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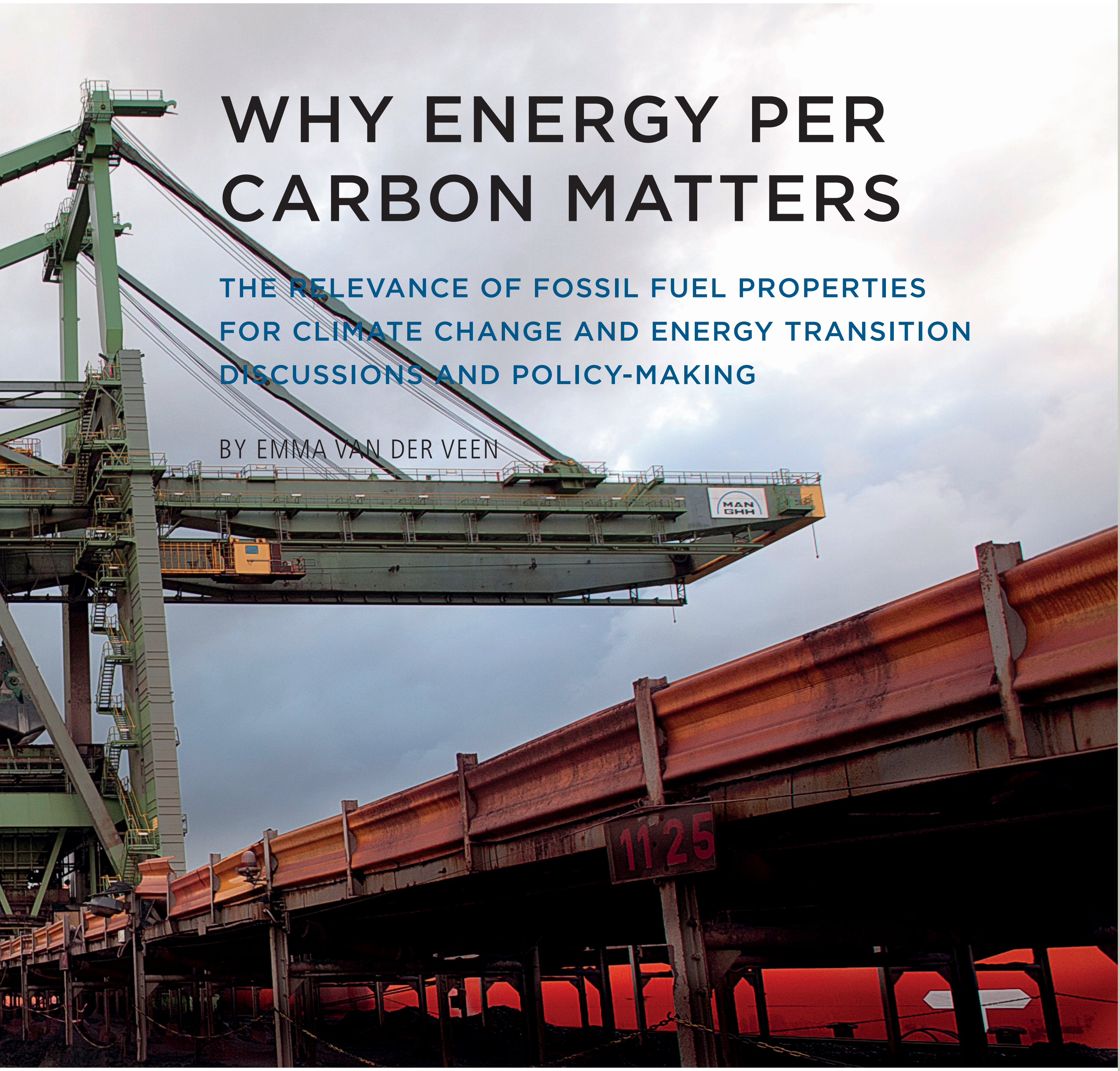

WHY ENERGY PER CARBON MATTERS

THE RELEVANCE OF FOSSIL FUEL PROPERTIES FOR CLIMATE CHANGE AND ENERGY TRANSITION DISCUSSIONS AND POLICY-MAKING

BY EMMA VAN DER VEEN

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INTRODUCTION

In 2009, both the G8 countries and the major newly industrialising countries, which were then convened in L'Aguila, Italy, committed to 'limit[ing] the average temperature increase to a maximum of 2 degrees as compared to the pre-industrial level (so-called 2°C target)'.[1] The impetus was that average global surface temperatures are rising due to an increased greenhouse effect caused by anthropogenic emissions from land use change and fossil fuel combustion. Further global warming would have increasingly serious consequences, and to prevent the world from the most severe damage, the 2°C target was agreed upon as an upper limit.

A GLOBAL CARBON BUDGET

Scientists have determined that in order to be 80% certain of being able to stay below this 2°C target, carbon dioxide (CO_2)[2] emissions will need to be capped at a total of 886 Gt during the first half of the 21st century.[3] Of this so-called 'global carbon budget', 321 Gt of CO_2 was already emitted in the years 2000-2010 (282 Gt of CO_2 from burning fossil fuels and 39 Gt of CO_2 from land use change).[4] This leaves a budget of only 565 Gt of CO_2 for the period 2011-2050.[5]

In this paper, the 'New Policies Scenario' of the International Energy Agency's (IEA) World Energy Outlook is used as the default outlook for the future.[6] Under this scenario, the share of low-carbon energy sources (e.g. nuclear or renewable energy) will be too small to satisfy total primary energy demand (TPED),[7] such that fossil fuels will remain part of the world energy mix in the coming decades. Their corresponding CO_2 emissions will be inevitable unless CCS or other abatement technologies are employed, and thus the amount of CO_2 from fossil fuels will continue to build up in

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[1] http://www.bmub.bund.de/en/topics/europe-international/international-environmental-policy/g7g8-and-g20/g7g8-summit/.

[2] Table 3 in the Appendix lists all abbreviations that are used in this paper.

[3] Meinshausen et al. (2009), 'Greenhouse-Gas Emission Targets for Limiting Global Warming to 2°C', *Nature*.

[4] Friedlingstein et al. (2010), 'Update on CO_2 Emissions', *Nature*.

[5] Carbon Tracker Initiative (2012), 'Unburnable Carbon – Are the World's Financial Markets Carrying a Carbon Bubble?'.

[6] International Energy Agency (2013, 2014), 'World Energy Outlook 2013' and 'World Energy Outlook 2014'.

[7] International Energy Agency (2014), 'World Energy Outlook 2014', pp. 606 – Categories 'hydro', 'bioenergy', and 'other renewables' are taken together as renewable energy sources and amount up to 15 and 19% of TPED for the years 2020 and 2040, respectively. In this scenario nuclear energy accounts for 5 and 7% of TPED in 2020 and 2040, respectively.

the atmosphere. Calculations[8] show that under the New Policies Scenario emissions will exceed the global carbon budget, and thus the limit of 2°C temperature increase, already by the year 2027.

RELEVANCE OF FOSSIL FUEL PROPERTIES

Considering the significant role of fossil fuels in future energy mix scenarios and their potential impact on climate, their properties should be carefully considered in climate discussions and energy policy-making. Coal, oil and gas differ significantly in the amount of carbon dioxide that they emit as well as in the amount of energy that they contain per unit of, for instance, weight or volume. In this paper the latter is referred to as the 'energy content', in other words the energy (heat) released by complete combustion of the fuel. Consequently, when burned, each fuel contains a specific amount of energy per unit of carbon that it emits.

The basic argument of this paper is the relevance of the 'energy per carbon' concept, especially in light of discussions on the carbon budget and the claim that most of the world's fossil fuel reserves should stay in the ground[9] if the global temperature increase is to remain below the 2°C limit.

OBJECTIVE REPRESENTATION?

The fact that a portion of the available fossil fuels might not be burned was illustrated by the Carbon Tracker Initiative (CTI) by depicting the potential carbon dioxide release of all proven fossil reserves and showing that this would by far exceed the carbon dioxide budget of 565 Gt (see Figure 1, left bar graph[10]).[11] More specifically, though, CTI drew the huge coal reserves at the *bottom* of the graph – in essence the traditional way of stacking energy resources – leaving the reader with the suggestion that only a minor part of the coal reserves and none of the oil and gas reserves (without CCS) may be exploited if the world is to stay within the carbon budget.

However, by turning the figure upside-down, CIEP introduced an alternative way of looking at the issue. We stacked the fuels with the lowest emitting sources at the bottom (see Figure 1, right bar graph). What emerges is the insight that burning all of the world's gas reserves and part of the oil reserves is not necessarily[12] in conflict with

---

[8] Linear interpolation and linear extrapolation were used to obtain annual values for global CO_2 emissions from fossil fuels over the period 2011-2050.

[9] Since these reserves are part of national and international companies' balance sheets, it is claimed that companies will be left with many stranded assets.

[10] Originally, CTI drew stacked circles for the fuel reserves, with gas on top of oil on top of coal. However, CIEP has redrawn the representation of these reserves in a bar graph.

[11] Carbon Tracker Initiative (2012), 'Unburnable Carbon – Are the World's Financial Markets Carrying a Carbon Bubble?'.

[12] Provided that no coal reserves are used.

meeting the carbon budget.[13] What we do not see here, but what we will explain in the following section, is that this way of prioritising the energy mix also produces more energy for the same amount of CO_2 emissions.

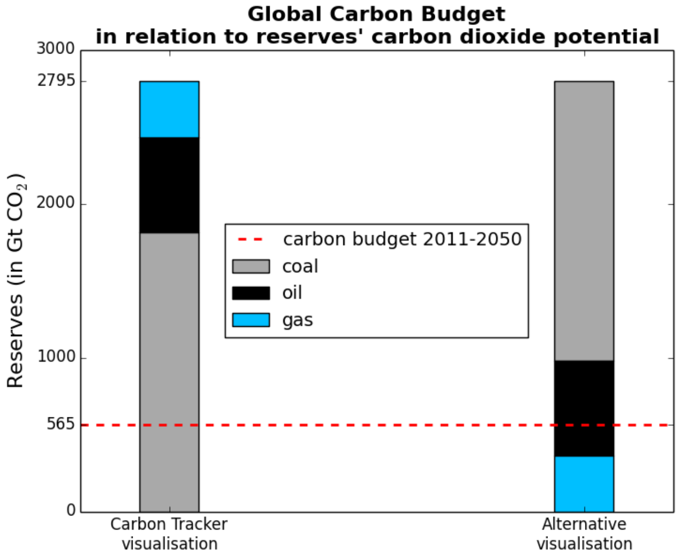

FIGURE 1.

IMPORTANT IN ENERGY POLICY-MAKING

The nuance above is clearly important in the public debate on paths to sustainability and the possible roles of the various fossil fuels, yet it is often overlooked. A generic approach to all fossil fuel reserves and an anti-fossil tone predominates the discussions, obfuscating the fact that the carbon contents of fossil fuels differ widely, as does the efficiency of the technologies with which the various types of energy consumption (heat, electricity, transportation) are satisfied. By not taking these factors into account in the debate about future energy policies, important transition paths might be left underexplored, whereas the right choice of fuels could reduce emissions and ultimately push back the time of hitting the carbon ceiling.

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[13] Clingendael International Energy Programme (2014), 'Transition? What Transition? Changing Energy Systems in an Increasingly Carbon Constrained World'.

In this paper, the different carbon and energy properties of fossil fuels are examined based on certain assumptions about the efficiency of energy technologies. We explain, and where possible quantify, that:

1. energy content differs among fuels;
2. the energy output possible within the carbon budget depends on fuel choice; and thus
3. through fuel choices the world can push back the time that we will hit the carbon ceiling.

The paper concludes with some reflections on the theoretical nature of this work, because not all relevant factors have been taken into account, nor is the real energy mix as 'black and white' as is here reviewed.

1 ENERGY CONTENT AND THE CARBON BUDGET

In addition to the insight that burning the world's gas reserves would not be in conflict with the global carbon budget,[14] the alternative visualisation as presented by CIEP would provide more energy than the traditional one. More precisely, the energy content of the gas reserves and a portion of the oil reserves is 60% higher than the energy content of the relevant part of the coal reserves (see Figure 2). Calculations[15] include emission factors, Net Calorific Values (NCVs) and more general conversion factors.[16]

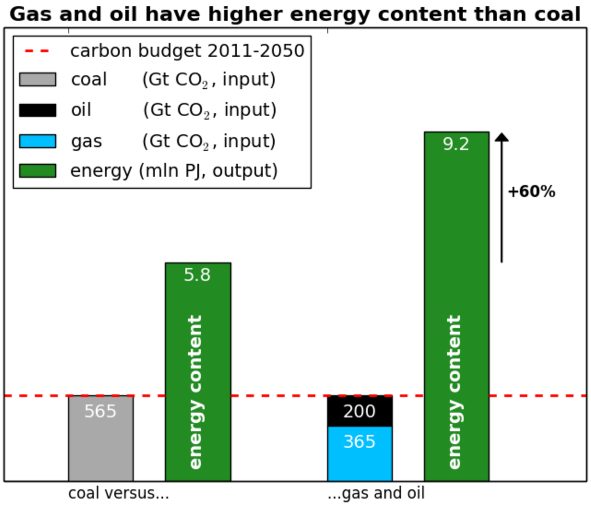

FIGURE 2.

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[14] Clingendael International Energy Programme (2014), 'Transition? What Transition? Changing Energy Systems in an Increasingly Carbon Constrained World'.

[15] Results were verified by comparing the carbon dioxide potential from the total proved reserves with data from Carbon Tracker Initiative's report. Table 1 in the Appendix shows that the two outcomes closely match.

[16] Table 2 in the Appendix lists all factors, including conversion factors, that are used for the calculations of this paper.

2 ENERGY OUTPUT AND THE CARBON BUDGET

As the energy content per unit of carbon emitted differs between coal, oil and gas, so does actual energy output (also per carbon unit), largely due to the differences in conversion efficiency among these fuels. In other words, fuels are not solely combusted to produce heat, but are often transformed into, for instance, electricity, motion (transport), or space heating and cooling. This transformation of energy is associated with conversion efficiency, and hence an energy loss, that is specific for each fuel type and the corresponding technology or form of energy use.

The example below illustrates that a significantly higher total energy output could be achieved if the carbon space were to be spent by first utilising gas and a part of the oil reserves, rather than filling it between now and 2050 with the burning of coal.

Since the highest usage of coal is in power generation,[17,18] it is straightforward to determine the potential electricity output from coal-fired generation that can be achieved within the carbon emissions budget. This total output amounts approximately to 722,000 TWh_{el} (see Figure 3). To keep calculations feasible, we have assumed generation in up-to-date 'advanced supercritical' (ASC) coal plants,[19] which can operate at 45% efficiency.[20]

For comparison purposes, we determined the potential electricity output from the gas reserves[21], and this appears to be significantly higher than with coal: approximately 1,068,000 TWh_{el}, which is 48% more. This can be explained by the higher amount of 'energy per carbon emitted' of gas compared to coal (see previous section), but moreover by the modern combined cycle gas turbine (CCGT) technology[22] that allows gas plants to generate electricity at 59% efficiency rates.[23] In addition, part of the carbon space is still 'empty', such that a part of the oil reserves might be tapped as well: around 465 billion barrels.[24]

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[17] The power sector accounted for 63% of global coal use in 2011 and – under influence of a decline in OECD and increase in non-OECD countries – is expected to remain so in the future.

[18] International Energy Agency (2013), World Energy Outlook 2013.

[19] In the Netherlands, the *Eemshavencentrale* is an example of an ASC coal plant. See also http://www.essent.nl/content/overessent/het_bedrijf/opwekking/centrale_eemshaven/werking/index.html.

[20] Mott MacDonald (2010), UK Electricity Generation Costs Update'.

[21] Recall that the gas reserves by themselves do not use up the entire carbon budget.

[22] In the Netherlands, the *Nuon Magnum* plant in the *Eemshaven* and the *Hemweg 9* plant in Amsterdam are examples of CCGT plants. See also http://powerplants.vattenfall.com/powerplant/magnum and http://powerplants.vattenfall.com/powerplant/hemweg.

[23] Mott MacDonald (2010), 'UK Electricity Generation Costs Update'.

[24] Note that the actual energy output from these barrels depends on the conversion efficiencies of the appliances (mostly transportation vehicles).

Even though these calculations clearly show that electricity output is higher with gas-fired than with coal-fired generation, it is important to mention that this is only one way of presenting the results. Forms of energy use besides electricity are relevant as well, and the 'extra' gas could, for instance, be used instead for industrial and/or heating purposes.

Assume that an equal amount of electricity is generated in coal-fired and gas-fired plants (let's say approximately 722,000 TWh_{el}, such that emissions from the coal plants stay within the budget). The carbon space that would be freed in the case of gas (and 'worth' approximately 346,000 TWh_{el}) could be used, for instance, to supply heating: in this case approximately 527,000 TWh_{th} (see also Figure 3).[25] Recall that the use of gas also leaves room for oil (approximately 465 billion barrels) to be utilised while remaining within the carbon budget.

Overall, exploiting highly energy-intensive fuels (i.e., fuels that produce a large amount of energy per unit of carbon emitted) is important in a world in which energy demand is expected to grow and the carbon space is limited, since it could help satisfy energy needs without clashing with the climate goals for 2050.

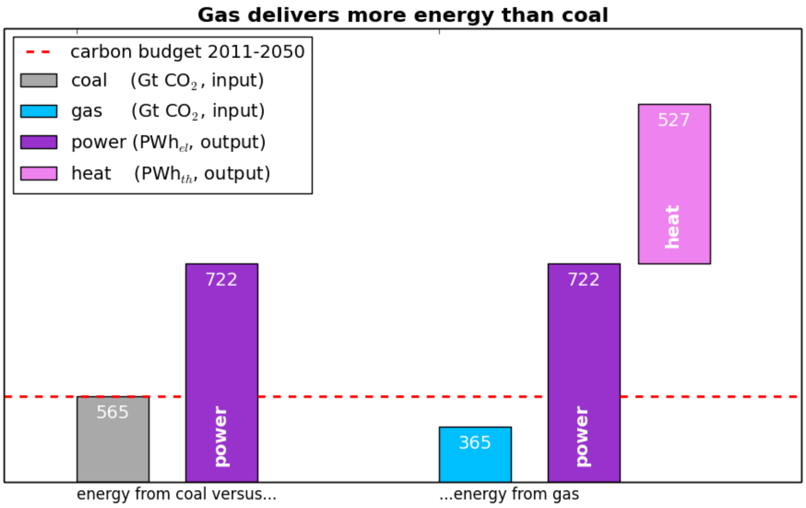

FIGURE 3.

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[25] The conversion efficiency for heating is assumed to be 90%.

3 HOW TO PUSH BACK THE TIME OF HITTING THE CARBON CEILING

Setting a cap on emissions and optimising energy output within the carbon budget, by wisely choosing the world's fossil fuel use, might seem easier said than done. Namely, energy demand, rather than the emissions budget, is the leading commercial determiner of how much fuel is burned.[26] In this context, very often the response of policy-makers, rather than focusing on how to maximise energy production within the carbon budget, is to develop policies that minimise carbon emissions. The latter approach aims to 'buy time', i.e., to postpone the moment that the world surpasses the carbon budget.[27] It is this focus that also provides us with interesting insights about the impact of policy-makers' choices when comparing the carbon content of fuels and the technologies that should be used to satisfy demand.

Based on the previous sections, it is easy to argue that using natural gas to satisfy energy demand would give the world more time 'within budget' than if, as in the default scenario, coal were used.[28] Calculations on this trade-off between coal and natural gas are particularly relevant in the power sector since there they are the two dominant – and hence competing – fuels.[29] Moreover, emissions from the power sector are significant: calculations[30] show that in the New Policies Scenario fossil power generation alone would already consume the whole carbon budget of 565 Gt of CO_2 by 2049, leaving energy demand in other types of energy use (such as mobility, heating and cooling) unaddressed.[31]

To fully understand the potential impact of fuel-switching in the power sector, three different scenarios are assessed below: one in which electricity is generated with coal, oil and gas while coal and gas plants utilise up-to-date technologies; one in which

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[26] Recall that if meeting demand, projected as in the New Policies Scenario, is the objective without taking emissions into account, the carbon budget will be exceeded years before 2050.

[27] As mentioned earlier, calculations based on the New Policies Scenario of the IEA indicate that emissions will outpace the carbon budget as early as 2027.

[28] Idem.

[29] Oil is not often used to generate power. The Energy Information Administration (EIA) states in its 'International Energy Outlook 2013' that in 2010, 40% of global electricity demand was generated by coal, 22% by natural gas, 12% by nuclear, 12% by renewables and 5% by petroleum and other liquids (and also mentioned that this figure was part of a decreasing trend). A later update on its website provides specific data for the United States in 2013: 39% of generation there was from coal, 27% from natural gas, and only 1% from petroleum. See also: http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3.

[30] Recall from the Introduction that linear interpolation and linear extrapolation are used to obtain annual values for global CO_2 emissions and electricity generation for 2011-2050.

[31] Emissions approximate 555 Gt of CO_2 at the end of 2048, and 571 Gt of CO_2 at the end of 2049.

electricity is generated exclusively in modern ASC coal plants; and one in which electricity is generated exclusively in modern CCGT gas plants.[32]

Keep in mind that electricity generation in these scenarios includes only the share of total output that is generated with fossil fuels as in the New Policies Scenario, and not with nuclear and/or renewable energy sources.

GENERATION IN UP-TO-DATE COAL AND GAS TECHNOLOGIES

Equipping power plants with modern technologies, and thus increasing their efficiency, would reduce emissions from power generation and postpone the moment at which emissions would exceed the carbon budget. In its forecasts, the IEA assumes average coal plant efficiencies of around 33% (in 2011), up to 37% (in 2040), and average gas plant efficiencies of around 37% (in 2011), up to 47% (in 2040).[33] However, as discussed earlier, current ASC coal plants can in fact operate at 45% efficiency, while modern CCGT gas plants can achieve 59%.

Upgrading actual efficiencies for all coal-fired and gas-fired electricity brings cumulative emissions to approximately 485 Gt of CO_2 by 2050, which is a reduction of 17% compared to the New Policies Scenario.[34] Even though the decline is rather modest, it does imply that it is possible for the carbon budget to not be exceeded – that is, not by the power sector alone.

GENERATION EXCLUSIVELY IN MODERN COAL PLANTS

Rather than producing power from a mix of (upgraded) coal, gas, and a minor share of oil plants, in this scenario only coal is used. On the one hand, generating power exclusively in modern ASC coal plants delivers more efficient coal-fired electricity than predicted in the New Policy Scenario, but on the other hand, since coal is the only fuel in this 'mix', an overall lower energy per carbon factor is achieved. The effect of the latter appears to be the strongest, and cumulative emissions amount to approximately 623 Gt of CO_2 in 2050. Moreover, in this scenario the carbon budget is already exceeded by 2048,[35] meaning that replacing all fossil power plants with the most efficient coal plants to date is even worse than following the New Policies Scenario.

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[32] ASC coal plants with 45% conversion efficiency and CCGT plants with 59% conversion efficiency, as discussed in the previous section.

[33] The efficiencies are inferred from New Policies Scenario data in the 'World Energy Outlook 2013' and 'World Energy Outlook 2014' of the International Energy Agency.

[34] For the New Policies Scenario, cumulative emissions approximate 587 Gt of CO_2 by the end of 2050.

[35] Emissions approximate 565 Gt of CO_2 at the end of 2047 and 584 Gt of CO_2 at the end of 2048.

GENERATION EXCLUSIVELY IN MODERN GAS PLANTS

In contrast with the previous scenario, replacing fossil-fired generation exclusively with modern CCGT gas plants more than halves emissions compared to the New Policies Scenario: cumulative emissions would approximate 272 Gt of CO_2 by 2050. Consequently, emissions from the power sector remain well within the global carbon budget, and the time of reaching the carbon ceiling is pushed back at least another 39 years.[36] Alternatively, the remaining 293 Gt of CO_2 could also be used before 2050 as other forms of energy output like heating and/or transport.

Figure 4 illustrates the cumulative CO_2 emissions from the power sector by 2050 in relation to the global carbon budget for the different scenarios. Remember that emissions from outside the power sector are not considered here, while they actually contribute and are expected to produce around 60% of total global CO_2 emissions.[37] Hence, some 'reconsiderations' with respect to fossil fuel use should be part of your discussions about these sectors as well.

