“Tragedy of the Planet?”

Characterizing Climate Change as a Tragedy of the Commons Type of Challenge

Anders Winther Mortensen – 322321
Kasper Dalgas Rasmussen – 326498

June 1st, 2018

Master Thesis

Printed in Denmark.

Please use the following reference to the whole report:

Rasmussen, Kasper D. & Mortensen, Anders W., 2018: “Tragedy of the Planet?”: Characterizing Climate Change as a Tragedy of the Commons Type of Challenge. University of Southern Denmark, Odense, Denmark

Cover photo: Artic Sea Ice

On July 12, 2011, crew from the U.S. Coast Guard Cutter Healy retrieved a canister dropped by parachute from a C-130, which brought supplies for some mid-mission fixes.

The ICESCAPE mission, or "Impacts of Climate on Ecosystems and Chemistry of the Arctic Pacific Environment," is NASA's two-year shipborne investigation to study how changing conditions in the Arctic affect the ocean's chemistry and ecosystems. The bulk of the research takes place in the Beaufort and Chukchi seas in summer 2010 and 2011.

Photo and photo text credit: NASA/Kathryn Hansen

Summary

In 2016, most of the world's leaders signed the Paris Agreement, wherein two goals for the global temperature increase are stated. The first goal is to pursue efforts to limit the temperature increase to 1.5 °C, and the second goal is to limit the global average temperature increase to well below 2 °C. Both temperature increases measured against the pre-industrial temperature levels. Considering that the global average temperature increase reached 1.1°C in 2016, staying below the temperature limits from the Paris Agreement is going to be a huge challenge. In this master thesis, we try to characterize the challenge that we are facing in relation to global warming and climate change.

In 1759 and 1776, the Scottish economist, philosopher, and author Adam Smith published, *The Theory of Moral Sentiments* and *An Inquiry into the Nature and Causes of the Wealth of Nations*. In these books he, among many other things, presents the idea of the market economy as an 'invisible hand' that guides individual optimization also to be the optimum for society. If this were also the case for the economic activities leading to global warming and climate change, we would not need to worry. But are economic activities behind global warming and climate change a schoolbook example from economic theory obeying the principle of the 'invisible hand'?

Our main hypothesis is that this is not the case. On the contrary, we hypothesize that global warming and climate change relate to economic activities leading to a so-called 'Tragedy of the Commons' type of challenge.

The classic tragedy of the commons was formulated by the American ecologist and philosopher Garret Hardin in 1968, and it takes its offset in the school book example of a common-pool resource. The tragedy of the commons relates to a so-called commons, a pasture open to all, where herdsmen can let their cattle graze for free. The herdsmen's survival depends on raising cattle, and when only a few cattle grazes on the commons, there are no problems. The challenge arises, when the carrying capacity of the commons is violated due to too much cattle grazing in the commons. The problem is that, unlike Adam Smith's theory of the invisible hand, individual optimization, in the case of this common-pool resource example, does not lead to the societal optimum, but to the opposite. The individual herdsman receives all the benefits of adding an extra cow, whereas the diminished returns due to overgrazing are spread on all herdsmen.

The tragedy lies in the fact that if one herdsman realizes the threat of overgrazing and refrains from adding an extra cow, another herdsman may just add that extra cow instead, because this herdsman will receive the full benefit while sharing the cost of overgrazing with the other herdsmen. Thus, there is a necessity or strong incentive of the individual herdsman towards adding more cattle than what the commons can sustain. From this classic tragedy of the commons case, three criteria for a tragedy of the commons type of challenge have been derived. First, the challenge shall be related to a common-pool resource, second there shall be enough users of the common-pool resource, i.e. herdsmen/cows in the classic tragedy of the commons example, available to violate the carrying capacity of the common-pool

resource, and third there shall be an absence of feasible, alternative technical solutions. In this context, the word ‘feasible’ is understood as both technically feasible and economically feasible in the sense that the solutions should be cost-efficient and cost competitive enough to outcompete the prevailing, non-sustainable solution on an unregulated market basis.

According to Hardin (1968), the tragedy of the commons also appears in a reverse way for pollution: Where the full saving of not cleaning a waste stream before discarding it fully benefits one individual, the cost of polluting the environment receiving the waste stream is spread on all agents in society. In this ‘reverse’ case, the common-pool resource is the environment receiving the waste stream.

The hypothesis of our study is that climate change is such a reverse case of a tragedy of the commons type of challenge, TCTC. Nobody makes a living from just emitting greenhouse gases, so the criterion of absence of alternative, feasible, technical solutions in the reverse case, of course, relates to the technology(ies) to which the release of pollutants is bound. In the case of climate change, these technologies are the fossil fuel based technologies leading to greenhouse gas emissions. When the fossil fuels are burned, greenhouse gases are emitted to the atmosphere which accelerates global warming. Thus, for global warming and climate change, we are facing a tragedy of the commons type of challenge if; first, the atmosphere is a common-pool resource, second, the potential greenhouse gas emissions from burning fossil fuels are large enough to violate the carrying capacity of the atmosphere in relation to climate change, and third, the technical alternatives to fossil fuels and their related emission of greenhouse gases are not feasible. The carrying capacity has in this case been defined as being in compliance with the two goals set in the Paris Agreement i.e. to pursue efforts to stay below 1.5 °C and to stay well below 2.0 °C.

The hypothesis of the study was tested using the three criteria for a tragedy of the commons type of challenge. First, we find the atmosphere to be a common-pool resource in relation to global warming and climate change. This conclusion was derived from studying existing literature on common-pool resources and the characteristics of the atmosphere in relation to greenhouse gas emissions and global warming.

Second, we find that the potential greenhouse gas emissions from burning fossil fuels are more than enough to violate the carrying capacity of the atmosphere multiple times. This conclusion was reached by comparing data from different sources on fossil fuel *reserves* and *resources* on the one hand to the available models of the relation between greenhouse gasses in the atmosphere and the temperature increase on the other hand. *Reserves* are the technically and economically exploitable amounts of fossil fuels at current prices and technology. *Resources* are the amounts of fossil fuels, which are judged to exist, but not yet technically and/or economically exploitable. Adding the two gives the total estimated resources of fossil fuels.

More concretely, we find that the reserves of fossil fuels as estimated in 2015 contain more than 11 times more carbon than what we can emit without violating the 1.5 °C limit and more than 4 times more carbon than what we can emit without violating the 2.0 °C limit. Considering the total resources, the same numbers are more than 192 times more carbon and more than 78 times more carbon for each temperature limit respectively. Thus, running out of fossil fuels only becomes a problem after we have violated the carrying capacity of the atmosphere multiple times. At the current rate of consuming fossil fuel, we run out of all fossil fuel resources in year 3350. Earlier, though, for oil and gas.

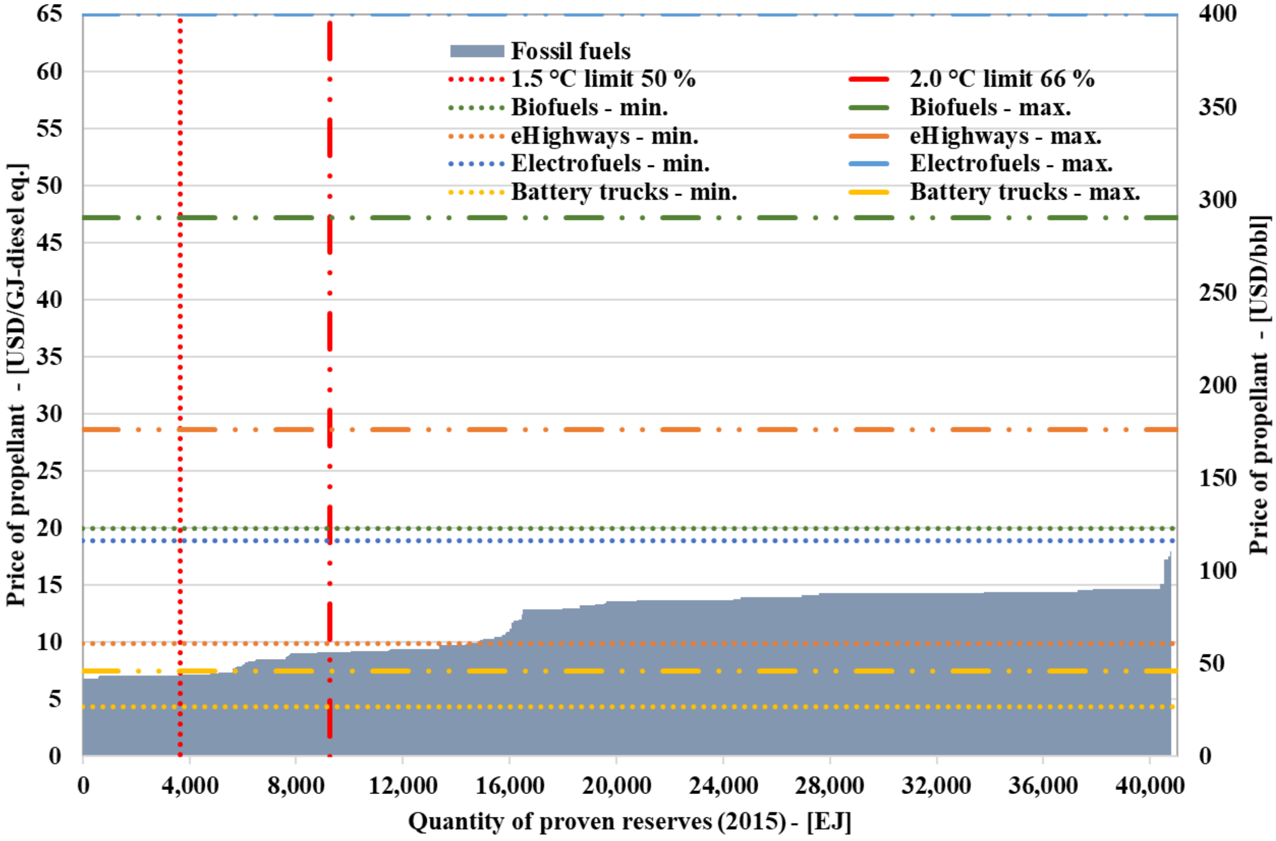
At the current rate of greenhouse gas emissions, we can go on for around 19 years only, before we violate the 2.0 °C temperature limit. The same number for the 1.5 °C temperature limit is less than 8 years, and this is with a likelihood of 50 %. We can only go on for another 4 years at the current rate of emissions if the likelihood of staying below 1.5 °C were to be 66 %. Even when considering only the coal mines, and the oil and gas fields already operating today, these contain more carbon than what we can emit without violating the carrying capacity of the atmosphere. Thus, to stay within the limits of the Paris Agreement, we must shut down some of these already operating fields and mines – or alternatively start capturing and storing the greenhouse gas releases elsewhere than in the atmosphere.

Third, we find that there, especially for sectors demanding liquid hydrocarbons, are no feasible (incl. competitive on a non-regulated market), alternative technical solutions to emitting greenhouse gasses from burning fossil fuels. This conclusion was reached by comparing price data for fossil fuels and the alternative propellant i.e. biofuels, electrofuels, and electricity. The transportation sector was found to be the key challenge, especially aviation and long distance sea transportation seem to need liquid hydrocarbons for many years to come.

The price data used for this analysis is based on the pure production costs of the propellants excluding subsidies, taxes, and externalities. Only the pure operational and capital expenses of producing, refining, and distributing the propellants are included. The results of our analyses of the third criterion for a tragedy of the commons type of challenge are presented in what we call “Tragedy of the Planet?” graphs. These graphs show the total cost of extracting, liquefying, refining, and distributing coal, oil, and gas into a liquid diesel-type fuel for each individual country in the world. The prices are sorted in merit order which gives the ‘grey staircase’ on the graph below.

In the same graph, a price span for the alternative propellant is also shown. Battery electrification and to some extent direct electrification in the form of eHighways seem to be able to compete with fossil fuels, thus they are feasible, technical alternatives. This would imply that we are not facing a tragedy of the commons type of challenge in relation to global warming to the extent that these technologies can cover the demand and substitute fossil fuel based hydrocarbons. The problem is that electrification cannot cover aviation and long distance sea transportation. Both need liquid hydrocarbons, and it seems very unlikely within the time horizon in which we must act to mitigate climate change that this is going to change. None of the alternative liquid hydrocarbons can compete with fossil fuels, see the graph below.

Thus, according to our study, we are facing a tragedy of the commons type of challenge in relation to global warming. The only way to mitigate the tragedy is by political intervention. The market is not going to solve the problem and the *invisible hand* is guiding us directly into the tragedy.



The political intervention could take on many forms. It could be as a ban of fossil fuels, which is a very *effective* tool or a quota market with tradeable quotas for greenhouse gas emissions in a cap and trade type of market which is a very cost-*efficient* tool. The cap of the market should, then, be set within the limits of the carrying capacity of the atmosphere. If a ban were to be set in place, it could either be a total ban, or it could be a ban that limits the extraction of fossil fuels to be within the carrying capacity of the atmosphere. By arranging the different types of fossil fuels in merit order according to the total price of extracting, liquefying, refining, and distributing, it is possible to make a prioritization of which fossil fuels, we should leave in the ground, and which we can extract without violating the carrying capacity of the atmosphere.

Considering the *reserves* as of 2015, all coal should be left in the ground to stay within both temperature limits. For the 1.5 °C limit, all gas should stay in the ground, and only a limited amount of oil can be extracted. It would be reasonable to prioritize the oil for the transportation sector, especially aviation and long distance sea transport. For the 2.0 °C limit, all oil can be extracted, but only a limited amount of gas, which it would be reasonable to prioritize for infrastructure that support and follow the amount of biogas/green gas that we might have available in the future. Considering the *total resources* estimated by 2015, all coal and gas should stay in the ground, and only a limited amount of the total resources of oil can be extracted to stay within both temperature limits.

Electrofuels are produced by reacting hydrogen produced from electrolysis with carbon from any source. For the last part of this summary, electrofuel produced at an electricity price of 15 EUR/MWh is considered. The 15 EUR/MWh represents the lowest cost of renewable electricity currently available at certain locations. The carbon is assumed to be supplied from direct air capture at the same location.

Under these circumstances, a tax on greenhouse gas emissions, which is another political intervention, would have to be 210 USD/ton of carbon dioxide equivalent to make this specific type of electrofuel competitive with fossil fuels at the 1.5 °C limit. For the 2.0 °C limit, the tax would have to be 190 USD/ton of carbon dioxide equivalent. Another intervention could be to subsidize the production of this type of electrofuel. The total societal cost of such annual subsidies would add up to as little as around 0.46 % of the global GDP in 2015 for the 1.5 °C limit and around 0.40 % of the global GDP in 2015 for the 2.0 °C limit. Here it is assumed that the demand for liquid hydrocarbons is 33 EJ/year based on the worlds projected demand for aviation fuels in 2040 together with the gasoline that is a co-product of the jet fuel production.

Costs in the same orders of magnitude are also what a transition of the Danish energy system would end up at. A study conducted by the Danish Energy Agency in 2014 found the annual additional cost of a fully renewable energy system to be 0.5 % of Danish GDP or approximately 1.67 billion USD. The annual societal cost of health effects related to air pollution in Denmark was, in another study, estimated to be around 4.67 billion USD, thus, if we transition into a fully renewable energy system focusing mainly on no or low emission technologies the cost of converting the system is already recovered be considering the lower societal cost of health effects. The transition to a fully renewable energy system is, thus, not a cost, but an investment with a fine return on investment.

To conclude, therefore, it is safe to say that socio-economically, the cost of solving this tragedy of the commons type of challenge and implementing a transition to a fully renewable energy system is small. The technical solutions are there – with existing technology, we can already today produce fuels, including jet fuels, via electrofuel production technologies. At the same time, we face the challenge that the invisible hand of market economy guides us to soon exceed the carrying capacity of the atmosphere as defined in the Paris agreement. In the light of this challenge, one may ask: why is it so difficult to prioritize the relatively small societal cost? We wish to wrap this summary up by setting the cost in perspective:

- Comparing the 0.5 % of GDP with other aspects of the Danish economy; Denmark uses 1.2 % of their GDP on defense, 0.7 % on foreign aid, and the Danes throw out food with a value of 0.7% of GDP each year. When speaking on the phone to president-elect Donald Trump in 2017, the Danish Prime Minister promised without hesitation to live up to the agreement to use 2 % of Danish GDP on defense.

- In May 2018, the US president expressed a wish for all NATO countries to use 4 % of their GDP on NATO, which was strongly encouraged by NATO general secretary Jens Stoltenberg. This is not mentioned as any argument against prioritizing defense, but only to show our apparent willingness to prioritize very short term safety and protection compared to how difficult it still seems to be to decide paying the much smaller cost of ensuring a sustainable world for future generations.

Looking at a more private economic perspective, Danes show willingness to pay for many types of services. How does the cost of solving the climate challenge compare to other costs that we show willingness to pay for in our everyday lives?

- For example, we often take a flight while going for holidays. If jet fuels were to be electrofuels, we can illustrate the significance on the cost of the plane ticket. The cost of a plane ticket for a round trip between Copenhagen and New York would increase by 975 USD, if the fuel were produced at today's electricity price of 40 EUR/MWh and used in an inefficient air craft. The same number would be 625 USD if the fuel were used in an efficient aircraft. However, at a future electricity price of 15 EUR/MWh and subsequent to technological developments, a future additional cost of 115 USD seems likely, which would be a 20 % increase of the average plane ticket. Is this too much to pay?
- In Denmark, monthly subscriptions for fitness, music, streaming services, etc. are quite popular. In relation to transitioning the Danish energy system, all Danes would have to pay 150 DKK per month to get an energy system, where no fossil fuels will be burned. This is equivalent to a monthly subscription for Netflix, and besides a sustainable energy system it would provide the benefit of clean air. Is this too much to pay for a sustainable future – and is it worth less than a subscription for Netflix?
- As a last comparison, the 150 DKK per month could also be seen as an insurance against climate change – an insurance that our coming generations receive a livable planet. A sum of 150 DKK per month is way less than what people usually pay to insure themselves, their houses, their cars, their furniture, etc. Is this too much too pay for ensuring the planet for coming generations?

Summary in Danish

I 2016 underskrev de fleste af verdens ledere Paris-aftalen, hvori to mål for den globale temperaturstigning er formuleret. Det første mål er at stræbe efter at holde den globale temperaturstigning på kun 1,5 °C, og det andet mål er at holde den globale temperaturstigning et godt stykke under 2,0 °C. Begge temperaturstigninger målt i forhold til de præindustrielle temperaturniveauer. I betragtning af, at den globale temperaturstigning nåede 1,1 °C i 2016, bliver det en enorm udfordring at holde os under temperaturgrænserne fra Paris-aftalen. I dette speciale prøver vi at karakterisere den udfordring, vi står overfor i forhold til global opvarmning og klimaforandringer.

I 1759 og 1776 publicerede den skotske økonom, filosof og forfatter Adam Smith bøgerne *Teorien om de moralske følelser* og *Nationernes velstand.* I disse bøger beskriver han, blandt mange andre emner, ideen om markedsøkonomien som en ’usynlig hånd’ der guider individuel optimering til også at være det optimale for samfundet. Hvis dette også er sandt for de økonomiske aktiviteter bag global opvarmning og klimaforandringer, så har vi ingen grund til bekymring. Men er de økonomiske aktiviteter bag global opvarmning og klimaforandringer et klassisk eksempel fra økonomisk teori, der følger princippet om den ’usynlige hånd’?

Vores hovedhypotese er, at dette ikke er tilfældet. Tværtimod antager vi, at global opvarmning og klimaforandringer relaterer sig til økonomiske aktiviteter, der fører til en såkaldt ’Fælledens tragedie’ udfordring.

Den klassiske fælledens tragedie blev formuleret af den amerikanske miljøforsker og filosof Garret Hardin i 1968 og tager udgangspunkt i skoleeksemplet på en fælles naturressource. Fælledens tragedie relaterer til en såkaldt fælled, som er en græsmark tilgængelig for alle, hvor bønder gratis kan lade deres kvæg græsse. Hver bondes overlevelse afhænger af at opdrætte kvæg, og så længe der kun er få græssende kvæg på fælleden, er der ingen problemer. Udfordringen opstår, når fælledens bærevne overskrides, fordi for mange kvæg græsser på fælleden. Problemet er, i modsætning til Adam Smiths teori om den usynlige hånd, at individuel optimering *ikke* fører til det samfundsmæssige optimum i tilfælde af dette eksempel på en fælles naturressource, men til det modsatte. Den enkelte bonde modtager alle fordelene ved at sætte flere kvæg på fælleden, mens det faldende udbytte, på grund af overgræsning, deles med alle de andre bønder.

Tragedien ligger i det faktum, at selv hvis en bonde indser truslen om overgræsning og derfor afholder sig fra at sætte flere kvæg på fælleden, så vil en anden bonde måske sætte flere kvæg på fælleden i stedet, da denne bonde modtager det fulde udbytte, samtidig med at omkostningen ved overgræsning deles med de andre bønder. Der er derfor en nødvendighed, eller i hvert fald et stærkt incitament, for hver enkelt bonde til at tilføje mere kvæg, end hvad fælleden kan bære.

Fra den klassiske udgave af fælledens tragedie, har vi udledt tre kriterier for, hvornår en given problemstilling af økonomisk og miljømæssig/ressourcemæssig art er en fælledens tragedie problemstilling. For det første, skal udfordringen være relateret til en fælles naturressource. For det andet,

skal der være nok brugere af den fælles naturressource, dvs. bønder/kvæg i den klassiske fælledens tragedie, til at overskride bæreevnen af den fælles naturressource. For det tredje, skal der være en mangel på realiserbare alternative tekniske løsninger. I denne sammenhæng skal realiserbar forstås som både teknisk og økonomisk realiserbar, i den forstand at løsningerne skal være kosteffektive og konkurrencedygtige nok til at udkonkurrere de eksisterende, ikke bæredygtige løsninger på et ureguleret marked.

Ifølge Hardin (1968) finder fælledens tragedie også sted i en omvendt form hvad angår forurening: Når en økonomisk aktivitet forurener, går den fulde besparelse, for ikke at rense en affaldsstrøm før den udledes, til den enkelte aktør/forureneren, mens omkostningen for forureningen deles af alle aktører i samfundet. I denne 'omvendte' udgave er den fælles naturressource, ifølge Hardin (1968), det miljø, der modtager affaldsstrømmen.

Hypotesen for vores studie er, at klimaforandringer er en sådan omvendt fælledens tragedie. Ingen ernærer sig ved bare at udlede drivhusgasser, derfor relaterer kriteriet om fraværet af realiserbare tekniske løsninger sig, i den omvendte udgave af fælledens tragedie, til den eller de teknologier, der udleder forurening. Når de fossile brændsler bliver afbrændt, udledes der drivhusgasser til atmosfæren, hvilket accelererer global opvarmning. I forhold til global opvarmning og klimaforandringer, står vi derfor overfor en udfordring med fælledens tragedie karakter, hvis; for det første, atmosfæren er en fælles naturressource, for det andet, de potentielle drivhusgasudledninger ved afbrænding af fossile brændsler er store nok til at overskride bæreevnen for atmosfæren i forhold til klimaforandringer og for det tredje, de tekniske alternativer til at udlede drivhusgasser ved at afbrænde fossile brændsler ikke er realiserbare. Bæreevnen for atmosfæren er i dette tilfælde defineret i overensstemmelse med de to mål, der er sat i Paris-aftalen. Det vil sige at stræbe efter en temperaturstigning på kun 1,5 °C og at blive et godt stykke under 2,0 °C.

Hypotesen i dette studie blev testet ud fra de tre kriterier for, om en given økonomisk-miljømæssig problemstilling er et fælledens tragedie problem. Vi finder, at atmosfæren er en fælles naturressource i forhold til global opvarmning og klimaforandringer. Denne konklusion er nået ved at studere eksisterende litteratur om fælles naturressourcer og karakteristika for atmosfæren i forhold til drivhusgasudledning og global opvarmning.

Vi finder også, at de potentielle drivhusgasudledninger fra afbrænding af fossile brændsler er mere end nok til at overskride bæreevnen for atmosfæren flere gange. Denne konklusion blev nået ved at sammenligne data fra forskellige kilder om fossile *reserver* og *ressourcer*, på den ene side, med tilgængelige modeller for sammenhængen mellem drivhusgasser i atmosfæren og globale temperaturstigninger, på den anden side. *Reserver* er de mængder af fossile brændsler, der kan udnyttes med de nuværende økonomiske og tekniske rammer. *Ressourcer* er de mængder af fossile brændsler, der vurderes at findes, men som ikke kan udnyttes under de nuværende tekniske og økonomiske rammer. Ved at lægge disse to sammen fås det totale estimat på mængden af fossile ressourcer.

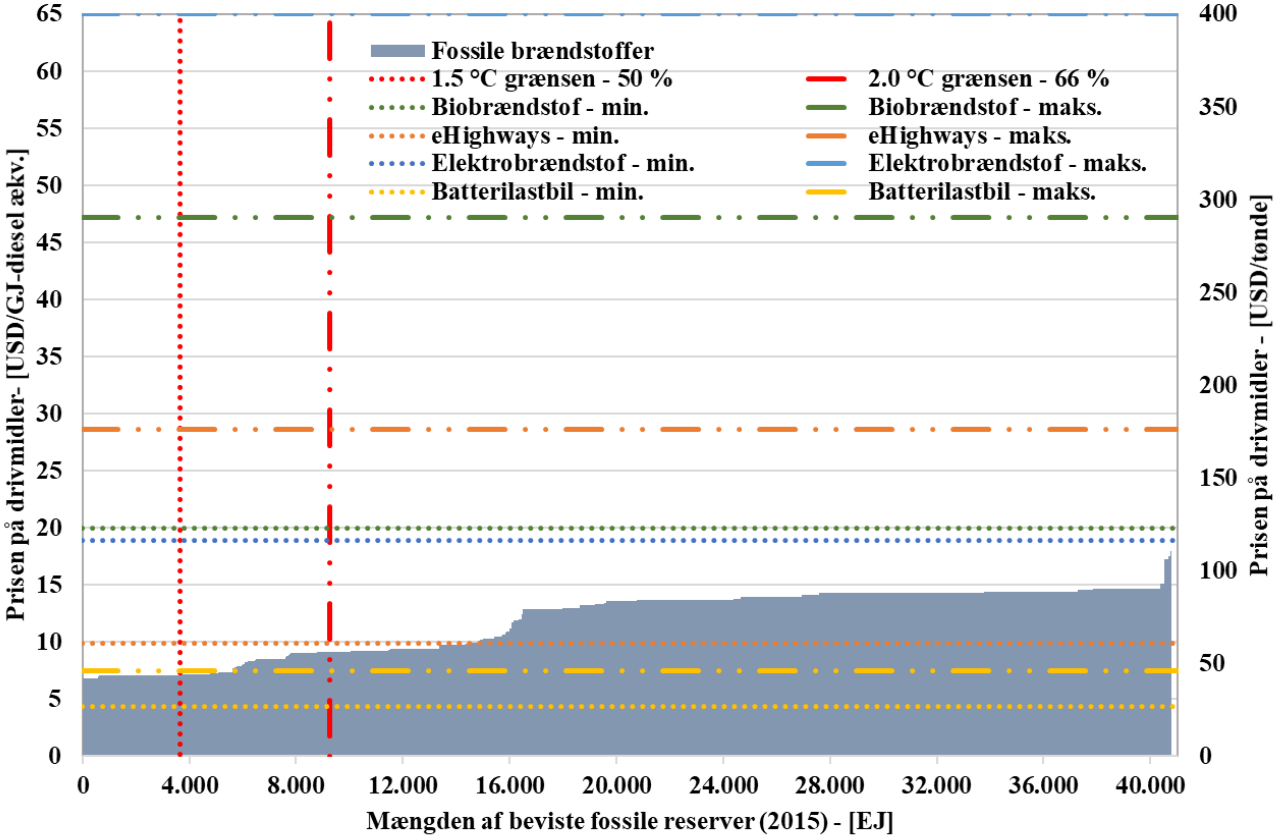
Mere specifikt finder vi, at de kendte fossile reserver i 2015 indeholder mere end 11 gange mere karbon, end hvad vi kan udlede uden at overskride 1,5 °C grænsen. For 2,0 °C grænsen er dette tal mere end 4 gange mere karbon. Hvis de totale fossile ressourcer tages i betragtning, så er de samme tal mere end 192 gange mere karbon og mere end 78 gange mere karbon for hver enkelt temperaturgrænse. At løbe tør for fossile brændsler bliver derfor først et problem efter, at vi har overskredet bæreevnen for atmosfæren flere gange. Med det nuværende forbrug af fossile brændsler, så vil vi løbe tør for fossile brændsler i år 3350, dog tidligere for olie og gas. Med uændret udledning af drivhusgasser kan vi kun fortsætte omkring 19 år, før vi overskrider 2,0 °C grænsen. Det samme tal for 1,5 °C grænsen er mindre end 8 år, og dette er med 50 % sandsynlighed. Vi kan kun fortsætte 4 år mere, ved de nuværende drivhusgasudledningsrater, hvis sandsynligheden for at blive under 1,5 °C grænsen skal være på 66 %. Selv når vi kun betragter de kulminer, og olie- og gasfelter, der <u>allerede er i drift i dag</u>, indeholder disse mere karbon, end hvad vi kan udlede uden at overskride bæreevnen af atmosfæren. For at blive indenfor grænserne i Paris-aftalen, bliver vi derfor nød til at lukke nogle af de miner og felter, der allerede er i drift i dag – eller alternativt fange og lagre drivhusgasudledningerne andre steder end i atmosfæren.

Vi finder også at der, især for sektorer der efterspørger flydende kulbrinter, ikke er nogen realiserbare (inkl. konkurrencedygtige på et ureguleret marked) alternative tekniske løsninger til at udlede drivhusgasser ved afbrænding af fossile brændstoffer. Denne konklusion er nået ved at sammenligne prisdata for fossile brændstoffer med alternative drivmidler, det vil sige biobrændstoffer, elektrobrændstoffer og elektricitet. Transportsektoren blev identificeret til at være hovedudfordringen i forhold til drivhusgasudledninger fra afbrænding af fossile brændsler. Specielt fly og langdistance skibstrafik ser ud til at efterspørge flydende kulbrinter mange år endnu.

De prisdata, der blev benyttet til denne analyse, er baseret på rene produktionsomkostninger for drivmidlerne, hvor subsidier, afgifter og eksternaliteter er ekskluderet. Kun reelle udgifter til drift og anlæg for produktion, raffinering og distribution er inkluderet. Resultaterne af vores analyser for det tredje kriterie er præsenteret i, hvad vi kalder ”Klodens tragedie?” grafer. Disse grafer viser den totale omkostning ved at udvinde, raffinere og distribuere kul, olie og gas til et diesellignende brændstof for hvert enkelt land i verden. Priserne er rangeret efter størrelsesorden, hvilket giver den ’grå trappe’ på grafen nedenfor.

På samme graf er prisspændet for alternative drivmidler også indsat. Fra grafen nedenfor kan det ses, at batterier, og i nogen grad direkte elektrificering i form af eHighways, er i stand til at konkurrere med fossile brændstoffer, derfor er de realiserbare, tekniske løsninger. Dette indebærer, at vi ikke står overfor en udfordring af fælledens tragedie karakter i forhold til global opvarmning i det omfang, at disse teknologier kan dække behovet og substituere kulbrinter baseret på fossile brændsler. Problemet er, at elektricitet ikke kan dække fly og langdistance skibstrafik. Begge behøver flydende kulbrinter, og det ser ikke sandsynligt ud, at dette kommer til at skifte, inden for den tidshorisont vi har til rådighed for at imødegå klimaforandringerne. Ingen af de alternative flydende kulbrinter kan konkurrere med de fossile, se nedenstående figur.

I følge vores studie står vi derfor over for en udfordring med fælledens tragedie karakter i forhold til global opvarmning. Den eneste måde at imødegå tragedien på er ved politisk intervention. Markedet løser ikke selv problemet, og den *usynlige hånd* guider os direkte ind i tragedien.



Den politiske intervention kan tage mange former. Det kunne være et forbud mod fossile brændsler, hvilket vil være et meget *effektivt* værktøj eller et kvotemarked med omsættelige kvoter for drivhusgasudledninger i et lofts- og handelsmarked, som er et meget *omkostningsefficient* værktøj. Loftet på markedet skulle så sættes inden for atmosfæren bæreevne. Hvis et forbud mod fossile brændsler blev vedtaget, kunne det enten være et totalforbud, eller det kunne være et forbud, der begrænser udvinding af fossile brændsler, så udledningerne holder sig inden for atmosfærens bæreevne. Det er muligt at lave en prioritering af, hvilke fossile brændsler vi skal efterlade i jorden og hvilke vi kan udvinde uden at overskride atmosfærens bæreevne, ved at ordne de forskellige typer af fossile brændsler i størrelsesorden efter totalomkostningen for udvinding, raffinering, og distribution.

Med udgangspunkt i *reserverne* fra 2015 så skal al kul blive i jorden for at holde os inde for begge temperatur grænser, det samme gælder al gas for 1,5 °C grænsen. Kun en begrænset mængde olie kan blive udvundet indenfor 1,5 °C grænsen, og det vil være fornuftigt at prioritere denne til transportsektoren, specielt fly og langdistance skibstrafik. I forhold til 2,0 °C grænsen kan al olie udvindes, men kun en begrænset mængde gas, som det ville være fornuftigt at prioritere til infrastruktur, der understøtter og følger de fremtidige mængder af biogas/grøn gas. Med udgangspunkt i de *totale fossile ressourcer* som estimeret i 2015 skal al kul og gas blive i jorden og kun en begrænset mængde af de totale olieressourcer kan udvindes uden at overskride begge temperaturgrænser.

Elektrobrændsler er produceret ved at reagere hydrogen fra elektrolyse med karbon fra en hvilken som helst kilde. I resten af resuméet antages elektrobrændsler produceret til en elpris på 112 kroner/MWh. De 112 kroner/MWh repræsenterer den nuværende laveste elpris som vedvarende energikilder kan præstere på særlige lokationer. Det er antaget, at karbonet bliver leveret fra et direkte luftudvindingsanlæg på samme lokation.

Under disse omstændigheder skal en afgift på drivhusgasudledninger, som også er en politisk intervention, i givet fald være på 1260 kroner/ton-kuldioxid-ækvivalent for at gøre dette specifikke elektrobrændstof konkurrencedygtig med fossile brændstoffer ved 1,5 °C grænsen. Afgiften skulle tilsvarende være 1140 kroner/ton-kuldioxid-ækvivalent ved 2,0 °C grænsen. En anden type intervention kunne være at yde tilskud til produktionen af elektrobrændstoffer. Den totale samfundsomkostning ved denne støtte ville, i givet fald, årligt ende på omkring kun 0,46 % af det globale BNP i 2015 ved 1,5 °C grænsen og omkring 0,40 % af det globale BNP i 2015 ved 2,0 °C grænsen. Her er det antaget, at efterspørgslen efter flydende kulbrinter er 33 EJ per år baseret på det estimerede fremtidige forbrug af flybrændstof i 2040 og den medproducerede mængde benzin, der kommer som biprodukt ved flybrændstofsproduktion.

En omstilling af hele Danmarks energisystem vil ende op i de samme størrelsesordener. Et studie udført af Energistyrelsen i 2014 finder, at den årlige ekstraomkostning ved et fuldt vedvarende energisystem ligger på omkring 0,5% af det danske BNP svarende til cirka 10 milliarder kroner årligt. De årlige sundhedsomkostninger relateret til luftforurening i Danmark blev, i et andet studie, estimeret til omkring 28 milliarder kroner årligt, hvilket vil sige, at omkostningen for en omstilling til et fuldt vedvarende energisystem, hvor fokus ligger på nul- eller lavemissions teknologier, allerede er dækket i form af lavere samfundsøkonomiske skadesomkostninger. Omstillingen til et fuldt vedvarende energisystem er derfor ikke en omkostning, men en god investering med et højt samfundsøkonomisk afkast.

Som konklusion, er det derfor sikkert at sige, at den samfundsøkonomiske omkostning for at løse denne fælledens tragedie og implementere en omstilling til et fuldt ud vedvarende energi system er lille. De tekniske løsninger er her – med den nuværende teknologi kan vi allerede i dag producere brændstoffer inklusive flybrændstoffer via elektrobrændstofsproducerende teknologier. På samme tid står vi overfor den udfordring, at den usynlige hånd meget snart guider os til at overskride atmosfærens bæreevne som den er defineret i Paris-aftalen. I lyset af denne udfordring kunne man spørge; hvorfor er det så svært at prioritere den relativt lille samfundsomkostning? Vi ønsker at afslutte dette resume ved at sætte omkostningen lidt i perspektiv:

- Når man sammenligner de 0,5 % af BNP med andre aspekter af den danske økonomi så bruger Danmark; 1,2 % af BNP på forsvar, 0,7 % på ulandsbistand og hver dansker smider årligt mad ud

med en værdi på 0,7 % af BNP. Da den danske statsminister, i 2017, snakkede med den nyvalgte amerikanske præsident Donald Trump lovede statsministeren uden tøven at Danmark ville leve op til NATO-forpligtigelsen om at bruge 2 % af BNP på forsvar.
- I maj 2018 udtrykte den amerikanske præsident et ønske om at alle NATO-lande brugte 4 % af deres BNP på forsvar. Dette mødte stor opbakning fra NATO's generalsekretær Jens Stoltenberg. Dette er ikke nævnt som et argument imod at prioritere penge til forsvar, men kun for at vise den umiddelbare betalingsvillighed for meget kortsigtet sikkerhed og beskyttelse sammenholdt med, hvor svært det er, at finde de meget færre penge, der skal til for på lidt længere sigt at sikre en bæredygtig fremtid for jordklodens fremtidige beboere.

Set fra et mere privat økonomisk perspektiv, så er danskernes betalingsvillighed høj i relation til mange former for ydelser. Hvordan relaterer omkostningen ved at løse klimaudfordringen sig til de andre omkostninger, som vi er villige til at betale i vores hverdag?

- For eksempel tager vi ofte flyet, når vi tager på ferie. Betydningen af, at flybrændstof var elektrobrændstof, kan illustreres ved den prisændring på en flybillet, det ville medføre. Prisen på en returbillet mellem København og New York ville stige med 5850 kroner, hvis brændstoffet blev produceret ved de nuværende elpriser på 298 kroner/MWh og brugt i et ineffektivt fly. Det samme tal ville være 3750 kroner hvis brændstoffet blev brugt i et effektivt fly. Ved en fremtidig elpris på 112 kroner/MWh og en samtidig teknologiudvikling ser en sandsynlig fremtidig ekstraomkostning ud til at være på 690 kroner, hvilket vil være en stigning på gennemsnitsflybilletten på 20 %. Er dette for meget at betale?
- I Danmark er månedlige abonnementer for fitness, musik, streaming tjenester, etc. meget populære. I relation til en omstilling af Danmarks energisystem, skal alle danskere betale 150 kroner om måneden for at få et energisystem uden fossile brændsler, dvs. de 0,5 % af BNP fordelt per dansker. Dette beløb er i samme størrelsesorden som et Netflix abonnement, og udover et vedvarende energisystem giver det også fordelen ved renere luft. Er dette for meget at betale for en bæredygtig fremtid – og er det mindre værd end et Netflix abonnement?
- Slutteligt kunne de 150 kroner om måneden ses som en *forsikring* imod klimaforandringer – en forsikring for at de fremtidige generationer har en beboelig jordklode. Et beløb på 150 kroner om måneden er meget mindre, end hvad de fleste normalt betaler for at forsikre sig selv, deres hus, deres bil, deres møbler, etc. Er dette for meget at betale for at sikre jordkloden til de fremtidige generationer?

Preface

This master thesis corresponds to a workload of 60 ECTS points. It was conducted in the period from February 1st, 2017 to June 1st, 2018 by Anders Winther Mortensen and Kasper Dalgas Rasmussen at SDU Life Cycle Engineering (LCE) under the Department of Chemical Engineering, Biotechnology, and Environmental Technology (KBM) at the Faculty of Engineering, University of Southern Denmark. The study was carried out as part of a 4+4 Ph.D., which explains the long duration of the working period, each student had on average 10 ECTS point per semester to conduct the study. This also implies that the study is a pre-study for the Ph.D., the aim being to gain a fundamental understanding of the challenge related to climate change and of transitioning the energy system to renewable energy.

The main supervisor was professor, Henrik Wenzel, and the co-supervisor was professor, Gang Liu, both from SDU LCE under KBM at the Faculty of Engineering, University of Southern Denmark.

A special thank goes to our supervisors for the many discussions and guidance that we have received during the process of conducting this study. We would also like to give a special thanks to our colleagues, friends, and families who supported us during hard times, but also helped us with fun and good times throughout this period.

Many more people and organizations have helped us during the process of conducting this study. Without their inputs, data, ideas, suggestions, and discussions, it would not have been possible for us to make a study on this level in the given timeframe. Here follows a list of some of the events we have participated in to gather information and ideas for the study:

- Cognition Group, (2018), CO2 Reuse Summit, Zürich, Switzerland, 16 to 17 May
- Climeworks, (2018), Site-visit at Climeworks, Hinwil, Switzerland, 15 May
- Hydrogen Denmark, (2018), Annual Meeting, Aalborg, Denmark, 18 April
- Hydrogen Denmark, (2017), The Danish Hydrogen and Fuel Cell Day, Odense, Denmark, 28 November
- RE-INVEST, (2017), Workshop on Modelling the Gas Sector, Søborg, Denmark, 24 November
- The Mads Clausen Institute at University of Southern Denmark, (2017), 100% Climate Neutrality Conference, Sønderborg, Denmark, 4 to 5 October
- V-sustain, (2017), Site-visit from the Villum Foundation, Lyngby, Denmark, 19 September
- International Association for Ecology, (2017), The 12th International Congress of Ecology, Beijing, China, 20 to 25 August
- Energiforsk, (2017), GasAkademin 2017, Vara, Sweden, 14 to 18 August
- CONCITO, (2017), Dialogue on the Global Energy Realities, Copenhagen, Denmark, 13 June
- SDU Energy Club, (2017), Standards and Technologies for Future Energy Systems and Innovation, Odense, Denmark, 23 May
- Danish Technological Institute, (2017), International Methanol Conference, Copenhagen and Taastrup, Denmark, 8 to 10 May

- IDA, (2017), Sustainable Aviation Fuels, Copenhagen, Denmark, 4 May
- CONCITO, (2017), Discussion of Master Thesis, Copenhagen, Denmark, 4 May
- V-sustain, (2017), Stakeholder Meeting, Lyngby, Denmark, 4 May
- Hydrogen Denmark, (2017), Annual Meeting, Copenhagen, Denmark, 25 April
- SDU Energy Club, (2017), Biorefining Technologies Towards a Circular Economy, Odense, Denmark, 31 March
- SDU Energy Club, (2017), Hydrogen – just another fuel, Odense, Denmark, 17 March
- Energy Plan Funen, (2017), Workshop with Siemens on eHighways, Odense, Denmark, 13 to 14 March
- Future Gas, (2017), Course on Natural Gas and Renewable Gas in the Danish Energy System, Lyngby, Denmark, 30 January to 3 February
- SDU Energy Club, (2017), Technology for Electrolysis, Odense, Denmark, 20 January

List of abbreviations

AEC	Alkaline Electrolyzer Cell
ASTM	American Society for Testing and Materials
bbl	Barrel
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
BP	British Petrol
CAPEX	Capital expenses
CCS	Carbon Capture and Storage
CDIAC	Carbon Dioxide Information Analysis Center
CO_2	Carbon Dioxide
CO_2 eq.	Carbon Dioxide equivalent
CTL	Coal to Liquid
DAC	Direct Air Capture
DCL	Direct Coal Liquefaction
DEA	The Danish Energy Agency (Energistyrelsen)
DEF STAN	UK Defence Standardization
DKK	Danish kroner
DST	Statistics Denmark (Danmarks Statistik)
EIA	Energy Information Administration
EJ	Exa Joule
EU ETS	EU Emissions Trading System
EUR	Euro
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GBP	Great British Pound
GHG	Greenhouse gas
GJ	Giga Joule
GJ diesel-eq.	Gigajoule-diesel-equivalent
Gt	Giga tonne
h	Hour(s)
IATA	International Air Transportation Association
ICL	Indirect Coal Liquefaction
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KBM	Chemical Engineering, Biotechnology, and Environmental Technology
km	Kilometer
kWh	Kilowatt hour
L	Liter
LCE	Life Cycle Engineering
LCOE	Levelized Cost of Energy
min	Minute(s)
MMGPY	Million Gallon Per Year
MWh	Megawatt hour

NASA	National Aeronautics & Space Administration
NATO	The North Atlantic Treaty Organization
Nm^3	Normal cubic meter
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenses
PEC	Primary Energy Consumption
PEM	Proton Exchange Membrane
PCC	Post Combustion Capture
PVs	Photovoltaics
sec	Second(s)
SOEC	Solid Oxide Electrolyzer Cell
TAB	Threshold Avoidance Budget
TCTC	Tragedy of the Commons Type of Challenge
TEB	Threshold Exceedance Budget
TSO	Transmission System Operator. Energinet is the Danish TSO
UNEP	United Nations Environment Program
USD	United States Dollar

Contents

1 Introduction

The Intergovernmental Panel on Climate Change is now 95 percent certain that humans are the main cause of current global warming. (Pachauri & Meyer, 2014)

When the globe is warming, the climate starts changing, and we already see the consequences of the changing climate today, such as accelerated sea level rise and longer, more intense heat waves (NASA, 2017). Ninety-five percent is a very big likelihood for humans being the main cause of current global warming therefore we need to take urgent action to fight climate change and its impacts.

Several studies have focused on the consequences of global warming, among them "*The Economics of Climate Change*, (Stern, 2006)" and "*Climate Change 2014 – Synthesis Report*, (Pachauri & Meyer, 2014)". Both reports predict tremendous changes such as more extreme weather events, rising sea levels, failing crop yield, mass extinction of species, acidification of the oceans, failing water supply from glaciers, etc. Some of which has happened, happens now, and will continue to worsen during this century. Both Stern (2006) and Pachauri & Meyer (2014) are focusing on a temperature rise between 1 to 5 °C compared to the pre-industrial period. In 2016, the global average temperature rise reached 1.1 °C above the pre-industrial period, with a rise of 0.06 °C in 2016 alone (World Meteorological Organization, 2017).

In the report by Stern (2006), climate impacts at different temperature increases are presented. At an increase of 1°C Stern (2006) predicts that small glaciers in the Andes will disappear completely, threatening the water supply for 50 million people, that at least 10 % of land species are facing extinction, and that the Atlantic thermohaline circulation starts to weaken. This is very similar to the climate impacts that we see in the world today where e.g. Chile (Constable, 2016) and Bolivia (Rocha, 2016) are facing water shortages' due to diminished glaciers, where 47 % of terrestrial non-volant threatened mammals and 23.4 % of threatened birds have already been negatively impacted by climate change (Pacifici et al., 2017), and where the Atlantic thermocline circulation has slowed down (Rahmstorf et al., 2015). This is a validation of the first predictions made in the report.

The question is if the predictions are going to hold true at an increase of 2 °C as well. Stern (2006) predicts a potential 20 to 30 % decrease in water availability in some vulnerable regions, a sharp decline in crop yields in tropical regions, 40 to 60 million more people exposed to malaria in Africa, up to 10 million more people affected by coastal flooding each year, and 15 to 40 % of species facing extinction. Today, this seems likely and these climate impacts are quite severe. Thus, a global temperature increase of 2 °C is a record we should not break.

The article by Kelley, Mohtadi, Cane, Seager, and Kushnir (2015) shows that climate change already have a huge impact today. Due to climate change, the drought in Syria was much worse than usually. According to the authors, this was one of the contributing factors to why the civil war in Syria started. When resources become scarce tensions start to arise.

Another study by Guiot and Cramer (2016) explore the future consequences of climate change by modelling a reconstruction of the ecosystems over the past 10,000 years in the Mediterranean basin ecosystem. According to this study, we might face alterations in the ecosystems that we have not seen during the last 10,000 years. If business as usual continues, southern Spain will likely turn into desert according to Guiot and Cramer (2016). Only by keeping the temperature below 1.5°C we might remain within the limits, we have experienced within the Holocene era.

The aforementioned reports and articles stress the need for urgent action to avoid the consequences of global warming. They do not give us much time to act. We need to act now. We need to take actions towards reducing the causing factors of global warming. Here, the major anthropogenic source contributing to global warming is the greenhouse gas (GHG) emissions from burning fossil fuels (Pachauri & Meyer, 2014). The question is what actions are needed.

Figure 1: From left to right, French Ambassador for International Climate Negotiations Laurence Tubiana, UNFCCCs Executive Sectary Christiana Figueres, United Nations Secretary-General Ban Ki-moon, French Foreign Affairs Minister Laurent Fabius, and French President François Hollande celebrating the Paris agreement

The world's leaders have started to act. In 2015, the world's leaders met in Paris to try to reach a global agreement on how to combat climate change. At the end of this climate summit the *Paris Agreement* was presented and in this agreement, an ambitious objective is formulated:

> *"Holding the increase in the global average temperature to well below **2°C** above pre-industrial levels and pursuing efforts to limit the temperature increase to **1.5°C** above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change"* (United Nations, 2015)

Time is, however, running out if we want to limit the temperature increase to 1.5° C and it seems to be more and more unrealistic, especially keeping in mind that the accumulation of GHGs in the atmosphere has not slowed down (Kennedy, 2016) and that the global average temperature increase reached 1.1 °C in 2016. With no time to waste, reaching an agreement in Paris was of great importance. The question is if the delegates and world's leaders from Paris even know the implications of what they are celebrating in Figure 1. The implications and actions needed depends and the type of challenge that we are facing in relation to global warming. In this report, we will study if global warming can be characterized as a Tragedy of the Commons Type of Challenge and what this implies.

2 Background

In 1759 and 1776, the Scottish economist, philosopher, and author Adam Smith published, *The Theory of Moral Sentiments* (Smith, 1759) and *An Inquiry into the Nature and Causes of the Wealth of Nations* (Smith, 1776). In these books he, among many other things, presented the idea of market economy as an invisible hand that guides individual optimization also to be the optimum for society. This invisible hand seems to be the foundation for the neoliberal economic theory, but unlike Adam Smith, the neoliberals often seems to think that the invisible hand always will give the optimal solution for society in an unregulated market. This *laissez-faire* attitude to imperfect markets might not always lead to the societal optimum as can be seen from e.g. a Tragedy of the Commons Type of Challenge (TCTC).

The focus of this report is to dig into whether climate change can be characterized as a TCTC. To do this we should clarify the essence of the classic tragedy of the commons which also proves that the invisible hand does not lead to the societal optimum.

2.1 The Classic Tragedy of the Commons

The tragedy of the commons was formulated by Hardin (1968) and takes its offset in the schoolbook example of a common-pool resource. The commons are mostly known from towns in earlier times and is a pasture open to all. Thus, there is no specific owner of the commons. Each herdsman in the town will try to have as many grazing cattle in the commons as possible. The rational herdsman would ask himself, what the utility of adding one more cow to his herd would be for him.

There is a positive and a negative part of this individual optimization. On the positive side, there is all the products from the cow such as milk, meat, hides, etc. On the negative side, there is the potential overgrazing created by adding too much cattle to the pasture. The difference in magnitude for the herdsman between the positive and negative side is big. The positive gains only go to the herdsman, while he shares the negative effect with every other herdsman using the pasture. Further, if he does not harvest his private benefit, other herdsmen will, and the negative side of the overgrazing will hit him anyways. The overgrazing is not a problem as long as the herdsmen do not have enough assets available in the form of cattle to eat the grass faster than it grows. Thus, the carrying capacity of the commons will not be violated as long as the herdsmen are poor or the demand for meet is low.

To illustrate this we will use an example cited by Edney and Harper (1978). Ten herdsmen live in the same town sharing the same commons. Each of the ten herdsmen owns one 1,000-pounds bull, and all ten bulls graze in the commons. If one of the herdsmen adds an extra bull to the commons, the weight of each bull will decrease to 900-pounds. Now the commons only support 9,900 pounds of cattle instead of 10,000. The individual introducing the bull increases his wealth with 800 pounds, because he now owns two 900-pounds bulls instead of one 1,000 pounds bull. However, the total wealth of the commons has been reduced by 100 pounds, just like the wealth of each of the other herdsmen.

Adding an extra bull gives a personal surplus. Therefore, an individual optimization tells each herdsman to add more cattle to the commons. If they keep adding cattle to the commons at some point, the pasture will be completely overgrazed and the cattle will starve, which is here the tragedy of the commons materializes. Not that the tragedy should be understood as unhappiness but as the solemnity of remorseless working of things (Hardin, 1968). Fishing on international waters is another example of a TCTC because like the pasture, no one owns the sea and it is hard to exclude potential beneficiaries.

The divergence in individual optimization against societal optimization within the tragedy of the commons has been formulated by Hardin:

> *"The individual benefits as an individual from his ability to deny the truth even though society as a whole, of which he is part, suffers." (Hardin, 1968)*

The tragedy of the commons relates to a pasture which is a private good since it is easy to exclude potential beneficiaries i.e. by fencing the pasture, and the subtractability of use is high i.e. the grass can only be eaten once. When the pasture is regarded as a common-pool resource in the tragedy of the commons it is because the pasture is open to all and that no property rights are assigned to the pasture. Now, the subtractability of use is still high, but excluding potential beneficiaries is by definition high, since nobody owns the commons. Thus, the pasture moves from being a private good and into the category of being a common-pool resource, see Table 1.

Table 1: In economics, goods or services can be categories into four categories by considering two attributes (Ostrom, 2005). The first attribute is subtractability of use or rivalrousness, which means whether one person's use of a good diminishes other people's use of that good. An example of a good that is substractable is a hamburger and a non-subtractable good could be a streetlight. The second attribute is the difficulty of excluding potential beneficiaries, which relates to the possibility of restraining people from benefitting from the usage of the good. An example of a non-excludable good could be national security and an excludable good could be a movie in the cinema

Attributes		Subtractability of use	
		Low	High
Difficulty of excluding potential beneficiaries	Low	Toll goods	Private goods
	High	Public goods	Common-pool resources

The article by Hardin (1968), focuses on population growth in the context of a tragedy of the commons. In relation to population, Hardin states that a finite planet can only support a finite population and that there is no technical solution to the problem of overpopulation. Garret Hardin defines a technical solution as follows:

> *"A technical solution may be defined as one that requires a change only in the techniques of the natural sciences, demanding little or nothing in the way of change in human values or ideas of morality." (Hardin, 1968)*

There might exist technical solutions to mitigate the tragedy of the commons, but if they require too many changes in the existing structures of society or if they are not cost-efficient and competitive enough to be cheaper than and outcompete existing solutions, the technical solutions are not feasible. Thus, one of the criteria that defines a TCTC is the absence of feasible, technical solutions to the problem. For the remainder of this report, a feasible, technical solution should not only be technically feasible but also cost-efficient and competitive enough to outcompete existing solutions on a market basis.

Thus, a TCTC can be characterized by three points and if they are fulfilled we are facing a TCTC;

1. Being related to a common-pool resource.
2. Having enough assets available to violate the carrying capacity of the common-pool resource.
3. Absence of feasible, technical solutions.

Since Garret Hardin published his debate awakening essay 50 years ago many discussions have arisen within academia. The debates continue, and so far, many years of debate and research shows that the tragedy of the commons is indeed well founded. The report by World Commission on Environment and Development (1987) created an awareness of how we should tackle the issues related to common-pool resources, but still in the next decades that followed:

> *"[…]humans have failed to halt the tragedy of massive overfishing of the oceans, major deforestation and excessive dumping of carbon dioxide in the atmosphere." (Ostrom, 2008)*

Which brings us to the question: why do humans fail to solve the issues related to common-pool resources, when we know they are there?

2.2 The analogy to global warming

In Hardin's original article, the tragedy of the commons is stated to reappear in a reverse way in relation to pollution. The article exemplifies this reverse situation by taking a body of water as the commons and emissions to the water as the assets or the cows, to use the wording from the classic tragedy of the commons. This time, the rational man finds that his share of the cost of discarding waste into the commons is less than the cost of purifying the waste before discarding it (Hardin, 1968). Thus, individual optimization leads to societal suffering.

For global warming, the analogy would be that the atmosphere is regarded as the commons and the GHG emissions as the assets or the cows. By a first glance, this might seem off since GHG emissions are not really an asset, fossil fuels are. Fossil fuels have also been the cheapest type of energy and have thus been a necessity for companies in order to stay competitive in the market. In the classic tragedy of the commons, there is also a necessity for the herdsmen to grow cattle. Their survival depends on their ability to grow cattle. If one herdsman realizes the possibility of overgrazing, putting less cattle on the commons would not help, since, as the example from the previous section showed, any of the other herdsmen benefits from adding more cattle to the commons. The same goes for the use of fossil fuels.

For the reverse tragedy of the commons there is an extra layer to this necessity. Fossil fuels are not a problem in relation to global warming, the problem is the GHG emissions related to burning fossil fuels.

No one’s survival in the market depends on emitting GHGs to the atmosphere, the survival depends on being competitive enough to stay alive in the market while not having any other feasible way to produce the products than without emitting GHG emissions. In this way, GHG becomes the assets or the cows in relation to our analogy for global warming.

There might exist technical solutions that does not emit GHGs or that can remove GHG emissions from the atmosphere and exhaust pipes and stacks. If none of these solutions are cheap or competitive enough, we will be facing a TCTC in relation to global warming since the solutions are not feasible in both a technical and economic sense.

Relating the three criteria for a TCTC to our analogy for global warming, we are facing a TCTC if;

1. The atmosphere is a common-pool resource.
2. The potential GHG emissions from fossil fuels are big enough to violate the carrying capacity of the atmosphere.
3. The technical alternatives to emitting GHGs from burning fossil fuels are not feasible.

2.3 Hypothesis and objectives

In this report, we will use the classic tragedy of the commons type of challenge as an analogy for the problem we are facing in relation to global warming. Thus, our main hypothesis is that global warming and climate change is a TCTC where the key challenge is fossil fuels burned in the transportation sector.

Our sub-hypotheses are, first, that the atmosphere can be interpreted as a common-pool resource and thus be interpreted as the commons from the classic tragedy of the commons. Second, that we have enough fossil fuels to violate the carrying capacity. Third, that we do not have any feasible, technical solutions available to avoid this violation. Where feasible should be understood as both technically and economically feasible in the sense that the technical solution can outcompete the existing solutions on a market basis.

The objectives are to prove or disprove our hypotheses. This is done through a report that is structured as a classical research report with the following chapters: introduction, background, methodology, results, discussion and conclusions. Each of the chapters from methodology and onward is structured to follow the three main characteristics defining a TCTC, which are also our three sub-hypotheses. The background section will be used to introduce and delimit the scope of the study by testing whether fossil fuels burned in the transportation sector is the key challenge in relation to preventing global warming and which technical solutions we have available to solve this challenge.

The motivation of using the TCTC as a fundamental theory and analogy in our thesis is to study and exemplify the potential need for regulation or behavioral change in order to refrain from using fossil fuels. Our further objectives are to study how we prevent a TCTC, if it exists, by looking at the discrepancy between private and socioeconomics, and the options for political intervention. Also studying what is socioeconomically needed to prevent the TCTC, if there is a technical solution that is only technically and not economically feasible on a market basis.

In summary, are we facing a tragedy of the commons type of challenge in relation to global warming?

2.4 Delimiting the scope of the study

Tackling climate change is a massive task that should be broken into smaller pieces to be studied. The burning of fossil fuels is the major anthropogenic source contributing to global warming as it is shown in Figure 2. That is why the focus of this report is delimited to fossil fuels. If the atmosphere is a common-pool resource and we have the potential to emit enough GHGs to violate the carrying capacity of the atmosphere then only a feasible, technical solution to stop anthropogenic GHG emissions can help us escape the TCTC. By omitting the other GHGs, we might omit sectors that are also facing a TCTC in relation to global warming. If, just, one sector is facing a TCTC in relation to global warming we are all facing a TCTC in relation to global warming. Considering our hypothesis this is a reasonable delimitation.

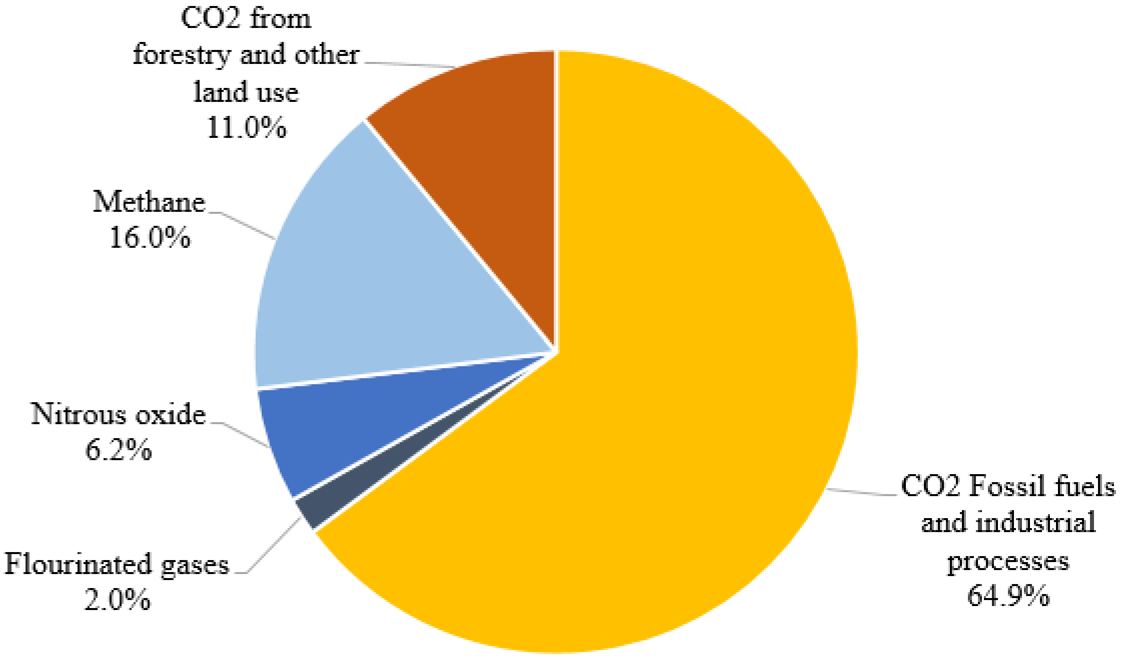


Figure 2: Share of anthropogenic GHG emissions by groups of gases for the year 2010. In 2010 the GHG emissions were 49 Gt CO_2 *eq.* (Pachauri & Meyer, 2014)

To analyze the feasible, technical solutions to avoid burning fossil fuels, the sectors of society in which fossil fuels are used should be analyzed. The emissions per sector is shown in Figure 3. Some of these sectors are easier to convert from fossil fuels and on to a sustainable alternative than other sectors.

Coal, oil, and gas used to be the cheapest ways to produce electricity but in many regions of the world this is now changing due to lower prices of renewable energy (Watanabe, 2016). Furthermore, since the economy, especially, of coal fired power plants are challenged since more renewable electricity production means more fluctuating electricity production. The challenge for the coal fired power plants is that they are baseload plants where ramping the production up and down is a slow process, thus they become less competitive when the number of consecutive hours of operation decreases. This phenomenon and the price drop on renewables makes it likely that renewable energy will outcompete fossil fuels in the heat and electricity sector. The question is if it will happen fast enough to meet the targets set in the Paris Agreement. We might already face a technology lock-in where we need to shut down operating plants before their technological or economical lifetime is reached.

The emissions from agriculture are mainly due to land-use change, nitrogen oxide emissions, and methane emissions. Only a minor part of the emissions from agriculture stems from fossil fuels (Edenhofer et al., 2014). Due to the delimitation of only looking a fossil fuels the agricultural sector is outside the scope of this report. The agricultural sector, though, may still be facing a TCTC in relation to global warming. Buildings and industry seems easier to convert from fossil fuels and onto a renewable energy source than transportation since they are stationary and in many cases not as space limited as the transportation sector, which opens many opportunities that the transportation sector does not have.

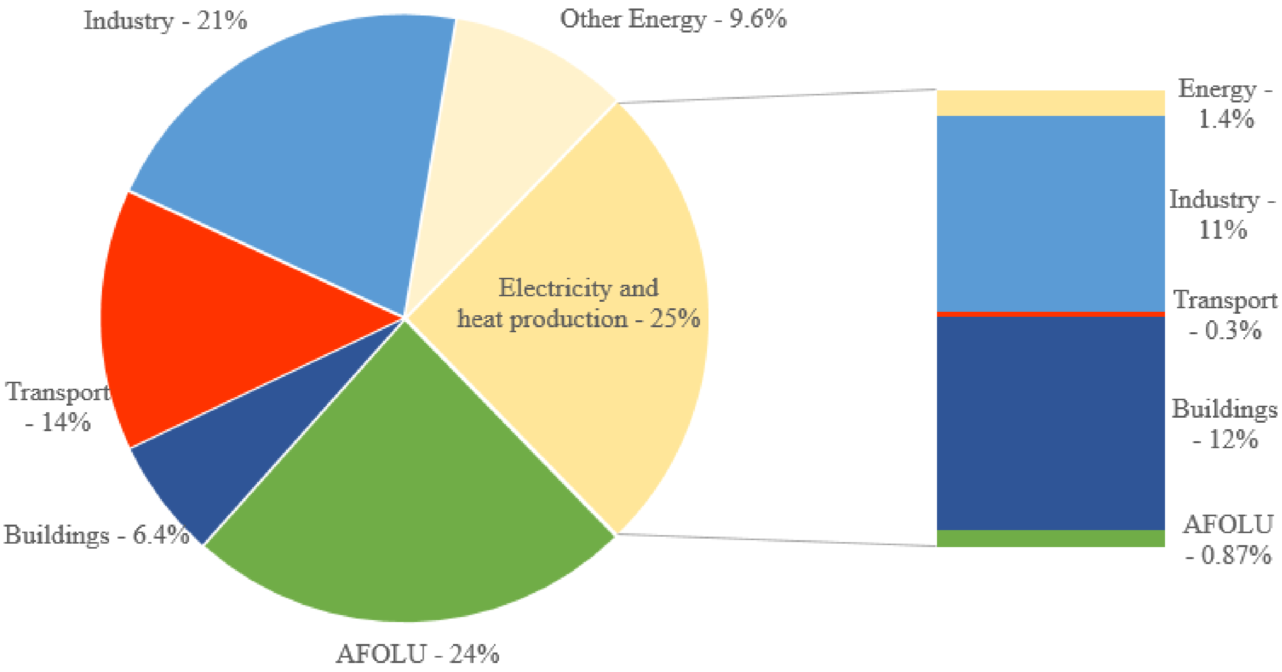


Figure 3: GHG emissions by economic sector from 2010 where the total emissions were 49 Gt CO_2 eq. (Edenhofer et al., 2014)

Considering the reasons mentioned above we can conclude that the trickiest sector to convert is the transportation sector. Which is why, the transportation sector is the focus of this report and the other sectors are omitted. Furthermore, the quote below suggest the transportation sector is the key challenge for making a sustainable transition into a low carbon society:

> *"Reducing greenhouse gas emissions from the transportation sector may be the most difficult aspect of climate change mitigation." (Zeman & Keith, 2008)*

The transportation sector is so hard to transform due to high requirements for safety and energy densities, which does not mean it should be omitted. First, we will reach a sub optimized system if we leave it out. Secondly, by solving the other sectors but leaving one sector out might slow down the pace at which we are moving towards the edge of the planetary boundaries, but we will eventually reach and pass the edge.

Thus, when we are looking for a feasible technical solution for global warming as a TCTC we should look within the transportation sector. For the remainder of this report we will assume that renewable energy will outcompete fossil fuels in the heat and electricity, buildings, and industry sectors. The fossil fuels will also be outcompeted in the agricultural sector for stationary applications but not for mobile applications. This leaves us with the fact that only mobile applications need fossil fuels, which makes the further analysis more straightforward since the fossil fuels only supply mobility services and no other types of services such as heat and power.

2.4.1 Alternatives in the transportation sector

There are many ways to handle the TCTC and reduce the GHG emissions from the transportation sector as can be seen from Figure 4. These ways fall into two categories technical and political. In this report we will analyze the technical solutions and discuss the political solutions in case of a TCTC. The most drastic solution to reduce GHG emissions is to reduce the number of people on earth, since this would lower the demand for transportation in our analogy and the demand for cattle in the classic tragedy of the commons. In large scale, this option does not seem possible due to the ethical and moral issues related to it. Except if the tools are family planning, gender equality, education, and contraceptives.

There are other less drastic political steps to take; the most convenient solution would be to find an exact copy of the fossil based liquid hydrocarbons that we use today, just without the GHG emissions. Then we could use the same infrastructure as today and no behavioral change or planning would be needed. The question is if this would be economically and technically feasible. The last technical step requiring a little more effort is finding another propellant such as electricity.

Propellants are used as terminology instead of fuels because we are interested in all technologies that could provide mobility services, not only fuels. There is a wide range of propellants that are more or less suitable to use in transportation. To determine the interchangeability of fuels, some requirements, such as the energy densities of the fuels, should be accounted for together with safety issues and availability of the propellant. Three groups of propellants have been identified to fulfill the mentioned requirements at a satisfactory level: biofuels, electrofuels, and electricity. None of these propellants are fully developed yet, so the time horizon for the price estimates are around 2030 if nothing else is specified.

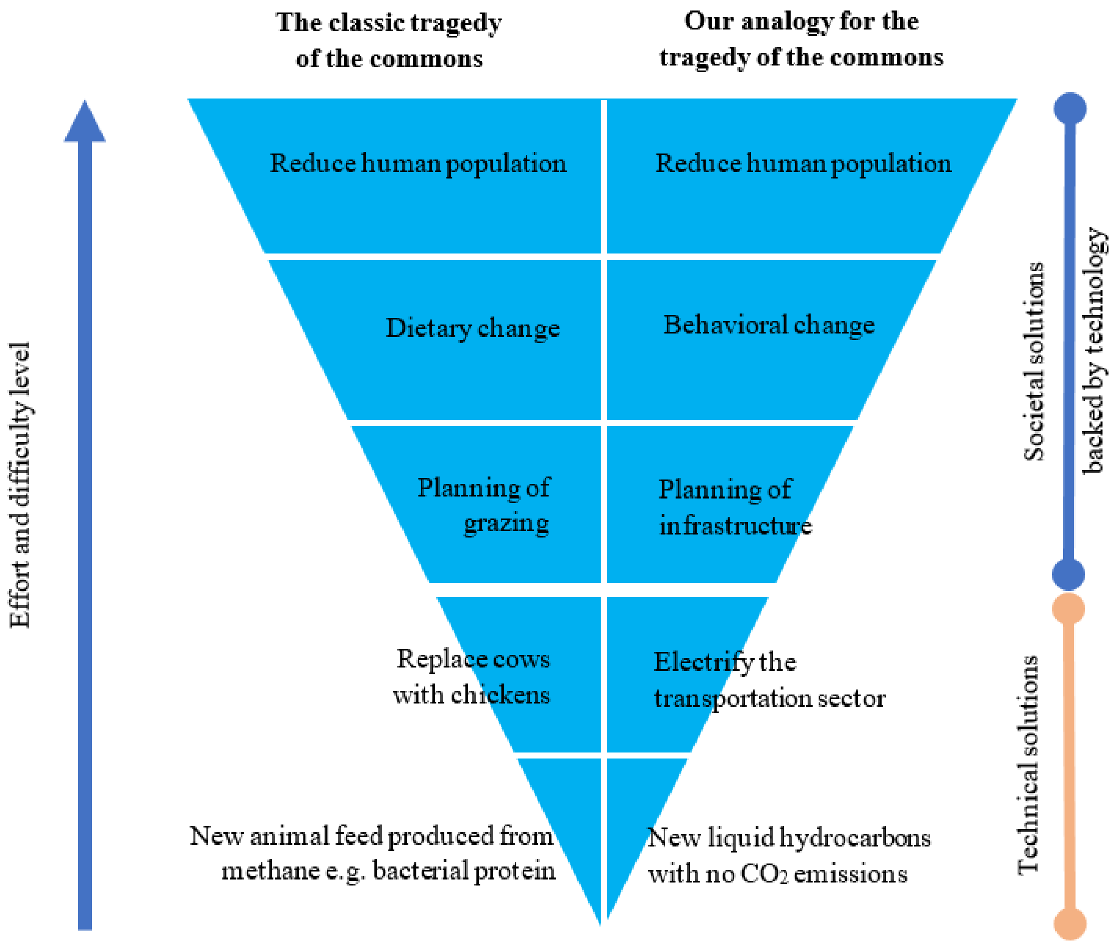


Figure 4: A comparison between the classic tragedy of the commons and our analogy in relation to technical and societal solutions to the challenge. The analogies are not one to one but mere examples of what they could be

The biofuels and electrofuels considered in this study are produced by a Fischer-Tropsch process, with an exception for the price intervals for biofuels in Section 4.3.2 where ethanol is included as well. The Fischer-Tropsch process is able to produce both jet fuel, diesel of good quality and gasoline of low quality. (Clifford, 2017). Jet fuel, diesel, and gasoline from a biofuel process or electrofuel process are all liquid hydrocarbons very similar to those derived from fossil fuels. Thus, the end-product of a biofuel process and an electrofuel process is assumed to be identical for the remainder of this report. There are many other techniques to produce both biofuels and electrofuels but they are omitted from this report. The rationale for splitting biofuels and electrofuels into two separate groups should be found on the input side of the processes.

2.4.2 Biofuels

Biofuels consists of hydrocarbons based on newly harvested biotic sources (IEA, 2011). The *newly harvested* has been added to exclude fossil fuels from the definition of biofuels. Otherwise, fossil fuels were also biofuels. The great similarities between the two types of fuels is also one of the reasons why it is interesting to look at them. As pointed by Karatzos, Mcmillan, and Saddler (2014) biofuel are the most likely near term renewable alternative to fossil fuels for the transportation sector, especially those that cannot be easily electrified.

The feedstock for biofuels could be anything from cereals, over straw to woody materials, animal carcasses and manure. There are two main pathways to turn the feedstock into biofuels. A thermochemical and a biochemical pathway. The thermochemical process uses a thermal conversion of the feedstock, which is then catalytically upgraded into hydrocarbons. The biochemical process is a biological conversion of the feedstock into alcohols or hydrocarbons (Karatzos et al., 2014).

There is a certain limit to the amount of biomass that can be produced (Chum et al., 2011). The main constraint is the fact that we only have one planet with limited resources (i.e. arable land). Land as a scarce resource raises some dilemmas between food and energy production. First-generation biofuels are in direct competition with food production, while second-generation biofuels are limited by being based on residues and waste products from a primary production (details on this dilemma in Appendix A.6.1). For example, straw from cereal production or manure from pig farms. These constraints on land and feedstock availability might influence the prices of biofuels in the future.

2.4.3 Electrofuels

Electrofuels are based on hydrogen and carbon, where the hydrogen is produced from electrolysis. The electricity source in this study is fully renewable since the task is to avoid emitting GHG. There are several sources for carbon which can be carbon dioxide (CO_2) from biogas (Bio), post combustion capture (PCC) from cement production or heat and power production from biomass and direct air capture (DAC). The amount and availability of carbon varies from source to source. CO_2 captured from the air is an infinite source of carbon since the CO_2 is emitted again during combustion of the produced fuels. The other sources are limited to a certain extent since they rely on the demand for cement, the amount of biomass used for biogas and the combustion of biomass for heat and power.

There are several different types of electrolysis. The three considered in this study is the proton exchange membrane (PEM), the solid oxide electrolyzer cell (SOEC), and the alkaline electrolyzer cell (AEC). In this study the electrofuels are produced from an FT-synthesis which depending on the CO_2 source and the hydrogen source gives a broad span of prices for the final liquid hydrocarbons.

2.4.4 Electrification

Electrification has been included in this study since it looks as the most viable alternative to liquid hydrocarbons in the transportation sector. The challenge with electrification is the low energy densities for batteries and the lacking flexibility of direct electrification, i.e. electrification that requires continues contact to an electricity source. Cars, scooters, city busses, trains and, with two new potential game changers, also trucks are the means of transportation that are and seems to be feasible for electrification within a foreseeable future. The two potential game changing technologies is the battery truck, such as Tesla Semi and the eHighways.

Today, planes and ships for long distance transportation does not seem feasible to electrify. Some short routes might be electrified within a near future, but for now the electrification options that we will consider only includes trucks, since they are on the frontier of electrification. Electricity is further divided into two subcategories, direct electrification vs. battery electrification, because there is a big difference in the methods used to quantify the cost.

2.4.4.1 Direct electrification

Currently, direct electrification is only feasible for road and rail transportation, and it had been used for railways for many years. The same concept is being tested for road transportation, specifically trucks. The concept will be referred to as eHighways. The idea of eHighways is to install wires over the inner lane on the current highways, where trucks with a pantograph can connect to the wires. Thus, the concept is very similar to electric trains but without the train tracks. With eHighways it is possible to electrify a big share of the demand for transporting goods on trucks.

The potential for eHighways seems big for long distance transportation which is often conducted on highways. There is a big capital expense related to constructing eHighways, for this reason, they will be limited to high-density roads with a lot of trucks and maybe busses. Patrik Akerman (2017) found that 60 % of emissions from heavy-duty vehicles in Germany occur on 2 % of the German road network. Covering these 2 % with eHighways might turn out to be a good business and a good alternative to liquid hydrocarbons in the transportation sector. The same pattern is likely to be found in many other countries than Germany.

2.4.4.2 Battery electrification

Batteries has the potential to cover all means of transportation for short distances within a near future. For long distances, the battery frontier seems to be at trucks, with vans, cars, and scooters on one side, and planes and ships on the other side. For this reason, the focus will once again be only on trucks.

In 2017, the co-founder and CEO of Tesla, Inc, Elon Musk presented Tesla Semi, a fully electric truck that has the potential to revolutionize the truck industry (Tesla, 2017). The range of Tesla Semi is reported to be 800 km. If this holds true, Tesla Semi has the potential to cover a huge percentage of the trucking demand, especially because the battery within 30 minutes can be charged to reach another 650 km. Due to legislation in many countries truck drivers are not allowed to drive for many hours without rest, which seems to fit perfectly with the charging needs. Furthermore, according to Elon Musk, 80 % of all truck routes is less than 250 miles (402 km). He does not specify whether it is a global number or specifically for the USA. Either way, Tesla Semi and similar future technologies has a big potential.

The first Tesla Semi should be on the road in late 2019. The promised specifications seems to depend on a development in the battery technology or a drop in battery costs. This could be possible because of mass production of batteries. The only specifications not listed is the battery lifetime and its price.

3 Methodology

The project flow diagram for the overall process of the study is shown in Figure 5. In the Figure circles indicates methods and knowledge inputs to each task, which is presented in the rectangles with full boarders. The rectangles with punctured borders represents data inputs.

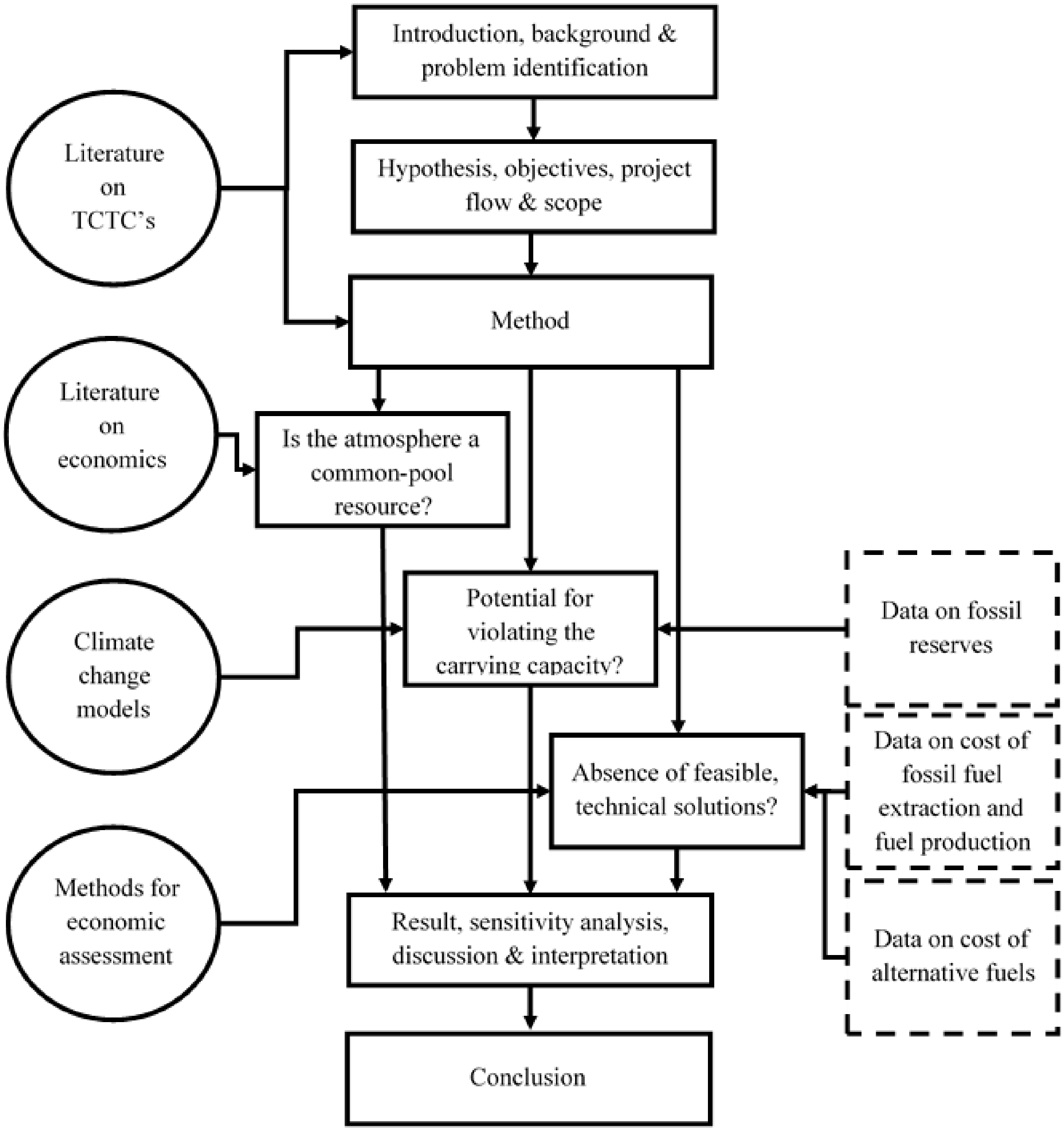


Figure 5: Project flow diagram. The circles represent methods and knowledge inputs, the rectangles with full borders represents tasks, and the rectangles with punctured lines represents data input

The project flow diagram gives, to some extent, an idea of how extensive the study is. What the project flow diagram does not depict is how the work load has been distributed. The main body of the report is like the tip of an iceberg supported by the ice spreading, like a pyramid, beneath the water. The Appendices A and B represent the first layer of ice submerged in water while our data input in the form of the analyses conducted in Excel spreadsheets described in Appendix C represents the whole ballast of the iceberg which make up the majority of the iceberg and the majority of our work. Characterizing climate change as a TCTC could easily become to hazy, philosophic, and imprecise due to the global and extensive scale of the challenges.

To avoid this, we have followed a strict analytical approach where three criteria for a TCTC, described in Section 2.1, are being studied to verify whether we are facing a TCTC in relation to global warming. The criteria were studied in the same order as they were described in Section 2.1. Figure 6 shows the logical flow of the research of whether we are facing a TCTC in relation to global warming or not. If the answer to a question in the flow diagram results in climate change not being a TCTC the following questions are irrelevant.

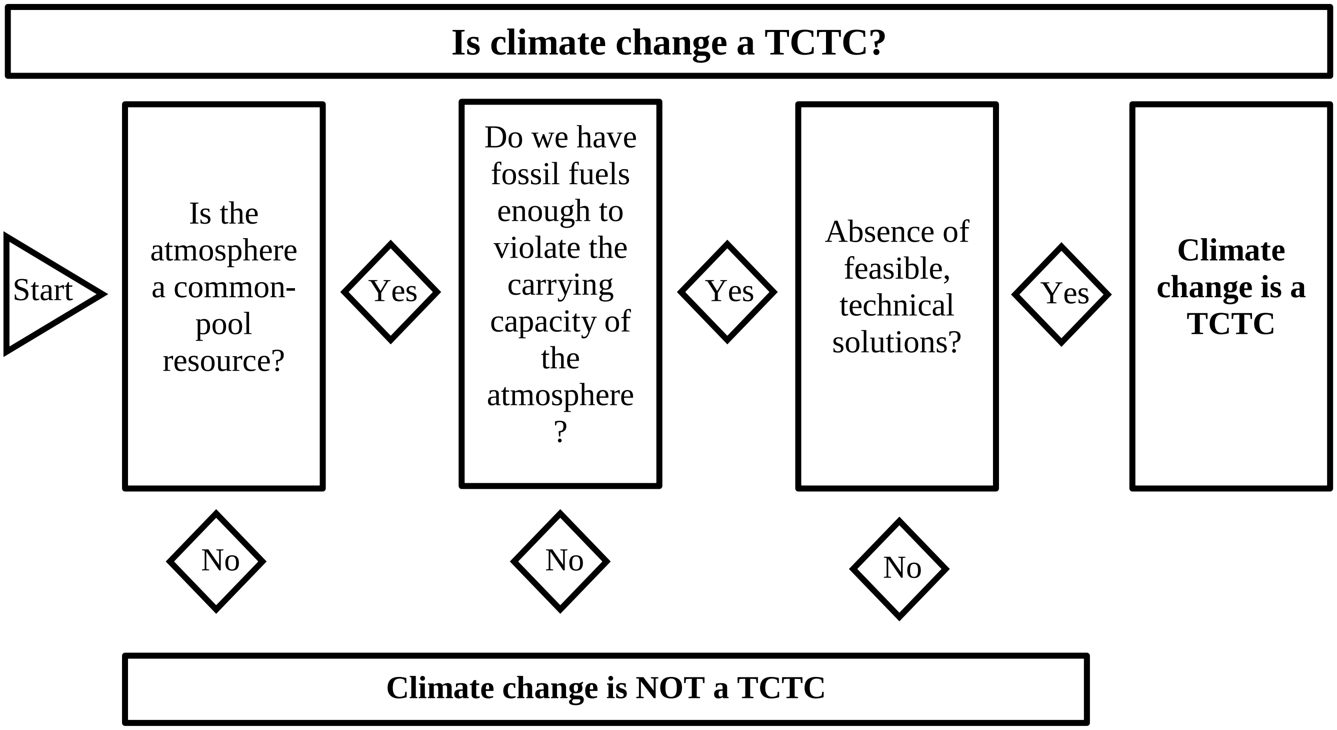


Figure 6: Flow diagram of the logical flow of our study. Trying to answer whether global warming is a TCTC

3.1 The atmosphere as a common-pool resource

To determine whether the atmosphere is a common-pool resource in relation to global warming, we have studied the economic definitions of goods as explained in Section 2.1. Furthermore, we have looked at the definitions from the Oxford dictionaries of commons and common-pool resources. The article by

Hardin (1968) and other articles considering common-pool resources have also been used in the study of common-pool resources.

3.2 Enough fossil fuels to violate the carrying capacity?

To answer this question, we should define and quantify the carrying capacity of the atmosphere, also, find and quantify the amount of fossil fuels that are available. Fossil fuels consists of both coal, oil, and gas. However, coal is not just coal, gas is not just gas, and oil is not just oil. Coal is divided into lignite, sub-bituminous, bituminous, and anthracite depending on the calorific value of the coal (World Coal Association, 2017). Gas, or natural gas, mostly consists of methane but also of a range of higher alkanes. The composition varies from field to field and so does the content of sulfur (Alberta Energy, 2007). Oil also comes in different compositions depending on the field, and the sulfur content in the oil varies as well (EIA, 2012). Lastly, there are several ways to extract each type of fossil fuel and each extraction method has different energy requirements, land-use requirements, safety issues, and environmental issues related to them that again differentiate each field or mine from another.

To enable the comparison, between all these different types of fossil fuels and the carrying capacity of the atmosphere we need a functional unit. A functional unit, which can convert everything into the same unit to make things comparable. To do this we need to make some assumptions on the average type of coal, oil, and gas. Since most of the fossil fuels extracted today are used for energy purposes or ends up as an energy source, it makes most sense to express the amounts in an energy unit. We use two databases in this study on fossil fuel reserves and resources, BP (2017a) and BGR (2016). Both databases express the amounts of fossil fuels in tons, barrels, and cubic meters respectively. These units have been converted into an energy unit and the result is depicted in Table 2. For an overview of the full process refer to Appendix A.4.

Table 2: Comparison between BP's and BGR's data form 2015 on reserves and resources for coal, oil, and gas in functional units

	BP - reserves	BGR - reserves	BGR - resources	BGR - total
Oil (EJ)	9,644	9,050	14,858	23,908
Gas (EJ)	7,046	7,473	24,791	32,263
Coal (EJ)	27,247	24,261	551,011	575,272
Total (EJ)	**43,937**	**40,783**	**590,660**	**631,443**

The data provided by BP and BGR on reserves are quite similar as Table 2 depicts. The background data for these tables indicates that on a country-by-country scale the two sources are quite similar as well. The major discrepancy for coal is due to a difference in coal reserves in China (BGR, 2016; BP, 2017a). The resource data from BGR shows that we have more than 10 times the amount of energy in resources as compared to reserves. Our analyses will be conducted based on the BGR data, since it is more specific when it comes to which countries holds the fossil fuel. It also contains data on resources, and since the reserve quantities from the two sources are very similar we should reach similar conclusions.

The quantities for fossil fuels are now in the same unit. The next step is to relate these quantities to the carrying capacity of the atmosphere. This consist of two steps defining the carrying capacity of the atmosphere and converting the amounts of fossil fuels into CO_2 equivalents (CO_2 eq.).

Usually, the carrying capacity refers to the number of people, animals, or crops which a region can support without environmental degradation (Oxford Dictionary of English, 2018). In relation to the classic tragedy of the commons, this could refer to two endpoints. The first, when adding and extra cow diminishes the total output from the commons and the second, just before the cattle starve and die.

Relating these two points to global warming and climate change, the first point is crossed when climate change starts to diminish the livability of the planet as a whole and the second point is crossed if we reach a tipping point or when mass extinctions starts to occur and humans starts to be severely affected by a changing climate. The second endpoint is not a distant dystopia it might well become reality before 2100 (Rothman, 2017). According to IPCC a tipping point is defined like this:

> *"A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated"* (Pachauri & Meyer, 2014)

There are no certainties about when or if these tipping points will be reached. All we know is that already today, we see the consequences of global warming (NASA, 2017) and it is only going to get worse as temperatures increases (Stern, 2006).

Finding the exact carrying capacity of the atmosphere is hard. This again makes it hard to decide which definition of carrying capacity to use. The Intergovernmental Panel on Climate Change (IPCC) has estimated carbon budgets for staying below 1.5 °C, 2.0 °C, and 3.0 °C (Pachauri & Meyer, 2014), which can be found in Table 7, Appendix A.2. There has been made other carbon budgets and they are all in the same order of magnitude and leads to the same conclusions in relation to carrying capacity (Rogelj et al., 2016). Each of these limits could be used to identify the carrying capacity of the atmosphere in relation to global warming and depending on which one we choose we are moving between the two endpoints mentioned earlier.

To be pragmatic and specify the carrying capacity more concretely, we have chosen a carrying capacity in compliance with the Paris Agreement. In this case the carrying capacity is determined be the following quote:

> *"Holding the increase in the global average temperature to well below **2 °C** above pre-industrial levels and pursuing efforts to limit the temperature increase to **1.5 °C** above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change"*(United Nations, 2015)

The last task is to calculate the equivalent CO_2 emissions related to the use/incineration of the fossil fuels and quantify them. In their Fifth Assessment report, IPCC states that the total reserves of carbon available in 2011 is in the range of 3,670 to 7,100 Gt CO_2 and that the total resources of carbon available in 2011 is in the range of 31,300 to 50,050 Gt CO_2 (Pachauri & Meyer, 2014). Converting our data into CO_2 eq. with the information in Table 14, Appendix A.5, gives us the total reserves of carbon available in 2015 to be in the range of 3,480 to 3,800 Gt CO_2 and the total resources of carbon available in 2015 to be approximately 64,140 Gt CO_2.

Both of our estimates are in the same order of magnitude as the estimates from IPCC but our estimate on total resources is higher than the range set by IPCC. The key issue in relation to estimating reserves and resources are coined out in this quote:

> *"Nobody knows or can know how much oil exists under the earth's surface or how much it will be possible to produce in the future"* (BP, 2017b)

There could be several other reasons for the discrepancy. First, IPCC's figures are from 2011 while BP's and BGR's figures are from 2015. During these years, new resources might have been discovered. Second, slightly different conversion factors from coal, oil, and gas to carbon emissions might have been used. Third, the definition of reserves and resources differentiate. It seems very likely that IPCC's carbon estimates would be lower than BGR's since everything should be economic to extract according to IPCC's definition and only exploitable in the future according to BGR's definition. For a more thorough discussion on the definitions, refer to Appendix A.3.

From the carrying capacity amounts of fossil fuels available, we can now answer the second question. Comparing the carrying capacity to the current rate of emissions, we can also quantify the urgency for actions towards reducing global warming.

This is not the first study that relates GHG emissions to the carrying capacity of our planet. It has been done in both Muttitt et al. (2016), McGlade and Ekins (2015), and by IPCC.

The first report concludes that more than 65% of the fossil fuel reserves should stay in the ground or at least remain unburned to stay below 2 °C warming. This also implies that already operating fields and mines should be shut down. Thus, new fields or mines should not be opened. The first report does not consider at what prices the fossil fuels can or will be produced.

The second study uses cost curves for fossil fuels to explore which of the fossil fuel reserves can be used in the future without violating the carbon budgets for the targets set in the Paris agreement. This is a good approach because we get to know the prices that alternative solutions to fossil fuels will compete against. The questions are: what should replace the fossil fuels? At what price comes the alternative solutions? Are the alternatives going to be competitive on an unregulated market or do we have to intervene? To answer these questions, we need to look at the feasible, technical solutions.

3.3 Feasible, technical solutions

To verify if there is a feasible, technical solution to the challenge, we first need to create an overview of the current situation before comparing to the alternative technical solutions. By comparing the current situation to the alternative ones, we can analyze the feasibility of the solutions, but first we need to find a unit that can be used for this comparison.

The functional unit is developed with inspiration from working group III of IPCC. They stated that the exhaustion of fossil fuels is not going to drive the decarbonization of society. The development is rather driven by economics, technological and scientific advances, socio-political decisions, and other driving forces (Edenhofer et al., 2014). As discussed in Section 2.4.1, it is important to figure out if the economics, technological and scientific advances can solve the problem of global warming or if we need socio-political decisions. In the latter, we could be facing a tragedy of the commons type of problem, if the two first requirements for a TCTC are fulfilled.

As mentioned in Section 2.4, this report mainly deals with the transition of the transportation sector, due to it being the key challenge and crucial point for a transition towards a low carbon society. Therefore, we want to find a functional unit that can be used to compare the price differences of different suppliers of mobility services or propellants. The basis for the functional unit is expressed in terms of a unit used in the transportation sector and still reflect the fact that we are dealing with energy. Currently, the transportation sector is heavily dependent on liquid hydrocarbons, which are relatively easy to compare to each other. Comparing an electricity-based propellant to one based on liquid hydrocarbons is harder if we do not choose the right functional unit.

For our study, we have chosen a gigajoule diesel-equivalent (GJ diesel-eq.) as the base for the functional unit. Note that this is one GJ diesel-eq. on the input side, i.e. before conversion to any kind of kinetic energy. The goal is to find an expression that allows us to compare two completely different propellants based on the cost for traveling a given distance. To do this we express our functional unit in US dollars (USD) per GJ diesel-eq. As a secondary unit, we depict the corresponding price in USD per barrel (bbl) on our figures.

The basis for our comparison is the price of propellants expressed in USD per GJ diesel-eq. Therefore, the electrification options should be converted into this unit as well. We do not expect that all parts of the transportation sector can be covered by electricity but it can supply a big share of the transportation sector, which is why it is included in Section 2.4.4.

3.3.1 Methods for economic assessments

First, the terms CAPEX and OPEX will be defined. CAPEX is the capital expenses used for buying long term services or products e.g. the investment and installation cost for assets. Assets mainly being buildings, infrastructure, machines, etc. The capital expenses are independent of whether the asset operates or not. OPEX is the operational expenses used for the daily operation and is thus dependent on whether the asset operates or not. The OPEX could be e.g. energy, raw materials, transport, salaries, etc.

The economic assessment method of this study is based on a hybrid of socioeconomic and business economic assessment methods. The pure socioeconomic and business economic assessment method have also been used to verify our results and study the effects of externalities and taxes.

The business economic assessment method is made from the perspective of a company or a business. The method includes all incomes and expenses that a company incur during a specified time frame. The time frame is often defined by the lifetime of the most capital intense asset. The cost includes both CAPEX and OPEX and income includes the selling price of the products and potential subsidies. The business economic assessment method does not account for externalities, except if they are internalized in the market due to political intervention. The result of this method is often referred to as the net present value (NPV) of a project. To make the NPV, a discount rate should be chosen to reflect the potential benefits of alternative investments. This way, money today is worth more than money in the future. The discount rate is often set higher for the business economic method than for the socioeconomic method.

The socioeconomic assessment method is conducted from the perspective of a society e.g. a city, country, or region. This method includes all benefits and costs to the society. What differentiates the cost in the socioeconomic method from the business economic method is that negative externalities are included e.g. pollution and noise, while salaries are excluded. Salaries are excluded because the money spend on salaries stay within the society, thus it is just a transfer between agents in the society. On the benefit side many of the same aspects are included in the socioeconomic method as for the business economic method. The difference being that, here, positive externalities are included e.g. health benefits from biking or the joy from watching a beautiful building. Once again, the result is often expressed as an NPV but for the socioeconomic analyses the discount rate is often substantially lower than for the business economic method. The current socioeconomic discount rate in Denmark is 4 % for the first 35 years of the project period where after it gradually reduces to 2 % (Danish Ministry of Finance, 2013).

The goal of our main economic assessment is not to determine whether a given project has a positive NPV or not, which is often the goal for the business economic and socioeconomic assessment. The goal is to enable a price comparison between liquid hydrocarbons and the sustainable alternatives. Our main analysis is based on a hybrid version of the socioeconomic and business economic method. To analyze the fossil fuels and how the alternatives compare on an unregulated market our assessment is conducted without externalities. Since we do not consider a project as such, we do not include a project period and thus not a discount rate. Though, for some of our sub analyses this has been a necessity due to time delays of the investments. Our economic assessment method is based solely on CAPEX and OPEX with a socioeconomic perspective, meaning that costs for salary are not included, but investment cost, energy, etc. are included. The following sections will show concrete assumptions and underlying assumptions for the calculations made for each technology.

3.3.2 Fossil fuels

With the functional unit in place, we can find the prices for the fossil based fuels. Finding these prices or production costs for coal, oil, and gas has been a difficult task since cost data often is held confidential by the companies. This concealment of data made it hard to find the data we needed. As a guidance on this quest, we checked the data against the current market prices for coal, oil, and gas and if we stayed within the same order of magnitude as those, we should be on safe grounds. For further details on cost data and the construction of "The Tragedy of the Planet?" graphs refer to Appendix A.5.

3.3.3 Biofuels

The prices for biofuels have been found in Ea Energianalyse (2016), which includes many different types of biofuels for the transport sector. We have chosen to focus on the cheapest and the most expensive biofuels to create a price range for biofuels in general that can be inserted on our "Tragedy of the Planet?" graph. The cheapest biofuel is biogas and the most expensive is the second-generation bioethanol. This implies that all other types of fuels fall within this price range, including first- generation bioethanol, FT diesel, jet fuel, and gasoline. For full explanation of the literature study, see Appendix A.6.1

3.3.4 Electrofuels

The prices for producing electrofuels have been calculated by us in our own model, see Appendix C.9 for full analysis. The prices have then been verified through a literature review conducted on the following sources; (Becker, Braun, Penev, & Melaina, 2012; Dimitriou, García-Gutiérrez, et al., 2015; Fu, Mabilat, Zahid, Brisse, & Gautier, 2010; Graves, Ebbesen, Mogensen, & Lackner, 2010; Hannula, 2015; König, Baucks, & Dietrich, 2015; Schmidt, Zittel, Weindorf, & Raksha, 2016; Smejkal, Rodemerck, Wagner, & Baerns, 2014; Tremel, Wasserscheid, Baldauf, & Hammer, 2015).

The electricity price is a big part of the cost for both electrofuels and electrification. Electricity is the most important parameter used in the analysis of these two propellants. For this reason, a sensitivity analysis was conducted for varying electricity prices. The interval of the electricity price spans from zero cost, which is the marginal production cost of wind and photovoltaics to the highest electricity price estimated by the Danish Energy Agency and the Danish Transmission System Operator, Energinet. The high end of the price span is the estimated electricity prices in the period 2035 to 2040 and it is estimated to be more than 500 DKK/MWh or approximately 70 EUR/MWh. Thus, the high end of the span is labeled ENS and ENDK projections (DEA, 2016a; Energinet, 2016).

Between the end points of the electricity price intervals we have inserted three intermediate prices (Table 3). The spot price of 50 EUR/MWh is chosen since this was the winning bid from Vattenfall for the tender of the offshore windfarm, Krieger's Flak (DEA, 2016b). The spot price of 30 EUR/MWh is chosen since the average electricity price for Denmark on Nordpool Spot in 2017 were 30-31 EUR/MWh (details on the last sheet of Appendix C.9). The spot price of 15 EUR/MWh is chosen since this was the winning bid for the tender on a windfarm in Mexico in November 2017 (gtm, 2017). 10 EUR/MWh is added to all prices to cover transmission costs of electricity based on Danish tariffs (Energinet, 2018).

The cost of hydrogen for electrofuels will be based on the average Danish electricity prices from 2017 and the price of wind in Mexico from Table 3 and the efficiencies are based on data from ENS (2012). The price of CO_2 is also sensitive to the electricity price, the source, and the technology chosen to extract the CO_2. Three source/technology pairs have been chosen. First, CO_2 from biogas (Bio) is set to zero cost, since the CO_2 is already separated from the biogas during the upgrading process to natural gas quality. For this reason, CO_2 is considered as a waste product, which would imply a very low price. Second, CO_2 from PCC is sensitive to electricity prices but falls in the range around 50 USD per ton (IEA, 2005) in future projections. Third, CO_2 from DAC the price is calculated based on data from the company Climeworks. The price of the heat and electricity in this process is a variable in our calculations. Climeworks made the world's first commercial DAC plant (Magill, 2017). All data for Climeworks is extracted from an interview (Evans, 2017) and from a site-visit at the Climeworks plant in Hinwil, May, 2018.

Table 3: An overview of the different electricity prices used for our analyses and sensitivity analyses. The distribution cost covers the transmission tariff and system tariff in Denmark (Energinet, 2018). *This is added to the spot prices to give the final electricity price*

Electricity price	Distribution cost	Spot price	Price labels
EUR/MWh	EUR/MWh	EUR/MWh	
80	10	70	ENS & ENDK projections
60		50	Krieger's Flak
40		30	Average 2017 - DK1
25		15	Wind in Mexico
10		0	Marginal cost for wind and solar

3.3.5 Electrification

Electrification has been included because it looks like the most viable alternative to liquid hydrocarbons in the transportation sector. It seems likely that electricity could cover a large share of the global transportation demand except long journey aviation and ship transport. To provide a perspective and to verify the results of prices found for biofuels, electrofuels, and electrification a socio- and corporate economic net present value (NPV) analysis is made for eHighways, battery trucks, biodiesel trucks, and conventional diesel trucks.

3.3.5.1 Direct electrification

An analysis was conducted to find the ratio between capital expenses (CAPEX) and operation expenses (OPEX) for an eHighway, which is sensitive to the number of trucks using it. The CAPEX represents the installation, manufacturing, and maintenance cost of the eHighway. Furthermore, the price difference of manufacturing a diesel truck versus an electric truck is also included for the whole lifetime of the eHighway. The lifetime is 35 years lifetime and the wires should be replaced after 20 years. The maintenance cost of the eHighway is part of CAPEX since it is a fixed cost almost independent of the number of users. All data on the eHighway was obtained through collaboration with Siemens AG where the contact persons were Patrik Akerman, Lise Jonasen, and Benjamin Wickert.

The OPEX represents operation and maintenance for the trucks together with the price of propellants. The electricity prices used for this analysis can be seen in Table 3. To compare the cost of eHighways to fossil-based fuels the total cost of both OPEX and CAPEX is converted into a GJ diesel-eq. (see Appendix A.6.3 and Appendix C.10 for the calculations). A sensitivity analysis of the electricity price was also performed for the eHighway using the data presented in Section 3.3.4.

3.3.5.2 Battery electrification

The focus of this part of electrification is once again trucks. The data for battery trucks has been found from Tesla (2017), referring to the Tesla Semi. The only specifications not listed are the battery lifetime and the battery price. The battery is estimated to have the same lifetime as the truck which may be an oversimplification but we do not have information to assess this.

The CAPEX/OPEX ratio is studied for the Tesla Semi as well. For the Tesla the ratio is sensitive to the lifetime of the truck where eHighways were sensitive the number of users. For comparison, the lifetime of a diesel trucks is estimated to 2,000,000 km and the lifetime of a Tesla truck is estimated to 1,600,000 km to 3,200,000 km based on the guaranteed lifetime. The CAPEX represents the price difference of manufacturing the Tesla Semi and a diesel truck, divided by the lifetime in kilometers. The OPEX represents operation and maintenance for the trucks and the price of the propellants, refer to Appendix C.10 for further details.

To compare the cost of a battery truck to a conventional diesel truck the total OPEX and CAPEX are converted into a GJ diesel-eq. (Appendix A.6.4). The electricity price is a major factor in the OPEX of a battery truck like eHighways. The estimations of future electricity prices are uncertain and for this reason, a sensitivity analysis of the electricity price in relation to the Tesla Semi was conducted. The same price range was used for the battery truck as for the eHighways and electrofuels (see Section 3.3.4).

4 Results

4.1 The atmosphere as a common-pool resource

Going through the criteria for common-pool resources, as understood in the ‘reverse way’ when looking at pollution (Hardin, 1968) we find the atmosphere to meet these criteria. There is no doubt that it is hard to exclude potential beneficiaries from using the atmosphere since it is all around us. Being hard or impossible to exclude potential beneficiaries from using a resource is, however, the case for both public goods and common-pool resources. A further criterion for being classified as a common-pool resource, as opposed to just a public good, is the aspect of subtractability of use, i.e. that one stakeholder’s use of the resource (here the pollution sink) delimits the capacity of the resource to be used by others.

In relation to climate change, we find that there is a relatively high subtractability of use. The reason is that if we emit too much CO_2 to the atmosphere the climate starts to change. In other words, there is a certain carrying capacity of the atmosphere in relation to CO_2 emissions. Under these conditions, if one person releases one ton of CO_2 to the atmosphere it actually limits another person’s possibility to do the same without getting closer to violating the carrying capacity of the atmosphere. For the atmosphere to be classified as a public good, the emission of GHG should not delimit other people’s possibility to do the same.

The last argument is that a commons is also defined by having no owners neither private nor governmental and is thus free to use for everybody (Oxford Dictionary of Economics, 2018). The same holds true for our atmosphere, but not for streetlights or national security, which are public goods.

In Hardin’s reverse way of understanding the Tragedy of the Commons, i.e. the pollution situation, the atmosphere, therefore, meets all criteria for classifying as a common-pool resource. First, it is impossible to exclude beneficiaries from using it, second, there is a clear subtractability of use, and third nobody owns it.

4.2 Enough fossil fuels to violate the carrying capacity

As described in Section 3.2, the carrying capacity of the atmosphere is in our study defined from the targets set in the Paris Agreement. A comparison of the available fossil carbon reserves and total resources as of 2015 to the carbon budgets, also for 2015, for staying within the Paris Agreement reveals that we must leave many of the fossil fuels in the ground to stay within the targets set in the Paris Agreement, see Figure 7. A solution that is easy to phrase but harder to set into action.

By comparing the carrying capacity to the current rate of GHG emissions we find an urgency to take actions towards reducing GHG emissions. It seems almost impossible in practice to reduce GHG emissions in time to limit the temperature increase to 1.5 °C, and we must take drastic action now if we want to stay well below 2 °C. According to our interpretation of the large variety of internationally published climate change models, we can go on for around 19 years from 2017 at the current rate of emissions, before we exceed the 2 °C limit. For the 1.5 °C limit, we have less than 8 years, before we exceed it, which is with a 50 % likelihood. For a 66 % likelihood to stay below the 1.5 °C limit, we only have 4 years from 2017. For further details, refer to Appendix A.2.

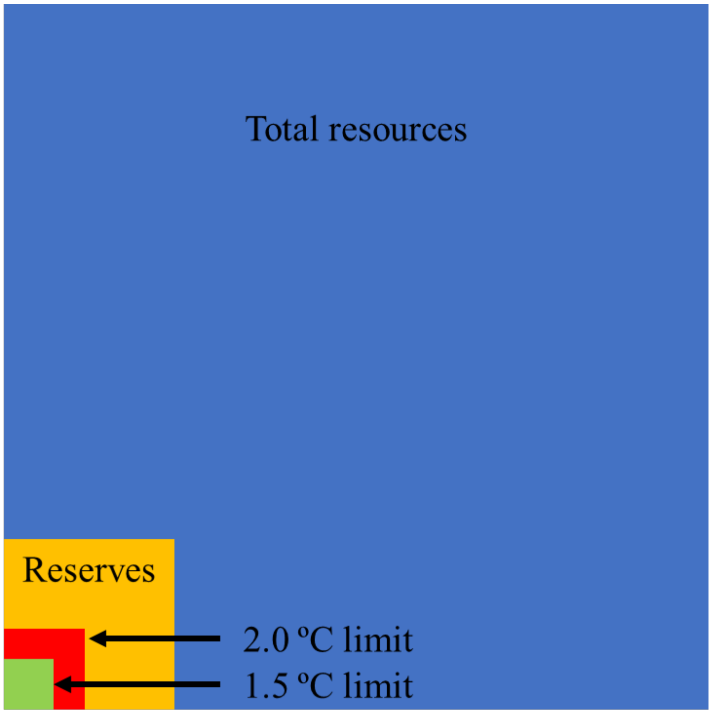


Figure 7: The CO_2 eq. available in fossil fuels as of 2015 from burning the total resources and reserves (BGR, 2016) *compared to the CO_2 eq. that can be emitted as of 2015 to stay within the limits set in the Paris agreement, i.e. 1.5 °C and 2 °C*

Expressed in another way, we have between 4 and 19 years at the current rate of emissions, before we must stop our emissions completely to stay below each of the 1.5 °C and 2 °C limits respectively. The emissions could also be gradually reduced to give us more time to act, including the option of achieving net negative emissions later. For a discussion on this, see section 5.1.2.

To give a perspective on the amounts of fossil fuels we have left, we will look at the global primary energy consumption[1] (PEC) for 2015. In 2015, the PEC of fossil fuels was approximately 470 EJ (BP, 2016). If the PEC of fossil fuels continues at the same rate as in 2015, we have enough fossil fuel reserves for the next 85-90 years judged by the 2015 reserve estimate and enough fossil fuel resources for more than a millennium judged by the 2015 total resource estimate. See Appendix A.3 for further explanations of the definitions for reserves, resources and total resources. In other words, we are 'running out' of fossil fuels in year 3350, based on these estimates, which is nearly 1335 years from now. The argument for finding alternatives to fossil fuels should, therefore. not be that we are running out of fossil fuels, it should be that we are running out of time in relation to global warming.

---

[1] Primary energy consumption refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process.(OECD, 2001)

It is important to note that at the current rate of consumption we will deplete our oil and gas reserves and resources sooner than we will deplete our coal reserves and resources. Especially, the fact of depleting our oil reserves and resources might cause some problems in relation to produce the right amount of fuels that we need. As an example, jet fuel has to be approved most commonly by ASTM or DEF STAN and this requires a certain mix of alkanes and aromatic rings (ASTM, 2017; IATA, 2015). This mix is hard to produce synthetically (Sniderman, 2011), but it has been done by Sasol in South Africa (Sasol, 2008, 2010). At the moment, most bio based or synthetically produced jet fuel has to be blended with fossil based jet fuel to obtain the right properties (Hansen & Jørgensen, 2014).

Considering the breakdown of the fossil fuels into coal, oil, and gas and prioritizing them in line with the trend from the following section, then if we want to stay well below 2 °C warming, we should leave all coal in the ground, but we do have some room for still extracting some oil and gas. The gas that the 2 °C limit allows us to extract should be prioritized for supporting or building infrastructure that can also be used for upgraded biogas in the future. The oil should be prioritized for the sectors such as aviation or sea transportation that are more challenging to convert onto a competitive, sustainable alternative.

If we want to stay below 1.5 °C, we should leave all coal and gas in the ground. Furthermore, we should leave most of the oil in the ground. Once again, the oil that we do extract should be prioritized for sectors such as aviation and sea transportation. It might even be so that already operating fields should be shut down if we want to meet the targets, especially the one of staying below 1.5 °C, see Figure 8 and Figure 9. The more of the fossil fuels that we manage to leave in the ground the less severe the consequences of global warming will be.

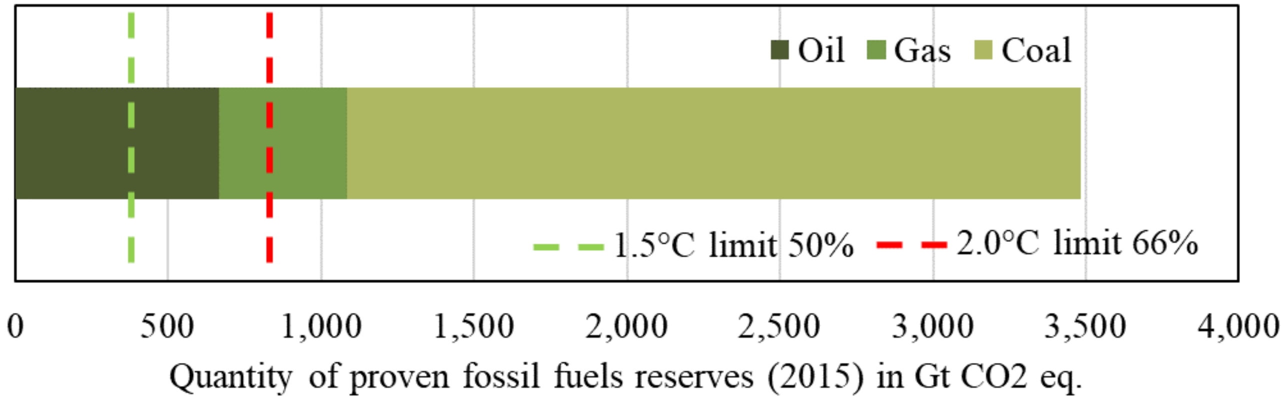


Figure 8: The quantity of fossil fuel reserves as of 2015 from BGR (2016). The ranking of coal, oil, and gas is based on the overall tendencies from the economic analysis from Section 4.3.1. No more coal should be extracted if we want to meet the 2.0 °C limit, and no more coal and gas should be extracted if we want to meet the 1.5 °C limit. The extraction of gas and oil, respectively, should also be limited to meet each target

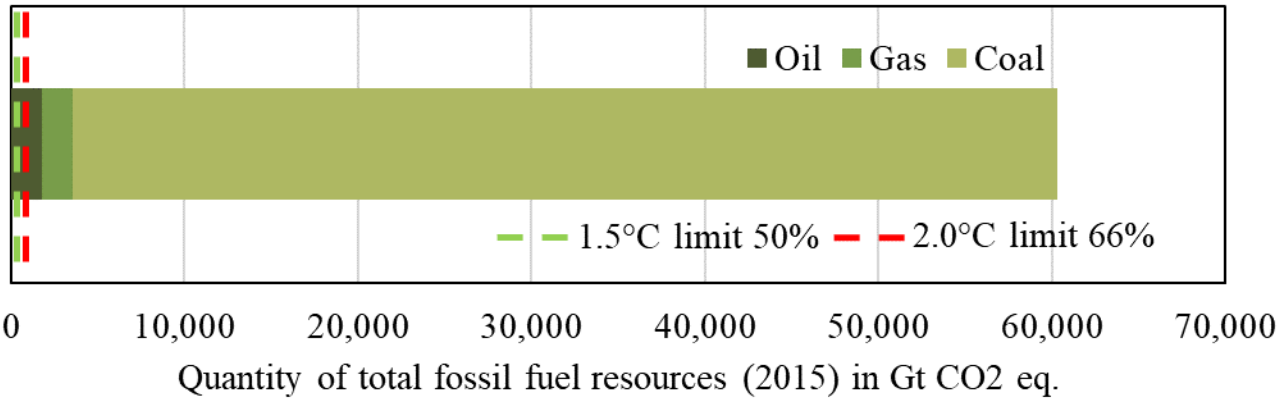


Figure 9: The quantity of total fossil fuel resources as of 2015 from BGR (2016). The ranking of coal, oil, and gas is based on the overall tendencies from the economic analysis from Section 4.3.1. Only considering the resources no more coal or gas should be extracted and the extraction of oil should be limited. Running out of fossil fuels, especially coal, is not a problem to be considered in this millennium

Considering the results so far, only a feasible, technical solution can disprove the fact that we are facing a TCTC in relation to global warming, so far, it seems that we are.

4.3 Feasible, technical solutions

There are, at present and within the available time frame of meeting the 2 °C scenario, no economically feasible solutions to all parts of the transportation sector. This will be elaborated in the following sections. First, the elaborated overview of proved fossil fuel reserves and related cost of transport fuel production is presented.

4.3.1 Fossil fuels

An overview of the current fossil fuel situation can be seen in Figure 10 which depicts the proven reserve quantity data for 2015 from BGR (2016) and the corresponding production costs obtained from Knoema (2014), Remme, Blesl, and Fahl (2007), and WSJ News Graphics (2016). Figure 10 is a frequency function, i.e. a price/quantity graph that illustrates the quantities available at different prices or costs. The prices are sorted after merit order with the lowest price first and the highest last. All graphs in this report constructed like this will be referred to as “The Tragedy of the Planet?” graphs.

The production costs are approximated for each fuel in each individual country producing fossil fuels including CAPEX and OPEX for both extraction/mining, transportation/administration, and refining into a diesel like fuel. The production costs are calculated as the true cost of production, i.e. as in socioeconomic calculation, but excluding externalities, since these externalities are only valued in the market if there is a political intervention. In a later chapter, the externalities are discussed and put in proportion. This raw societal production costs allows us to see the effects of an unregulated energy market, where technologies are competing on pure production costs. A distribution cost is added on top of the production costs to make the comparison to electricity based transportation easier.

Generally, all “The Tragedy of the Planet?” graphs have a quantity on the x-axis, this is either a quantity of reserves, resources or a total of both. The primary y-axis shows the price of a diesel-eq. fuel in USD/GJ diesel-eq. The secondary y-axis shows a conversion of the price on the primary y-axis into USD/bbl. There is a triple colored line in yellow, purple, and black along the x-axis. This line represents whether the given quantity and the corresponding price information is for gas, oil, or coal respectively. On top of this line lies the production price information. The light blue color represents the extraction/mining CAPEX, the orange color represents the extraction/mining OPEX, the grey color the transportation/administration CAPEX+OPEX, the yellow color the refining CAPEX+OPEX and the dark blue color the distribution CAPEX+OPEX.

From the figures, it is visible that the refining cost differs quite substantially for coal, oil, and gas, especially, coal has a high refining cost, which is intuitively understandable as it includes a coal-to-liquid conversion, here represented by the so-called Fischer-Tropsch conversion process. Each ‘step’ of the ‘staircase’ on the graphs represents the extraction of coal, oil, or gas and the subsequent conversion path to a liquid fuel for each of the individual fossil fuel supplying countries in the world. Each step thus represents a country, or a cluster of countries, with similar production costs. To see where each fossil fuel supplying country is represented on the graph, please refer to Appendix C.2.

Using the terminology or metaphor from the original tragedy of the commons example by Hardin (1968), Figure 10 shows the price and ‘the number of cows that we have available to set onto our commons’. Using this metaphor, Figure 11 shows, then, the ‘size of our commons’ and ‘how many cows we can set onto our commons’ before the carrying capacity is violated. The new lines on the Figures are based on the data from Section 4.2. The green lines represent the 1.5 °C limit and the shades indicate the fraction of models not exceeding the temperature limit at the given CO_2-acumulations. The same goes for the red lines, which depicts the 2.0 °C limit. Refer to Appendix A.2 for more details on the temperature limits.

Figure 12 and Figure 13 are extended versions of Figure 10 and Figure 11 where the resources as of 2015 are added to the proven reserves as of 2015 to give the total resource as of 2015. Thus, showing the total quantity of fossil fuels on our planet. When the total quantity of fossil fuel resources is included, it can be seen from Figure 13 that the quantity of fossil fuels that can be extracted with subsequent CO_2 emission into the atmosphere while still staying within the temperature limits get all crammed up in the left-hand side of the graph. This tells us, that we have many more fossil carbon resources available than we can afford to extract and burn without violating the temperature limits.

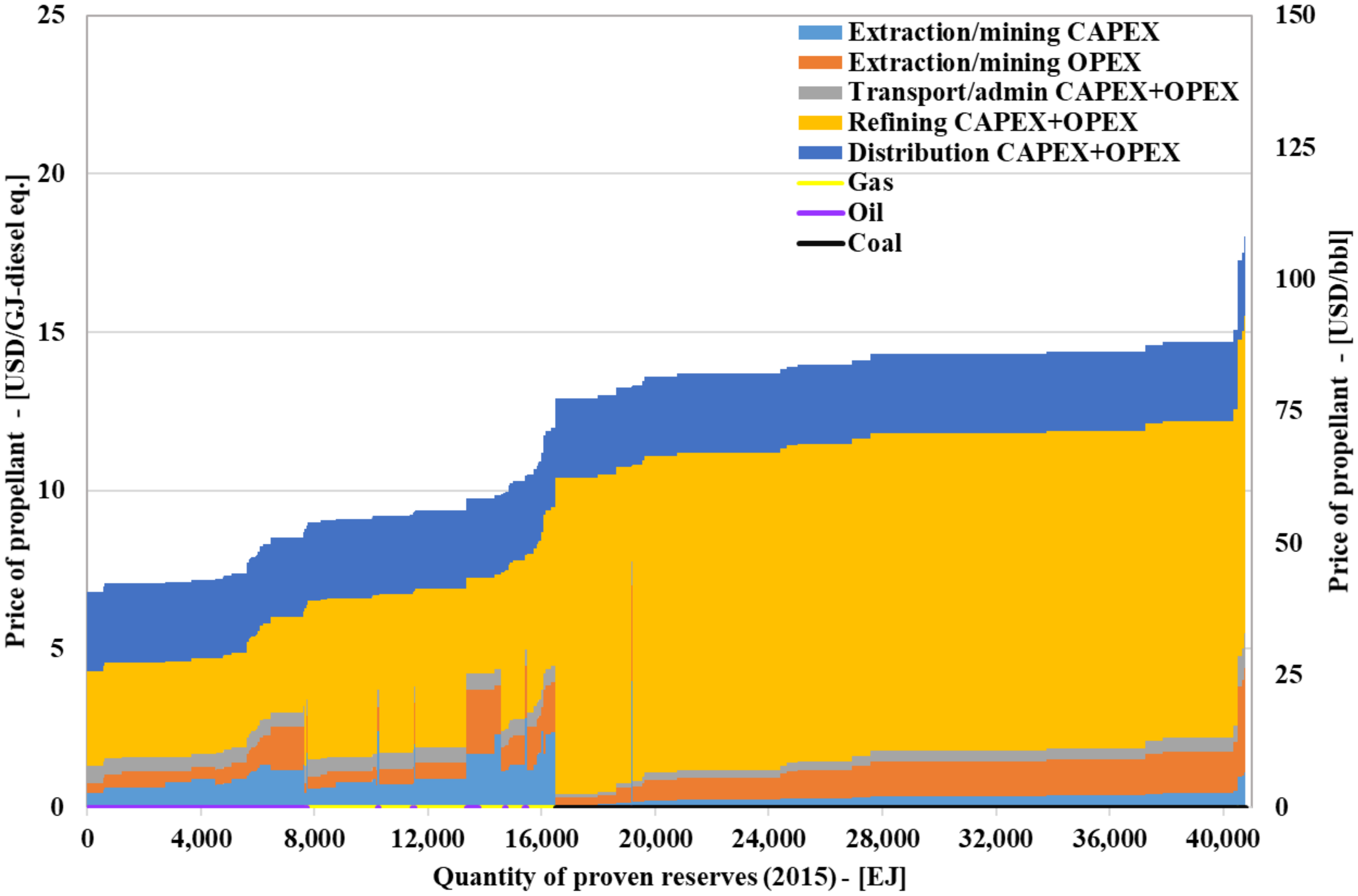


Figure 10: "The Tragedy of the Planet?" illustration of proven fossil fuel reserves based on BGR's reserve data from 2015 for coal, oil, and gas. The cost of producing one GJ diesel-eq. divided into extraction/mining CAPEX, extraction/mining OPEX, transport/admin CAPEX+OPEX, and refining CAPEX+OPEX

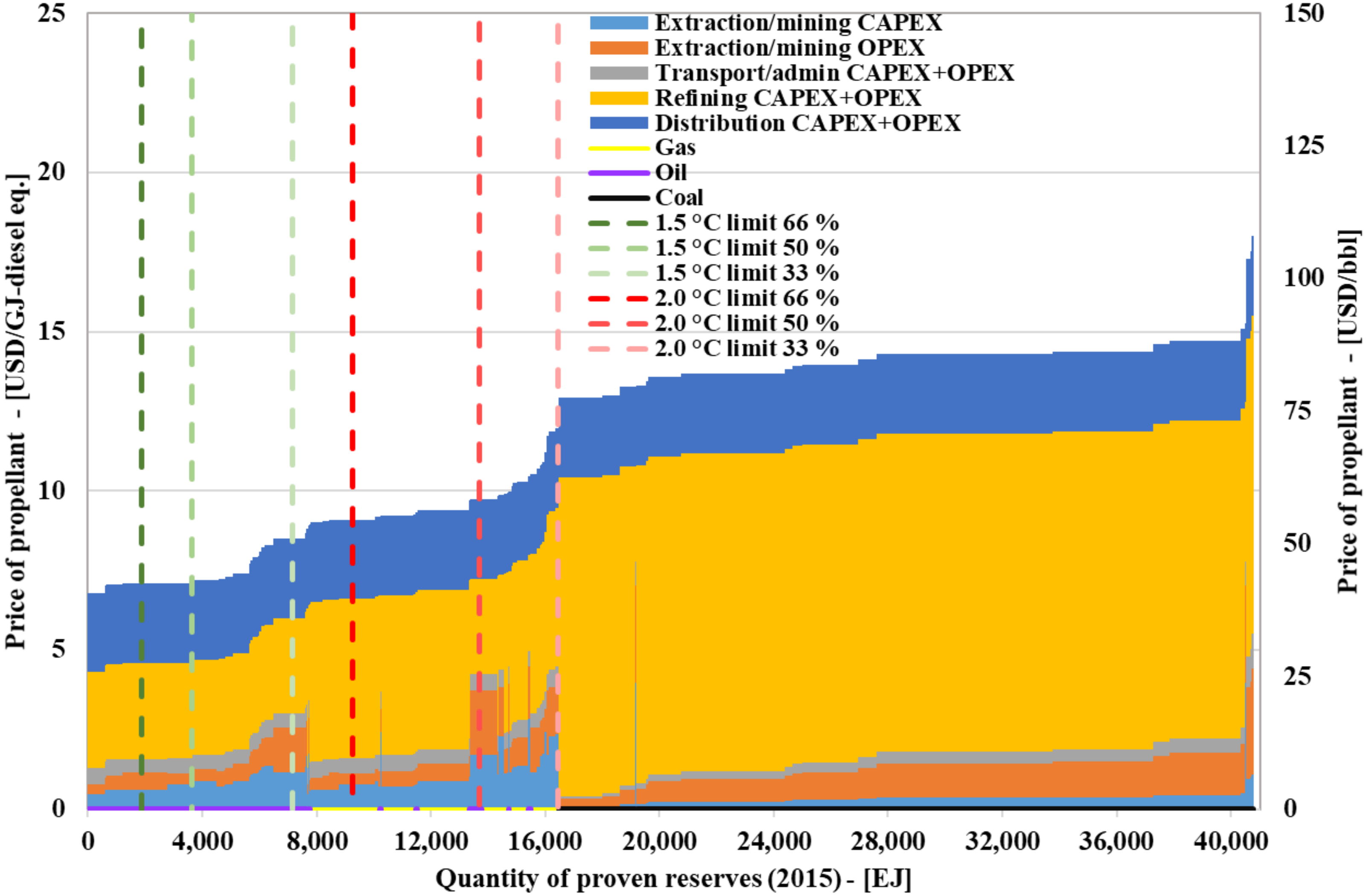


Figure 11: "The Tragedy of the Planet?" illustration of proven fossil fuel reserves based on BGR's reserve data from 2015 for coal, oil, and gas. The cost of producing one GJ diesel-eq. divided into extraction/mining CAPEX, extraction/mining OPEX, transport/admin CAPEX+OPEX, and refining CAPEX+OPEX. Emission thresholds for CO_2-emissions depicted to quantify the amount of proven fossil fuel reserves that we must leave in the ground in order to stay within the given temperature limits

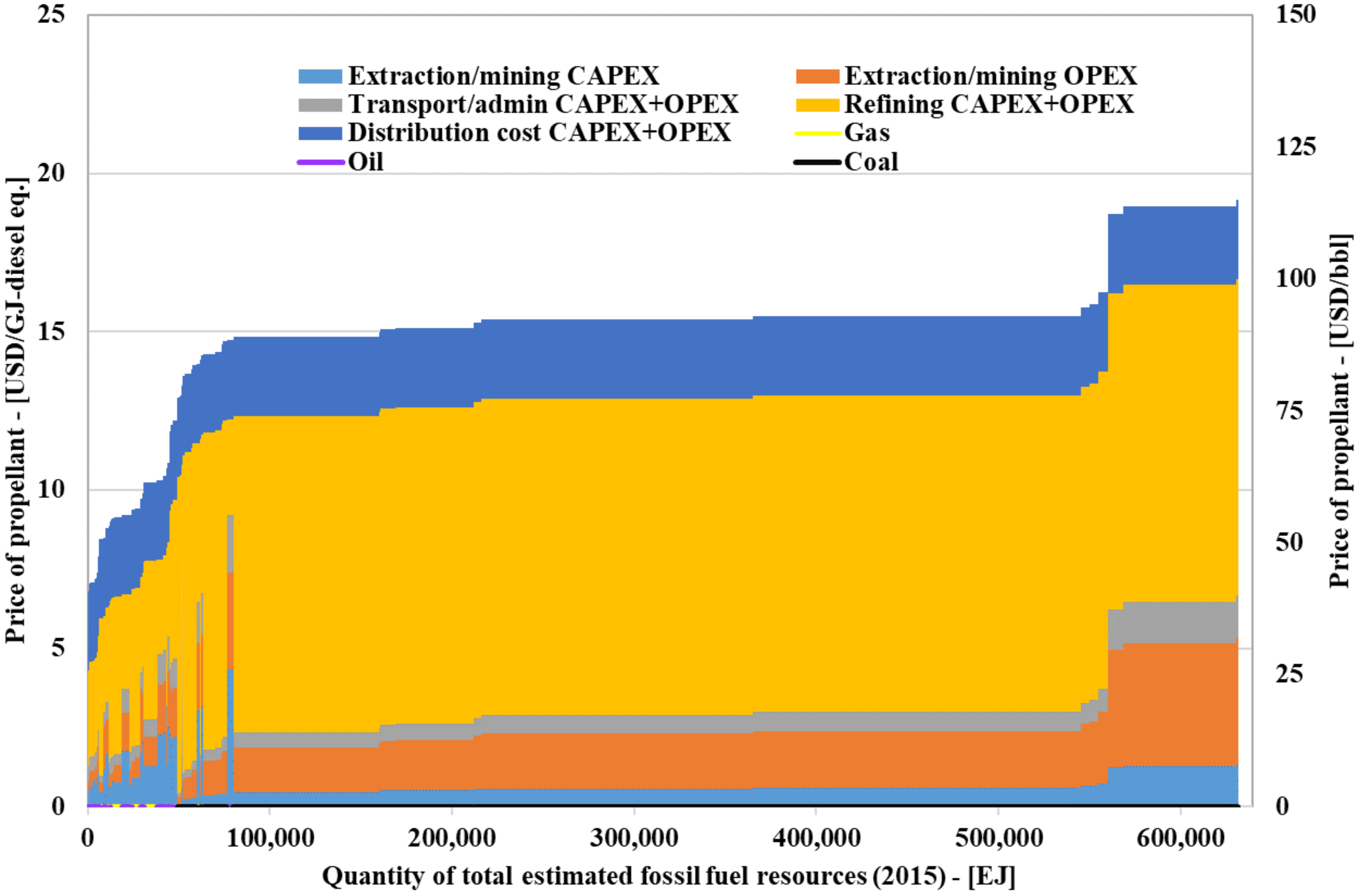


Figure 12: "The Tragedy of the Planet?" illustration of estimated total fossil fuel resources based on BGR's reserve and resource data from 2015 for coal, oil, and gas. The cost of producing one GJ diesel-eq. divided into extraction/mining CAPEX, extraction/mining OPEX, transport/admin CAPEX+OPEX, and refining CAPEX+OPEX

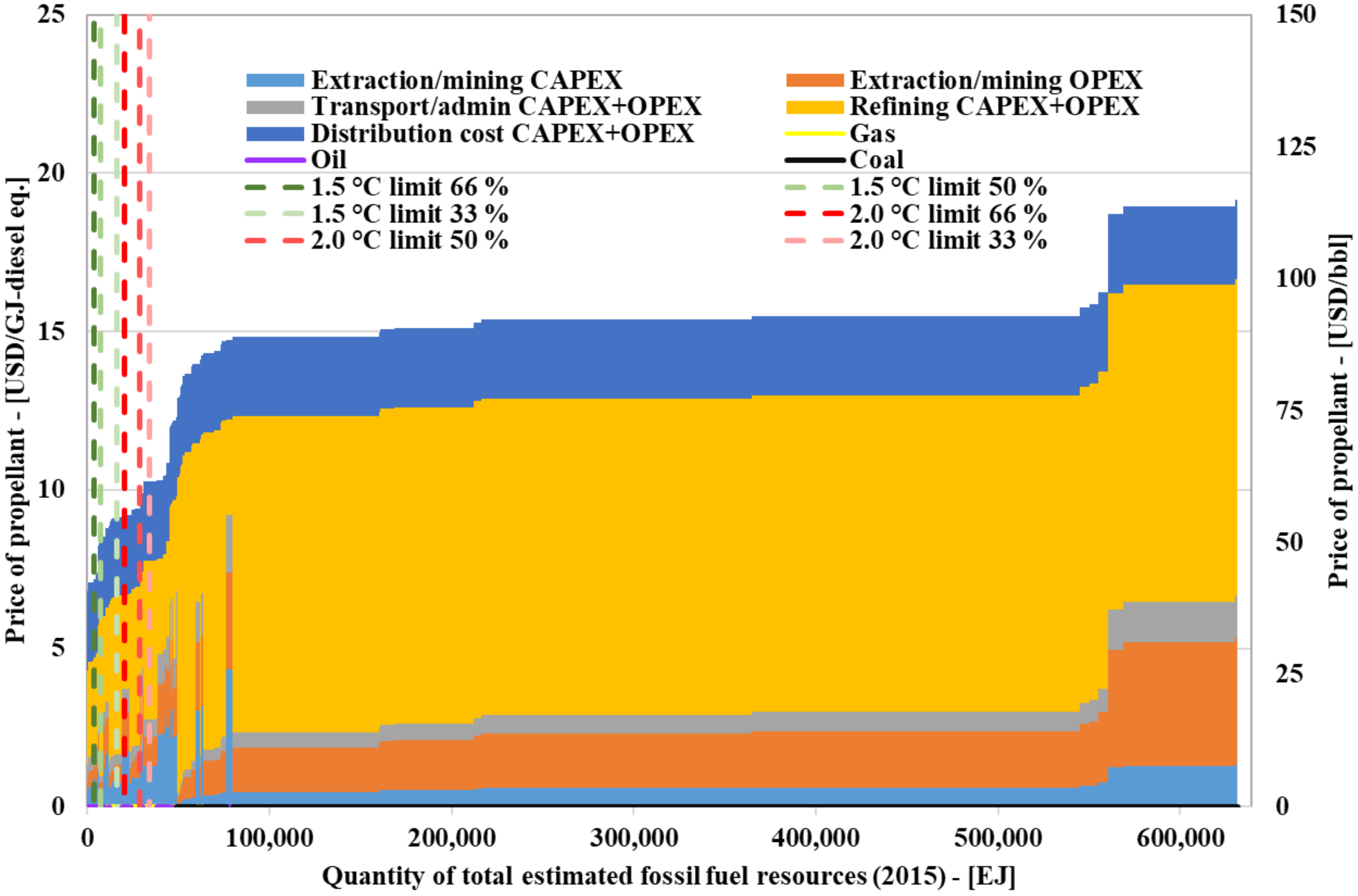


Figure 13: "The Tragedy of the Planet?" illustration of estimated total fossil fuel resources based on BGR's reserve and resource data from 2015 for coal, oil, and gas. The cost of producing one GJ diesel-eq. divided into extraction/mining CAPEX, extraction/mining OPEX, transport/admin CAPEX+OPEX, and refining CAPEX+OPEX. Emission thresholds for CO_2-emissions depicted to quantify the amount of fossil fuels that we can extract and that should stay in the ground

4.3.2 Biofuels

Figure 14 shows the price range of biofuels on “The Tragedy of the Planet?” graph. All price data for biofuels are from Ea Energianalyse (2016). There is an annual limitation to the quantity of production of biofuels, but in the long run it is a renewable resource within this limitation. From Figure 14 it is visible that not even the cheapest biofuel can compete with fossil based fuels.

The lower price limit is for upgraded biogas where the price is set to 118 DKK/GJ (19.67 USD/GJ). The higher price limit is for second-generation bioethanol, which is reported to be based on agricultural straw residues, and the price is set to 283 DKK/GJ (47.17 USD/GJ). The price of second-generation bioethanol is based on Måbjerg Energy Concept that already includes the utilization of process heat (Ea Energianalyse, 2016). The abovementioned prices all reflect a Danish setting. There might be regions in the world, where the prices will be lower or higher, but in general, many types of biomass are traded globally which diminishes the price gap to some extent. Constraints on land might influence the prices of biofuels in the future, which has to some degree been taken into account by Ea Energianalyse (2016), but since it depends on a future demand for land it is hard to predict.

4.3.3 Electrofuels

Figure 15 shows the price range for electrofuels on “The Tragedy of the Planet?” graph. The price of electrofuels is inserted as a horizontal band on the graph represented by the two blue, horizontal lines. The price is represented by horizontal lines, which indicates that the production is unlimited. This is not entirely true for CO_2 from biogas and PCC. It is outside the scope of this report to estimate the size of these carbon sources, but evidently their annual quantity is much smaller than today’s use of fossil fuels. For DAC the potential production is in theory unlimited.

The graph shows that the production cost of electrofuels cannot compete with the production cost of fossil fuels within the carrying capacity of the atmosphere. With our electricity price assumptions, the current, and the foreseeable future technologies, it is not going to be cheaper to produce hydrocarbons from sustainable sources than to extract fossil fuels from the ground. This is under the assumption that negative externalities are not accounted for and internalized into the market price. If the externalities were accounted for, the socioeconomic assessment will give another result, but when looking at the challenge of climate change as a TCTC, externalities should, of course, not be included when addressing the third criterion on availability of feasible, technical solutions, as the question here is, if they are feasible and competitive within the prevailing market conditions.

The production cost of electrofuels ranges from 18.9 USD/GJ diesel-eq. to 65 USD/GJ diesel-eq. The low estimate is for an SOEC fuel cell with an electricity price of 25 EUR/MWh where transmission costs are included and the CO_2 is supplied for free from biogas. The high estimate is based on an alkaline electrolysis using 5.0 kWh of electricity to produce 1 Nm^3 of hydrogen and the DAC technology as of 2017. The electricity price for the high estimate is 40 EUR/MWh. The results have been verified through a literature review presented in Appendix A.6.2.

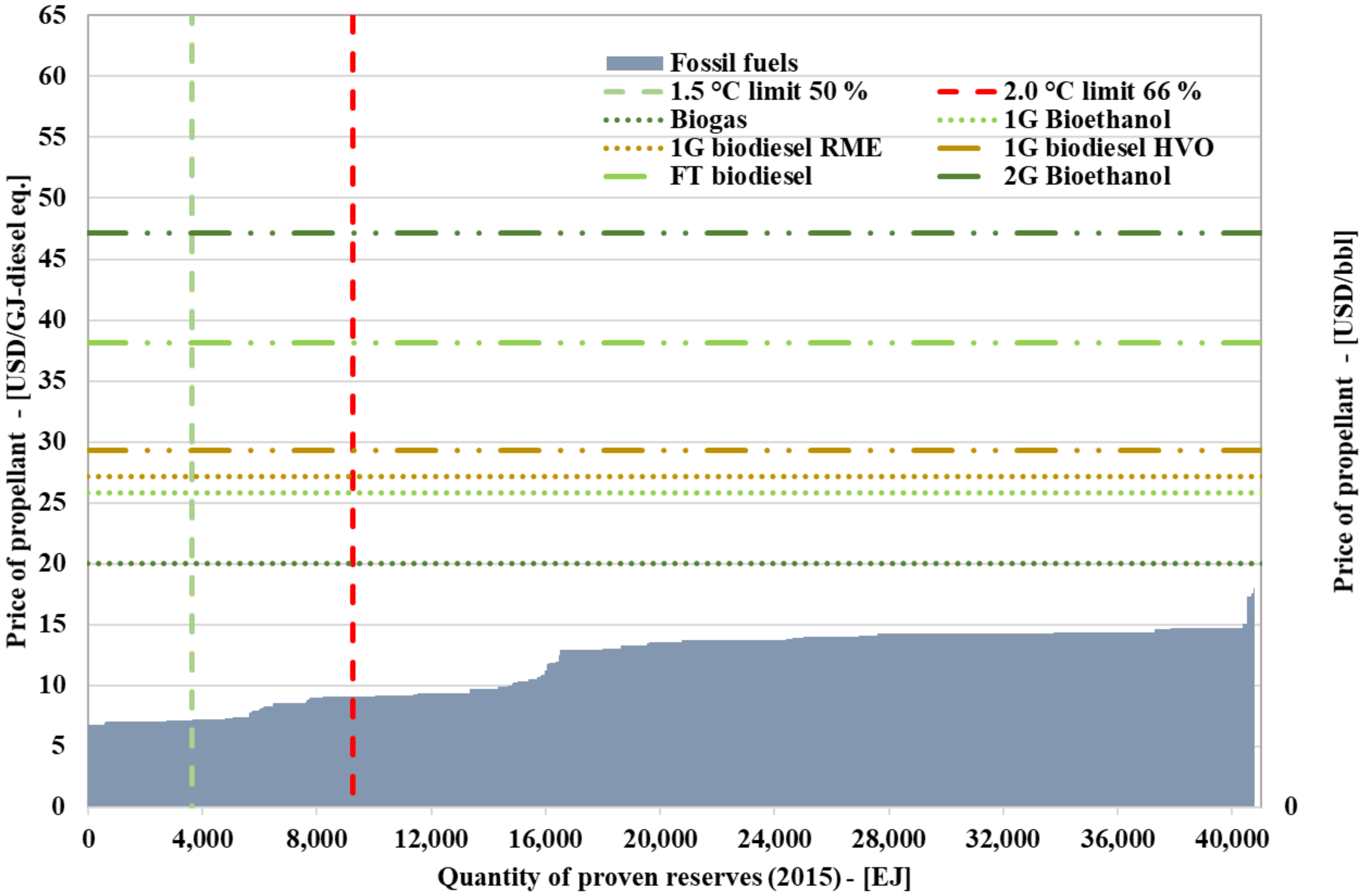


Figure 14: "The Tragedy of the Planet?" comparison based on BGR's reserve data from 2015 for coal, oil, and gas and the cost of biofuels. The two horizontal lines represent the cheapest and most expensive biofuel technologies: first-generation and second-generation bioethanol. Emission thresholds for CO_2-emissions depicted to quantify the amount of fossil fuels that we must leave in the ground

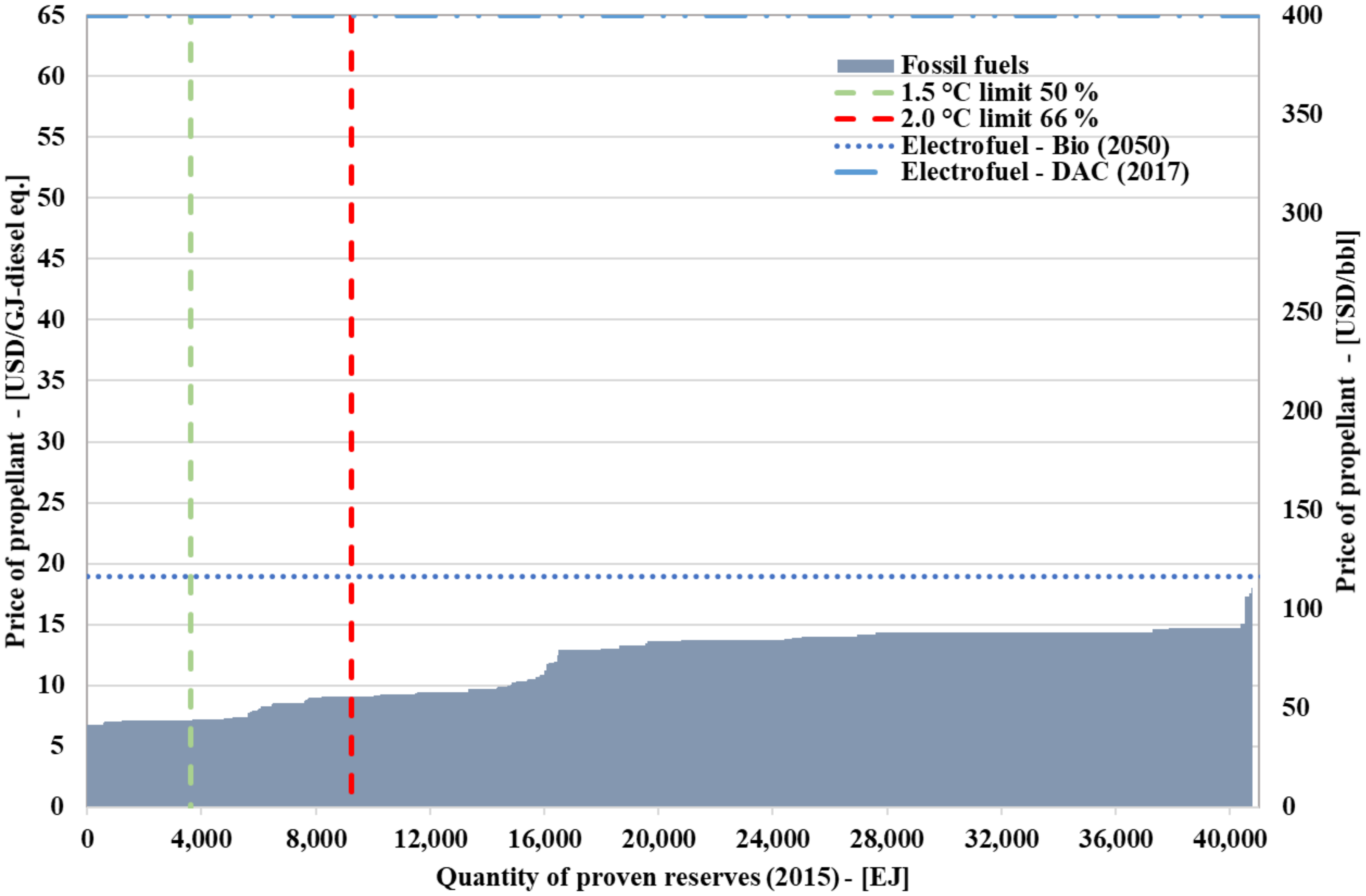


Figure 15: “The Tragedy of the Planet?” comparison based on BGR’s reserve data from 2015 for coal, oil, and gas and the production cost of electrofuels. The horizontal line represents the cheapest way to produce electrofuels. Emission thresholds for CO_2-emissions depicted to quantify the amount of fossil fuels that we must leave in the ground

4.3.4 Electrification

At the moment, the electrification frontier seems to be at trucks for all distances. This is also the main reason for trucks being such a big part of this analysis. Both electrification alternatives seem, almost, to be economically feasible compared to fossil based fuels under certain circumstances in an unregulated market. By conducting both a socioeconomic and a business economic analysis for both types of electrification compared to a standard diesel truck, this is also what we find in both our socioeconomic and business economic analysis for a Danish scenario. For all details please refer to Appendix A.6.5 and Appendix C.10. Conducting the socioeconomic and business economic analysis where made to verify our results and to study the dynamics and effects of externalities and taxes. As an example, when externalities are included higher electricity prices and a lower density on the roads becomes feasible before break even between fossil fuels and electrification.

