I have sinned,

I have sinned – over the last 22 years as a freelance design engineer, I have developed 50 plastic chairs. And only one of them could be called sustainable - the S-1500 designed by Snøhetta and produced by NCP in Norway. The plastic shell is made of recycled plastic from the local Norwegian fishing industry.

Figure 1 – 50 plastic chairs

Without praying for the remission of sins, I would try to outline the impact of the sin and come up with ideas how to produce sustainable CO2 neutral plastic chairs in the future.

Annually 359 million tons of plastic[1] is produced worldwide. It means that 4% to 6% of the annually oil and gas consumption in Europe is used for manufacturing plastic. Half of the oil and gas is converted into plastic and the other half is used as processes energy for converting oil and gas into plastic (distillation, pyrolysis, polymerization, etc.). The inexpensive plastics like polyethylene and polypropylene use less energy, where more expensive plastics like nylon (polyamide), acrylic and polycarbonate use more energy.

I think plastic in the future should be based on renewable resources. That means some of the carbon embedded in our vegetation should be converted into plastic. This process require energy, so it is very important also to generate a lot of renewable energy (sun, wind, etc.). At the same time, the global carbon budget should be treated in a way, where it will not add additional CO2 to the atmosphere. This is done by securing that the amount of carbon embedded in products and vegetation is stable. In this way it is possible to generate CO2 neutral plastic materials.

But is it possible and realistic? That what you can read about in this note.

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[1] M. Garside, "Global plastic production 1950-2018", *Statista*, November 2020

Why is plastic interesting at all?

Plastic molding have the advantage that products can be produced without waste (effective molds with hot runner systems) and products can be designed where a minimum of material is used, as the material can be placed exactly where needed. Wooden products require machining (ex. Milling) where waste is produced or can only be flat like plywood. Wood is of course CO2 neutral and will often be more environmentally friendly than plastic, of course depending on the material and energy consumption to produce the product.

Is it possible to make plastic from renewable resources?

I think the future manufacturing of plastic materials must be based on renewable resources (vegetation). It is also important that the plastic have at least the same properties as the plastic of today. It must be plastic that is produced effectively and under controlled conditions – not plastic which are made in a simple "kitchen pot".

We do already have plastics on the marked, which are based on carbon from vegetation. An example is PLA, that is based on starch from corn. PLA is also biodegradable, which does not make much sense, as the material over time will lose properties and anyway in the end will decompose to CO2 and/or methane. When plastic is marked biodegradable, it tends to appeal people to drop the material in the nature or the sea. From an environmental point of view, it is much better to recycle, incinerate with heat recovery or gasificate the material. Biodegradable plastic materials do only help the deafness of humanity, as we do not want to bring the material to the right place after use.

More interesting are plastics based on traditional monomers made from vegetation. Monomers are the basic building block of making plastic (polymers). There seems to be 2 basic routes:

- Route 1 is based on sugar, which is transformed to alcohol by fermentation. By a chemical dehydration process is the alcohol converted to ethylene, which is the monomer used for producing polyethylene. Ethylene is also one of the building blocks for producing PVC and polystyrene. Source: [2]

- Route 2 is based on lignin, which represent 20-30% of the dry matter in plants. Pyrolysis is a process where the lignin is heated to high temperature in an atmosphere without oxygen. In the process it is possible to break down lignin to a mixture of among others aromatic carbon compounds. The carbon compounds can be processed to monomers by traditional petrochemical process, and then be input for polymerization of new plastic materials.

The sugar route seems to be at the forefront of the developing process. The polyethylene named *"I'M GREEN™"* produced by the Brazilian company Braskem is already on the marked. From an ethical point of view, it can be questioned whatever it is OK to use sugar (in principle food) for plastic production.

The Lignin route is interesting, as it is not food, but it might be more energy consuming, as the pyrolysis process require high temperature and other petrochemical processes do also require energy.

Another route not based on vegetation could be *Carbon Capture and Utilization* (CCU), where CO2 is captured and converted to several products, that might be used for plastic production. The process is probably very energy consuming.

[2] Valentina Siracusa and Ignazio Blanco: "Review: Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly (ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications", Polymers, MDPI, October 2020

Why should we use renewable resources?

Sustainability should be based on the definition expressed by the Brundtland Commission: *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* That means we must behave properly to the people living on the earth today and at the same time behave in a way, so future generation can also full fill their needs. Needs for food, housing, protection, etc. Or we could say, we must behave in a way, that ensure the earth generates the same resources, that it is generating today. We are not allowed to poisoning soil and sea, so food and materials cannot be generated, and on the same time we must be sure, that the materials, we are using today, does not disappears or are diluted in a way, that makes them inaccessible.

Assumed that it is correct (what almost all scientist does) that climate changes will make it more difficult for future generations live on the earth, it is important that the amount of greenhouse gasses does not increase. About 73% of the anthropogenic greenhouse gasses are related to combustion of fossil fuels (oil, gas, and coal), which are used for production of electricity, heating buildings, heating production processes and engines for transportation and production. Not only greenhouse gasses are related to combustion of fossil fuels also acidification, nitrogen oxide, ozone, tar, and volatile organic substances are related to combustion. Substances it is often possible to extract from the chimney smoke, but anyway a reason trying to avoid combustion of fossil fuel. Consuming all oil, gas, and coal, will make it impossible for future generations to use these resources for relevant products.

What happens in the atmosphere, can be seen in the global carbon budget, see figure 2 on the next page and table 1 in appendix. It is seen that the annual emission of carbon (not CO2 which is 3,7 times more due to the oxygen molecules) from fossil fuels is about 9,5Gt (Giga-tons). Deforestation is responsible for another 1,5Gt carbon in the atmosphere. Human activities increase the annual amount of carbon in the atmosphere with 11Gt, which is mainly present as CO2. Both soil and oceans absorb some of the carbon emitted by humans so the net growth og carbon in the atmosphere should be around 5,3Gt in 2019. It is all of course with some uncertainty and we must remember that the atmosphere contains about 845Gt carbon where about 259Gt is anthropogenic.

The annual plastic consumption of 359 million tons contains about 285 million tons of carbon which is between 0,04% og 0,06% of the carbon embedded in the vegetation of the world. In this way it should be possible to extract enough carbon from vegetation for plastic production without disturbing the global carbon budget.