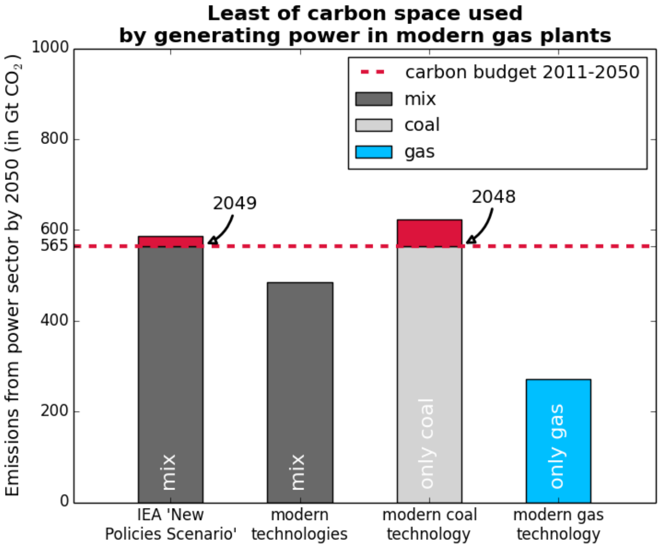

FIGURE 4.

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[36] Less than half of the carbon budget is filled when 272 Gt of CO_2 is emitted. Therefore, an equally long period of 39 years (=2050-2011) of electricity generation might fit before emissions exceed the 565 Gt of CO_2 limit.

[37] New Policies Scenario of the International Energy Agency's (2013, 2014), 'World Energy Outlook 2013' and 'World Energy Outlook 2014'.

4 REFLECTIONS

The analysis in this paper shows that using up-to-date gas-fired power stations to generate the world's fossil-fuelled electricity demand between now and 2050 would leave the most room for other fuels or forms of energy to be utilised while remaining under the climate-related ceiling for CO_2 emissions. Most likely, the same would be true for other types of energy use besides electricity. Nevertheless, it is worth emphasising that the exercise of this paper is a theoretical one, providing generic insight into the impact of choices with respect to fossil fuel use in the energy mix rather than focussing on details, and should be interpreted accordingly.

One uncertainty factor that is not considered in the calculations is the extent of life cycle emissions for the different fossil fuels. If these emissions were to appear to be much larger than anticipated, the fuel(s) would produce less energy per unit of carbon emitted, which would result in a lower energy output being able to be achieved within the carbon budget. Also, the priority position of one fuel in relation to the others might change. However, both the International Energy Agency and the Intergovernmental Panel on Climate Change (IPCC) find that 'well-to-burner' and 'life cycle' emissions, respectively, are larger for coal than for natural gas.[38,39] These notions are in line with the narrative of the paper and support, if not reinforce, the results as presented above.

Finally, in reality, energy demand is not provided only by coal or only by gas and/or oil, nor is this a realistic pathway. Rather, the world should reconsider and improve the energy mix as a whole, including nuclear, hydro, and renewable energy sources, without overlooking the properties (including energy output per unit of carbon) of fossil fuels. A visualisation of the carbon budget which reflects all these properties is crucial for future discussions on transition and policy-making. The aim of the abstract scenarios in this paper was to provide a step in this direction by illustrating the trade-offs among fuels, their emissions and the corresponding energy output. Insights in this matter are essential to being able to properly address the challenge of climate change as well as to making the right decisions in energy policy-making with regard to prioritising certain transition paths and determining the future energy mix.

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[38] International Energy Agency (2012), 'Golden Rules for a Golden Age of Gas – World Energy Outlook Special Report on Unconventional Gas'.

[39] Intergovernmental Panel on Climate Change (2012), 'Renewable Energy Sources and Climate Change Mitigation – Special Report on the Intergovernmental Panel on Climate Change', p.19 and p.124. Note that these life cycle emissions are not general, but specific for electricity generation technologies.

APPENDIX

TABLE 1. TOTAL PROVEN FOSSIL FUEL RESERVES AS PROVIDED BY BP (SOURCE: BP STATISTICAL REVIEW OF WORLD ENERGY 2010) AND THE ASSOCIATED CARBON DIOXIDE EMISSIONS POTENTIAL AS CALCULATED BY THE AUTHOR, LEFT COLUMN; AND THE POTENTIAL EMISSIONS AS CALCULATED BY CTI (SOURCE: CARBON TRACKER INITIATIVE (2012), 'UNBURNABLE CARBON – ARE THE WORLD'S FINANCIAL MARKETS CARRYING A CARBON BUBBLE?'), RIGHT COLUMN. THE TWO SETS OF FIGURES COMPARE CLOSELY.

Fuel	Reserves	Units	Carbon Dioxide Potential	Units	Carbon Dioxide Potential CTI	Units
Coal	826001	*million tonnes*	1872	*Gt* CO_2	1817	*Gt* CO_2
Oil	1476.4	*milliard bbl*	634	*Gt* CO_2	615	*Gt* CO_2
Gas	187.5	*trillion* m^3	365	*Gt* CO_2	363	*Gt* CO_2
Total			**2871**	*Gt* CO_2	**2795**	*Gt* CO_2

TABLE 2. FACTORS USED IN CALCULATIONS

	Value	Unit	Source
Coal			
NCV (average)	0.533	*toe/tonne*	IEA (2013), 'Key World Energy STATISTICS 2013'
Emission factor (average)	97800	*kg* CO_2*/TJ*	IPCC (2006), '2006 Guidelines, Volume 2: Energy'
Emission factor (average)	0.00410	*Gt* CO_2*/Mtoe*	Calculated with IEA and IPCC data
Oil			
Volume per barrel	0.159	m^3*/bbl*	IEA (2013), 'Key World Energy STATISTICS 2013'
Density (average)	953	*kg/*m^3	IEA (2010), 'Oil information IEA STATISTICS 2010'
NCV (average)	1.031	*toe/tonne*	IEA (2013), 'Key World Energy STATISTICS 2013'
Emission factor	73300	*kg* CO_2*/TJ*	IPCC (2006), '2006 Guidelines, Volume 2: Energy'
Emission factor	0.00307	*Gt* CO_2*/Mtoe*	Calculated with IEA and IPCC data
Natural gas			
NCV (average)	34.75	*MJ/*m^3	IEA (2013), 'Key World Energy STATISTICS 2013'
Emission factor	56100	*kg* CO_2*/TJ*	IPCC (2006), '2006 Guidelines, Volume 2: Energy'
Emission factor	0.00235	*Gt* CO_2*/Mtoe*	Calculated with IEA and IPCC data
All			
Conversion	1e-9	*milliard bbl/bbl*	-
Conversion	1e-3	*tonne/kg*	-
Conversion	1e12	*trillion* m^3/m^3	-
Conversion	1e-12	*Gt/kg*	-
Conversion	1e-6	*Mtoe/toe*	-
Conversion	2.39e-11	*Mtoe/MJ*	IEA (2013), 'Key World Energy STATISTICS 2013'
Conversion	2.39e-05	*Mtoe/TJ*	IEA (2013), 'Key World Energy STATISTICS 2013'
Conversion	2.39e-02	*Mtoe/PJ*	IEA (2013), 'Key World Energy STATISTICS 2013'

TABLE 3. LIST OF ABBREVIATIONS

Abbreviation	Meaning
ASC	Advanced Supercritical (coal plants)
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CIEP	Clingendael International Energy Programme
CO_2	carbon dioxide
CTI	Carbon Tracker Initiative
EIA	Energy Information Administration
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
NCV	Net Calorific Value
TPED	Total Primary Energy Demand
bbl	barrel
Gt	gigatonne
kg	kilogram
m^3	cubic metre
mln	million
MJ	megajoule (=10^6 J)
Mtoe	million tonnes of oil equivalent
PJ	petajoule (= 10^{15} J)
PWh_{el}	petawatt hour (= 10^{15}Wh), electric energy
PWh_{th}	petawatt hour (= 10^{15}Wh), thermal energy
toe	tonne of oil equivalent
TJ	terajoule (=10^{12} J)
TWh_{el}	terawatt hour (= 10^{12}Wh), electric energy
TWh_{th}	terawatt hour (= 10^{12}Wh), thermal energy

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