4.3.4.1 Direct electrification

Figure 18 shows the cost for the eHighway on “The Tragedy of the Planet?” graph. The lines inserted on the graph are for 2,000 to 8,000 trucks per day, respectively. eHighways have almost the potential to compete with fossil fuels on an unregulated market if the roads are densely packed and the electricity price is low.

The overall cost and the CAPEX/OPEX ratio for eHighways depending on the number of trucks per day can be seen from Figure 16. The range from 500 to 10,000 trucks using the power lines per day is chosen to study both low and high dense roads. The high influence of the number of trucks on the ratio diminishes from around 3,500 trucks per day. This implies that not only high density roads have potential but also medium density roads. In 2016, around 3,500 trucks drove on the Funish highways each day according to data received from the Danish Road Directorate (Vejdirektoratet). This is approximately where the cost drop starts to flatten and also the reason to choose the interval from 2,000 to 8,000 trucks per day. A sensitivity analysis on the electricity price and the number of trucks per day can be seen in Table 4. For further details including how the conversion was made from EUR/km to USD/GJ diesel-eq., please refer to Appendix A.6.3 and to Appendix C.10.

Table 4: Results of the price sensitivity to electricity prices and number of trucks per day on the total cost of an eHighway. The price range that will be used in Figure 18 will be the one from 40 EUR/MWh to 25 EUR/MWh, which is in line with the prices used for electrofuels. The two endpoints are marked in bold

Total cost (USD/GJ diesel-eq.)				
	Number of trucks per day			
Electricity price	**2000**	**4000**	**6000**	**8000**
80 EUR/MWh	34.90	23.95	20.31	18.48
60 EUR/MWh	31.85	20.91	17.26	15.44
40 EUR/MWh	**28.64**	17.70	14.05	12.23
25 EUR/MWh	26.29	15.35	11.70	**9.88**
10 EUR/MWh	23.95	13.01	9.36	7.54

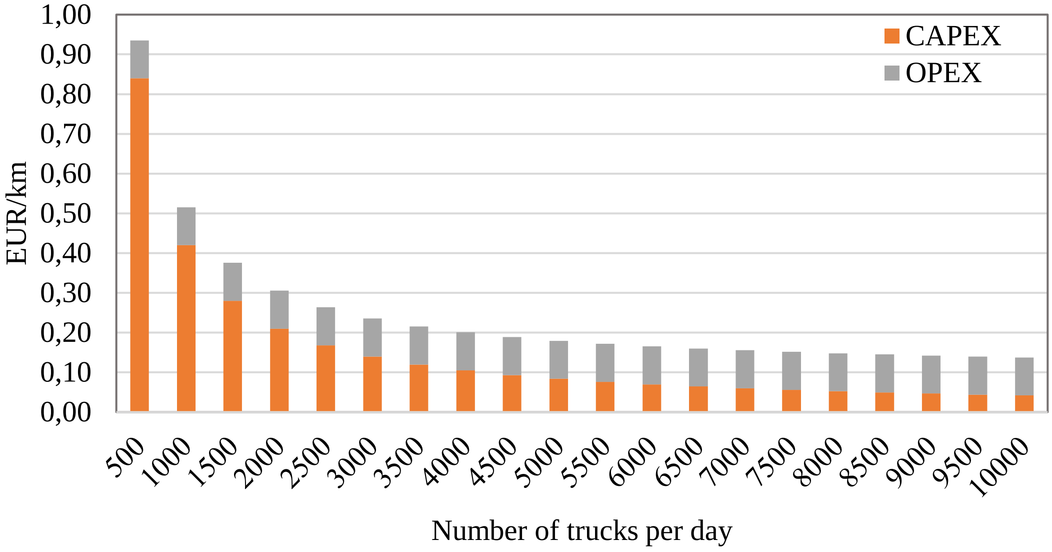


Figure 16: The CAPEX/OPEX ratio for a standard eHighway based on the number of trucks per day

4.3.4.2 Battery electrification

Figure 19 depicts the cost for a Tesla Semi truck on “The Tragedy of the Planet?” graph. The band inserted is for a truck with a lifetime of 3.2 million kilometers and an electricity price on 25 EUR/MWh, and a truck with a lifetime of 1.6 million kilometers and an electricity price on 40 EUR/MWh. Furthermore, it is clear that the battery truck has the potential to outcompete fossil fuels on an unregulated market, far more convincing than the eHighway. This of course depends on Tesla’s, or other future suppliers’, ability to deliver on the announced specification for the Tesla Semi or similar.

Table 5: Results of the price sensitivity to electricity prices and lifetime on the total cost of a Tesla Semi. The price range that will be used in Figure 19 will be the one from 40 EUR/MWh to 25 EUR/MWh, which is in line with the prices used for electrofuels. The two endpoints are marked in bold

Total cost (USD/GJ diesel-eq.)					
	Lifetime (million km)				
Electricity price	**1.6**	**2.0**	**2.4**	**2.8**	**3.2**
80 EUR/MWh	12.52	12.02	11.68	11.44	11.26
60 EUR/MWh	10.02	9.52	9.18	8.94	8.76
40 EUR/MWh	**7.52**	7.02	6.68	6.44	6.26
25 EUR/MWh	5.65	5.14	4.81	4.57	**4.39**
10 EUR/MWh	3.77	3.27	2.93	2.69	2.51

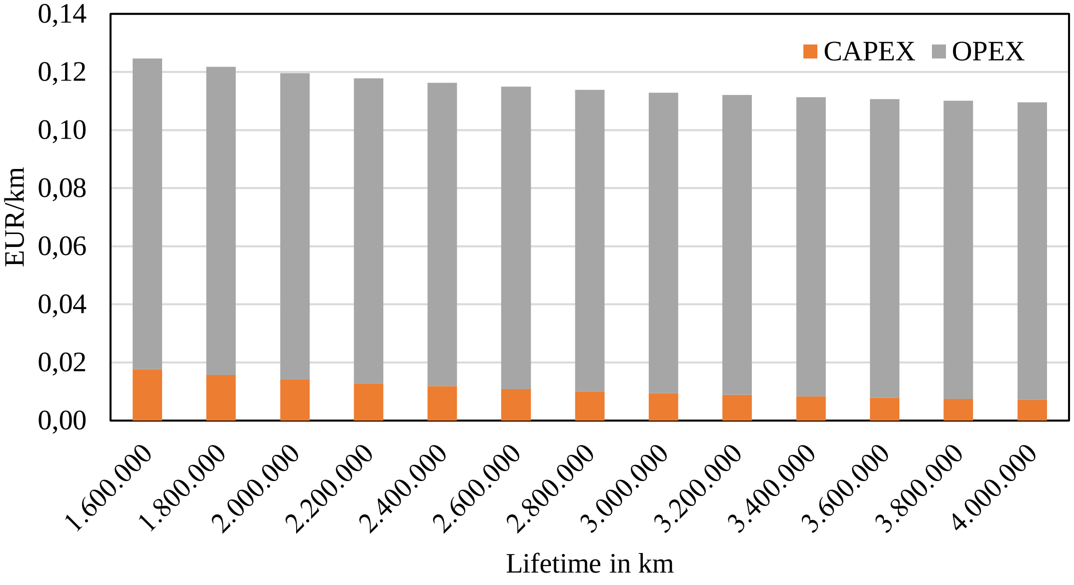


Figure 17: The CAPEX/OPEX ratio for a Tesla Semi based on the lifetime measured in kilometers

In relation to the CAPEX/OPEX ratio for battery trucks the biggest share is, by far, OPEX. The lifetime of the truck has a small influence on it. The sensitivity analysis confirms this tendency as presented in Table 5. Comparing this to Table 4 the densest eHighway with an electricity price of 10 EUR/MWh is more expensive than the battery trucks that has an electricity price of 40 EUR/MWh or less. The lifetime span for battery trucks was estimated based on the 1.6 million kilometers that Tesla guarantee and the assumption that the Tesla Semi would have a longer lifetime than the guarantee. See Appendix C.10 for all details for the analysis of battery electrification and how to convert from EUR/km to USD/GJ. As seen in Table 5, the electricity price has larger impact on the total cost than the lifetime does.

Figure 18 and Figure 19 shows that only very highly dense eHighways with 8,000 users comes close to fossil fuel, and that Tesla Semi is able to compete with fossil fuel prices within the carbon limits. This means that only a small percentage of the transportation demand from heavy duty trucks is cheaper with eHighways in an unregulated market, where the socioeconomic cost of emissions like CO_2 and NOx is not considered, but Tesla Semi could take a large share, if Tesla realizes the announced specification of the truck.

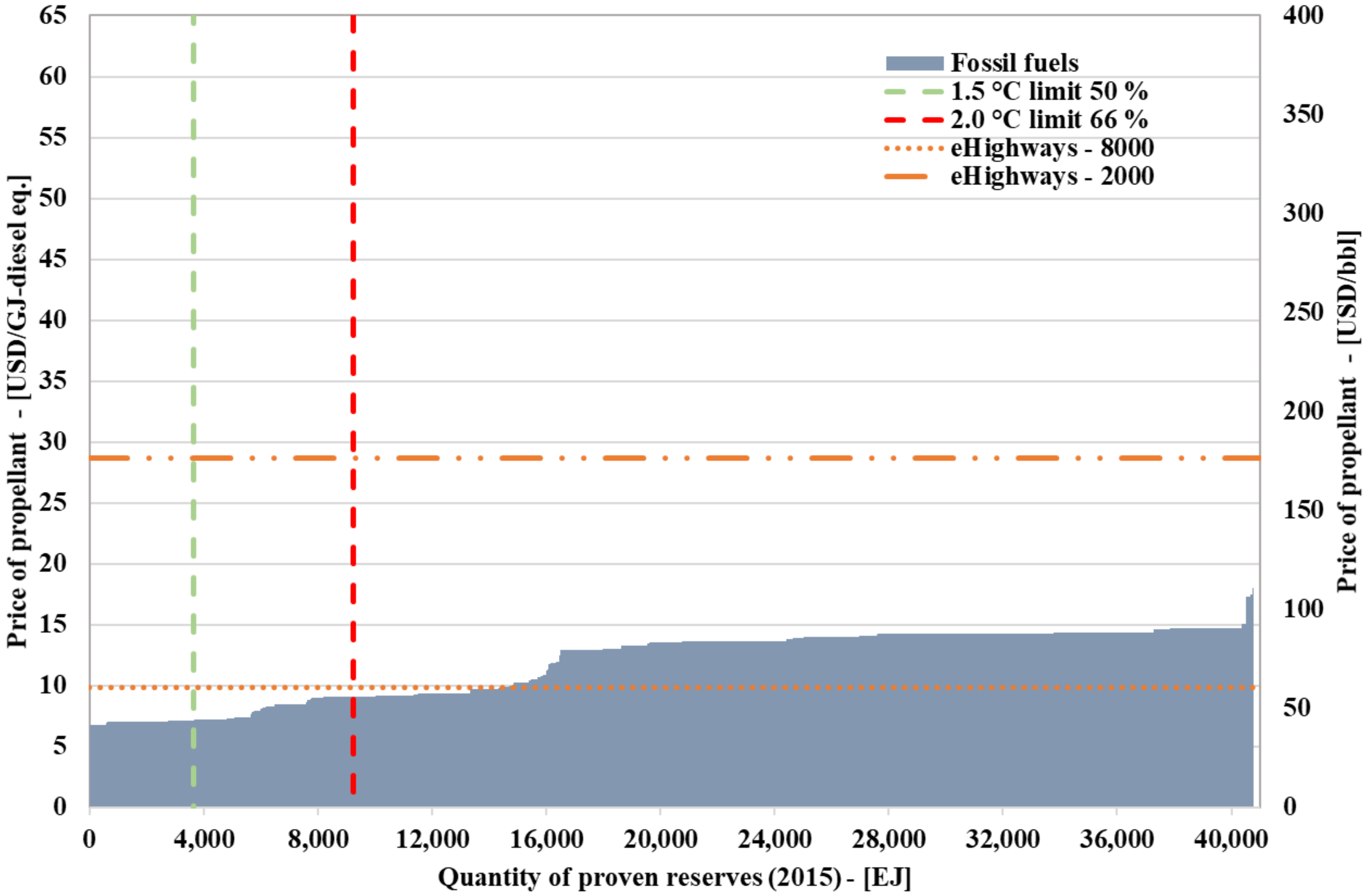


Figure 18: "The Tragedy of the Planet?" comparison based on BGR's reserve data from 2015 for coal, oil, and gas and the cost of eHighways. The two horizontal lines represent the poorly and highly dense eHighway. Emission thresholds for CO_2-emissions depicted to quantify the amount of fossil fuels that we must leave in the ground

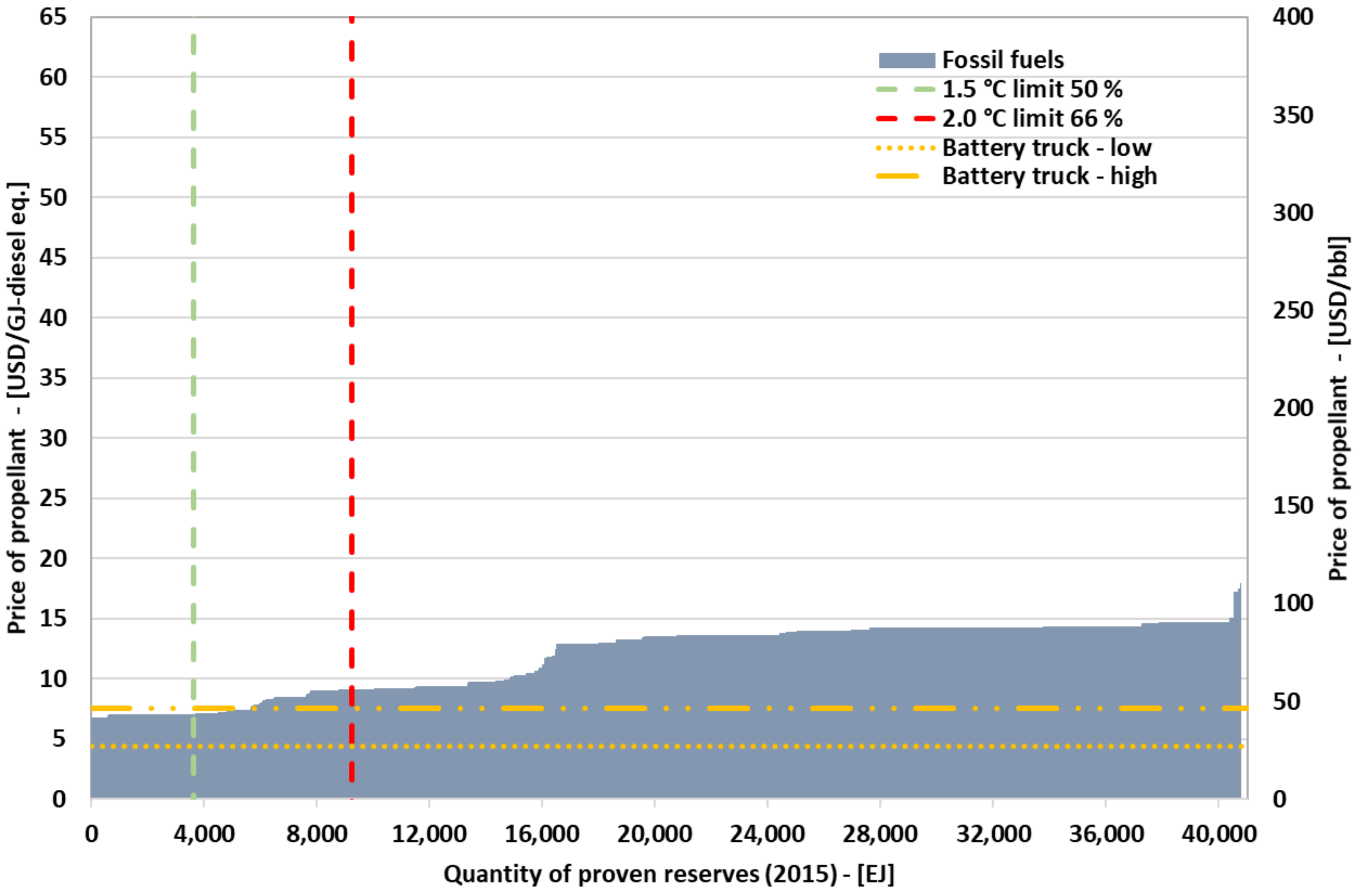


Figure 19: "The Tragedy of the Planet?" comparison based on BGR's reserve data from 2015 for coal, oil, and gas and the cost of a Tesla Semi. The two horizontal lines represent the costs with a low and high electricity price and a long and short lifetime of Tesla Semi. Emission thresholds for CO_2-emissions depicted to quantify the amount of fossil fuels that we must leave in the ground

4.4 Are we facing a tragedy of the commons type of challenge?

We are now able to answer this question, based on the three characteristics for a TCTC. First, the atmosphere can be interpreted as a common-pool resource in relation to climate change. Thus, the atmosphere is our commons. Second, with the fossil fuel reserves and resources we have available, we could violate the carrying capacity of the atmosphere multiple times. We have way more than enough ‘cattle to violate the carrying capacity of our commons’. With respect to the first two of the three criteria, therefore, it seems that we are facing a TCTC. Third, the technical solutions we have available to produce sustainable liquid hydrocarbons of diesel quality will most likely never become economically feasible according to our study. For these alternatives, we are facing a TCTC in relation to global warming. This is mostly an issue for aviation and long distance sea transportation.

We have seen that direct electrification and battery electrification might be an economically feasible, technical solution for trucks, trains, vans, and cars. In relation to these means of transportation, we are not facing a TCTC, if the technologies live up to their promises and can be spread fast enough. The time to act is short so the technologies might not mature in due time.

Figure 20 depicts “The Tragedy of the Planet?” graph with all the technical solutions from the results section. This is a static picture since only the production, refining, and distribution costs have been considered. On the real market, prices also depend on royalties, subsidies, market power, and other strategic trading tools. During the last ten years, the crude oil price have been fluctuating between 30 USD per barrel and 130 USD per barrel (EIA, 2018).

Summing up, we must leave a high fraction of the proven reserves of fossil fuels in the ground if we want to stay within the sustainable limits of our planet. We need urgent action towards mitigating climate change and stopping the emissions of GHG. New technologies have the potential to break the tragedy of the commons on an unregulated market only under very special conditions.

We are facing a TCTC in relation to global warming, which implies we need political interventions and regulations to avoid the tragedy. Several economic tools could be applied to avoid it, and we must act fast. We do not have much time to act, with a time horizon of only 4 to 19 years from 2017, with the current rate of GHG emissions.

Running out of coal, oil, and gas is not the reason nor the argument for finding alternatives to fossil fuels. Using enough fossil fuels to run out of coal, oil, and gas would imply a huge violation of the carrying capacity of the atmosphere. We must be willing to leave fossil fuels in the ground even if this means economic losses in the short term and shutting down already operating fields. We have the technologies, but do we have the will?

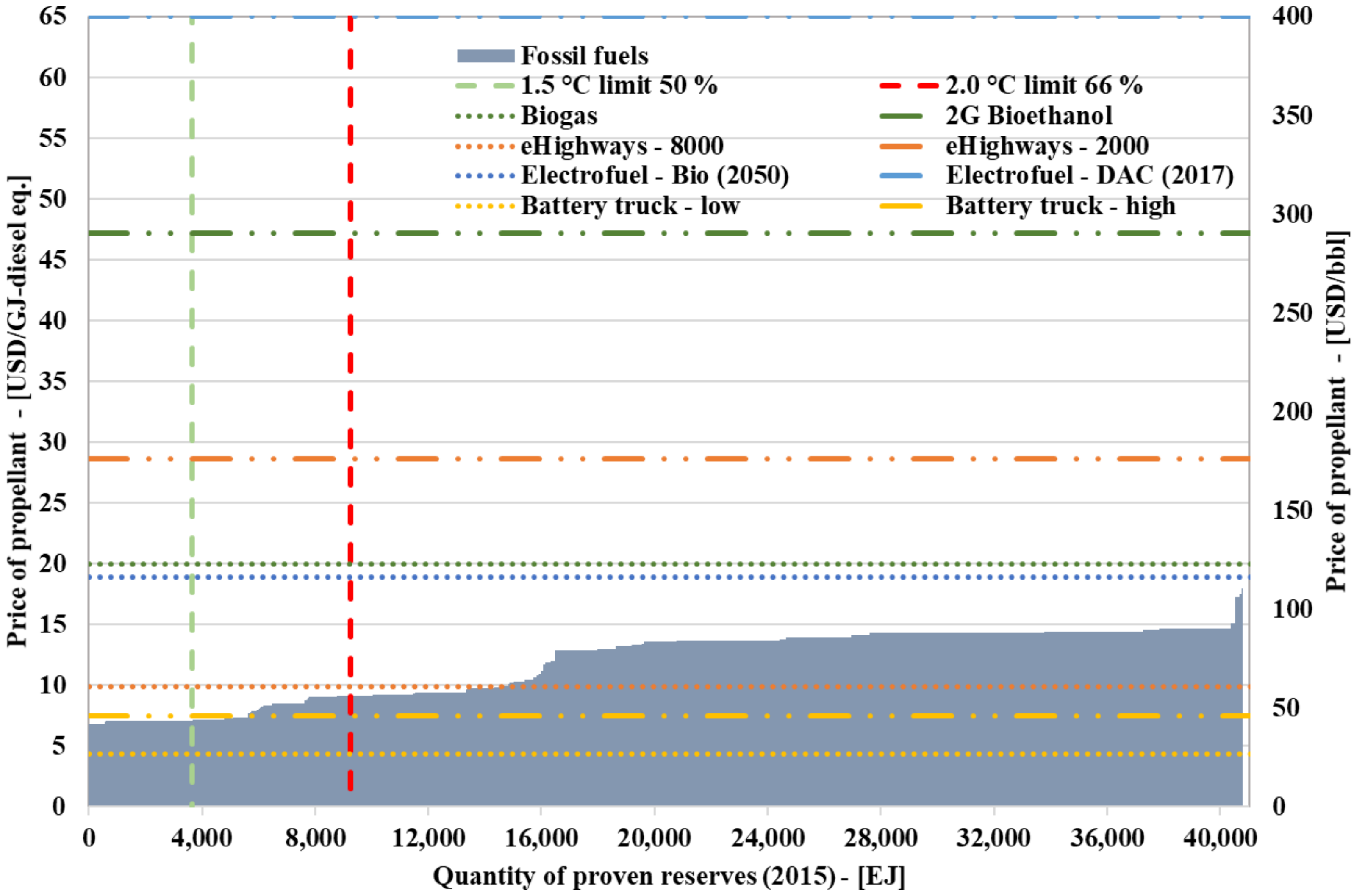


Figure 20: Complete picture of the transportation sector in "The Tragedy of the Planet" graph. The comparison is based on BGR's reserve data from 2015 for coal, oil, and gas and the cost for the alternative propellants. The blue lines represent the span for electrofuels. The orange lines represent the span for eHighways. The green lines represent the span for biofuels. The yellow lines represent the span for battery trucks such as Tesla Semi or similar

5 Discussion

We are, thus, facing a tragedy of the commons type of problem in relation to global warming. Only in specific cases and for part of the transport services, electricity has the chance to outcompete fossil fuels on an unregulated market. In this discussion, we will look at how different time horizons give rise to new problems and new solutions. Furthermore, we will look at which policy instruments to use for mitigating this TCTC. Finally, we will put the challenges of global warming into an economic perspective with all the co-benefits there are related to refraining from using fossil fuels.

The risk profile for global warming and climate change is not clear. This implies that it is hard to assess the worst case scenario for climate change, which in turns makes it difficult to find the cost of not acting. This raises the question of whether so-called utilitarian ethics as the moral code for solving climate change as a TCTC is the right approach. Another approach would be the moral ethics of Emmanuel Kant: the categorical imperative. With this type of ethics, we should act in a way in which all our actions should become a universal law (Johnson & Cureton, 2018).

In relation to global warming and climate change, this would imply that we should either burn all fossil fuels or none. Having clean air and a livable planet are basic needs for a human being, thus the burning of fossil fuels is immoral and should stop immediately. With this type of ethics, we would not start to calculate the cost of refraining from burning fossil fuels, we would just stop because it was immoral. The dominating world ethic is, however, the utilitarian; thus, the rest of the discussion will be based on this ethical code.

5.1 The importance of time horizons

The time horizon is very important when we discuss the feasible, technical solutions. Many of the solutions and tendencies that we have studied are associated with big inertia and low maturity levels. On the longer run, we might have the feasible, technical solutions, but not on the short run, where it really counts in relation to not violating the carrying capacity of the atmosphere. The time horizons of 4 and 19 years before violating the 1.5 °C and 2.0 °C limits respectively at the current rate of emissions does not leave much time for maturing and applying the feasible, technical solutions. In the future, it is likely that it will be cheaper to use electricity than fossil fuels for transportation. The question is, if we dare to take the gamble and wait.

5.1.1 Production prices on the short term

The prices that we have presented in this study are the pure production prices of fossil fuels. With the time horizons that we are facing, it might not be the correct price to compare against, since the capital expenses are already sunk costs, and since the residual lifetime of the capital investments in most cases is longer than the time, we have to act. The marginal cost or cash cost of producing fossil fuels should maybe have been used instead. The argument is that to stay below the 2.0 °C limit many of the already operating fields and mines for fossil fuel production should be shut down (Muttitt et al., 2016). Thus, no new fields and mines should be opened and no further investments should be made. Here, we face the marginal cost and not the breakeven price.

Considering the marginal cost of producing fossil fuels might change the conclusion of our study. We might be facing a TCTC in relation to global warming, because none of the alternatives are competitive with the marginal cost of producing fossil fuels. The main component in the cost of transport fuels is the refining cost. Refining is a capital-intensive industry, but it is hard to find the data needed to assess the marginal cost of refineries. The issues with marginal costs also affect our assumption that renewable energy is going to outcompete fossil fuels in the heat and electricity sector. According to IEA (2016) onshore wind turbines and Photovoltaics (PVs) have the lowest levelized cost of energy (LCOE). This does not mean that onshore wind turbines can outcompete already existing fossil based plants, but that new capacity of onshore wind would be cheaper than new fossil capacity.

To give an idea of how big the possible source of error is, we have compared the reserves in already operating fields to the carbon budgets for the 1.5 °C and 2.0 °C limit (see Table 6). For the 1.5 °C limit we see that the already operating fields contain fossil reserves equivalent to 612 Gt CO_2 more than what can be emitted within this budget. For the 2.0 °C limit the same number is 226 Gt CO_2. From these figures, we see that the marginal prices should have been used as the basis for comparison with alternatives in the feasibility assessment to a much larger extent than what we have done.

Table 6: Comparison of reserves in already operating fields to the carbon budget for the 1.5 °C and 2.0 °C limit as of 2015 adjusted for emissions from cement and land-use emissions. Data from CDIAC (2016), Le Quéré et al. (2016), and Muttitt et al. (2016). *Refer to Appendix B.1 for more details*

Categories	**Oil**	**Gas**	**Coal**	**Total**
Reserves in operating fields [EJ]	4.635	3.111	4.278	11.383
Reserves in operating fields [Gt CO_2]	340	175	433	948
Carbon budget for 2.0 °C limit, 2015 [Gt CO_2]	722			
The available reserve compared to the carbon budget	47 %	24 %	60 %	131 %
Carbon budget for 1.5 °C limit, 2015 [Gt CO_2]	336			
The available reserve compared to the carbon budget	101 %	52 %	129 %	282 %

From Table 6, it is clear that we should shut down a big fraction of the already operating fields and mines. To make the decision of which fields and mines to close is a political issue. The decision could be based on the relation between energy and CO_2 emissions. For the 2.0 °C limit, this would imply that around half of the already operating coal mines should be closed due to the higher CO_2 emissions per energy content from coal. For the 1.5 °C, this would imply that all already operating coal mines should be closed and around half of all already operating oil fields. Another solution could be, to close the fields with the highest socioeconomic cost seen from a global perspective.

Taking marginal costs into account, we are facing an even bigger challenge in relation to refining from burning fossil fuels. The fact that many companies and countries have huge investments bound in production facilities in operating fields and mines drastically lowers their will to give up a lucrative business. Solving the tragedy of the planet will, thus, take some sacrifices in the short run, but it pays of in the long run.

5.1.2 Net negative emissions on the medium term

Sticking to the idea, that the unregulated market is going to solve the issues we are facing in relation to global warming, will lead us to a scenario where we violate the carrying capacity of the atmosphere. If this happens, we are facing some serious issues in relation to climate change. The positive thing is that the effect of emitting GHGs to the atmosphere is delayed slightly. This gives us the opportunity to have net negative emissions at a later point in time to avoid the worst impacts of climate change and bring us within the carrying capacity of the atmosphere again. Today we have all the technologies to do it.

DAC and PCC are two options to capture CO_2 from the air and from combustion processes. When the CO_2 is captured, it can then be stored in the ground either as a liquid (Gibbins & Chalmers, 2008) or as a solid (Matter et al., 2016). To have a net negative emission, the carbon capture and storage (CCS) should be made on biomass or other sources that are not based on fossil fuels. Applying CCS to fossil fuels would remove the CO_2 emissions, but it would not imply net negative emissions. Likewise, the DAC should extract more CO_2 than what is emitted by fossil fuels to imply net negative emissions. Furthermore, CCS could be used when burning fossil fuels to add the price of removing the CO_2 emissions associated with burning fossil fuels. This would make the price comparison to alternative fuels fairer, but the emissions will not become net negative.

Assuming that we decide not to refrain from burning fossil fuels, but instead go for net negative emissions in the future, which is the way we are heading today, the first thing to consider is the area needed to construct all the necessary DAC and PCC facilities including the energy it will take to run the facilities. The next thing to consider is how to implement such a system. How much would it cost, who should pay, where should the facilities be located, and where should the CO_2 be stored? Then there are the issues of monitoring the system. How do we make sure that all countries contribute with their fair share and how do we quantify what the fair share is? And how do we assure that ‘the pumps are always running’ and not shut off, when ‘we’ turn our back to them?

Going for net negative emissions seems to require an incredible amount of international trust, which now seems more as a utopia. The technology is here to do it. The experience of storing CO_2 in the ground might be lacking and the long-term consequences are unknown. At the moment, it seems that we have put our faith in the hands of this technology. The question is if it is going to work.

5.1.3 Solar Fuels, the long-term alternative?

In our study, we find that alternative, sustainable, liquid hydrocarbons will never be able to compete with fossil based liquid hydrocarbons. This might not be entirely true if we look into the future. Solar fuels could turn out to disprove our conclusion, since they rely on the principle of artificial photosynthesis (Lempriere, 2017). The inputs to the solar fuel process are sunlight, CO_2, and water and the output could be either a liquid or a gaseous fuel. With the most advanced types of solar fuels, liquid hydrocarbons could be produced in only one step (Styring, 2011). The one step process decreases the investment cost of the system and removes energy losses in the intermediate conversion steps.

For biofuels and electrofuels, many more steps are needed and the losses in the intermediate steps are bigger. Hydrogen produced from electricity from PVs is not considered a solar fuel, but an electrofuel. The reason is that electricity is one of the intermediate steps in the electrofuel process. For solar fuels electricity is only used to drive auxiliary services.

Solar fuels might have the potential to compete with fossil fuels and be able to replace fossil based liquid hydrocarbons in both airplanes, long distance sea transport, and trucks. Solar fuels are still in a very early development face and far from commercialization. This is also the reason why we did not consider solar fuels in the main analysis. Solar fuels are the only liquid hydrocarbon that we foresee to have the potential to outcompete fossil fuels on market basis. The reason is that the solar fuel process skips several intermediate processes compared to electrofuels and biofuels and that the energy used from the sun is free. Electrofuels might have the potential as well, but the electricity prices would have to be extremely low, please refer to Section 5.3.1 for a further discussion on this. Solving the tragedy of the commons with solar fuels does not seem likely due to the maturity level of the technology.

5.2 Policy instruments for mitigating the tragedy of the commons

We are facing a TCTC in relation to climate change. Thus, political intervention is needed. First, let us consider how other TCTCs are solved. For the classic example of a pasture open to all, a typical way to solve the challenge is to specify ownership rights. Each herdsman gets ownership of a piece of the pasture.

If the commons is split into smaller pieces there are historical evidence that each of the new territories degenerate because they are simply too small (Edney & Harper, 1978). The commons is used less efficiently compared to the case, where the cattle could move around freely. Thus, this solution is not giving the best outcome for society in the traditional case of mitigating the classic tragedy of the commons.

The suitability to solve the climate change challenge through ownership rights of the atmosphere is also very poor, because not everybody can own a piece of the atmosphere, it would be impossible to control and monitor your own part of the atmosphere. Ownership of the atmosphere would not even work on a national level, because the flow in the atmosphere in between areas makes it impossible to control who is violating their limits. Global warming and climate change is by nature a global problem.

We are going to look at policy instruments falling in the following categories: using markets, creating markets, environmental regulation, and engaging the public (Sterner & Coria, 2012). We are not making an exhaustive presentation and discussion of all instruments in each category. We are going to pick some instruments and relate them to the tragedy of the planet.

5.2.1 Using markets

These types of policy instruments make use of already existing markets. This could be in the form of subsidy reduction, taxes, charges, deposit-refund systems, or targeted subsidies (Sterner & Coria, 2012). Markets are used in many situations and they are thought to be an efficient way to allocate resources. The efficient allocation of resources is only obtained under perfect market conditions, such as large number of small buyers and sellers, identical products, full information, negligible transaction costs, and free entry and exit (Perloff, 2014).

It is not given, and in many cases very unlikely, that an unregulated market is a perfect market due to all the conditions that should be fulfilled to obtain a perfect market. We have tried to study an unregulated market since this is in many cases and by-and-large what we are facing in relation to fossil fuels, because there are no global regulations. One of the main reasons that this is not a perfect market is, however, that the negative externalities associated with burning fossil fuels have not been taxed and internalized in market prices on a global scale. The above-mentioned policy instruments can be used both to distort market, but also to correct the flaws in the market. A taxation of fossil fuels will help correct the market, where a subsidy will distort it even more.

Today, fossil fuels are subsidized heavily. The estimate is that fossil fuels globally received a total subsidy of 260 billion USD in 2016 (IEA, 2017a) and 493 billion USD in 2014 (IEA, 2015). This is from a narrow definition of subsidies called pretax subsidies. Estimating the undercharging for externalities, this number is estimated to be 5.3 trillion USD in 2015 or approximately 6.5% of global Gross Domestic Product (GDP) (Coady, Parry, Sears, & Shang, 2017). For comparison, the subsidies for renewable energy is estimated to 135 billion USD in 2014 (IEA, 2015) – equivalent to 2.5 % of the full subsidy of fossil fuels including externalities.

By looking at how subsidies are used today, it is clear that none of the markets, where fossil fuels are competing, are perfect markets. The policy instruments of subsidies and taxes are used completely opposite of what the economic theory suggests. This creates a market failure that adds to the challenges related to the tragedy of the planet. The effect of taxing the CO_2 emissions from burning fossil fuels is depicted in Figure 21. A tax on 100 USD/ton is shown in Figure 21, chosen because this is the price that Climeworks projects to obtain for DAC in 2030. This would imply, that, compared to renewable alternatives, it might be better to emit the CO_2 from burning fossil fuels, then extract it directly from the air and storage it in the ground. Caution should be taken before choosing this option as discussed in Section 5.1.2.

5.2.2 Creating markets

Another type of policy instruments is creating markets. This can be done by policy instruments, such as: property rights and decentralization, tradable permits and rights, and international offset systems (Sterner & Coria, 2012). The example of property rights in relation to the classic tragedy of the commons have been discussed in the introductory part of this section. Property rights could also be given to just one person. In this case, that one person can decide to 'take in cattle' from other herdsmen who are then going to pay the owner of the pasture. Their willingness to pay in this case declines, if the value of their cattle declines due to overgrazing. This creates an incentive to the owner of the commons of not violating the carrying capacity of the commons. The issue about property rights in relation to the atmosphere is not about finding an owner, but to facilitate and monitor such a system. Especially, because the responsibility in this case lies with only one person or entity.

A more feasible solution could be to create a market for CO_2 emissions such as the EU Emissions Trading System (EU ETS). EU has created a market for CO_2 emissions, where e.g. power plants must buy quotas for the CO_2 that they are emitting. Not all sectors are included in the EU ETS, but they could have been. The market is a cap and trade market, which implies that a fixed amount of quotas are available on the market. The price is then determined by the demand for quotas. In relation to a global solution for the tragedy of the planet, the cap could be set equivalent to either the 1.5 °C or 2.0 °C limit, which would imply that no more CO_2 was emitted than what was within the carrying capacity of the atmosphere.

Creating a market for CO_2 or GHG emissions would in principle be a functional and efficient way to solve the challenge that we are facing in relation to global warming. Such a market would give a clear picture of the abatement cost and the players in the market could decide to buy a quota or find a cheaper alternative that would not emit any CO_2 or GHG. The issue with this model is that all countries in the world would have to agree on it, and then there is the issue of where in the value chain the quota should be bought. In the EU ETS, the quota should be bought when the emissions occur, which is e.g. at the power plants. Another solution would be to move the responsibility of buying quotas to the place of extraction. This would be easier to administrate because there are fewer extraction sites than places of burning fossil fuels. This could also be a potential downside, if the players were so few in numbers that they could gain market power.

In relation to our study, the effect of adding a tradeable quota system for CO_2 emissions, where the price ends up at 100 USD/ton is depicted in Figure 21. But as can be seen from Figure 21, if we were to avoid the tragedy of the planet using the electrofuel technologies known today, the quota price should be around 990 USD/ton to stay within the 1.5 °C limit. The same number should be around 790 USD/ton to stay within the 2.0 °C limit.

Tradeable quotas have also been used to solve overfishing, another traditional TCTC. This solution has proven to be very effective in places that can be monitored and controlled with an acceptable cost, such as lakes and national waters. The individual fishing quotas from New Zealand is an example where quotas have been used to reach a sustainable population of fish (Sanchirico & Newell, 2003).

The difference between overfishing and global warming in relation to transferable quotas is that overfishing is often restricted to a certain area, as opposed to emissions to the atmosphere, which affect the global climate. This implies that a global quota system might be even harder to enforce than a national or regional fishing quota system. A quota system would, however, be a functional and efficient way to avoid the tragedy of the planet. The challenge lies in implementing and enforcing such a system globally.

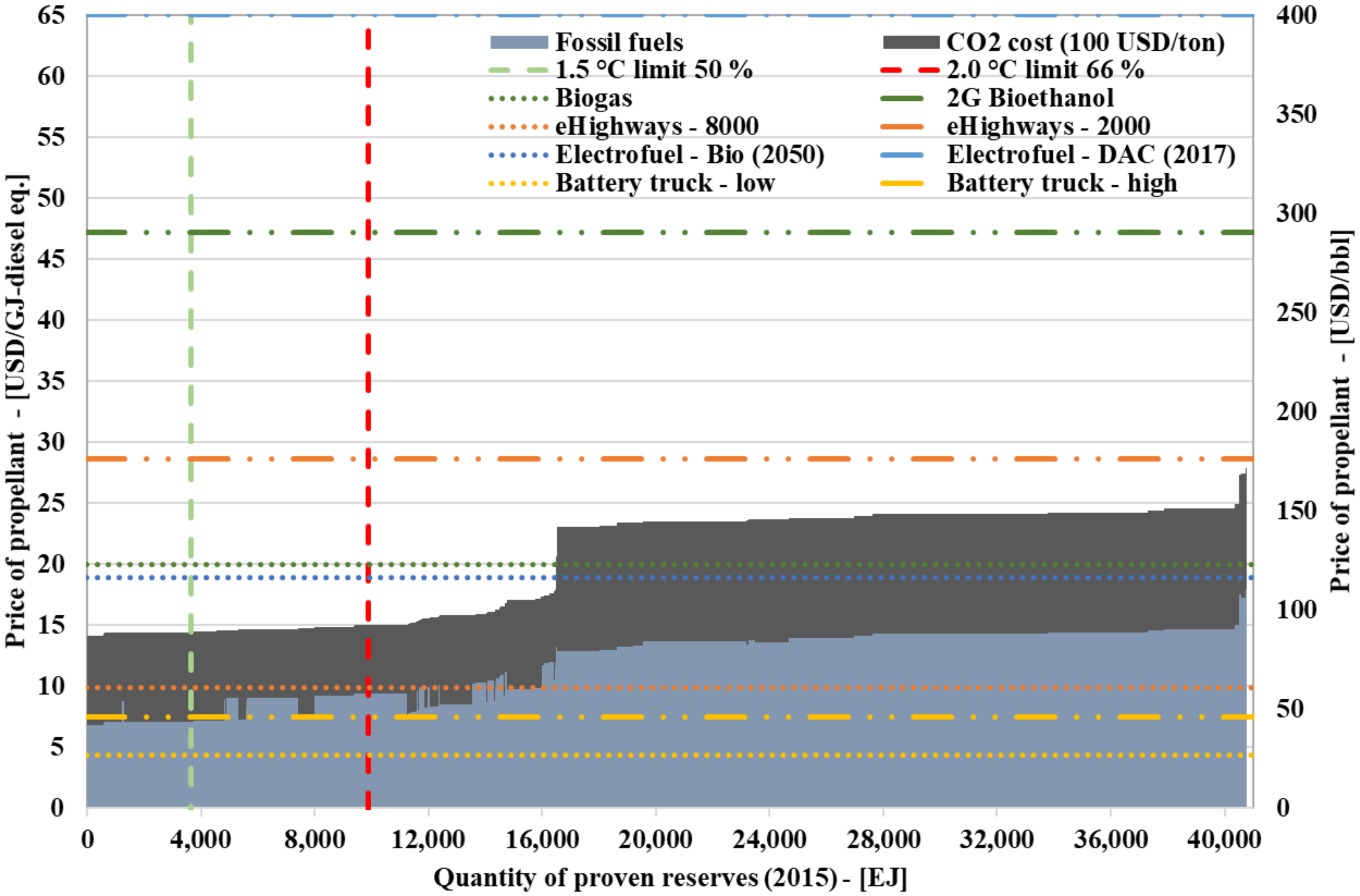


Figure 21: The effect of having a quota price or carbon tax at 100 USD per ton of CO_2 is illustrated on the final version of "The Tragedy of the Planet?" graph. When the CO_2 price is added more alternatives becomes feasible. Another effect is that the relative order of the fossil fuels rearranges due to differences in emission intensities per energy unit. (Refer to Appendix C.11 and Appendix C.12 for further details.)

5.2.3 Environmental regulations

These types of policy instruments include: standards, bans, permits and quotas, zoning, and liability. The ethics from the categorical imperative is reflected in some of these policy instruments, especially bans. A ban on fossil fuels is a simple tool to formulate, but harder to set into action and enforce. A ban might not give the most efficient transition away from fossil fuels and onto renewable alternatives. No global policy instruments are easy to enforce, but a ban might be one of the simpler ones. To mine and extract coal, oil, and gas in big scale, large infrastructure complexes are needed. These structures would be easy to spot from a satellite. The challenge would then be to get the local, national or regional authorities to act.

Standards are the last policy instrument in this group that will be discussed. They are guidelines that specify specific ways to act, limits to stay within for emissions, and for energy consumption. Furthermore, they can also set limits to which technology is allowed to be used or not to be used. Lastly, standards can also specify how economic modelling should be conducted. Especially interesting, is the discount rate used in socioeconomic analyses in relation to standards for economic modelling and global warming.

Discount rates are used to give an idea of the time value of money, which implies that money available today is worth more than an identical amount of money available in the future. This concept works relatively well for projects or actions that only have short-term effects. The complications occur when the projects or actions have intergenerational links. What is the value of the future, and what is the value of future generations? Discount rates could in this case be used to downgrade the value of future generations. Determining the discount rate is very tricky and too technical to go into details here. A zero or near-zero discount rate have been suggested by a number of authors (Edenhofer et al., 2014), not to penalize future generations just because they are born later.

5.2.4 Engaging the public

The last type of policy instruments that are discussed is engaging the public, which includes public participation and information disclosure. This is the softer category of policy instruments, but this does not diminish the importance of these instruments. Experiments have shown that receiving expert information on climate research enhance the altruistic behavior of individuals. Furthermore, the possibility to publicly invest to gain social reputation also enhances altruistic behavior (Milinski, Semmann, Krambeck, & Marotzke, 2006).

This suggests that reputation, information, and communication play a vital role in the behavioral reinforcement. This has also been found in several psychological studies by Edney and Harper (1978), Milinski, Semmann, and Krambeck (2002), Milinski et al. (2006) and Wedekind and Milinski (2000). Reputation, information, and communication seem to help mitigate the challenges we are facing in relation to common-pool resources and global warming. The challenge is that global warming consists of many players. It is hard for each individual player to see what others are doing thus no reputation is gained. The many players also make communication and information sharing challenging on a global level.

The set of tools from this category deals with full information, which is one of the assumptions for a perfect market. This might be the most crucial assumption for a perfect market because missing information or a wrong perception of information often makes us act against our values. If we had full information of all consequences of taking an airplane to Thailand fueled by fossil fuels, we might not enjoy our trip as much or even refrain from conducting it. Knowing that you actively destroy the future for your kids and the coming generations might make you act differently.

5.3 What does it take?

When the utilitarian way to view the world is chosen as one's ethical code, it is important to consider both pros and cons of an action or inaction. This section of the discussion will first focus on the costs of applying some of the policy instruments mentioned in Section 5.2, then focus on the co-benefits of refraining from using fossil fuels including the perspective of the cost for Denmark to transition their energy system into a fully renewable system. This section will be wrapped up with a short discussion on aviation and the cost of flying.

5.3.1 The cost of intervention

In this section, the focus is on the price sensitivity of electrofuels related to the cost of fossil fuels. Thus, this is not a full sensitivity analysis since both biofuels and electricity are omitted from the analysis. Biofuels have been omitted due to their high cost and the limited nature of the supply. Electricity has been omitted since, for now, full electrification of the whole transportation sector does not seem technically feasible. Furthermore, electricity has the potential to outcompete fossil fuels already today.

In an unregulated market, electrofuels are competing with fossil fuels at a price of 7.19 USD/GJ for the 1.5 °C limit, and at 9.22 USD/GJ for the 2.0 °C limit, see Figure 22. For electrofuels to be competitive with fossil fuels at the 1.5 °C limit, the electricity price should be 0.27 EUR/MWh and the CO_2 should be supplied for free. At the 2.0 °C limit, the electricity price should be 3.81 EUR/MWh and the CO_2 should be supplied for free. Both these situations will require political intervention in the form of subsidies to become reality on a large scale.

Another type of political intervention could be made, where a CO_2 tax or a quota market was set in place resulting in a CO_2 emission cost of 100 USD/ton. In this market, the electrofuels are competing with a fossil fuel price of 14.53 USD/GJ for the 1.5 °C limit and of 15.59 USD/GJ for the 2.0 °C limit. At these prices, the electricity prices should be 14.84 EUR/MWh and 17.29 EUR/MWh for electrofuels to be competitive at the 1.5 °C limit and 2.0 °C limit respectively. The CO_2 should still be supplied for free. Once again, subsidies might be needed to make electrofuels competitive in a market where CO_2 emissions cost 100 USD/ton.

Imagine an electrofuel factory based onsite or near to a wind farm and/or a PV farm where the electricity would be supplied at 15 EUR/MWh just like the Mexican wind farm mentioned in Section 3.3.4. By placing a DAC plant at the electrofuel factory all inputs for producing liquid fuels are present; water, carbon, and electricity. With such a setup, the price for electrofuels including distribution cost would end at 21.11 USD/GJ, see Figure 22. If no subsidies were to be given to make these electrofuels competitive with fossil fuels, the CO_2 emission cost would have to be around 210 USD/ton for the 1.5 °C limit and 190 USD/ton for the 2.0 °C limit.

The true cost of intervening is hard to determine but starting from the unregulated market an estimate can be made. To make the estimate the future demand for electrofuels should be determined. The future demand for electrofuels is hard to predict, so here it is assumed that mainly the aviation industry is demanding liquid hydrocarbons. The global jet fuel demand has been estimated to around 20 EJ in 2040 (IEA, 2015). According to de Klerk (2011), a high jet fuel producing setup of a Fischer-Tropsch process gives 60% of the mass output as jet fuel. The remainder mainly being gasoline. This gasoline is assumed to be able to cover long distance sea transportation, which might not hold true for the future. The demand for electrofuels is thus 33.33 EJ. Multiplying the quantity with the price difference between our imaginary electrofuel factory and the market prices for fossil fuel, and relating this cost to the global GDP the cost of intervention is estimated to end up at around 0.46% of GDP for the 1.5 °C limit and around 0.40 % of GDP for the 2.0 °C limit.

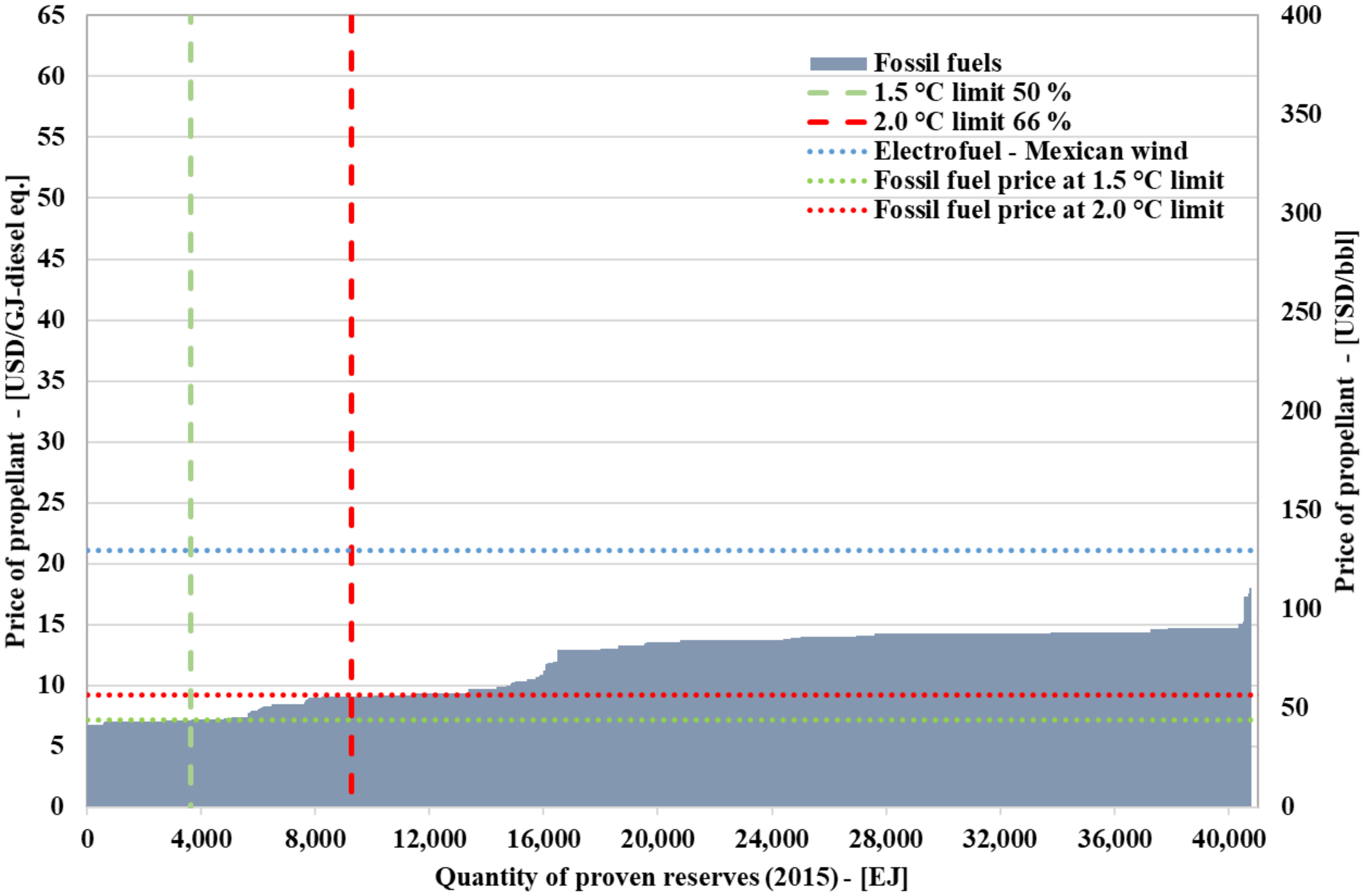


Figure 22: "The Tragedy of the Planet?" illustration of proven fossil fuel reserves based on BGR's reserve data from 2015 for coal, oil, and gas. The cost of producing one GJ diesel-eq. Emission thresholds for CO_2-emissions depicted to quantify the amount of proven fossil fuel reserves that we must leave in the ground in order to stay within the given temperature limits. Green and red lines showing the market price of fossil fuels in an unregulated market at the 1.5 °C limit and the 2.0 °C limit respectively. The price of producing electrofuels at an electricity price of 15 EUR/MWh is depicted as a blue line

5.3.2 The global perspective

During our study we have on purpose not included externalities in the illustrations, because the aim has been to assess the feasibility of alternative solutions under prevailing price formation on the markets of hydrocarbons in question. As we have seen till now, the sustainable alternative hydrocarbons all imply an additional cost in this picture. But there may be co-benefits of refraining from using fossil fuels that are not internalized in market prices, and these benefits could be quite large. Working group III of the IPCC works with six such co-benefits of refraining from using fossil fuels. These include reduction in air pollution, improved health, quality of life and comfort, improved productivity, employment and creation of new business opportunities, improved social welfare and poverty alleviation, and energy security (IPCC, 2007). The health benefits have been estimated to be the most important environmental impact (Staff Mestl et al., 2004), and it is closely related to air quality. It is so important that the:

> *"Monetized health benefits from improved air quality have been estimated to make up a substantial fraction of, or even exceed, GHG mitigation costs"*(Takeshita, 2012)

According to UNEP (2005), the cost of air pollution in developed countries is approximately 2 % of GDP, and for developing countries it is between 5 and 20 % of GDP. We see the same tendencies for the Danish case in the next section.

The four last co-benefits are briefly described here. Improved productivity includes e.g. increased agricultural productivity due to lower ground level ozone (O'connor, Zhai, Aunan, Berntsen, & Vennemo, 2003). Employment creation and new business opportunities could emerge from the transition towards a full renewable energy system. When the whole energy system changes, this will open new business opportunities.

The improved social welfare and poverty alleviation comes into play through more energy efficient household equipment and low energy building design. These two improvements will decrease the cost of living, which will free up money for education or other purposes. Energy security is obtained, because countries do not have to rely on some few oil or gas producing countries. Wind and solar as examples can be located nationally, which then produces energy where the fuel source cannot be interrupted from other nations.

5.3.3 Setting the cost of intervention in perspective

In this section, we will set the cost of intervention into perspective by comparing the cost to other areas of our everyday life that we gladly pay. First, let us consider flying, the trickiest part of the transport sector to convert into a sustainable alternative. The rules and regulations for jet fuels are very strict due to safety reasons. Consequently, the number of alternative propellants is limited. The question is, how much our plane tickets would rise in price, if the trip had to be done with sustainable jet fuel.

Consider a roundtrip from Copenhagen to New York. The total length is approximately 12,400 kilometers. Depending on the type of aircraft, the fuel consumption per seat is in the range of 0.025 to 0.039 liters per kilometers for an Airbus A320neo and an Airbus A340-300, respectively

(Christensen, 2013). The average jet fuel price in 2017 was 11.17 USD/GJ (IATA, 2018);with the technology and average Danish electricity prices of today (40 EUR/MWh incl. transmission), we would be able to produce jet fuel from DAC and electrolysis for less than 65 USD/GJ (as shown in Appendix C.9). With the technology advances expected before 2050 and the average Danish electricity prices of today (40 EUR/MWh incl. transmission), the price would be less than 25 USD/GJ. With the technology advances expected before 2050 and the imaginary electrofuel factory described in Section 5.3.1 the price would be 21.11 USD/GJ (as shown in Appendix C.9).

This would imply a substantial increase in the cost of jet fuel, and it would add between 625 and 975 USD per ticket, if the fuels were to be produced today or 115 to 250 USD if the fuel were to be produced in 2050 (Appendix C.9). The 115 USD corresponds to a price increase of 20 % for the plane ticket and the difference is only going to get smaller as the efficiency of jet engines is improved. Do we need to travel with planes as much as we do today? If so, then paying 975 USD, in the worst case, is what keeps us from using the most sustainable fuel we can produce instead of fossil fuels.

Second, let us take the cost of transitioning the entire Danish energy system into a fully renewable energy system, transportation included using an analysis from the Danish Energy Agency (DEA, 2014). This analysis shows that it will cost around 10 billion DKK extra a year towards 2050 to transition the Danish energy system from a fossil based system into a fully renewable system, which is approximately 0.5% of the Danish GDP (DEA, 2014; DST, 2017). The cost depends on which transition strategy is used. The above mentioned cost is for the so-called wind scenario from DEA (2014), and in this scenario, a large share of hydrogen production through electrolysis and subsequent electrofuel production is included. Since the study was finalized in 2014, the prices for wind and solar have drop drastically, which may result in an even lower extra cost than 10 billion DKK a year.

If we make the transition into a fully renewable energy system, where electrification covers a larger share of the demands for heat and transport, we are looking into a future with reduced amounts of air pollution compared to a fossil fuel based scenario. The total cost of anthropogenic emissions from Denmark in relation to societal cost of health effects is 27.3 billion DKK as of 2013 (Brandt, Solvang Jensen, Andersen, Plejdrup, & Nielsen, 2016) a large part of which is due to emissions from the use of fossil fuels in the transport sector, especially fossil diesel. This figure covers approximately 3,500 premature deaths. If the transition strategy for Denmark is focused on electrification instead of burning biomass, it will be self-financing if the air pollution is cut by one-third. A larger reduction would make the transition a very sound socioeconomic decision. The same results are found on a global scale (Takeshita, 2012).

Comparing the 0.5 % of GDP with other aspects of the Danish economy; Denmark uses 1.2 % of their GDP on defense (Danish Ministry of Defence, 2018), 0.7 % on foreign aid (Danish Ministry of Foreign Affairs, 2017), and the Danes throw out food with a value of 0.7% of GDP each year (Danish Agriculture and Food Council, 2016). When speaking on the phone to president-elect Donald Trump in 2017, the Danish Prime Minister promised without hesitation to live up to the agreement to use 2 % of Danish GDP on defense (Ritzau, 2016).

In May 2018, the US president expressed a wish for all NATO countries to use 4 % of their GDP on NATO, which was strongly encourage by NATO general secretary Jens Stoltenberg (NATO, 2018). This is not mention as any argument against prioritizing defense, but only to show our apparent willingness to prioritize very short term safety and protection compared to how difficult it still seems to be to decide paying the much smaller cost of ensuring a sustainable world for future generations.

Transitioning into a fully renewable energy system would imply that we would rely less on other countries, which arguably might decrease the need for defense. Furthermore, it could be argued that the best type of foreign aid Denmark could give, is in the form of not contributing to climate change, since this would make it easier to make a living in the developing countries. It is hard to make a living when your food is lost through droughts or floods. Unfortunately, it is too late to stop all the consequences of climate change so foreign aid is still needed.

In Denmark, monthly subscriptions for fitness, music, streaming services, etc. is quite popular. In relation to transitioning the Danish energy system, all Danes would have to pay 150 DKK per month to get an energy system, where no fossil fuels will be burned. This would add up to 150 DKK a month, equivalent to a monthly subscription for Netflix, and besides a sustainable energy system it would provide the benefit of clean air, where the smell and particles from gasoline and diesel exhaust would not exist. Is this too much to pay – and is it worth less than a subscription for Netflix?

Lastly, the 150 DKK per month, could also be seen as an insurance against climate change. 150 DKK per month is way less than what people usually pay to insure themselves, their houses, their cars, their furniture, etc. Is this too much too pay for a future without climate change?

6 Conclusion

We are facing a Tragedy of the Commons Type of Challenge in relation to global warming and climate change. The first characteristic that is fulfilled is the fact the atmosphere is a common-pool resource in relation to greenhouse gas emissions. The second characteristic that is fulfilled is the fact that we do have enough fossil fuels to violate the carrying capacity of the atmosphere. At the current rate of emissions, we are going to violate the carrying capacity of the atmosphere within 4 to 19 years depending on which carbon budget you set as the carrying capacity, i.e. the 1.5 °C target or the 2.0 °C target. The short time horizon is also what affects the third and last characteristic that is fulfilled. This is the fact that we do not have any feasible, technical solutions today and not within the timeframe, in which we have to act.

All alternative hydrocarbons come at higher cost than the fossil fuel based hydrocarbons in an unregulated market. The fact that the already operating coal, oil, and gas fields and mines contains more fossil fuels than what we can afford to burn if we want to stay well below 2.0 °C, makes the technical solutions compete against the marginal cost of producing fossil fuels which is even lower than the breakeven price.

Political intervention is, therefore, needed, as we have all the technical solutions that come at a higher production cost. Some technologies might turn out to be able to outcompete fossil fuels in an unregulated market. Electricity seems to be one of them. The problem is that aviation and long-distance sea transport is not well suited to be electrified. The conclusion from this is that everything that can be electrified should be electrified, i.e. cars, busses, trains, trucks, short distance aviation, and short distance ferries.

The natural horse was not outcompeted from transportation because we found a better and cheaper way to produce a synthetic horse. It got outcompeted because we found a new technology; the car. The same is likely to be true for liquid hydrocarbons. They are probably not going to be outcompeted because we find a better and cheaper way to produce them synthetically, but because we find a new technology; electricity for transportation. There might be one exemption in terms of liquid hydrocarbons produced as solar fuels, which is still very immature and might never materialize with its full potential.

Political will is needed if we are to avoid playing hazard with the tragedy of the planet. There are many policy instruments that could be used to avoid it. The most effective would be a ban of fossil fuels, and the most efficient would be a quota system with tradeable quotas in a cap and trade type of market. None of this is going to happen without communication, information sharing, and a huge international effort. The technology is here, the extra cost seems to be outweighed by the benefits in health improvements alone, therefore, we need to act and it pays off to act. Around 25 US dollars a month per Dane is what it costs to get a fully renewable energy system in Denmark. Similar results seem reasonable for the planet. Is this too much to pay to avoid the tragedy of the planet?

7 Bibliography

Akerman, P. (2017). eHighway - Electrified heavy duty road transport.

Alberta Energy. (2007). What is Natural Gas? Retrieved from http://www.energy.alberta.ca/NaturalGas/723.asp

ASTM. (2017). *ASTM D7566 - Standard specification for aviation turbine fuel containing synthesized hydrocarbons*.

Bechtel. (2017). Sour Gas Treating - Amine Gas Treating - BHTS - Bechtel. Retrieved September 21, 2017, from http://www.bechtel.com/services/oil-gas-chemicals/bhts/sulfur/sour-gas-treating/

Becker, W. L., Braun, R. J., Penev, M., & Melaina, M. (2012). Production of FischereTropsch liquid fuels from high temperature solid oxide co-electrolysis units. *Energy*, *47*, 99–115. https://doi.org/10.1016/j.energy.2012.08.047

BGR. (2016). *Energy Study 2016. Reserves, resources and availability of energy resources*. Hannover. Retrieved from https://www.bgr.bund.de/EN/Themen/Energie/Downloads/energiestudie_2016_en.pdf;jsessionid=81E96DBF1FADFD1E82D9BD702B00CC0C.1_cid331?__blob=publicationFile&v=2

Blesl, M., & Bruchof, D. (2010). Liquid Fuels Production from Coal & Gas, 4. Retrieved from https://iea-etsap.org/E-TechDS/PDF/P06-CTLGTL-GS-gct-AD_gs.pdf

Boerrigter, H., & Boerrigter, I. H. (2006). Economy of Biomass-to-Liquids (BTL) plants An engineering assessment. Retrieved from www.ecn.nl/biomass

BP. (2016). *BP Statistical Review of World Energy June 2016*. Retrieved from https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf

BP. (2017a). BP Statistical Review of World Energy 2017 - underpinning data, 1965-2016 [Microsoft Excel spreadsheet]. Retrieved from http://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf

BP. (2017b). Oil reserve definitions. Retrieved from http://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-oil-reserve-definitions.pdf

Brandt, J., Solvang Jensen, S., Andersen, M., Plejdrup, M., & Nielsen, O.-K. (2016). *Health effects and health costs from emission sectors in Denmark [In Danish: Helbredseffekter og helbredsomkostninger fra emissionssektorer i Danmark]*. Retrieved from http://dce2.au.dk/pub/SR182.pdf

Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2017). Electrofuels for the transport sector: A review of production costs. https://doi.org/10.1016/j.rser.2017.05.288

Cazzola, P., Morrison, G., Kaneko, H., Cuenot, F., Ghandi, A., & Fulton, L. (2013). *Production costs of alternative transportation fuels - Influence of Crude Oil Price and Technology Maturity*. Retrieved from https://www.iea.org/publications/freepublications/publication/FeaturedInsights_AlternativeFuel_FINAL.pdf

CDIAC. (2016). 2016 Global Carbon Project. Retrieved June 29, 2017, from http://cdiac.ornl.gov/GCP/carbonbudget/2016/

Christensen, O. K. (2013). This much fuel is used by the differenet SAS-planes [In Danish: Så meget fuel bruger de forskellige SAS-fly]. Retrieved February 9, 2018, from https://www.check-in.dk/saa-meget-fuel-bruger-de-forskellige-sas-fly/

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., … Kingdom, U. (2011). Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, et al.]* (pp. 209–332). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Clifford, C. B. (2017). Fischer-Tropsch Process to Generate Liquid Fuels | EGEE 439: Retrieved September 21, 2017, from https://www.e-education.psu.edu/egee439/node/679

Coady, D., Parry, I., Sears, L., & Shang, B. (2017). How Large Are Global Fossil Fuel Subsidies? https://doi.org/10.1016/j.worlddev.2016.10.004

Constable, E. (2016). Patagonian ice melts as Chile experiences its worst drought on record. Retrieved May 21, 2018, from https://www.sbs.com.au/news/patagonian-ice-melts-as-chile-experiences-its-worst-drought-on-record

Danish Agriculture and Food Council. (2016). *Christmas food in large quantities - but unfortunately a lot of it ends in the trash can [In Danish: Julemad i store mængder - men meget af det ender desværre i skraldespanden]*.

Danish Ministry of Defence. (2018). Economy for the portfolio functions [In Danish: Ministerområdets økonomi]. Retrieved February 22, 2018, from http://www.fmn.dk/videnom/Pages/ministeromraadetsoekonomi.aspx

Danish Ministry of Finance. (2013). New and lower socio-economic discount rate [In Danish: Ny og lavere samfundsøkonomisk diskonteringsrente], 1. Retrieved from https://www.fm.dk/nyheder/pressemeddelelser/2013/05/ny-og-lavere-samfundsoekonomisk-diskonteringsrente

Danish Ministry of Foreign Affairs. (2017). About Danida [In Danish: Om Danida]. Retrieved February 22, 2018, from http://um.dk/da/danida/om-danida/

de Klerk, A. (2011). *Fischer- Tropsch Refining*.

DEA. (2012). Data sheet for production and conversion of energy carriers [In Danish: Datablad for energibaerer produktion og konvertering 1].

DEA. (2014). *Energy scenarios towards 2020, 2035, and 2050 [In Danish: Energiscenarier frem mod 2020, 2035 og 2050]*. Retrieved from https://ens.dk/sites/ens.dk/files/Basisfremskrivning/energiscenarier_-_analyse_2014_web.pdf

DEA. (2016a). Assumptions for socioeconomic analyses in the energy sector [In Danish: Forudsætninger for samfundsøkonomiske analyser på energiområdet], (april), 1–22.

DEA. (2016b). Kriegers Flak. Retrieved February 19, 2018, from https://ens.dk/service/aktuelle-udbud/kriegers-flak

DEA. (2017a). *Background report for the base projections 2017 [In Danish: Baggrundsrapport til basisfremskrivning 2017]*. Copenhagen. Retrieved from https://ens.dk/sites/ens.dk/files/Basisfremskrivning/baggrundsrapport_til_bf_2017.pdf

DEA. (2017b). *Underlying socioeconomic assumptions of calculations for energy prices and emissions [In Danish: Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner]*.

Dimitriou, I., Garcí a-Gutié rrez, P., Elder, R. H., Cué llar-Franca, R. M., Azapagic, A., & K Allen, R. W. (2015). Carbon dioxide utilisation for production of transport fuels: process and economic analysis. *Energy Environ. Sci. Energy Environ. Sci*, *8*(8), 1775–1789. https://doi.org/10.1039/c4ee04117h

Dimitriou, I., García-Gutiérrez, P., Elder, R. H., Cuéllar-Franca, R. M., Azapagic, A., & Allen, R. W. K. (2015). Carbon dioxide utilisation for production of transport fuels: process and economic analysis. *Energy Environ. Sci.*, *8*(6). https://doi.org/10.1039/C4EE04117H

DST. (2017). Annual survey of the National economy, the whole economy - Statistics Denmark [In Danish: Årligt nationalregnskab, hele økonomien - Danmarks Statistik]. Retrieved February 22, 2018, from https://www.dst.dk/da/Statistik/emner/nationalregnskab-og-offentlige-finanser/aarligt-nationalregnskab/aarligt-nationalregnskab-hele-oekonomien

Ea Energianalyse. (2016). *Biogas and other renewable fuels for heavy duty transport - analysis of the posibilities and challenges relaed to facing out fossil fuels [In Danish: Biogas og andre VE brændstoffer til tung transport - Analyse af muligheder og udfordringer ved udfasning* .

Ea Energy Analyses. (2014a). *Welfare economic prices of coal, petroleum products and natural gas - update of add-ons to international forecasts for projection of Danish prices at consumption*. Copenhagen. Retrieved from https://ens.dk/sites/ens.dk/files/Analyser/fossil_fuel_price_add-on_final.pdf

Ea Energy Analyses. (2014b). *Welfare economic prices of coal, petroleum products and natural gas - update of add-ons to international forecasts for projection of Danish prices at consumption*.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., … Minx, J. C. (2014). *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/CBO9781107415416

Edney, J. J., & Harper, C. S. (1978). The Commons Dilemma. *Environmental Management*, *2*(6), 491–507. https://doi.org/10.1007/BF01866708

EIA. (2012). Crude oils have different quality characteristics - Today in Energy - U.S. Energy Information Administration (EIA). Retrieved September 20, 2017, from https://www.eia.gov/todayinenergy/detail.php?id=7110

EIA. (2013). *Gas-To-Liquid (GTL) Technology Assessment in support of AEO2013*. Retrieved from https://www.eia.gov/outlooks/documentation/workshops/pdf/aeo2013_gtl_assessment.pdf

EIA. (2018). Spot Prices for Crude Oil and Petroleum Products. Retrieved February 13, 2018, from https://www.eia.gov/dnav/pet/pet_pri_spt_s1_m.htm

Energinet. (2016). Energinet.dk’s underlying assumptions for analyses 2016 [In Danish: Energinet.dk’s analyseforudsætninger 2016].

Energinet. (2018). Tariffs [In Danish: Tariffer]. Retrieved February 6, 2018, from https://energinet.dk/El/Tariffer

Evans, S. (2017). The Swiss company hoping to capture 1% of global CO2 emissions by 2025 | Carbon Brief. Retrieved February 19, 2018, from https://www.carbonbrief.org/swiss-company-hoping-capture-1-global-co2-emissions-2025

Fu, Q., Mabilat, C., Zahid, M., Brisse, A., & Gautier, L. (2010). Syngas production via high-temperature steam/CO 2 co-electrolysis: an economic assessment. *Energy and Environmental Science*. https://doi.org/10.1039/c0ee00092b

Gazprom. (2017). What is associated petroleum gas. Retrieved September 21, 2017, from http://www.gazprominfo.com/articles/associated-gas/

Gibbins, J., & Chalmers, H. (2008). Carbon capture and storage. *Energy Policy*, *36*(12), 4317–4322. https://doi.org/10.1016/j.enpol.2008.09.058

Graves, C., Ebbesen, S. D., Mogensen, M., & Lackner, K. S. (2010). Sustainable hydrocarbon fuels by recycling CO 2 and H 2 O with renewable or nuclear energy. *Renewable and Sustainable Energy Reviews*, *15*, 1–23. https://doi.org/10.1016/j.rser.2010.07.014

gtm. (2017). Updated: Mexico's Energy Auction Just Logged the Lowest Solar Power Price on the Planet | Greentech Media.

Guiot, J., & Cramer, W. (2016). Cliamte Change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science*, *354*(6311), 465–468. https://doi.org/10.1126/science.aaf2156

Hannula, I. (2015). Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: Performance and cost analysis. *Biomass and Bioenergy*, *74*, 26–46. https://doi.org/10.1016/j.biombioe.2015.01.006

Hansen, M. T., & Jørgensen, J. H. (2014). Technology data for advanced bioenergy fuels – Extension 1 Danish Energy Agency. Retrieved from https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_advanced_bioenergy_fuels_-_extension1_-_final_2014-05-09.pdf

Hardin, G. (1968). The Tragedy of the Commons. *Science*, *162*(3859). Retrieved from http://science.sciencemag.org/content/162/3859/1243/tab-pdf

IATA. (2015). *IATA Guidance Material for Sustainable Aviation Fuel Management*. Montreal-Geneva. Retrieved from https://www.iata.org/whatwedo/environment/Documents/IATA Guidance Material for SAF.pdf

IATA. (2018). IATA - Jet Fuel Price Monitor. Retrieved February 9, 2018, from http://www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx

IEA. (2005). Prospects for CO2 capture and storage.

IEA. (2012). *IEA Refinery Margins*. Retrieved from https://www.iea.org/media/omrreports/Refining_Margin_Supplement_OMRAUG_12SEP2012.pdf

IEA. (2013). *Resources to Reserves 2013*. Retrieved from http://www.iea.org/

IEA. (2015). *World Energy Outlook 2015*.

IEA. (2016). Next Generation Wind and Solar Power, 40. https://doi.org/10.1787/9789264258969-en

IEA. (2017a). Energy Subsidies. Retrieved February 23, 2018, from https://www.iea.org/statistics/resources/energysubsidies/

IEA. (2017b). *OECD CO2 emisisons from fuel combustion 2017 - preliminary edition*. Retrieved from http://wds.iea.org/wds/pdf/OECDco2_Documentation.pdf

IEA ETSAP. (2014). Oil Refineries. Retrieved from http://iea-etsap.org/E-TechDS/PDF/P04_Oil Ref_KV_Apr2014_GSOK.pdf

IEA, I. E. A. (2011). *Technology Roadmap: Biofuels for Transport*. Retrieved from www.iea.org

IPCC. (2007). *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

IPCC. (2014). Units, Conversion Factors, and GDP Deflators. Retrieved July 5, 2017, from http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=477

Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2008). Policy Analysis Comparative Analysis of the Production Costs and Life-Cycle GHG Emissions of FT Liquid Fuels from Coal and Natural Gas. *Environmental Science & Technology*, *42*(20). https://doi.org/10.1021/es8002074

Johnson, R., & Cureton, A. (2018). Kant's Moral Philosophy. Retrieved February 27, 2018, from https://plato.stanford.edu/entries/kant-moral/

Karatzos, S., Mcmillan, J., & Saddler, J. (2014). *The potential and challenges of "drop in" biofuels*. *IEA Bioenergy Task*.

Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R., & Kushnir, Y. (2015). Climate change in the Fertile Crescent and implications of the recent Syrian drought. *PNAS*, *112*(11), 3241–3246. https://doi.org/10.1073/pnas.1421533112

Kennedy, C. (2016). Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov. Retrieved September 21, 2017, from https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Knoema. (2014). Cost of producing a barrel of crude oil by country - knoema.com. Retrieved July 4, 2017, from https://knoema.com/rqaebad/cost-of-producing-a-barrel-of-crude-oil-by-country

König, D. H., Baucks, N., & Dietrich, R.-U. (2015). Simulation and evaluation of a process concept for the generation of synthetic fuel from CO2 and H2. *Energy*, *91*, 833–841. https://doi.org/10.1016/j.energy.2015.08.099

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Ivar Korsbakken, J., Peters, G. P., … Zaehle, S. (2016). Global Carbon Budget 2016. *Earth System Science Data*, *8*(2), 605–649. https://doi.org/10.5194/essd-8-605-2016

Lee, D.-Y., Thomas, V. M., & Brown, M. A. (2013). Electric Urban Delivery Trucks: Energy Use, Greenhouse Gas Emissions, and Cost-Effectiveness. *Environmental Science & Technology*. https://doi.org/10.1021/es400179w

Lempriere, M. (2017). Solar fuels: materials breakthrough could open new chapter. Retrieved February 23, 2018, from http://www.power-technology.com/features/featuresolar-fuels-materials-breakthrough-could-open-new-chapter-5832221/

Lieskovsky, J., & Gorgen, S. (2013). Drilling often results in both oil and natural gas production - Today in Energy - U.S. Energy Information Administration (EIA). Retrieved September 21, 2017, from https://www.eia.gov/todayinenergy/detail.php?id=13571

Magill, B. (2017). World's First Commercial CO2 Capture Plant Goes Live | Climate Central.

Malins, C. (2017). Thought for food - A review of the interaction between biofuel consumption and food markets.

Matter, J. M., Stute, M., Snaebjörnsdottir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., … Broecker,

W. S. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, *352*(6291), 1312–1314. Retrieved from http://science.sciencemag.org/content/sci/352/6291/1312.full.pdf

McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, *517*(7533), 187–190. https://doi.org/10.1038/nature14016

Milinski, M., Semmann, D., & Krambeck, H.-J. (2002). Reputation helps solve the 'tragedy of the commons.' *Nature*, *415*(6870), 424–426. https://doi.org/10.1038/415424a

Milinski, M., Semmann, D., Krambeck, H.-J., & Marotzke, J. (2006). Stabilizing the earth's climate is not a losing game: supporting evidence from public goods experiments. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(11), 3994–3998. https://doi.org/10.1073/pnas.0504902103

Muttitt, G., McKinnon, H., Stockman, L., Kretzmann, S., Scott, A., & Turnbull, D. (2016). *The Sky's the limit - why the Paris climate goals require a managed decline of fossil fuel production*. Retrieved from http://priceofoil.org/content/uploads/2016/09/OCI_the_skys_limit_2016_FINAL_2.pdf

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Midgley, P. M. (2013). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Gunnar Myhre (Norway)*. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf

NASA. (2017). Climate Change: Vital Signs of the Planet: Effects. Retrieved August 3, 2017, from https://climate.nasa.gov/effects/

NATO. (2018). Statements by NATO Secretary General Jens Stoltenberg and US President Donald Trump in the Cabinet Room at the White House, 17-May.-2018. Retrieved May 25, 2018, from https://www.nato.int/cps/en/natohq/opinions_154819.htm

O'connor, D., Zhai, F., Aunan, K., Berntsen, T., & Vennemo, H. (2003). Agriculatural and human health impacts of climate policy in China: A general equilibrium analysis with special reference to Guangdong, (206). Retrieved from http://ideas.repec.org/p/oec/devaaa/206-en.html

OECD. (2001). OECD Glossary of Statistical Terms - Primary energy consumption Definition. Retrieved July 31, 2017, from https://stats.oecd.org/glossary/detail.asp?ID=2112

OECD. (2017). *OECD Economic Outlook, Volume 2017 Issue 1* (Vol. 2017). OECD Publishing. https://doi.org/10.1787/eco_outlook-v2017-1-en

Ostrom, E. (2005). *Understanding Institutional Diversity*.

Ostrom, E. (2008). The Challenge of Common-Pool Resources. *Environment: Science and Policy for Sustainable Development*, *50*(4), 8–21. https://doi.org/10.3200/ ENVT.50.4.8-21

Oxford Dictionary of Economics. (2018). Commons. Retrieved January 29, 2018, from http://ordbog.gyldendal.dk/#/pages/result/enoup/commons/expert?cache=1517214653399

Oxford Dictionary of English. (2018). Carrying capacity. Retrieved January 29, 2018, from http://ordbog.gyldendal.dk/#/pages/result/enoup/carrying capacity/expert?cache=1517222895871

Pachauri, R. K., & Meyer, L. A. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth*

Assessment Report of the Intergovernmental Panel on Climate Change. Geneva. https://doi.org/10.1017/CBO9781107415324

Pacifici, M., Visconti, P., Butchart, S. H. M., Watson, J. E. M., Cassola, F. M., & Rondinini, C. (2017). Species' traits influenced their response to recent climate change. https://doi.org/10.1038/NCLIMATE3223

Perloff, J. M. (2014). *Microeconomics with Calculus* (Third). Pearson.

RAC Foundation. (2018). UK daily pump prices & predictor. Retrieved February 9, 2018, from https://www.racfoundation.org/data/UK-daily-fuel-table-with-breakdown

Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., & Schaaernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. https://doi.org/10.1038/NCLIMATE2554

Remme, U., Blesl, M., & Fahl, U. (2007). *Global resources and energy trade: An overview for coal, natural gas, oil and uranium*. Stuttgart. Retrieved from https://elib.uni-stuttgart.de/bitstream/11682/1758/1/FB101.pdf

Ritzau. (2016). Lars Løkke during phone call with Trump: The Danish Government will increase military spendings [In Danish: Lars Løkke i telefonen til Trump: Regeringen vil øge militærudgifterne]. Retrieved May 25, 2018, from https://www.dr.dk/nyheder/udland/lars-loekke-i-telefonen-til-trump-regeringen-vil-oege-militaer-udgifterne

Rocha, J. (2016, November 28). Shrinking glaciers cause state-of-emergency drought in Bolivia. *The Guardian*. Retrieved from https://www.theguardian.com/environment/2016/nov/28/shrinking-glaciers-state-of-emergency-drought-bolivia

Rogelj, J., Schaeffer, M., Friedlingstein, P., Gillett, N. P., van Vuuren, D. P., Riahi, K., … Knutti, R. (2016). Differences between carbon budget estimates unravelled. *Nature Climate Change*, *6*(3), 245–252. https://doi.org/10.1038/nclimate2868

Rothman, D. H. (2017). Thresholds of catastrophe in the Earth system. *Science Advances*, *3*. Retrieved from http://advances.sciencemag.org/content/advances/3/9/e1700906.full.pdf

Sanchirico, J., & Newell, R. (2003). Catching Market Efficiencies - quota-based fisheries management.

Sasol. (2008). Sasol achieves approval for 100% synthetic jet fuel | Sasol. Retrieved February 2, 2018, from http://www.sasol.com/media-centre/media-releases/sasol-achieves-approval-100-synthetic-jet-fuel

Sasol. (2010). Sasol takes to the skies with the world's first fully synthetic jet fuel | Sasol. Retrieved February 2, 2018, from http://www.sasol.com/it/media-centre/media-releases/sasol-takes-skies-world-s-first-fully-synthetic-jet-fuel

Schmidt, P. R., Zittel, W., Weindorf, W., & Raksha, T. (2016). Renewables in Transport 2050 Empowering a sustainable mobility future with zero emission fuels from renewable electricity.

Sims, R., & Taylor, M. (2013). *From 1st – to 2nd-Generation Biofuel Technologies – An overview of current industry and RD&D activities*. *Biofuel Technologies: Recent Developments*. https://doi.org/10.1007/978-3-642-34519-7

Smejkal, Q., Rodemerck, U., Wagner, E., & Baerns, M. (2014). Economic assessment of the hydrogenation of CO2 to liquid fuels and petrochemical feedstock. *Chemie-Ingenieur-Technik*, *86*(5), 679–686. https://doi.org/10.1002/cite.201300180

Smith, A. (1759). *The Theory of Moral Sentiments*.

Smith, A. (1776). *An Inquiry into the Nature and Causes of the Weatlh of Nations*.

Sniderman, D. (2011). New Options Emerge for Aviation Fuel. Retrieved September 21, 2017, from https://www.asme.org/engineering-topics/articles/aerospace-defense/new-options-emerge-for-aviation-fuel

Staff Mestl, H. E., Aunan, K., Fang, J., Seip, H. M., Skjelvik, J. M., & Vennemo, H. (2004). Cleaner production as climate investment—integrated assessment in Taiyuan City, China. *Journal of Cleaner Production XX*. https://doi.org/10.1016/j.jclepro.2003.08.005

Stern, N. (2006). The Economics of Climate Change. *Stern Review*, 662. https://doi.org/10.1257/aer.98.2.1

Sterner, T., & Coria, J. (2012). *Policy Instruments for Environmental and Natural Resource Management* (Second).

Styring, S. (2011). Artificial photosynthesis for solar fuels. https://doi.org/10.1039/c1fd00113b

Takeshita, T. (2012). Assessing the co-benefits of CO 2 mitigation on air pollutants emissions from road vehicles. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2011.12.029

Tesla. (2017). Semi | Tesla. Retrieved February 15, 2018, from https://www.tesla.com/semi?redirect=no

Tremel, A., Wasserscheid, P., Baldauf, M., & Hammer, T. (2015). Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis. *International Journal of Hydrogen Energy*, *40*, 11457–11464. https://doi.org/10.1016/j.ijhydene.2015.01.097

UNEP. (2005). *Urban Air Quality Management Toolbook*.

United Nations. (2015). Paris Agreement. *21st Conference of the Parties*, *21932*(December), 3. https://doi.org/FCCC/CP/2015/L.9

Volta Oil. (2015). What Determines Retail Prices for Gasoline and Diesel? | Volta Oil, MA RI CT. Retrieved February 9, 2018, from http://www.voltaoil.com/what-makes-up-retail-price-for-gasoline/

Watanabe, J. (2016). Giant fall in generating costs from offshore wind. Retrieved from https://data.bloomberglp.com/bnef/sites/4/2016/11/BNEF_PR_2016-11-01-LCOE.pdf

Wedekind, C., & Milinski, M. (2000). Cooperation through Image Scoring in Humans. *Source: Science, New Series*, *288*(5467), 850–852. Retrieved from http://www.jstor.org/stable/3075202

World Coal Association. (2017). What is coal? Retrieved September 20, 2017, from https://www.worldcoal.org/coal/what-coal

World Commission on Environment and Development. (1987). *Our Common Future*. Retrieved from http://www.un-documents.net/our-common-future.pdf

World Meteorological Organization. (2017). Climate breaks multiple records in 2016, with global impacts. | World Meteorological Organization. Retrieved September 21, 2017, from https://public.wmo.int/en/media/press-release/climate-breaks-multiple-records-2016-global-impacts

Wright, M. M., Brown, R. C., & Boateng, A. A. (2008). Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids. *Biofuels, Bioproducts and Biorefining*, *2*(3), 229–238. https://doi.org/10.1002/bbb.73

WSJ News Graphics. (2016). Barrel Breakdown. Retrieved July 4, 2017, from http://graphics.wsj.com/oil-barrel-breakdown/

Zeman, F. S., & Keith, D. W. (2008). Carbon neutral hydrocarbons. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *366*(1882), 3901–3918. https://doi.org/10.1098/rsta.2008.0143

Appendix A Methodology

Appendix A.1 Price information

Different currencies are used throughout the report depending on the data source and the product. Mostly United States Dollars (USD) are used, however Euros (EUR) are also referred to, Danish kroner (DKK) for the Danish examples and Great British Pounds (GBP) in the appendices.

The main reason for the variety of currencies is due to the two most common notations for oil prices and electricity prices in Europe. Prices for oil are often expressed in USD per barrel while electricity prices are often expressed in Euros per Megawatt hour.

The exchange rates are shown below.

1 EUR = 7.45 DKK
1 USD = 6.00 DKK
1 GBP = 8.38 DKK
1 EUR = 1.24 USD

All prices are expressed in 2015 prices

Appendix A.2 Enough fossil fuels to violate the carrying capacity

Table 7 depicts the data from Pachauri and Meyer (2014) that can be interpreted as the carrying capacities for the atmosphere. To quantify the urgency for actions towards reducing global warming a comparison between the carrying capacity and the current rate of CO_2-emissions should be conducted. To do this the data in Table 7 must be updated, since it is from 2011.

Table 7: Cumulative carbon dioxide (CO_2) emission consistent with limiting warming to less than stated temperature limits at different levels of probability, based on different lines of evidence (Pachauri & Meyer, 2014)

Cumulative CO_2 emissions from 2011 in $GtCO_2$									
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model WGIII scenarios [d]	No data	550-600	600-1150	750-1400	1150-1400	1150-2050	n.a. [e]	2350-4000	3500-4250

Notes:

[a] *Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861-1880 base period*

[b] *The 66%, 50% and 33% ranges in this table should not be equated to likelihoods. The assessment in this table is not only based on the probabilities calculated for the full ensemble of scenarios in IPCC's Working Group III (WGIII) using a*

single climate model, but also the assessment in IPCC's Working Group I (WGI) of the uncertainty of the temperature projections not covered by climate models.

[c] *Cumulative CO_2 emissions at the time the temperature threshold is exceeded that are required for 66%, 50% or 33% of the Coupled Model Intercomparison Project Phase 5 (CMIP5) complex models, Earth System Model (ESM) and Earth System Models of Intermediate Complexity (EMIC) simulations, assuming non-CO_2 forcing follows the RCP8.5 scenario (Representative Concentration Pathway where the radiative forcing reaches >8.5 W/m^2 by 2100). Similar cumulative emissions are implied by other Representative Concentration Pathways (RCP) scenarios. For most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of CO_2 emissions, these figures provide an indication of the cumulative CO_2 emissions implied by the CMIP5 model simulations under RCP-like scenarios. Values are rounded to nearest 50.*

[d] *Cumulative CO_2 emissions at the time of peak warming from WGIII scenarios for which a fraction of greater than 66% (66 to 100%), greater than 50% (50 to 66%) or greater than 33% (33 to 50%) of climate simulations keep global mean temperature increase to below the stated threshold. Ranges indicate the variation in cumulative CO_2 emissions arising from differences in non-CO_2 drivers across the WGIII scenarios. The fraction of climate simulations for each scenario is derived from a 600-member parameter ensemble of a simple carbon-cycle climate model, Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), in a probabilistic mode. Parameter and scenario uncertainty are explored in this ensemble. Structural uncertainties cannot be explored with a single model set-up. Ranges show the impact of scenario uncertainty, with 80% of scenarios giving cumulative CO_2 emissions within the stated range for the given fraction of simulations. Simple model estimates are constrained by observed changes over the past century, do not account for uncertainty in model structure and may omit some feedback processes: they are hence slightly higher than the CMIP5 complex models estimates. Values are rounded to the nearest 50.*

[e] *The numerical results for the cumulative CO_2 emissions for staying below 3°C with greater than 66% (66 to 100%) is greatly influenced by a large number of scenarios that would also meet the 2°C objective and therefore not comparable with numbers provided for the other temperature threshold.*

The data was updated to 2017 by using the data from Table 8, which displays anthropogenic CO_2 emissions related to land-use change, burning of fossil fuels and cement production for the period of 2005 to 2016. We only need the data from 2011 and onward, but since the data for land-use change is not yet available for 2016 the data from 2005 to 2015 is used to make an average which is then displayed for land-use change in the 2016 column. The carbon budget lines shown in "The Tragedy of the Planet?" graphs are only for fossil fuels, which implies that the emissions from cement and land-use change have been subtracted. This is done by assuming constant emissions from these to sources over the time left before exceeding the given temperature limit. The future emissions are set to the 2016 value for cement and the average emissions from land use change in the period from 2005 to 2015.

Table 8: Anthropogenic CO_2 emissions in $GtCO_2$ from fossil fuels and cement, land-use change, and totals for the period of 2005 to 2016. Data from CDIAC (2016)

Anthropogenic CO_2 emissions in $GtCO_2$												
Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Fossil fuel and cement emissions	30.15	31.25	32.17	32.83	32.50	33.75	34.95	35.50	35.98	36.24	36.27	36.40[a]
Land-use change emissions	3.77	3.99	3.55	2.45	2.75	3.22	3.33	3.55	3.37	4.03	4.84	3.53[b]
Total emissions	33.93	35.25	35.72	35.28	35.25	36.97	38.29	39.06	39.35	40.27	41.11	39.93

Notes:
[a] *Data from* (Le Quéré et al., 2016)

[b] *Average over the last 10 years used here*

The updating process is shown in Table 9. The "*Complex models, RCP scenarios only*" budgets from Table 7 is the basis for the update and they are shown in the row "*From 2011*". The summation of the total emissions from 2011-2016 are shown in the row "*From 2011 to 2016*" and is based on Table 8. By subtracting these rows, we get the row named "*From 2017*". This row is the new budget as of 2017.

By dividing the emissions from 2016 with the new budgets, the runway is calculated or the time left before we exceed the given temperature limits if we assume constant 2016 emissions. From these runways, it seems almost impossible to limit the temperature increase to 1.5 °C and we must take drastic action now if we want to stay well below 2 °C. Comparing Table 7 and Table 9, it gives us approximately 19 years at the current rate of emissions before we must stop our emissions completely.

Table 9: The updating process of the data from Table 7 to 2017. Furthermore, it is calculated how much time we have left before we exceed the given limits. The calculation is based on constant 2016 emissions.

Updating process of cumulative CO_2 emissions from 2011 to 2017 in $GtCO_2$									
	1.5			2			3		
Fraction of simulations meeting goal	66%	50%	33%	66%	50%	33%	66%	50%	33%
From 2011	400	550	850	1000	1300	1500	2400	2800	3250
From 2011 to 2016 [a]	238	238	238	238	238	238	238	238	238
From 2017	162	312	612	762	1062	1262	2162	2562	3012
Years left [b]	4.06	7.81	15.33	19.08	26.59	31.60	54.14	64.16	75.42
Time left [b]	4 years / 0 months	7 years / 9 months	15 years / 3 months	19 years / 0 months	26 years / 7 months	31 years / 7 months	54 years / 1 month	64 years / 1 month	75 years / 5 months

Notes:
[a] *2016 included*

[b] *at constant 2016 emissions*

Here follows a brief explanation of the two types of budgets for each temperature limit as seen in Table 7. The first budget is the "*Complex models, RCP scenarios only*" which is a threshold exceedance budget (TEB). A TEB is a budget for when the models will cross a specified threshold temperature. The temperature will keep increasing even after the threshold is passed. The other type of budget is the "*Simple model WGIII scenarios*" this type of budget is called a threshold avoidance budget (TAB). A TAB is a budget for cumulative emissions at peak warming. That is how much CO_2 we can emit and still stay below a specified threshold temperature (Rogelj et al., 2016).

The TEB budget was used in this study since data was available for all fractions of models meeting the goal. The TEB budget is made using information from more sophisticated models where the computations become slower (Rogelj et al., 2016). On the other hand TABs are made from models with high computational efficiency which allows for a lot more simulations (Rogelj et al., 2016). If the goals in the Paris Agreement should be met, we need to look at the TABs since the primary aim is to stay well below 2 °C warming. The TABs are important in relation to choosing the right scenario of how to meet the goals in the Paris Agreement. The result of our study should not be affected much by choosing a TEB where all data is available since the differences between the TEBs and the TABs from Table 7 are relatively small.

Appendix A.3 Definitions

This section contains definitions of some of the most crucial concepts in the study.

CAPEX or capital expenses: Refers to the expenditures used for buying long term services or products e.g. the investment cost for assets and the installation costs of these. Assets mainly being buildings, infrastructure, machines, etc. The capital expense is independent of whether the asset operates or not.

Feasible: In this study feasible is defined not only as technically feasible but also economically feasible in the sense that a feasible solution is cost-efficient and competitive enough to outcompete existing solutions on a market basis.

OPEX or operational expenses: Refers to the expenditures used for the daily operation and is thus dependent on whether the asset operates or not. The OPEX could be e.g. energy, raw materials, transport, salaries, etc.

Reserves: The definition of reserves are taken from (BGR, 2016), see below.

Resources: The definition of resources are taken from (BGR, 2016), see below.

Total resources: The definition of total resources are taken from (BGR, 2016) and is the sum of reserves and resources.

Appendix A.3.1 Definitions of reserves and resources

The definitions of reserves and resources:

> IPPC:
> *“[…]reserves are quantities able to be recovered under existing economic and operating conditions; resources are those where economic extraction is potentially feasible”* (Pachauri & Meyer, 2014)
>
> BP:
> *“[Reserves are] […]generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions.”* (BP, 2016)
>
> BGR:
> *“Reserves: Proven volumes of energy resources economically exploitable at today’s prices and using today’s technology”*(BGR, 2016)

> *"Resources: Proven amounts of energy resources which cannot currently be exploited for technological and/or economic reasons, as well as unproven but geologically possible energy resources which may be exploitable in future"*(BGR, 2016)

The definitions of resources alter slightly from IPCC to BGR. For IPCC *"resources are those where* ***economic*** *extraction is potentially feasible"* while BGR includes *"unproven but geologically possible energy resources which may be exploitable in future"*. From these definitions, it is very likely that IPCC's carbon estimates would be lower than BGR's since everything should be economic to extract for IPCC's definition and only exploitable in future for BGR's definition.

Appendix A.4 Quantification of reserves and resources

The two databases we have found on fossil fuel reserves, BP (2017a) and BGR (2016), expresses the amounts in tons, barrels, and cubic meters respectively as seen in Table 10. These units should be converted into an energy unit and this is done using the data from Table 11 and Table 12.

Table 10: Comparison between BP's and BGR's data on reserves and resources for coal, oil, and gas in original units.

Categories:	BP - reserves	BGR - reserves	BGR - resources	BGR - total
Oil (Thousand million barrels)	1,691	1,587	2,606	4,193
Gas (Trillion cubic meters)	185.4	196.6	652.4	849.0
Coal (Million tons)	1,139,331	1,028,996	21,984,205	23,013,201

Table 11: Conversion factors for oil, gas, and various types of coal.

Conversion factors				
Amount	Unit	Amount	Unit	Sources
1	barrel of crude oil	0.1364	ton	(BP, 2017a)
1	ton of crude oil	41.8	GJ	(BGR, 2016)
$1\cdot10^9$	ton of crude oil	41.8	EJ	(BGR, 2016)
1000	Nm^3 natural gas	38	GJ	(BGR, 2016)
$1\cdot10^{12}$	Nm^3 natural gas	38	EJ	(BGR, 2016)
1.5	ton of anthracite and bituminous coal	41.8	GJ	(BP, 2017a)
1	ton of anthracite and bituminous coal	27.9	EJ	(BP, 2017a)
3	ton of lignite and sub-bituminous coal	41.8	GJ	(BP, 2017a)
1	ton of lignite and sub-bituminous coal	13.9	EJ	(BP, 2017a)

Table 12: The breakdown off coal types from the data sources and the corresponding energy content of each category of coal.

Coal categories:	Anthracite and bituminous coal		Lignite and sub-bituminous coal		Total	
Sources:	Million ton	EJ	Million ton	EJ	Million ton	EJ
BP - reserves	816,214	22,745	323,117	4,502	1,139,331	27,247
BGR - reserves	712,212	19,847	316,784	4,414	1,028,996	24,261
BGR - resources	17,562,051	489,396	4,422,154	61,615	21,984,205	551,011
BGR - total	18,274,263	509,243	4,738,938	66,029	23,013,201	575,272

The results of the updating process can be seen in Table 13. Table 13 enables us to make a total for the energy of all the fossil fuels, which makes a comparison of the data sources easier.

Table 13: Comparison between BP's and BGR's data on reserves and resources for coal, oil, and gas in functional units.

Categories:	BP - reserves	BGR - reserves	BGR - resources	BGR – total resources
Oil (EJ)	9,644	9,050	14,858	23,908
Gas (EJ)	7,046	7,473	24,791	32,263
Coal (EJ)	27,247	24,261	551,011	575,272
Total (EJ)	**43,937**	**40,783**	**590,660**	**631,443**

Appendix A.5 The "Tragedy of the Planet" graph

The "Tragedy of the planet?" graphs are based on data for quantities of coal, oil, and gas for each individual country in the world. To see the underlying quantity data, refer to Appendix C.1 to Appendix C.7. The quantity data is assigned a corresponding CO_2-emission to enable a comparison between the carrying capacity of our atmosphere and the fossil fuel reserves and resources that we have available. The data used for this step is shown in Table 14.

Table 14: Carbon and CO_2-emissions for selected fossil fuels. The conversion between carbon and CO_2-emissions has been done using numbers from IPCC (2014) *and the carbon content has been found in* IEA (2017b) .

Carbon and CO_2-emisions		
Category:	Carbon	CO2 - emissions
Fossil fuel types:	kg/GJ	kg/GJ
Hard coal	26.8	98.36
Lignite	27.6	101.29
Natural gas	15.3	56.15
Crude oil	20	73.40
Oil shale	29.1	106.80
Bitumen	22	80.74

The quantity data is also paired with a cost of extracting, transporting, refining, and distributing the products. The distribution cost is included to make an easier comparison to the electricity based propellants that already has distribution included in the cost. The price estimates for the mentioned categories and the price sources for categories with a high number of data can be seen in Table 15.

Finding price data for coal, oil, and gas is not as simple as it might appear. There are many ways and techniques to extract and mine coal, oil, and gas. These differences are not only interregional but intraregional and even differs within a country. Finding the average production cost for coal, oil, and gas respectively for all countries in the world is thus a massive task. Likewise, finding the data for all individual mines and extraction sites as a massive task. The data we have found is aggregated to a national level and is interpreted as average production costs.

Some of the difficulties are presented here. Coal can be mined from a mountaintop mine to a shaft mine. All the different mining techniques has their own specific costs and implication on the environment. Especially, the depth of the coal seam affects the production price.

Table 15: Break down of the cost data used in "The Tragedy of the Planet?" graphs. Data sources are shown for sources with a high number of data. The distribution costs are the same for all fuels in this table, since the fuels are identical. The distribution costs are based on an assessment of Ea Energy Analyses (2014), RAC Foundation (2018), and Volta Oil (2015). *The refining cost for oil is based on and assessment of* Ea Energy Analyses (2014), EIA (2018), ENS (2017a), IEA (2012), IEA ETSAP (2014), and Volta Oil (2015). *The refining cost for gas is based on an assessment of Blesl and Bruchof (2010), Cazzola et al. (2013), EIA (2013), IEA (2013), and Jaramillo, Griffin, and Matthews (2008). The refining cost for coal is based on Blesl & Bruchof (2010), Cazzola et al. (2013), IEA (2013), and Jaramillo et al., (2008). Electrofuels are not on the graph yet but for comparison the refining cost of electrofuels are based on an assessment of* Boerrigter and Boerrigter (2006), and Wright, Brown, and Boateng (2008) *where the cost of gasifying and cleaning biomass is removed. The refining cost of electrofuels is also assumed to be lower than oil since there is no tars to handle and the FT-products has a narrower span of compounds, than crude oil.*

Categories:	Oil	Gas	Coal	Electrofuels
Extraction/mining	(Knoema, 2014; WSJ News Graphics, 2016)	(Knoema, 2014; WSJ News Graphics, 2016)	(Remme et al., 2007)	Not on graph in this step
Transport/admin				
Refining cost	3 USD/GJ	5 USD/GJ	10 USD/GJ	2 USD/GJ
Distribution cost	2.5 USD/GJ	2.5 USD/GJ	2.5 USD/GJ	2.5 USD/GJ

We got a data sample for oil and gas in Norway from Rystad Energy and here it is clear that the production prices within a country varies quite substantially from field to field. Another issue in relation to oil and gas is coproduction. There are three main options for oil and gas production. You can have a pure oil production where you only extract oil, or you can extract both oil and gas, or you can extract gas only. In the first and last case, it is not hard to determine the production price since there is only one product, but things are a bit more complicated in the coproduced case. Gas extracted together with oil is often referred to as associated petroleum gas or associated gas (Gazprom, 2017). Three things might happen to associated gas; it is either vented, flared, or captured.

In the case of venting and flaring the gas, the gas is a waste product that is discarded and there are no problems when determining the production price since the only product is oil. The issue with venting and flaring is that the energy content of the gas is wasted, and that especially venting, harms the environment. Methane is a very potent GHG and the global warming potential is 28 times that of CO_2 (Myhre et al., 2013).

Capturing the gas makes it possible to use it for either process energy at the extraction site or for further treatment and sale. In the case of capturing and selling the gas, we face an issue in relation to dividing the production cost between the two products. As it can be seen from the examples of venting and flaring gas, the gas is often the low value product and oil the high value product. The unwanted associated gas is often extracted because there is no other choice due to the pressure in the field.

We have assumed the same production costs for both oil and gas, if the gas is captured and sold. This might not reflect the true value of the gas but again it would be a massive task to assess the division. We do not have data on which fields that are coproducing and those that are not. For this reason, we have assumed that the production price for oil and gas is the same within each country. The process of extracting oil and gas separately is similar which makes it a fair assumption (Lieskovsky & Gorgen, 2013).

For the price data for oil and gas, we found a tool named UCUBE provided by Rystad Energy containing production costs including CAPEX and OPEX for both extraction/mining and transportation/administration for most fields globally.

The data from UCUBE is extremely detailed since they have data for almost all fields in the world. Unfortunately for us, the data is extremely expensive to access. Luckily, we found some data from UCUBE aggregated to a country level for 12 of the countries with the highest productions (WSJ News Graphics, 2016). We also found another source, Knoema (2014), containing 43 countries, but here it has not been possible to access the underlying data. For the remaining countries of the world, the prices were estimated to be the same as the closest neighboring country in the region where data were available.

The data from Knoema (2014) was validated through a comparison with the data from WSJ News Graphics (2016). From the validation it seemed as though Knoema (2014) was missing cost for administration and transportation. To make up for this an approximated average cost for administration and transportation from WSJ News Graphics (2016) was inserted.

We want the prices to be of the year 2015 but no data conversion has been made of the data from Knoema (2014) and WSJ News Graphics (2016) since the inflation from 2014-2016 has been low (OECD, 2017) and we are dealing with a short time span.

Price data for coal production is from Remme et al. (2007). This source contains price data for both coal, oil, and gas but since we were able to find a newer source for gas and oil reserves, we have only used Remme et al. (2007) for coal reserves and for all resource production prices. The data from Remme et al. (2007) is divided into 8 regions and 7 countries covering the whole world. The categorization can be seen in Table 16. The price data from Remme et al. (2007) is all expressed in real USD of the year 2000. The data has been updated to 2015 by using inflation data from OECD (2017).

The production price data, or supply data, from Remme et al. (2007) is not subdivided into CAPEX and OPEX for both extraction/mining and transportation/administration. Even though the price still consists of these components:

> *”The supply costs generally include the production costs at the mine, domestic transportation costs from the mine to the export harbor as well as harbor costs.”* (Remme et al., 2007)

The production cost has been subdivided into the three components we use; extraction/mining CAPEX, extraction/mining OPEX, and transportation/administration CAPEX+OPEX. The division is made as 20 % on extraction/mining CAPEX, 60 % on extraction/mining OPEX, and 20 % on transportation/administration CAPEX+OPEX. This is an estimate based on the assumption that mining coal requires less CAPEX than oil and gas and more for OPEX. We do not have any source for this estimate but we think this is a fair assumption since coal can be mined directly from an open pit mine with machinery like what is used in the construction sector and oil are extracted by drilling with specially designed equipment. Other types of coal mining exist that requires equipment that is more specialized but it is outside the scope of this report to investigate this further.

After mining and extraction, the products should be refined into a diesel-eq. fuel. The cost of refining the coal, oil, and gas is important since our functional unit is a cost per GJ diesel-eq.

The oil refining takes place at an oil refinery and is the most well-known refining technology for fossil fuels. Since this is a widespread commercial technology, it has been hard to obtain a specific refining cost due to confidential data and the big variety in refinery setups. The refining cost for oil have been assumed to be 3 USD/GJ based on an assessment of Ea Energy Analyses (2014), IEA (2012), IEA ETSAP (2014) and Volta Oil (2015) and an assessment of price data for crude oil and refinery products from EIA (2018), refer to Appendix C.8 for the full analysis. The cost of refining hugely depends on the size of the refinery and prices varies substantially from refinery to refinery. The refining cost is assumed the same for all countries. Our quantity data are on a country basis and it is outside the scope of this report to determine the average refinery for each country.

Gas can be converted into a liquid diesel-eq. fuel through a process referred to as gas to liquid (GTL). The gas is converted into a synthesis gas or syngas ($CO + H_2$) and then converted into a synthetic fuel (Blesl & Bruchof, 2010). The refining cost for gas has been estimated to 5 USD/GJ diesel-eq. output based on an assessment of Blesl & Bruchof (2010), Cazzola et al. (2013), EIA (2013), IEA (2013), and Jaramillo et al. (2008). This refining cost is assumed the same for all countries even though there might be some regional differences. It is outside the scope of this report to consider potential regional differences.

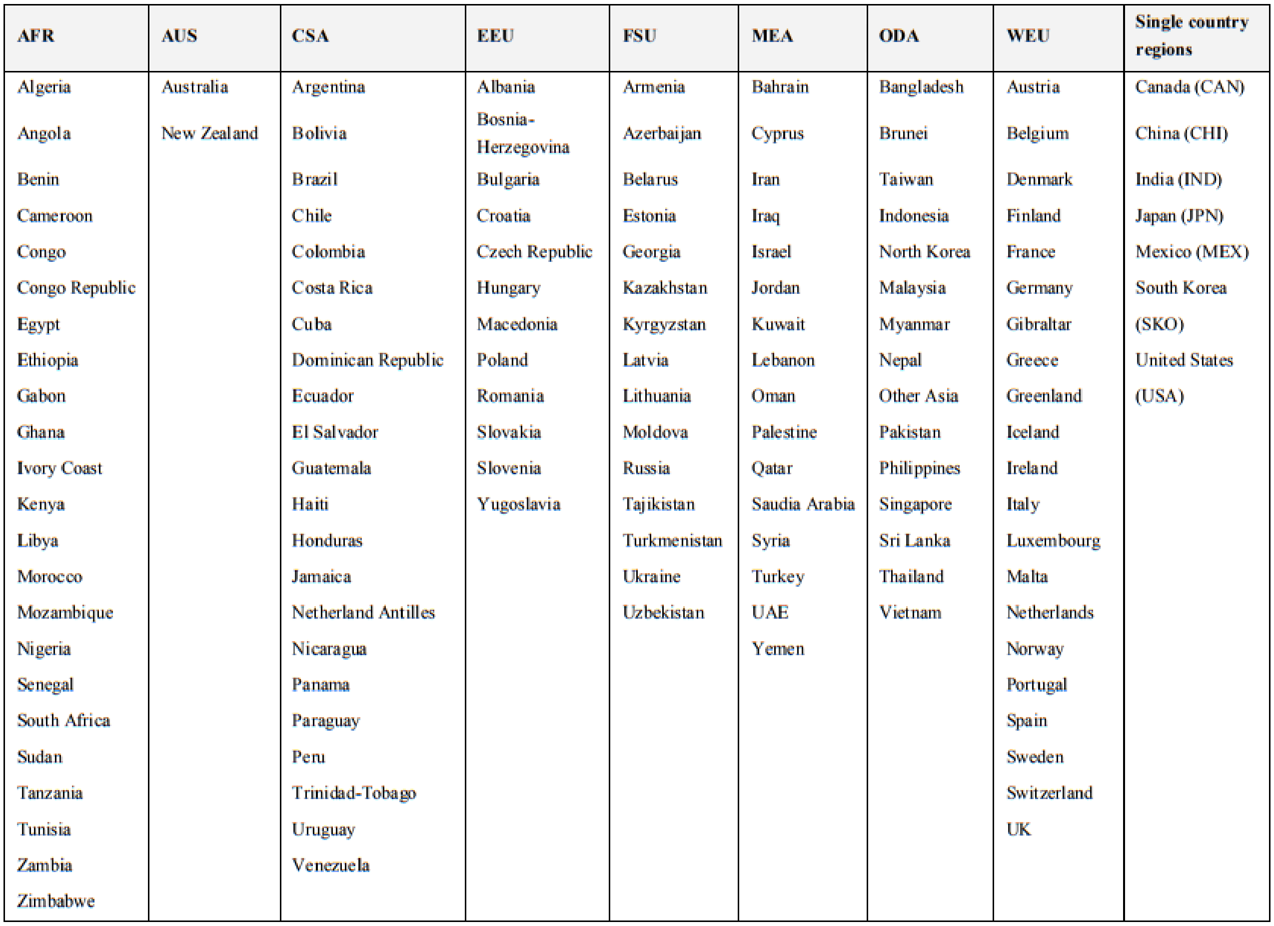
Coal can be converted into a diesel equivalent fuel by a process called coal to liquid (CTL). This can be done either directly or indirectly. Direct coal liquefaction (DCL) converts the coal into liquid form directly, while indirect coal liquefaction (ICL) uses an intermediate step where the coal is turned into a syngas (Blesl & Bruchof, 2010). For CTL almost 50% of the total investment cost goes to preparation and gasification of the coal the rest is the cost of the GTL process (Blesl & Bruchof, 2010).

The refining cost for coal has been estimated to 10 USD/GJ diesel-eq. output for both DCL and ICL based on an assessment of Blesl & Bruchof (2010), Cazzola et al. (2013), IEA (2013), and Jaramillo et al. (2008). The same number is used for all refining of coal even though there might be some geographical differences. It is outside the scope of this report to assess these geographical differences.

The production cost for resources is even harder to estimate than the production cost for reserves, since resources are not yet feasible to extract. First, we thought of making the resource production prices double the production prices of reserves, but this approach does not reflect the fact that there is a continuous increase in the price from reserves to resources. Depending on the current economic situation, some of the fossil fuels in the resource category might turn into a reserve and vice versa.

We managed to find resource estimates in Remme et al. (2007). This is the same source as we used for the production prices of coal. The data from Remme et al. (2007) is divided into 8 regions and 7 countries covering the whole world. The categorization can be seen in Table 16. The source has several cost estimates depending on the extraction technique, but they also have a resource price that we have used. The production prices for oil and gas comes in a price range. We have chosen the high value since some of the specified extraction techniques from the source has production prices higher than the high value of the price range. Coal is divided into lignite and hard coal and for both categories there is only one price estimate.

Table 16: The definitions of the 8 regions and 7 countries where price estimates for resources are available from Remme et al. (2007). EEU, furthermore includes Kosovo, Montenegro, and Serbia



AFR	**AUS**	**CSA**	**EEU**	**FSU**	**MEA**	**ODA**	**WEU**	**Single country regions**
Algeria	Australia	Argentina	Albania	Armenia	Bahrain	Bangladesh	Austria	Canada (CAN)
Angola	New Zealand	Bolivia	Bosnia-Herzegovina	Azerbaijan	Cyprus	Brunei	Belgium	China (CHI)
Benin		Brazil	Bulgaria	Belarus	Iran	Taiwan	Denmark	India (IND)
Cameroon		Chile	Croatia	Estonia	Iraq	Indonesia	Finland	Japan (JPN)
Congo		Colombia	Czech Republic	Georgia	Israel	North Korea	France	Mexico (MEX)
Congo Republic		Costa Rica	Hungary	Kazakhstan	Jordan	Malaysia	Germany	South Korea (SKO)
Egypt		Cuba	Macedonia	Kyrgyzstan	Kuwait	Myanmar	Gibraltar	
Ethiopia		Dominican Republic	Poland	Latvia	Lebanon	Nepal	Greece	United States (USA)
Gabon		Ecuador	Romania	Lithuania	Oman	Other Asia	Greenland	
Ghana		El Salvador	Slovakia	Moldova	Palestine	Pakistan	Iceland	
Ivory Coast		Guatemala	Slovenia	Russia	Qatar	Philippines	Ireland	
Kenya		Haiti	Yugoslavia	Tajikistan	Saudia Arabia	Singapore	Italy	
Libya		Honduras		Turkmenistan	Syria	Sri Lanka	Luxembourg	
Morocco		Jamaica		Ukraine	Turkey	Thailand	Malta	
Mozambique		Netherland Antilles		Uzbekistan	UAE	Vietnam	Netherlands	
Nigeria		Nicaragua			Yemen		Norway	
Senegal		Panama					Portugal	
South Africa		Paraguay					Spain	
Sudan		Peru					Sweden	
Tanzania		Trinidad-Tobago					Switzerland	
Tunisia		Uruguay					UK	
Zambia		Venezuela						
Zimbabwe								

The price data from Remme et al. (2007) are all expressed in real USD of the year 2000. The data has been updated to 2015 by using inflation data from OECD (2017). The results can be seen in Table 17 and Table 18. The refining cost for the resources are assumed the same as for reserves. Some of the unconventional resources of oil and gas contains high levels of sulfides that might add an extra cost to the refining process (Bechtel, 2017). Since we do not have any detailed data on the extent of these resources, we have assumed the refining cost to be the same.

From Remme et al. (2007) there is also price data for coal-bed methane, tight gas, gas hydrates, and aquifer gas. For oil, there is price data for oil sands, extra-heavy oil, and oil shale. All these different techniques come at different prices some as low as 2.1 USD/GJ and up to 17.2 USD/GJ. The data we have used for the resources are in the range of 0.7 to 4.9 USD/GJ for gas and 2.7 to 6.7 USD/GJ for oil dependent on the region. As mentioned earlier, since we do not have specific data on where and to what extent the above-mentioned techniques will be used, we have assumed everything to be at the resource production prices. It is important to keep this in mind when we start our analysis of alternatives (refer to Appendix C.1 to Appendix C.7 for the full analysis).

Table 17: Reserve and resource prices for lignite (Remme et al., 2007), and the updating process.

$/GJ [real 2000]	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU
Reserves	0.49	0.79	0.36	0.36	0.69	0.59	0.3	0.36	0.93	3.47	0.36	0.3	0.93	0.36	0.55
Resources	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
$/GJ [real 2015]	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU
Reserves	0.67	1.09	0.50	0.50	0.95	0.81	0.41	0.50	1.28	4.78	0.50	0.41	1.28	0.50	0.76
Resources	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47	6.47

Table 18: Reserve and resource prices for hard coal (Remme et al., 2007), and the updating process.

$/GJ [real 2000]	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU
Reserves	1.03	1.06	1.87	1.36	0.96	1.53	0.86	1.6	3.65	4	1.87	1.18	3.65	1.31	3.65
Resources	1.87	1.9	2.71	2.1	1.8	2.37	1.7	2.44	4.51	4.84	2.71	2.03	4.51	2.17	4.51
$/GJ [real 2015]	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU
Reserves	1.42	1.46	2.57	1.87	1.32	2.11	1.18	2.20	5.02	5.51	2.57	1.62	5.02	1.80	5.02
Resources	2.57	2.62	3.73	2.89	2.48	3.26	2.34	3.36	6.21	6.66	3.73	2.79	6.21	2.99	6.21

Appendix A.6 New technical solutions

Appendix A.6.1 Biofuels

The mentioned feedstocks are both first- and second-generation feedstocks. The main difference between first- and second-generation feedstocks are whether they are considered to be food or not. First-generation biofuel is made of food products grown on arable land, such as corn, sugar canes, wheat, and rapeseed oil (Karatzos et al., 2014). Second-generation biomass is a broader term, because there is more than one source with many different materials.

Table 19: Example of second-generation biomass sources and materials inputs to biofuels

Source	**Feedstock**
Residues from agriculture	Manure, straw
Residues from forestry	Wood residues
Residues from paper industry	Tall oil
Energy crops	Polar and willow
Municipal solid waste	Food scraps, cardboard, paper, plastic, etc.

Currently, the only large-scale commercial biofuel plants are based on first-generation feedstocks such as sugar and starch to produce bioethanol or feedstocks such as oilseed, waste oil, or tallow to produce biodiesel. The main producers are the USA and Brazil where the driver behind their production is energy security (Karatzos et al., 2014). This and the price is properly why they chose first-generation feedstock instead of second-generation feedstock.

There are both advantages and disadvantages of using first- and second-generation biofuels. The biggest concern is the use of food products to make first-generation biofuels, because the demand for food products would raise, which would create a price increase at least in a short or medium term, and that the food security impact is reduced by co-products but not eliminated (Malins, 2017). When there is an influence on a raw materials market price, one should differentiate between short, medium and long effects of the price impact.

In case of the price increase on food in 2006 to 2008, where the production of biofuels was an important factor to the price increase, we saw a short to medium term effect. The price increase triggered an efficiency increase within food production (Malins, 2017). However, it is important to remember that the observed response was made on a very small increase in first-generation biofuels production. A larger demand for biofuels in the future might not be possible to satisfy in this way.

This concern does not count for second-generation biofuels, but there are still major challenges regarding the technical and economic aspects of extracting biofuels from second-generation materials (Sims & Taylor, 2013). In the case of energy crops, which is a second-generation feedstock, the concern of first-generation biofuel could actually also apply, because energy crops would occupy arable land where food crops could have grown, also called direct land use change, but the technical and economic challenges could be minor.

There are other concerns related to first-generation biofuels: they are an expensive option for energy security, the GHG reduction potential is limited, they do not meet their claimed environmental benefits, they accelerate deforestation, they might impact biodiversity negatively, and they compete for scarce water resources in some regions (Sims & Taylor, 2013).

Literature study on biofuels

The literature study from Ea Energianalyse (2016) focus on many different kinds of biofuels for the transportation sector. We have chosen to focus on biogas and second-generation bioethanol, because biogas is the cheapest biofuel according to the report and second-generation bioethanol is the most expensive biofuel. Meaning that solutions like first-generation bioethanol, Fischer-Tropsch diesel, first-generation biodiesel/RME, and first-generation biodiesel/HVO, which are all included in the literature study, falls between the biogas and second-generation bioethanol prices.

First-generation bioethanol is in the report based on wheat and the price is set to 158 DKK/GJ. Second-generation bioethanol is in the report based on straw with a price on 283 DKK/GJ. The utilization of surplus heat is not taking into account in all studies, this is corrected with new price calculation where the utilization of the heat is accounted for. The new price for first-generation bioethanol is 155 DKK/GJ, which is slightly cheaper than before. The price of second-generation bioethanol has not changed, since the source to the literature study was the Måbjerg Energy Concept, which already included heat utilization. A few of the other biofuels get slightly cheaper after the included heat utilization, but they are all still in between biogas and second-generation bioethanol.

The supply of all biofuels has natural limits due to raw material limitations. The raw materials have different limits, we have already discussed the limit of food production and energy crops, which come down to availability of arable land. The availability of raw materials such as waste products or residues are dependent on the main product. One example is that the amount of straw depends on the demand for wheat, another example is that the amount of manure depends on the number of pigs. None of these limits are considered in this study, because we only focus on the price comparison between fossil fuels and the alternative solutions in the transportation sector.

Appendix A.6.2 Electrofuels

A literature review has been conducted to verify the results of our own calculations. First, the prices from a literature review conducted by Ea Energianalyse (2016) is used as a reference. The price for methanation of biogas with SOEC produced hydrogen is found to be 26-30 USD/GJ-natural gas-eq. A price for converting gas into a liquid fuel is added, so the final price becomes 32-36 USD/GJ diesel-eq.

Next, the literature review of electrofuels by Brynolf, Taljegard, Grahn, and Hansson (2017) is used to find relevant literature for a further scrutiny. Shown in Table 20 are the studies from the literature review that includes liquid electrofuels.

Table 20: Production cost of liquid electrofuels from studies in the report (Brynolf et al., 2017)

Author/article	Capacity factor	Electricity price	CO2 price	Capital cost	Fuel production cost	Fuel production cost
	%	EUR/MWh	EUR/ton	EUR/kW	EUR/MWh	USD/GJ
Becker et al. (2012)	40-90	0-100	10	1630	80-430	26-143
Dimitriou, Garcí a-Gutié rrez, et al. (2015)	90	38	?	1900	140	46
Fu et al. (2010)	?	20-80	20-160	417	110-160	37-52
Graves et al. (2010)	20- 100	0-83	30	?	80–165[a], 20–165[b]	26–55[a], 7–55[b]
Hannula (2015)	91	50	40	1820-2620	140, 150, 190	46-63
König et al. (2015)	?	110–180	40	10,14	300–510	99-170
Schmidt et al. (2016)	?	5–13	300–480	2050–6150	220–590	73-196
Smejkal et al. (2014)	91	35.4	40	400–2600	350–470	116-157
Tremel et al. (2015)	?	93	50	1000–1540	170-200	56-67

Notes:

[a] *20 % Capacity factor*

[b] *100 % Capacity factor*

The studies in the table indicates a big range in production prices, from 7 to 196 $/GJ. The reason behind the big range is the assumptions made by each study. The assumptions from each study on the most critical parameters is showed in Table 20. The parameters are the capacity factor, electricity price, CO_2 price and capital cost.

Three studies in the table have a price range much higher than the average price range and much higher than the prices from Ea Energianalyse (2016). The first study is by König et al. (2015) and the reason behind the high price range is the assumption that the electricity price is 110-180 €/MWh. None of the other studies, including Ea Energianalyse (2016), has this high electricity prices, not even near the low estimate from König et al. (2015). The reason behind the different electricity price is that König et al. (2015) claims that the price of offshore wind is 160 USD/MWh and use this as their reference price. The study by König et al. (2015) was conducted before the offer for Krieger's Flak on 50 EUR/MWh was made. If the electricity price was changed to 50 EUR/MWh the price of electrofuels would come very close to the other estimates.

The second study with a high price range is Schmidt et al. (2016) where the reason behind the high price range is the assumption made on the CO_2 price which is said to be 300–480 EUR/ton. All the other studies, except Fu et al. (2010), have a price range of CO_2 between 20-160 EUR/ton, most of them close to 40 EUR/ton. This indicates that Schmidt et al. (2016) used a too high CO_2 price. If the CO_2 price was lowered, the price of electrofuels would fall as well, but it has not been possible to assess the exact fall since the calculations are not included in the study.

The third study is Smejkal et al. (2014) which is the only study with a higher price range, where none of the assumptions stand out from the average assumptions. The difference in price could be caused by the fact that Smejkal et al. (2014) calculate all their capital cost and efficiencies based on demonstration and pilot plants.

Graves et al. (2010) is the only study with a price range where the lowest price is well below the average range. Their lowest value on 7 USD/GJ is found through a sensitivity analysis. The electricity price was identified to be the major cost component, when the capacity factor is a 100 percent. Thus, the capital costs are small or even negligible. Varying the electricity price from 0-10 US cents/kWh (0-80 EUR/MWh) gives the low estimate when the electricity price is zero. The literature review suggests that the price for electrofuels are in the range from 26-65 USD/GJ, where the reference price from Ea Energianalyse (2016) had a price on 32-36 USD/GJ.

The study by Graves et al. (2010) from the literature review has a very similar approach as us. If the electricity price is set to 7.4 US cents/kWh (60 EUR/MWh) the production price of electrofuels are approximately 35-45 USD/GJ. The difference in price ranges comes from different capacity factors in Graves et al. (2010) where in our calculations it comes from different methods of obtaining hydrogen and CO_2.

Appendix A.6.3 Converting cost of eHighways into a GJ diesel-eq.

To compare the cost of eHighways to fossil based fuels, the CAPEX/OPEX ratio for eHighways, based on the number of trucks per day had to be found. From this, the cost based on the number of trucks per day is converted into a cost per GJ diesel-eq. The procedure is described below and the results are shown in Table 21. The total cost in EUR/km is the sum of OPEX and CAPEX as seen in Figure 16, Section 4.3.4.1. To convert the cost into a price per GJ diesel-eq., three conversions are needed.

First, the total cost is divided by the energy consumption of an electric truck, which is 1.5 kWh/km. Second, the total cost, now in EUR/kWh, is divided by the conversion factor from kWh to GJ, which is 0.0036 GJ/kWh. Third, the total cost, now with the unit EUR/GJ electricity, is divided with a conversion factor of 2.2 GJ diesel-eq./GJ electricity. To explain the conversion factor between GJ electricity on an eHighway to GJ diesel-eq. the process is shown here. The difference basically comes from the efficiencies. The purpose of these calculations is to get the relation between how many kilometers a truck can drive on one GJ electricity and GJ diesel, because the relation can work as a conversion factor between GJ diesel-eq. and GJ electricity.

The electric trucks fuel efficiency in kWh/km is converted to kilometer/GJ:

$$1.5\frac{\text{kWh}}{\text{km}}=0.667\frac{\text{km}}{\text{kWh}}$$

$$\frac{1}{0.0036}\frac{\text{kWh}}{\text{GJ}}\cdot 0.667\frac{\text{km}}{\text{kWh}}=185\frac{\text{km}}{\text{GJ electricity}}$$

The diesel trucks fuel efficiency in kilometers/liter is converted to kilometer/GJ:

$$\frac{3\,\frac{\text{km}}{\text{L}}}{0.03587\,\frac{\text{GJ}}{\text{L}}}=84\,\frac{\text{km}}{\text{GJ diesel-eq.}}$$

The conversion factor becomes:

$$\frac{185\,\frac{\text{km}}{\text{GJ electricity}}}{84\,\frac{\text{km}}{\text{GJ diesel-eq.}}}=2.2\,\frac{\text{GJ diesel-eq.}}{\text{GJ electricity}}$$

The conversion factor of 2.2 GJ diesel-eq./GJ electricity is in line with the results of the study Lee, Thomas, and Brown (2013), where it is stated that the energy used for an electric truck is 48 % to 82 % lower than a diesel truck.

Table 21: Overview of unit calculation of the cost of eHighways into GJ diesel-eq.

Total electricity cost Cost of electricity per km	*80,00* *0,12*	EUR/MWh EUR/km	The Danish Energy Agency and Energinet's future electricity price.				
Number of trucks	*500*	*1000*	***2000***	*4000*	*6000*	***8000***	*10000*
Total cost (EUR/km)	0.96	0.54	**0.33**	0.23	0.19	**0.18**	0.17
Total cost (EUR/kWh)	0.64	0.36	**0.22**	0.15	0.13	**0.12**	0.11
Total cost (EUR/GJ electricity)	178.58	100.85	**61.98**	42.54	36.07	**32.83**	30.88
Total cost (EUR/GJ diesel-eq.)	81.09	45.79	**28.14**	19.32	16.38	**14.91**	14.02

Now that the cost is translated into a price per GJ diesel-eq. it can be compared with fossil based fuels. The range chosen for the graphs are 2,000 trucks per day as the lower limit and 8,000 trucks per day as the upper limit. If the eHighway gets less dense than 2,000 trucks per day the business case gets too poor.

8,000 trucks a day is equivalent to one truck every 10.8 seconds on average, and because the load is not equally distributed throughout the day, we see this as the upper limit. The full analysis and exact calculations can be seen in Appendix C.10.

$$\frac{8000\text{ trucks}}{24\text{ h}}=\frac{333.33\,\frac{\text{trucks}}{\text{h}}}{60\,\frac{\text{min}}{\text{h}}}=\frac{5.55\,\frac{\text{trucks}}{\text{min}}}{60\,\frac{\text{sec}}{\text{min}}}=0.093\,\frac{\text{trucks}}{\text{sec}}$$

$$\frac{1}{0.093\,\frac{\text{trucks}}{\text{sec}}}=10.8\,\frac{\text{sec}}{\text{truck}}=1\text{ truck every 10.8 seconds in average}$$

Appendix A.6.4 Converting cost of Tesla Semi into GJ diesel-eq.

As was done with eHighways, the same method to convert the cost for battery trucks into a price per GJ diesel-eq. is used. The only difference is the announced fuel efficiency for the Tesla Semi which is

1.2 kWh/km, which is a better efficiency than a regular truck, that is 1.5 kWh/km. The results are shown in Table 22. The Tesla Semi's fuel efficiency in kWh/km is converted to kilometer/GJ:

$$1.2\frac{\text{kWh}}{\text{km}}=0.83\frac{\text{km}}{\text{kWh}}$$

$$\frac{1}{0.0036}\frac{\text{kWh}}{\text{GJ}}\cdot 0.83\frac{\text{km}}{\text{kWh}}=231\frac{\text{km}}{\text{GJ electricity}}$$

The diesel trucks fuel efficiency in kilometers/liter is converted kilometer/GJ:

$$\frac{3\frac{\text{km}}{\text{L}}}{0.03587\frac{\text{GJ}}{\text{L}}}=84\frac{\text{km}}{\text{GJ diesel-eq.}}$$

The conversion factor becomes:

$$\frac{231\frac{\text{km}}{\text{GJ electricity}}}{84\frac{\text{km}}{\text{GJ diesel-eq.}}}=2.75\frac{\text{GJ diesel-eq.}}{\text{GJ electricity}}$$

The conversion factor of 2.75 GJ diesel-eq./GJ electricity is in line with the results of the study Lee, Thomas, and Brown (2013), where it is stated that the energy used for an electric truck is 48 % to 82 % lower than a diesel truck. The full analysis and exact calculations can be seen in Appendix C.10

Table 22: Overview of unit calculation of the cost of Tesla Semi into GJ diesel-eq.

Total electricity cost	*80.00*	EUR/MWh	The Danish Energy Agency and Energinet's future electricity price.		
Kilometer cost	*0.10*	EUR/km			
Lifetime (km)	*1,600,000*	*2,000,000*	*2,400,000*	*2,800,000*	*3,000,000*
Total cost (EUR/km)	0.12	0.12	0.12	0.11	0.11
Total cost (EUR/kWh)	0.10	0.10	0.09	0.09	0.09
Total cost (EUR/GJ)	27.83	26.71	25.96	25.43	25.21
Total cost (EUR/GJ diesel-eq.)	10.10	9.69	9.42	9.23	9.15

Appendix A.6.5 Socio- and corporate economic NPV analysis of truck propellants

To obtain a better understanding and to verify the conclusion of the OPEX/CAPEX analysis a socioeconomic NPV analysis was conducted for a Danish case. In the analysis, socioeconomic cost of emissions like CO_2, NO_X, SO_2 and $PM_{2.5}$ from ENS (2017b) is taken into consideration for both electricity, diesel, and methane. The tax distortion loss is also included on top of the socioeconomic production cost.

The CO_2 emission cost for the electric truck reflects the quota price on the EU ETS and this price is already included in the future estimated electricity price by ENS (2017b) since the electricity sector is part of the quota system. It is different for the diesel trucks, since the transport sector is not included in the system. It is extremely hard to calculate the true socioeconomic cost of emitting CO_2. The Danish

Energy Agency has made a vague estimate of 40 EUR/ton for emissions emitted outside the quota system based on EU's Impact Assessment for 2030 (DEA, 2017b).

This means that the CO_2 price for the electric trucks reflect the cost of avoiding the emission of CO_2, where the diesel truck reflects the estimated socioeconomic damage cost. The difference in cost, of emitting CO_2, in these methods is quite high because the quote price is much lower than the socioeconomic estimated damage cost.

The electricity price is based on the future projection made by the Danish energy agency, with a maximum electricity price in compliance with the 60 EUR/MWh from Krieger's Flak. The results can be seen in Figure 23.

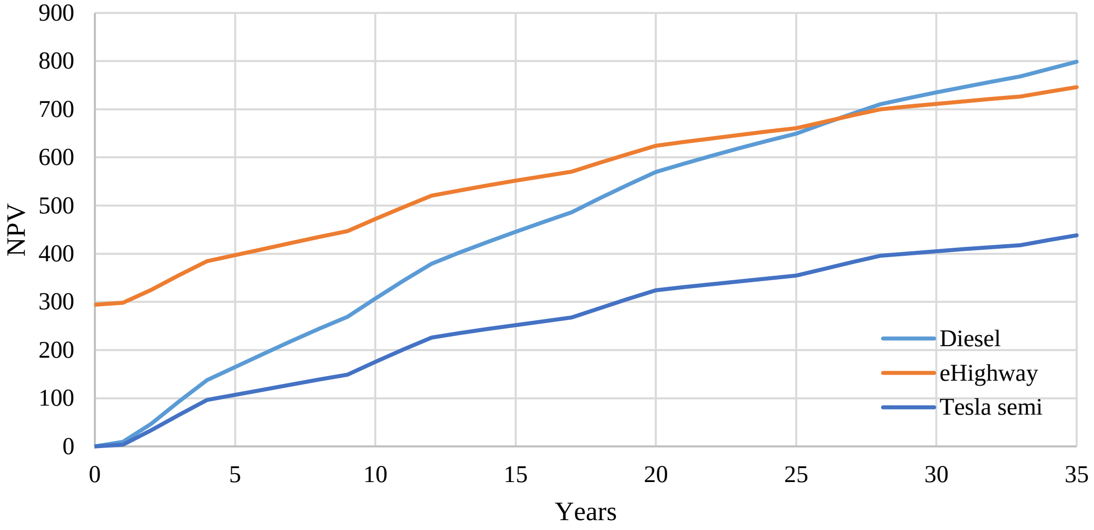


Figure 23: Danish socioeconomic net present value cost comparison between diesel trucks, eHighways, and Tesla Semi.

The Tesla Semi is almost half the cost of the diesel trucks under Danish framework conditions, also the eHighway is better than the diesel trucks. These results verify the results in Section 4.3.4, however the eHighway and Tesla Semi are better in a Danish socioeconomic NPV, than in our main analysis, and two main factors can explain this. First, socioeconomic costs of emissions from both electricity production and the burning of diesel is included in the Danish scenario, however the inclusion of the tax distortion loss minimize the effect of the emission cost. Second, the fuel prices used by the Danish Energy Agency are based on the average import cost/market price for all Danish companies when they buy coal, oil, and gas (Ea Energy Analyses, 2014b), which means that profit, taxes, transport, etc., are included before the goods arrive in Denmark. The cost in the main analysis has omitted some of these factors.

To finalize the analysis of eHighways a corporate-economic NPV analysis is made. The difference from the socioeconomic NPV analysis is that the prices on trucks, diesel, electricity, etc. reflects the prices from a consumer's perspective. Here the eHighway and Tesla Semi has quite a margin to diesel trucks, which is the most expensive. The full analysis and exact calculations can be seen in Appendix C.10

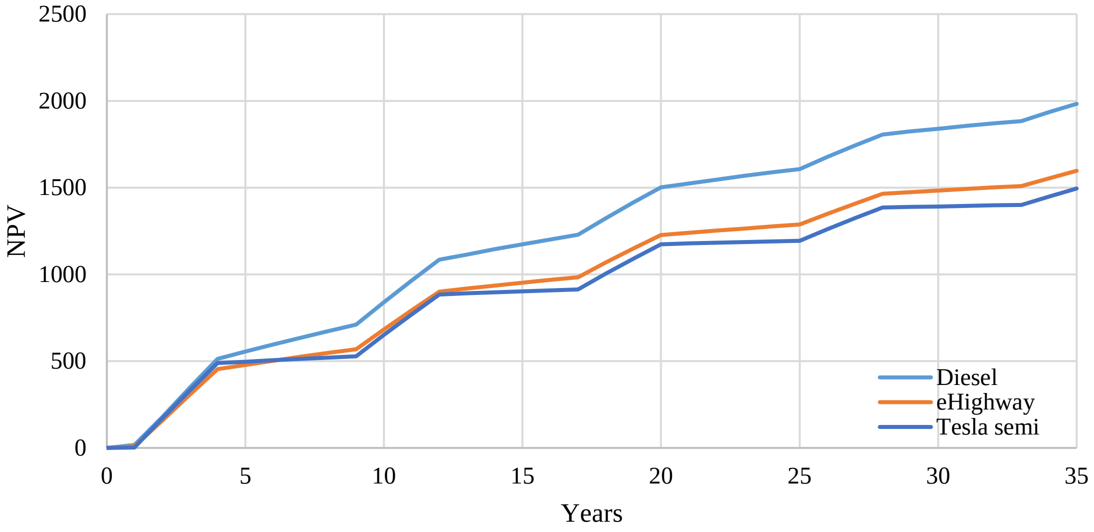


Figure 24: Danish corporate-economic net present value cost comparison between diesel trucks, eHighways, and Tesla Semi.

Appendix B Discussion

Appendix B.1 Operating fields

The data for the already operating fields have been found in Muttitt et al. (2016). The data have been converted into one of our functional units by conversion factors from BGR (2016) and BP (2017a). The amounts of proved reserves from BGR (2016) have been inserted for comparison. A large share of the proved reserves of oil and gas is found in already operating fields.

Table 23: Reserves of oil, gas and coal from existing and under-construction oil and gas fields, and existing coalmines (BGR, 2016; Muttitt et al., 2016).

	Reserves in operating fields 2015	Reserves in operating fields 2015	Proved reserves 2015 (BGR)
Oil	813 billion bbl	4,635 EJ	9,050 EJ
Gas	2,891 trillion cubic feet	3,111 EJ	7,473 EJ
Coal	174 Gt coal equivalents	4,278 EJ	24,261 EJ
Total		11,383 EJ	40,784 EJ

Appendix C Excel spreadsheets

Appendix C.1 Tragedy of the Planet – BGR reserves 1 – data processing

This spreadsheet is the first part of constructing the “Tragedy of the Planet?” graph. It contains all the data processing for the graphs. This spreadsheet is based on BGR’s reserve data which is used in our main analysis.

Appendix C.2 Tragedy of the Planet – BGR reserves 2 – graph processing

This spreadsheet is the second part of constructing the “Tragedy of the Planet?” graph. It contains all the graph processing. This spreadsheet is based on BGR’s reserve data which is used in our main analysis.

Appendix C.3 Tragedy of the Planet – BGR total 1 – data processing

This spreadsheet corresponds to Appendix C.1, but the data used here is the total of both reserves and resources from BGR.

Appendix C.4 Tragedy of the Planet – BGR total 2 – graph processing

This spreadsheet corresponds to Appendix C.2, but the data used here is the total of both reserves and resources from BGR.

Appendix C.5 Tragedy of the Planet – BP 1 – data processing

This spreadsheet is the first part of constructing the “Tragedy of the Planet?” graph. It contains all the data processing for the graphs. This spreadsheet is based on BP data which is not used in our main analysis due to the big similarities to the data from BGR.

Appendix C.6 Tragedy of the Planet – BP 2 – graph processing

This spreadsheet is the second part of constructing the “Tragedy of the Planet?” graph. It contains all the graph processing. This spreadsheet is based on BP data which is not used in our main analysis due to the big similarities to the data from BGR.

Appendix C.7 BGR and BP reserves, resources, and price matching

This spreadsheet compiles all data from BGR and BP for reserves and resources. Furthermore, prices for each individual country is assigned to each category of fossil fuel. It is not a neat and tidy sheet because it is compiled from some quite big spreadsheets. Never the less it is the backbone of our main analyses.

Appendix C.8 Refining costs

This spreadsheet has been used to calculate the crack spread, which has been used to estimate the refining cost for oil. We have not developed it our self, but modified it to conduct our analysis.

Appendix C.9 Electrofuel price calculator

This spreadsheet contains a tool that can calculate the price of electrofuels for a variety of configurations dependent on the electricity price. Furthermore, it contains some quick analyses of the global investment needed to cover the global aviation needs, of the electricity prices in 2017, and of the rise in airplane tickets if we were to fly on electrofuels.

Appendix C.10 Electricity as a fuel

This spreadsheet contains a tool that can calculate the capital and operational expenses for eHighways and the Tesla Semi for a variety of configurations dependent on the electricity price. The spreadsheet also contains an analysis of the net present value of eHighways, Tesla Semi, LNG, electric, and biodiesel fueled trucks in a Danish scenario. Furthermore, it contains a small analysis of the future electricity and CO_2 prices.

Appendix C.11 Tragedy of the Planet – BGR reserves 1 – data processing – CO2

This spreadsheet corresponds to Appendix C.1, but the data used here has included in it a CO_2 price.

Appendix C.12 Tragedy of the Planet – BGR reserves 2 – graph processing – CO2

This spreadsheet corresponds to Appendix C.2, but the data used here has included in it a CO_2 price.