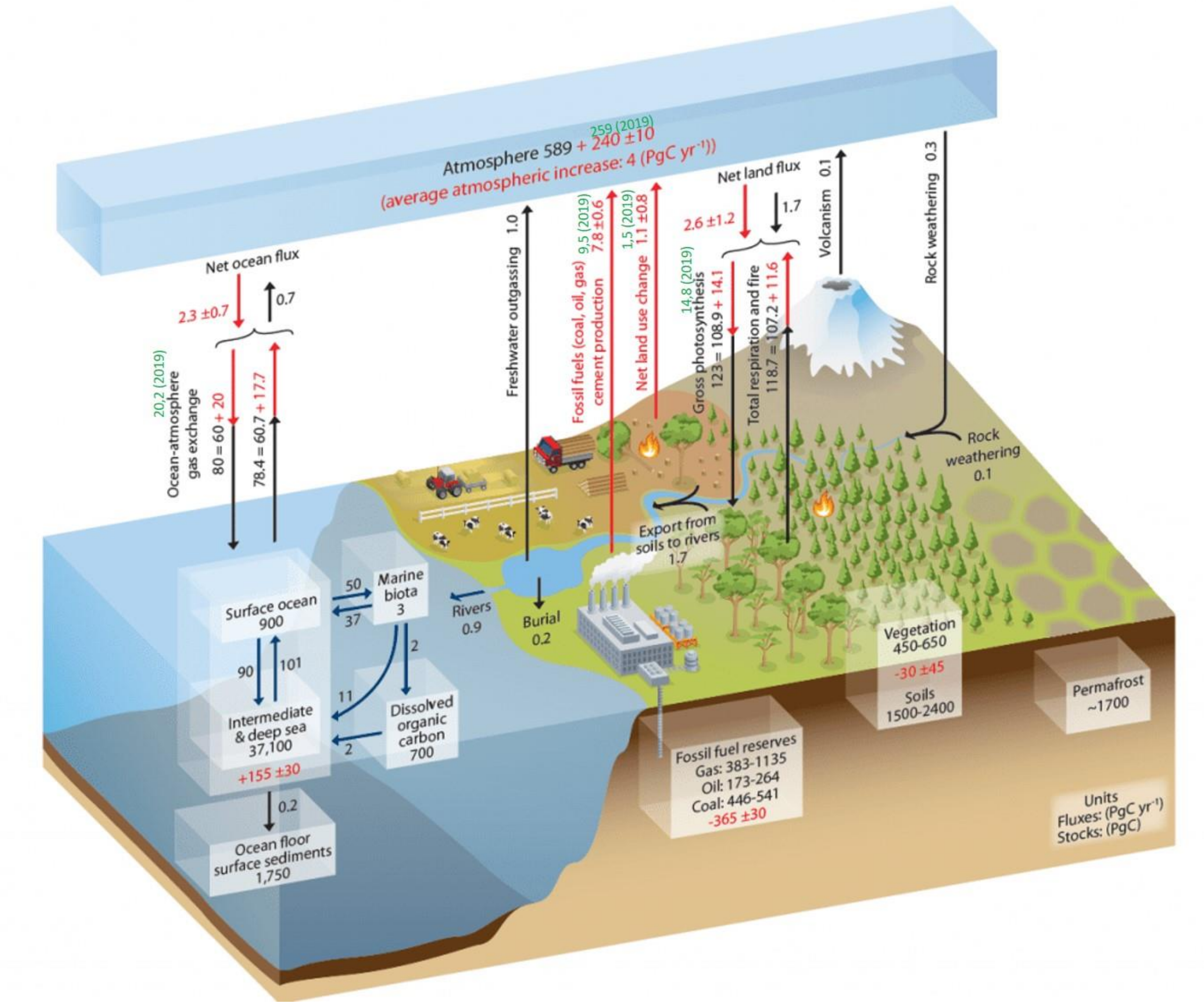

Figure 2 - Source: IPCC "Climate change 2013" og Earth System Science Data "Global Carbon Budget 2019". Data in red is from 2000-2009, data in green is from 2019

Reuse of plastic products and recycling of plastic materials does of course make sense if the "new" product have a utility value. Today's technologies make it often not possible to recycle plastic materials in a way that gives the material enough value. This is due to the fact, that the material might be partially decomposed, contaminated or mixed with other plastic materials. In these cases, we might use, what I in a "funky" way call "atomic recycling", which is incineration of the plastic, where CO_2 is emitted and converted back to vegetation by the sun and the photosynthetic process. The new vegetation materials are then used as input to new biobased plastic materials. With this recycling strategy it is of course important that the amount of carbon in vegetation is balanced, meaning forest must be plant to compensate the amount of burned bioplastic.

If we decide to burn all the 359 million tons of annual plastic consumption, it will increase the annually anthropogenic CO_2 emission to the atmosphere with about 3%.

Is it theoretical possible to achieve all the needed energy?

A strategy could be to incinerate vegetation and, in this way, produce energy. The amount of carbon embedded in vegetation of the earth is between 375Gt og 656Gt, which should be enough to cover our energy consumption. It is of course important that same amount of carbon is transformed into new vegetation via the photosynthetic process, otherwise we will increase the amount of carbon and CO2 in the atmosphere.

In my opinion it makes more sense using vegetation for food and material production and produce energy from other renewable sources. Energy is used for converting and processing vegetation into edible food and usable materials and products.

The annually income of solar energy to the earth is 3.850.000 EJ (Exajoule), which is 6.375 times our annually energy consumption of 604 EJ in 2019. One would think, it should somehow be possible to "harvest" enough energy to avoid using fossil fuel.

Furthermore UNDP (UN-organization) in 2000 assumed the potential of solar power is between 1.575–49.837 EJ[3], much than our needs of today.

Cristina L. Archer og Mark Z. Jacobson[4] assumed that the potential of wind power is 2.260 EJ, also more than our needs of today.

Is it practically possible?

Efficiency of solar panels depends on location on the earth, but a good estimate is that the panels can deliver 150 kWh/m^2 per year (0,54 GJ/m^2). To cover our energy consumption of 604 EJ it will require 1.118.519 km^2 of solar panels or 0,75% of the land on earth (1% is already used for human infrastructure – roads, cities, etc.[5]) or an area corresponding to the total area of France, Germany, and Italy.

Modern 9MW offshore wind turbines produce annually about 36.000 MWh (130 TJ). That means covering the total energy consumption of energy only by offshore wind turbines requires 4,6 million wind turbines. The diameter of a 9MW offshore wind turbine is about 160m, that means we need 743.385km of wind turbines (wingtip to wingtip), which correspond to about 19 times around equator.

According to Vestas the price for a wind turbine is about 733.000 Euro per MW[6] or all together astronomical 30.636.000 million Euro, which is 43% of the total BNP of the world 73.666.000 million Euro[7]

Furthermore, large investment must be done in infrastructure. Methods for electrical energy storage must be developed and new supply systems build. Transportation system and production must be electrified and/or based on CO2 neutral fuels, that can be based on atmospheric CO2 or biological material, which is under research at DTU[8] [9].

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[3] Dennis Anderson, et al., "Energy and the challenge of sustainability", *United Nations Development Program*, September 2000

[4] Cristina L. Archer og Mark Z. Jacobson, "Evaluation of global wind power", *Journal of Geophysical Research – Atmospheres,* AGU Journal, June 2005

[5] Hannah Ritchie, "Half of the world's habitable land is used for agriculture", *Our World in Data*, November 2019

[6] Ritzau Finans, Analytiker, "To priser presser Vestas' indtjening", *Energy Watch*, August 2018

[7] The World Bank, "World Bank national accounts data, and OECD National Accounts data files", *The World Bank website*, 2020

[8] Theis L. Skafte, m.fl., "Selective high-temperature CO2 electrolysis enabled by oxidized carbon intermediates", *Nature Energy, volume 4*, September 2019

[9] Sanne Wittrup, "Pyrolyse kan halvere udledning fra Landbruget", *Ingeniøren*, September 2020

This note does only deal with the energy consumption of the present. Due to population grow, and requirements for growth from developing countries the energy consumption might increase.

Whatever its realistic to produce all the required energy in the world based on solar and wind energy I cannot judge, but it will require enormous international agreements if it should be possible. And of course, it will make it easier if we could lower our energy consumption.

Fusions og fissions energy (nuclear power) does also have a potential, but we must consider the risk of nuclear accidents and problems with storage of radioactive waste.

All numbers in this note are based discretion and estimates, numbers multiplied among each other, which means failures might occur. But I think it gives a good sensation of the proportion of our challenges.

Appendix

2019			
	Before industrialization	**Anthropogenic**	**Total**
Carbon cycle	Gt	Gt	Gt
Ocean - atmosphere	60,7	17,7	78,4
Respiration and fire	107,2	11,6	118,8
Freshwater outgassing	1		1
Volcanism	0,1	0	0,1
Fossil + cement		9,5	9,5
Deforestation		1,5	1,5
Burial	0,2		0,2
Total	**169,2**	**40,3**	**209,5**
Atmosphere - ocean	-60	-20,2	-80,2
Photosynthesis	-108,9	-14,8	-123,7
Stone	-0,3		-0,3
Total	**-169,2**	**-35**	**-204,2**
Total	**0**	**5,3**	**5,3**
	Before industrialization	**Anthropogenic**	**Total**
Carbon stocks	Gt	Gt	Gt
Atmosphere	586	249 to 269	835 to 855
Ocean surface	900		900
Ocean deep sea	37.100	125 to 185	37.225 to 37.285
Ocean floor surface - sediments	1.750		1750
Marina biological	3		3
Dissolved organic carbon in sea	700		700
Gas	383 to 1.135		
Oli	173 to 264		
Coal	446 to 541		
Gas Oli and Coal total	1.002 to 1.940	-395 to -330	607 to 1610
Vegetation	450 to 650	-75 to 15	375 to 665
Earth	1.500 to 2.400		1.500 to 2.400
Permafrost	1.700		1.700

Figure 1

Table 1: Source: ICPP, "Climate change 2013" og Earth System Science Data "Global Carbon Budget 2019"