which shows that we both get a positive effect with respect to demand for new metal, but also reduces the energy demand per kg dramatically. This shows us that from a material use perspective increased material recycling is an important move to take.

The power demand for electric vehicles, replace fossil fuels in process industries and similar will be both higher and lower than today. For an electric vehicle consuming 5-10 kWh/10 km an electric vehicle may consume 1.5-2 kWh/10 km. This means only 1/3 of the energy demand compared to today. For energy calculations we use the set of equations presented earlier.

4 Discussion about uncertainties

Concerning energy, we have a lot of data on production and consumption of oil, coal and natural gas, but also electricity, biomass, waste and “others”. Usually, you recalculate all to be TWh/y or Mtoe/y, million-ton oil equivalents, for global figures. Then we must be aware of that heating values differ a lot between different qualities. For NG we have 13.5+- 1.8 kWh/kg; for crude oil 12.4+- 0,7; for coal 5.8+- 1.1. Even for Hydrogen, H2, we have a span 36.4+- 3.1 [14]. If you have detailed analysis of all materials and summarize these it should be very accurate, but we will have to expect that some values are more accurate than others. Even if everyone is trying to collect and report as correct as possible, we still will have uncertainties as this is done in many stages and with several recalculations from one sort to another. We see that the reported total production is 14 282 Mtoe 2018 for all products, while final consumption ends up at 9938 Mtoe 2018. The difference is losses in one way or another. If we for instance look at the deviation between produced and consumed electric power, we see losses of approximately 7% in many countries, but with extremes of more than 50% in e.g. Benin. Do people steal power or are the measurements just poor? If we extend the transmission of power over long distances we can expect higher losses, but with new technologies they can be reduced as well.

Another uncertainty is how materials are defined. When we look at official figures of cement the value is 4100 Mton/y, but in some official sources we have 4100 Mton/y of concrete as well, while others report 30 000 Mton/y for concrete, which makes more sense. These are all official figures, but the nomenclature has obviously not been correct.

When it comes to grouping data into categories it is also difficult to compare data from one source to data from another. If we look at the EU-27 data these are valid from 2020, but EU-28 before UK left the union, up to 2019. It is also difficult to know what components are aggregated in different sources.

Concerning CO_2 equivalent emissions, we come to even more tricky considerations. For agriculture we see figures stating that 9.3 $GtCO_2eq/y$ is emitted, from which 5.3 Gt from crops and livestock and 4 Gt from change in land use. These figures are built on some few measurements in a few countries and then extrapolated for the globe. The uncertainty is huge. If we look at N_2O we have seen in measurements that almost all is emitted during a few weeks when the land is covered by melting ice, and there has been a lot of Nitrogen left in the soil. If we avoid fertilizing before the crop has come up to some 10 cm, we can almost eliminate this. For methane the water level in wet land is very important. When water is almost up to the surface, we get larger emissions than if it is some 0.8 m below the surface, but it also depends on how the water is flowing through the wet land. We mostly guess how much is emitted by extrapolating from very uncertain measurements.

4. Summary and Conclusions

From the simulations we can determine effects of different developments with respect to population increase, fair distribution of materials, energy use from different sources and how long it will take until resources are depleted without recycling respectively with recycling. This is important for how politicians should make their decisions on rules to direct use of materials and how to reduce fossil CO_2 emissions. If all had EU-27 level of living standard the impact on metals, plastic and some chemicals will be very high while marginal on food, forest products and concrete. For increased population the increase will be in proportion to how many more people there will be.

Acknowledgment

We thank our cooperation partners LKAB (SUM Academy), Mälarenergi and Eskilstuna Strängnäs Energi och Miljö (ESEM) and EU ERA NET projects IFAISTOS and DISTRHEAT for financial support and technical input.

References

[1] Material flow accounts in raw material equivalents by final uses of products - modelling estimates [ENV_AC_RMEFD$DEFAULTVIEW]. 27/09/2021. https://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity

[2] Dahlquist, E., & Hellstrand, S. (2017). Natural resources available today and in the future: How to perform change management for achieving a sustainable world (pp. 1-304). Springer International Publishing. https://doi.org/10.1007/978-3-319-54263-8

[3] World bank indicators, (down loaded data 2022). https://data.worldbank.org/indicator

[4] SCB, https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/environmental-accounts-and-sustainable-development/system-of-environmental-and-economic-accounts/pong/tables-and-graphs/economy-wide-material-flow-accounts/domestic-material-consumption-per-category-of-material-sweden-1998-2020/

[5] Eurostat: Primary energy consumption [T2020_33]. By "Primary Energy Consumption" is meant the Gross Inland Consumption excluding all non-energy use of energy carriers. Last update 21 Dec 2021. Energy distribution on activities and fuels

[6] Fatih Birol: Key World Energy Statistics 2020. CO2 equivalents. IEA August 2020.

[7] U.S. Energy Information Administration. International Energy Outlook 2016.

[8] Hydrogen efficiency (IVA report 2022, not yet published May 2022)

[9] Elena Tomas-Aparicio, Erik Dahlquist, Jinyue Yan, Konstantinos Kyprianidis, Bertil Moritz: Comparison between different renewable energy solutions from a materials and CO2 perspective. Conference proceedings for International Conference on Applied Energy 2020, Dec. 1 - Dec. 10, 2020, Bangkok / Virtual, Paper ID: 518.

[10] Haapala, Karl R. * and Preedanood Prempreeda: Comparative life cycle assessment of

2.0 MW wind turbines. Int. J. Sustainable Manufacturing, Vol. 3, No. 2, 2014

[11] Jan Wenske: Article Monitoring the Oil of Wind-Turbine Gearboxes: Main Degradation Indicators and Detection Methods Diego Coronado 1 and Jan Wenske 2,* 1 OELCHECK GmbH, Kerschelweg 29, 83098 Brannenburg, Germany; dcg@oelcheck.de 2 Fraunhofer Institute for Wind Energy Systems IWES, Am Luneort 100, 27572 Bremerhaven, Germany * Correspondence: jan.wenske@iwes.fraunhofer.de Received: 15 March 2018; Accepted: 5 June 2018; Published: 8 June 2018.

[12] Spath Pamela L. , Margaret K. Mann [2000] : Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System. September 2000 ï NREL/TP-570-2771

[13] Spath Pamela L., Margaret K. Mann, and Dawn R. Kerr: Life Cycle Assessment of Coal-fired Power Production.
https://www.nrel.gov/docs/fy99osti/25119.pdf,
June 1999 • NREL/TP-570-25119.

[14] Higher heating values: https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx