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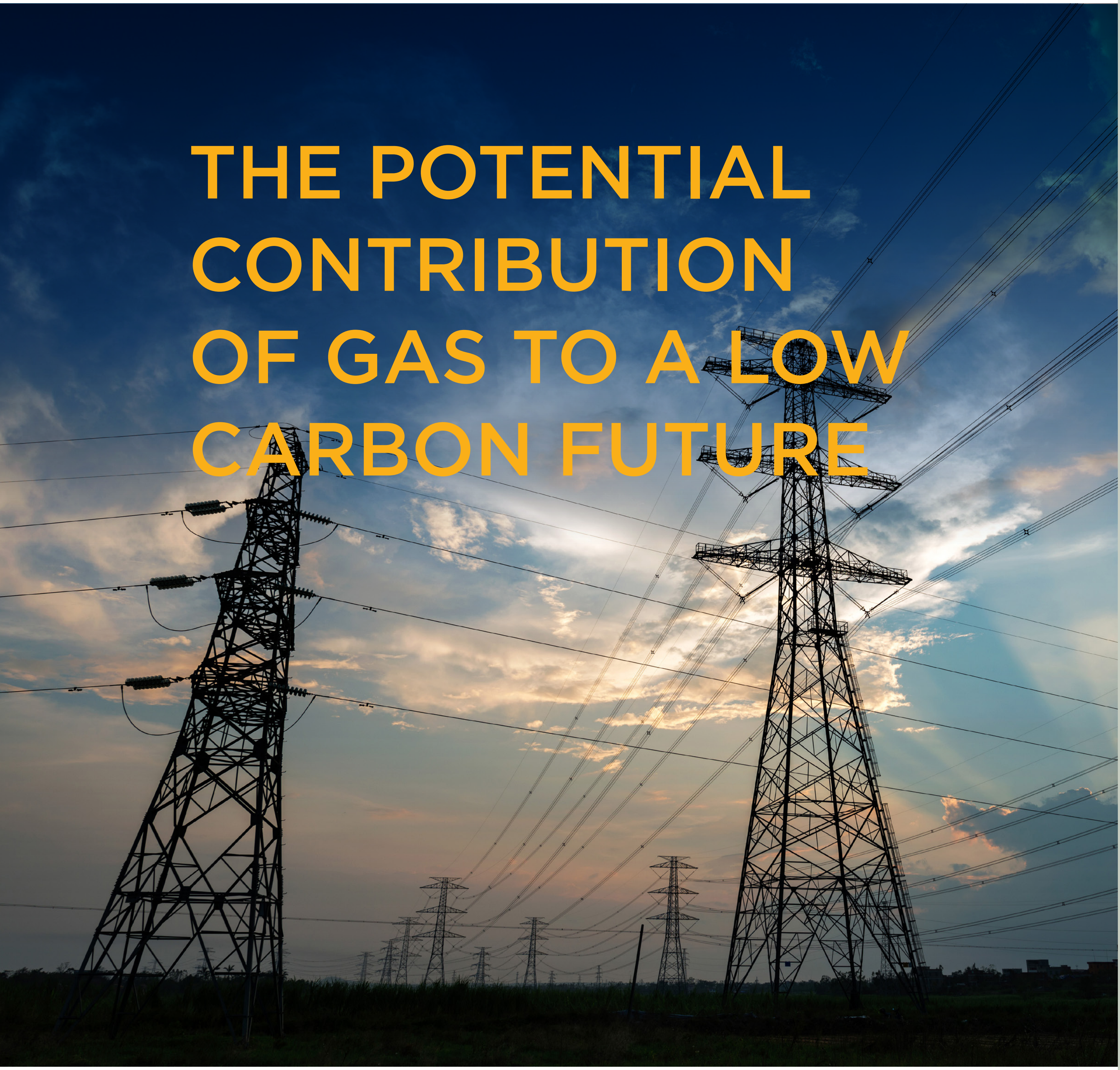
THE POTENTIAL CONTRIBUTION OF GAS TO A LOW CARBON FUTURE



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THE POTENTIAL CONTRIBUTION OF GAS TO A LOW CARBON FUTURE

BASED ON A STUDY COMMISSIONED BY THE STRATEGY COMMITTEE OF THE INTERNATIONAL GAS UNION (IGU)

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1 EXECUTIVE SUMMARY

This paper provides a scenario which highlights the role that natural gas can play in a low carbon future. It provides a complete step-by step approach to construct the 'Gas for Power' (G4P) scenario.

In any decarbonisation scenario, a rapid growth in renewable energy is essential. At the same time, it is highly questionable whether future greenhouse gas emissions can follow a pathway that is consistent to the objectives laid out in Paris, if renewables are supplemented by an unnecessarily high carbon intensive mix of power generation technologies. The G4P scenario demonstrates an alternative to the continued use of coal as a supplement to the rapid expansion of renewable energy production, in a dynamic decarbonising fashion.

The G4P scenario builds upon the IEA's New Policies Scenario (NPS), as a baseline for comparison. It is different to the Current Policies Scenario (CPS), which is seen as overly conservative, or the Sustainable Development Scenario (SDS) which is a back-casting scenario that is not meant to reflect an expectation of the future, given where we stand today. The NPS looks at all developments in energy and climate policy which have been implemented or announced, and shows the results assuming these materialise.

The NPS shows a significant growth in global electricity demand up to 2040, which is mostly met by renewable electricity sources and some increases in natural gas use. However, the share of coal in this scenario still hovers at around one quarter until 2040. Needless to say, the NPS does not meet the goals of the Paris agreement, releasing more greenhouse gas (GHG) emissions into the atmosphere than the carbon budget permits.

The first part of the G4P scenario presented looks at the effect of no new coal power generation coming online post-2020, with a phaseout of current coal capacity taking place according to plant lifetime. The coal capacity which goes offline is replaced by natural gas fired power plants. This is then followed by a step showing the effect of a global coal phaseout by 2040 (existing coal fired power plants), replaced by the same natural gas power plants. In a third step, the coal phaseout is explored from a more technologically efficient perspective. All current coal fired generation capacity is divided into three categories, based on efficiency level, and shows the results of closing the least efficient plants first, and replacing them with 'state-of-the-art' gas-fired generation, which in itself is technologically feasible and the most cost-efficient (both in terms of the economics, and carbon emissions). A 41% reduction in emissions in the power sector could be achieved following the 'efficiencies' scenario, compared to the NPS.

The fourth consideration discussed, takes the scenario further, by looking at the effects of a 10% and a 20% share of carbon neutral gases in the global electricity mix. All carbon neutral gases are taken into consideration in this paper, including synthetic gases (e.g. green hydrogen) and bio-gases. With a 20% share of carbon neutral gas in the electricity mix, cumulative CO_2 emissions would decrease to 196 Gt of CO_2. However, if this share is to be reached using only bio-gases (excluding green hydrogen), then a 31% increase in bio-energy demand will have to be dealt with by 2040, compared to the assumptions made in the NPS. Against this background, the use of synthetic gases, such as hydrogen from electrolysis of water, using solar and wind energy, should be considered.

The fifth development pushes the envelope one step further, and looks at the potential of using Carbon Capture, Utilisation, and Storage (CCUS). The further development of CCUS technologies also provides an opportunity for negative emissions, by capturing GHG emissions generated from bio-gas.

The complete scenario, the "G4P scenario", combines all the steps sketched here. Compared to the results of the IEA scenarios, the G4P scenario results in a level of CO_2 emissions from the power sector which is near identical to the SDS scenario towards 2040. Looking at these reductions compared to the whole energy system as opposed to just the power sector, a significant level of CO_2 reduction is also reached, just from these changes in the power sector alone. Further GHG emission reduction in other sectors (e.g. industry, transportation, agriculture) alongside the G4P scenario, would lead to results similar to the SDS.

The main guiding principle in this paper is that energy per carbon matters, and that the limited carbon budget available to the globe needs to be used wisely. Natural gas is a denser energy carrier per unit of GHG emitted than coal, making it the ideal transitional fuel into a low-carbon world.

The G4P decarbonisation scenario shows the potential in replacing coal-fired power plants with natural gas and new clean gases alone. It is crucial to stress, however, that the use of gas together with an accelerated expansion of renewable energy technologies, such as solar and wind, result in much more positive carbon reduction gains. The relatively low cost of constructing gas-fired power plants, combined with the flexible nature of such facilities, can in fact support a rapid decarbonisation of the power sector. At the same time, it still leaves other sectors, such as industry (with its high temperature heat requirements), the build environment (demand for low temperature heat), as well as the transportation sector (encompassing not only passenger vehicles, but also heavy-duty vehicles, marine traffic, rail and aviation), with a substantial but not insurmountable task of closing the gap further.

Although volumes of coal are internationally traded, most coal is produced and consumed within the borders of nations. The abundance of this resource, its inexpensive availability, and the high level of employability around the industry in geographies where often few other jobs are available, create large political-economic dilemmas in the short term, both in emerging economies and in OECD countries. The vast availability of natural gas at competitive prices is perhaps the best policy support for halting the trend of the continued expansion of coal-fired power plants.

2 INTRODUCTION

The Paris Agreement is aimed at guiding the world towards a low carbon future. Serving the public policy discourse, scenario work is continuously performed by a wide range of organisations, estimating 'business-as-usual' developments, exploring the effect of new policies, and identifying gaps that need to be addressed in order to achieve the targets formulated in Paris.

The scenario work in the annual World Energy Outlook (WEO) by the International Energy Agency (IEA) constitutes one of the most authoritative pieces of work in this area.[1]

In a world economy that moves away from carbon intensive power generation, natural gas, the most carbon-efficient fossil fuel, is well positioned. However, in none of the WEO scenarios, does the potential of gas as part of the decarbonisation process fully materialise.

For this reason, in 2017, the Strategy Committee of the International Gas Union (IGU) asked CIEP to explore, and to quantitively assess, the effects of a stronger role for natural gas in the world decarbonisation process, with a particular focus on the electricity sector, using the scenario work in the WEO as a basis. An assessment was made of the potential effects of a range of measures. This culminated in the Gas4Power (G4P) decarbonisation scenario for the global power sector.

Why is making such a scenario so important? In Asian countries, particularly in China, air quality and energy efficiency are central to their current energy policy, including their National Determined Contributions (NDCs). Moreover, Asian economies are predicted to increase their natural gas demand in the power sector, in addition to adopting solar and wind technologies. In the United States, we observe a similar development taking place, where natural gas, solar and wind energy sources are replacing coal-fired power generation, contributing to declining CO_2 emissions. The switch from coal to gas can be a powerful source of CO_2 emission reduction, evidenced by the US in last few years, although it is clear that replacing existing and not fully amortised plants might be difficult.

1 The scenarios in the World Energy Outlook (WEO) 2017 by the International Energy Agency (IEA) are used as the basis for this paper. See IEA (2017), World Energy Outlook 2017, available at https://www.iea.org/weo2017.

Another reason why making such a scenario is so interesting is that it reveals that leaving coal without carbon capture, use or storage (CCUS) in the world power system beyond today, requires deeper decarbonisation of other sources of energy demand, which might be much harder than decarbonising the power sector. This is a potential burden for countries that still have to embark on their energy intense phase of development because the carbon space might have been used, leaving no space for these latecomers.

Energy and climate narratives differ around the world. Apart from in the EU, natural gas is often seen as the transition or destination fuel, together with new energy technologies, such as solar and wind. In the EU, such a development is less obvious because domestic natural gas production is declining and imports are deemed fraught with geopolitical dimensions. Apart from these geopolitical considerations, the difference in the composition of the energy and power mix also plays a role in weighing the pros and cons of natural gas in the power sector. In the western EU member states, natural gas is seen as an integral part of their energy and climate policies, while for a number of member states in the east this is not always the case. In the US, the availability of relatively cheap natural gas, due to the shale gas revolution, has led to the retirement of substantial coal capacities. Here it was market developments that led to this change, while in other countries the incentive would have to come from more stringent climate policies.

It is relevant to stress that this scenario should not be considered as a representation of CIEP's view on the future global energy system, nor that of IGU or the Strategy Committee. The results do provide valuable insights into the potential benefits of a stronger role for natural gas and clean gases in global energy scenarios.

3 TOWARDS A G4P DECARBONISATION SCENARIO

The approach used for the development of the G4P decarbonisation scenario is schematically presented in Figure 1. The New Policies Scenario (NPS), as presented by the International Energy Agency (IEA) in the World Energy Outlook (WEO) 2017, was used as the starting point for this scenario.

It is relevant to highlight that the WEO NPS is not based merely on existing, but also on announced public policies worldwide, including pledges made by nations around the world in relation to the Paris process (i.e. the Nationally Determined Contributions, NDCs).

On these grounds, the NPS distinguishes itself from the WEO Current Policy Scenario (CPS). Although it remains to be seen whether all announced policies and measures will in fact materialise, the NPS was chosen as the most relevant baseline, given its function to policy discourse.

Moreover, the CPS was deemed too conservative for the analysis presented in this report, since it does not take announced policies into consideration. Opting for the NPS scenario shows the impact of this scenario compared to the first round of NDCs after the Paris Agreement was concluded. At the same time, alternative scenarios presented in the WEOs in recent years, such as the 450 scenario and the Sustainable Development Scenario (SDS), cannot be used as a baseline due to the back-casting nature of these scenarios, which are not meant to reflect an assessment of how the global energy system is developing when current and proposed policies were to materialise. These scenarios reflect a wide variety of measures that might be needed to reach a specific target. Having said that, it is worth stressing that the pledges made in Paris, and consequently, the NPS are not consistent with the 'well below 2 degrees Celsius' warming targets. As a matter of fact, the World Energy Outlook Special Briefing for COP21 hinted that the Paris pledges may imply a rise in temperatures of 2.7 degrees by 2100.[2] This study explores the impact, and the pledges that were made in the context of the Paris Agreement, of strongly addressing the negative impacts of coal use, the fossil fuel that is characterised by the highest emission intensity per unit of energy, i.e. the least carbon-efficient fossil fuel.

2 IEA (2015), Energy and Climate Change, World Energy Outlook Special Briefing for COP21, available at www.iea.org/cop21.

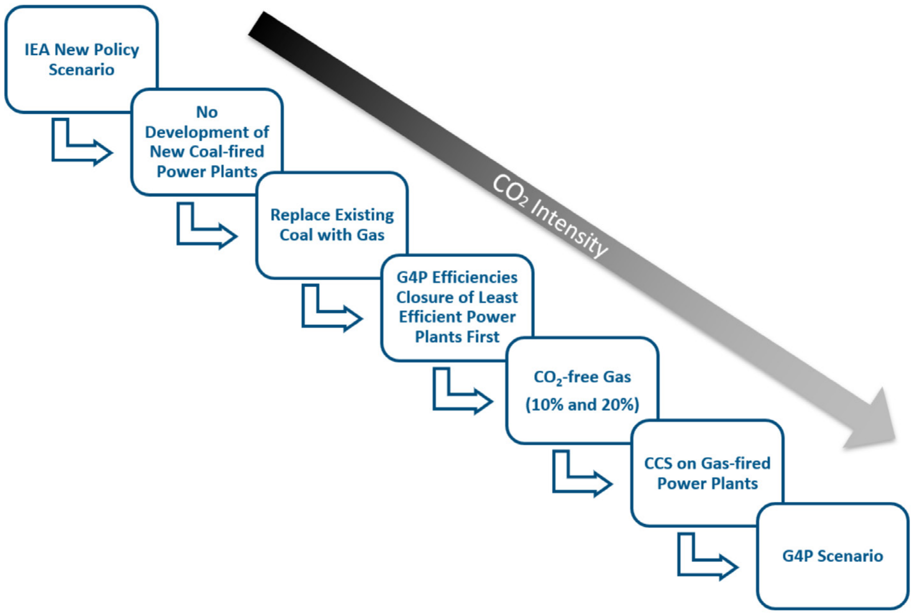

FIGURE 1. SCHEMATIC OVERVIEW OF THE APPLIED APPROACH

Figure 1 represents an overview of the measures considered in the analysis. The effect of a termination in the development of *new* coal-fired power plants, and substituting coal-fired power plants with natural gas-fired plants, was quantified first. Subsequently the effect of a gradual phaseout of *existing* coal-fired plants was assessed, starting in 2020, achieving a complete phaseout by 2040. 'Average' coal-fired generation capacity was taken out of the mix, characterised by an 'average' energy conversion efficiency, while 'average' gas-fired power plants were introduced, i.e. power plants which are characterised by the 'average' energy conversion efficiency for such gas-fired facilities.[3]

The result of a more effective and rational approach was then assessed. That is, the effect of phasing out the least efficient coal-fired power plants first, and the most efficient plants last, was quantified. To this end, the total global coal generation mix was subdivided into sub-critical, super-critical, and ultra-critical coal-fired capacity.[4] For each category, conversion efficiencies were derived from work done by the IEA.[5]

3 See the section 'Efficient gas-fired power plants' in the next chapter for the exact figures.

4 For this report, the July 2017 edition of the 'Coal Plant by Combustion Technology' file from EndCoal.org was used. Updated data is available at http://endcoal.org/global-coal-plant-tracker.

5 IEA (2012: 15), Technology Roadmap - High-Efficiency, Low-Emissions Coal-Fired Power Generation, available at https://webstore.iea.org/technology-roadmap-high-efficiency-low-emissions-coal-fired-power-generation.

Also, rather than replacing capacity with 'average' gas-fired power plants, state-of-the-art, yet currently commercially available, gas-fired power plants were introduced, which are characterised by lower emissions than an average plant.[6]

Next, the potential contribution of CO_2 free gas was introduced into the analysis, as a fuel for gas-fired power plants. Both the effect of a 10% and of a 20% share of CO_2 free gas in gas-use for power generation was quantified, starting from 2020, in a linear fashion towards 2040. In the work presented here, a specific preferred technology to produce CO_2 free gas was not chosen as this is beyond the scope of the project. Having said that, it should be noted that CCS was introduced in the next step of the development of the G4P scenario. The CO_2 free gas mentioned here could include synthetic gases such as hydrogen from electrolysis, i.e. 'green hydrogen', as well as gases from bio-energy.[7] It is worth stressing that in the assessment presented here, CO_2 free gas does not include hydrogen from steam methane reforming of natural gas, i.e. 'blue hydrogen', since the latter requires CCS and is therefore part of the next step in the analysis.

So, lastly, the effect of applying Carbon Capture Utilisation & Storage was assessed, which includes the use of 'blue hydrogen', which can function as an enabler (market development) of 'green hydrogen'. A full investigation of the potential of CCUS is beyond the scope of this project. For that reason, the amount of carbon that is assumed to be captured is derived from work done by the IEA in 2016 and 2017 (see the section on Carbon Capture Utilisation & Sequestration (CCUS) in the next chapter). As said earlier, this could include post-combustion approaches to CCS (environmental technologies applied to exhaust gases), pre-combustion approaches (such as hydrogen production in steam methane reformers), and any other energy technology that requires the sequestration of carbon emissions.

The resulting scenario is named the Gas for Power (G4P) decarbonisation scenario. It is relevant to bear in mind that the explorative analysis presented in this paper was static in nature rather than dynamic. That is to say, second order effects, third order effects, etc. as a result of shifts in the energy mix on cost levels of fuels and technologies, on economic growth, on energy demand, etc. are not included in this analysis.

6 IPCC (2014: 1335), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

7 For a better understanding of the potential of hydrogen, see IEA (2019), The Future of Hydrogen, available at www.iea.org/publications/reports/thefutureofhydrogen.

It must also be stressed that the amount of renewable energy, including solar, wind, and hydro energy, in the 'G4P scenario' is exactly in line with the amount available in the NPS developed by the IEA, which is the scenario that follows the national pledges laid down by countries in Paris. This means that renewable energy production increases substantially in this scenario. Naturally, an accelerated adoption of renewables can contribute positively to greenhouse gas emission reduction. The inclusion of CO_2 free gases such as hydrogen in the scenario can in fact be supportive to this, since it facilitates the systemic integration of solar and wind. While an increase in renewable energy production seems plausible, it seems fair to say that the future role of nuclear energy remains uncertain, as different countries and regions assess and approach this option differently, with radical policy shifts observed in the past years.

4 THE CO_2 BUDGET FOR ENERGY-RELATED CO_2 EMISSIONS

Before illustrating the effect of the various measures, a proper understanding is needed of the way CO_2 emissions are approached in the recent WEO scenario work. The IEA work focuses largely on energy-related CO_2 emissions, which account for about two thirds of human caused greenhouse gas emissions.[8] In order to assess how these emissions match the objectives of the Paris Agreement, cumulative energy-related CO_2 emissions up to 2040 have been calculated in each scenario, and the degree by which they fit into the budget for energy-related CO_2 emissions was assessed.

The IEA derived their budget for energy-related CO_2 emissions from earlier IPCC work.[9] As such, several factors are taken into consideration, including greenhouse gases other than CO_2 as well as non-energy-related CO_2 emissions. Greenhouse gases other than CO_2 include methane emissions, such as emissions from the upstream oil and gas industry, but also methane emissions from other sources and activities, such as agriculture and waste disposal. Non-energy-related CO_2 emissions include process emissions, such as those from the cement industry, which do not result from fuel combustion, but from the chemistry involved in certain production processes.

Global warming by 2100 is often expressed in terms of degrees Celsius warming compared to the pre-industrial era. Logically, uncertainties exist. Therefore, probabilities are generally attached to such warming figures. If a probability of 50% is attached to the 2°C target, the IEA explained, then the budget for energy related CO_2 emissions is 1080 gigatons (Gt) of CO_2 for the period between 2015 and 2100.[10] If a probability of 66% is attached to the 2°C target, the IEA explained, then the

8 Total greenhouse gas emissions were in the range of 49 Gt in 2016, while energy-related emissions were around 32 Gt in 2016. See https://www.pbl.nl/en/publications/trends-in-global-co2-and-total-greenhouse-gas-emissions-2017-report and see https://www.iea.org/geco/emissions.

9 IEA (2016: 334) World Energy Outlook 2016. The IEA is specifically referring to the 2014 IPCC publication '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', IPCC, Geneva.

10 IEA (2016: 334), World Energy Outlook 2016, available at https://webstore.iea.org/world-energy-outlook-2016.

budget is 250 Gt less.[11] This results in a budget for energy-related CO_2 emissions of 830 Gt of CO_2 for the years between 2015 and 2100.[12]

In the analyses presented in this paper, the 1080 Gt and 830 Gt budgets were both considered, in order to give meaning to the amounts of carbon saved by the measures investigated. The expected global annual CO_2 emissions for the years 2015-2019, according to the NPS, were subtracted from these since the G4P decarbonisation scenario does not start until 2020. In other words, the remaining budget for 2020-2040 is the relevant number to attach to energy scenarios that describe the 2020-2040 period.

The extent to which these budgets fit within the 1.5°C target, depends on assumptions made for the post-2040 period. Specifically, achieving negative emissions (CCUS applied to bio-energy, for instance) in that time frame, could make the WEO back-casting scenarios up to 2040, such as the SDS, consistent with 1.5°C pathways. However, without negative emissions, these back-casting scenarios at best fit the 2°C pathways. A transformation of the global energy system, consistent with 1.5°C pathways, while not incorporating negative emissions in the run of the century, may be technologically possible, but the economic, social and political challenges are severe.[13]

11 IEA (2016: 336), World Energy Outlook 2016, available at https://webstore.iea.org/world-energy-outlook-2016.

12 The 66% 2oC case was the basis for analysis in the joint IEA-IRENA publication in the context of the G20 summit in Germany in 2017. See IEA & IRENA (2017), Perspectives for the Energy Transition, Investment Needs for a Low-Carbon Energy System, available at https://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

13 IEA (2016: 75), World Energy Outlook 2016, see Figure 2.9 for the emissions since the year 2000 and the future emission trajectory required in the 1.5oC pathway in the case of no negative emissions in the long term.

5 A SHIFT AWAY FROM COAL

The WEO 2017 New Policies Scenario (NPS) is used as a starting point for the assessment done for the IGU Strategy Committee. The IEA explained that the NPS *"broadly serves as the IEA baseline scenario. It takes account of broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse-gas emissions and plans to phase out fossil-energy subsidies, even if the measures to implement these commitments have yet to be identified or announced".*[14] In other words, this baseline reflects the outlook for the energy system up to 2040, including the electricity generation mix, which could materialise, given the current energy system, and the commitments and plans by all countries, including the pledges in relation to the Paris Process, as of November 2017.

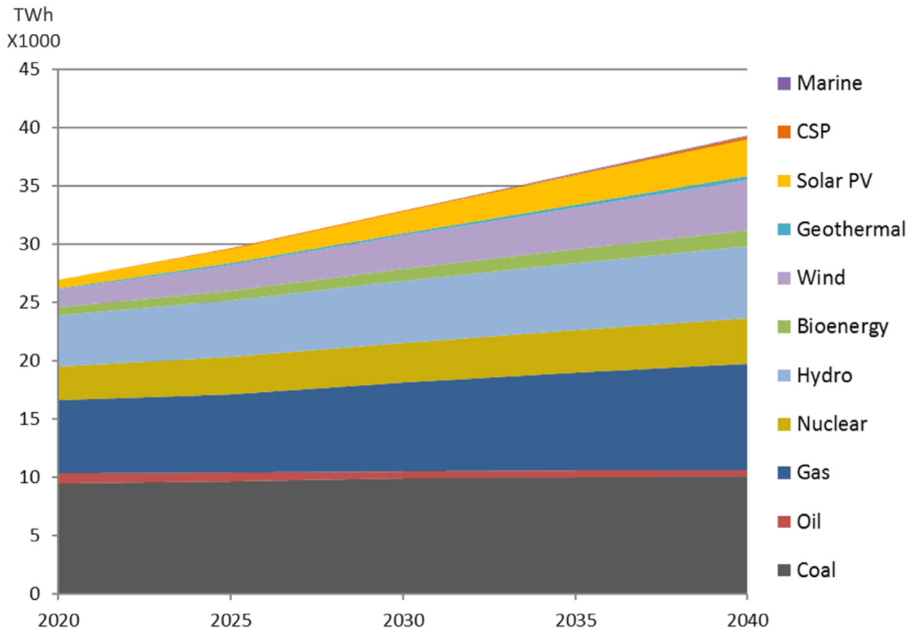

FIGURE 2. THE ELECTRICITY PRODUCTION MIX IN THE IEA NEW POLICY SCENARIO

14 IEA website, see https://www.iea.org/about/glossary/s, retrieved 7th October 2019.

The evolving electricity mix up to 2040 is shown in Figure 2. Taking announced policies & plans as a given, it exhibits growing electricity demand. The contribution of modern renewables, such as solar PV and wind capacity, increases multi-fold. Nevertheless, due to rising electricity demand, this chart also shows increased power generation from conventional fuels.

NO NEW COAL PLANTS AND A GRADUAL PHASEOUT OF EXISTING ONES

The contribution of natural gas will increase in the NPS, while the contribution of coal will stay fairly flat. In the NPS, new coal-fired capacity still enters the system, when existing coal-fired power plants reach the end of their lifetimes and are decommissioned. The left-side graph in Figure 3 illustrates what this mix would look like, in case no new coal-fired capacity would enter the system, while gas-fired power capacity was to be introduced instead, in order to ensure that sufficient electricity is generated, in line with demand figures taken from the NPS.

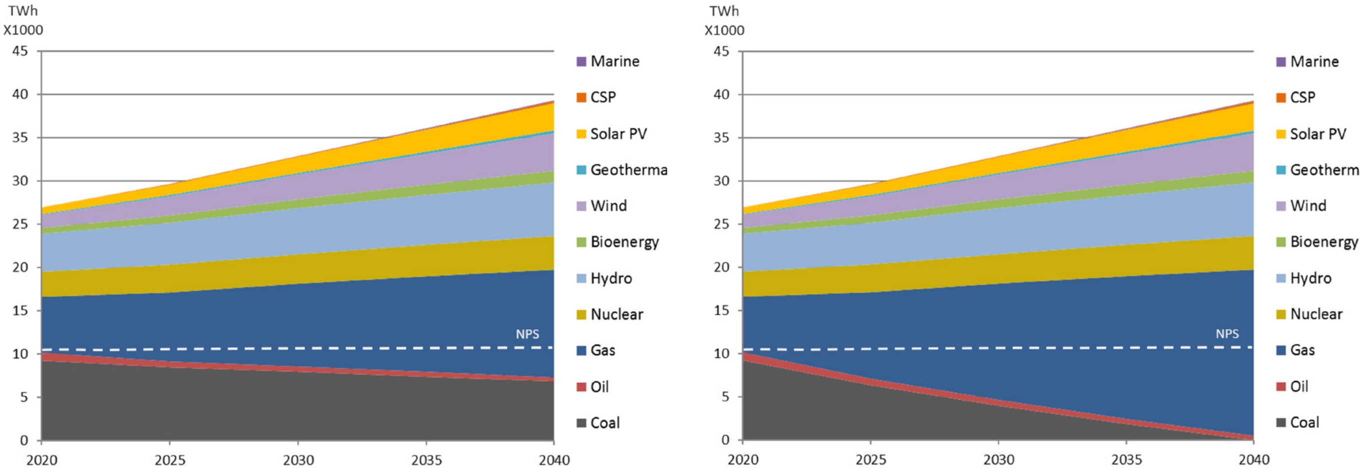

FIGURE 3. ELECTRICITY MIX WITHOUT NEWLY BUILT COAL PLANTS (LEFT) AND A COMPLETE PHASEOUT OF COAL (RIGHT)

The right-side graph in Figure 3 illustrates the electricity mix, if all coal-fired capacity would be phased out at a faster pace than in the NPS. In this latter case, a complete phaseout is achieved by 2040, starting from 2020, following a linear decline rate. Once again, electricity based on gas-fired power production will be introduced to fill the resulting supply gap in this scenario.

EFFICIENT GAS-FIRED POWER PLANTS

From a CO_2 viewpoint, it is more rational to close the least efficient coal-fired power plants first, and the most efficient last. To this end, in the assessment presented here, the total global coal generation mix is divided into sub-critical, super-critical, and ultra-critical coal-fired capacity.[15] To each category, an emission intensity is assigned, while ensuring the total CO_2 emissions are in line with today's figures.[16] This resulted in an emission intensity of 1125 gram CO_2/kWh, 840 gram CO_2/kWh, and 770 gram CO_2/kWh, respectively, given the three categories. Additionally, rather than replacing this capacity with 'average' gas-fired power plants, state-of-the-art yet commercially available gas-fired power plants are introduced, characterised by lower emission rates (370 grams CO_2/kWh).[17]

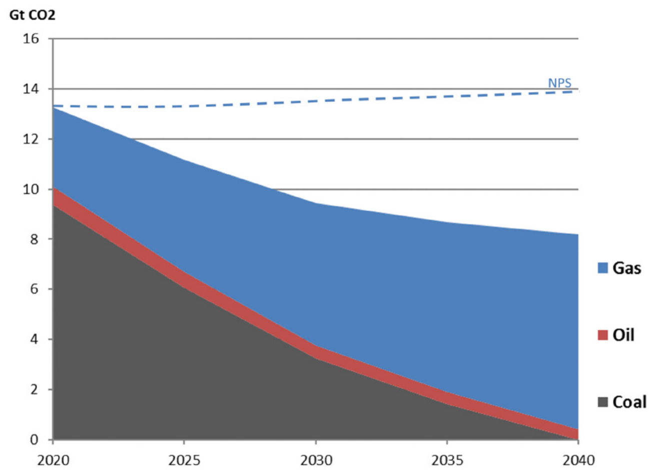

FIGURE 4. POWER SECTOR EMISSION TRAJECTORY WITH A COMPLETE COAL-TO-GAS-SWITCH VS. THE NPS (DOTTED LINE)

Figure 4 demonstrates the ultimate effect of a complete coal phaseout on CO_2 emissions in the electricity sector, replacing the least efficient power plants first by modern gas-fired power plants. Cumulative emissions in the 2020-2040 period would amount to 211 Gt of CO_2, down from 285 Gt. Not constructing any new coal-fired power plants yields 21 Gt of savings, gradually replacing existing ones with gas-fired power plants yields another 40 Gt of savings, and if the efficient phaseout pathway is to be realised, another 13 Gt of savings can be achieved,

15 For this report, the July 2017 edition of the 'Coal Plant by Combustion Technology' report from EndCoal.org was used. Updated data is available at http://endcoal.org/global-coal-plant-tracker.

16 IEA (2012: 15), Technology Roadmap - High-Efficiency, Low-Emissions Coal-Fired Power Generation, available at https://webstore.iea.org/technology-roadmap-high-efficiency-low-emissions-coal-fired-power-generation.

17 IPCC (2014: 1335), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

bringing the total to 74 Gt of savings. By 2040, power sector emissions would largely result from the use of natural gas, as coal-fired capacity would no longer be operational. Annual power sector emissions would be in the range of 8.2 Gt per year, down from the 13.9 Gt in the NPS, which is 41% lower. To put this reduction of 5.7 Gt *in the global electricity sector alone* in perspective: the annual emissions from combustion of fuels *in the entire economies* of India, the continent of Africa, and the EU amounted to 2.1 Gt, 1.2 Gt and 3.2 Gt, respectively.[18]

SUPPLY CHAIN EFFECTS

A proper understanding of the shifts in upstream emissions, and their effect on the available carbon budget is relevant, with a view to the increased use of natural gas in the G4P scenario, to the detriment of coal combustion. Supply chain emissions, which include energy-related CO_2 emissions, but also methane emissions, should be considered when assessing the environmental credentials of fuels. The World Energy Outlook 2017 dedicates a special section to the theme of methane emissions.[19]

A complete analysis of the complex issue of supply chain emissions in the global energy system is beyond the scope of the assessment presented here. Hence, readily available numbers are derived from the IPCC's Fifth Assessment report, in order to make a sensitivity analysis.[20] Figure 5 is derived from this work and shows direct emissions and supply chain emissions for coal-fired and gas-fired power plants respectively.

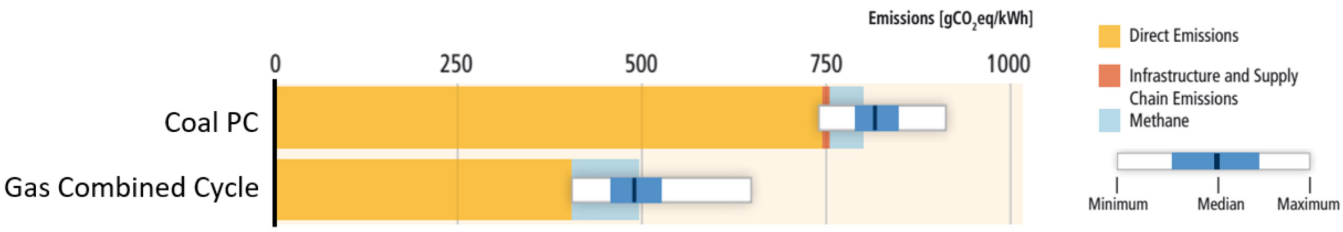

FIGURE 5. DIRECT AND SUPPLY CHAIN EMISSIONS (IPCC) FOR PULVERISED COAL (PC) AND COMBINED CYCLE GAS-FIRED POWER PLANTS[21]

18 These and other energy statistics are available at https://www.iea.org/statistics.

19 IEA (2017: 403), section 10.2 of the World Energy Outlook 2017, available at https://www.iea.org/weo2017.

20 IPCC (2014: 539), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 7.6, Comparative lifecycle greenhouse gas emissions from electricity supplied by commercially available technologies.

21 IPCC (2014: 539), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 7.6, Comparative lifecycle greenhouse gas emissions from electricity supplied by commercially available technologies.

From the IPCC figure, it follows that the combined upstream effects (less coal mining, more gas extraction) lead to changes in emissions in the supply chain (upstream from the power plant). While the positive effects of a switch from coal to gas remain substantial, because of the significant CO_2 reduction at the power plant level, there are changes elsewhere in the supply chain that need consideration.

At this point in the analysis, as indicated in the previous section, the cumulative emissions savings in the period of 2020-2040 would amount to 74 Gt, when supply change effects are not taken into account. Now, supply change effects in the 2020-2040 timeframe would constitute 4.3 Gt of CO_2 equivalents.[22] In other words, while the measures assessed in the previous section led to 74 Gt of CO_2 savings over the 2020-2040 period, the supply chain effects would slightly impact this result negatively, by 4.3 Gt, reducing the net savings to approximately 70 Gt. However, policies and actions aimed at reducing supply chain emissions are likely to materialise over the course of this period. In fact, the World Energy Outlook 2017 dedicates a special section to the issue of tackling methane emissions.[23] For example, if a 50% reduction were to be achieved by the gas industry, everything else being equal, then the potential increase in upstream emissions of 36 grams CO_2/kWh (gas vs. coal) is more or less neutralised. That is to say, from the IPCC figures it follows that greenhouse gas emissions (per kWh) across the natural gas supply chain would be in the same order of magnitude as emissions (per kWh) across the coal supply chain.[24] With this in mind, the limited negative supply chain effect of 4 Gt over the 2020-2040 period is not further included in the results presented in the next sections.

THE USE OF CO_2 FREE GASES

In the framework presented here, the concept of CO_2 free gas implies, by definition, that its use is carbon neutral. The work presented here does not favour a particular option to achieve this, but considers options such as CO_2 neutral bio-energy, and synthetic gases (e.g. hydrogen) produced from carbon-free electricity.[25] In any case,

22 The additional emissions (when switching from coal to gas) in the supply chain are 36-gram CO2-eq per kWh (IPCC, 2014: 539 & 1335). This equals an increase of 36 kiloton CO2-eq per TWh. The total amount of 'switched electricity' equals to 118,137 TWh. 118,137 TWh x 36 Mt = 4.3 Gt CO2-eq.

23 See Section 10.3 of the World Energy Outlook 2017, (2017: 418), available at https://www.iea.org/weo2017.

24 If this reduction in supply chain emissions were not only to be achieved in the additional gas that is used in the power generation sector in the work presented here, but rather to all the natural gas consumed in all sectors, across all economic strata, then greenhouse gas emission savings become significantly larger and additional budget space for greenhouse gas emissions would materialise.

25 In 2019 the IEA presented an extensive assessment of the hydrogen value chain. Hydrogen is not only a carbon-free fuel, it can also facilitate the further integration of variable renewable energy production. It must be noted that several challenges need to be overcome for a hydrogen future to emerge. See IEA (2019), The Future of Hydrogen, available at https://www.iea.org/publications/reports/thefutureofhydrogen.

gas should be carbon neutral across the complete value chain, i.e. any potential emissions created in the value chain, are considered as neutralised in this analysis, leading to a net zero contribution.

A 10% share and a 20% share of CO_2 free gas for power generation are included in the following assessment, to be achieved by 2040, in a linear fashion, starting in 2020. It should be stressed here, that this share does not refer to the share in total gas consumption, but only to the share in gas used for power generation, taking into account an increased use of gas due to substitution of coal in the power sector.[26] If a 20% share is to be achieved, cumulative emissions in the 2020 to 2040 period would decline to 196 Gt of CO_2. The use of bio-energy would likely be part of such a gas future. A high-level sensitivity analysis was therefore performed, in order to investigate the additional amount of bio-energy needed, compared to the NPS. The conclusion implies an increased cumulative requirement for bio-energy of 31% during the 2020-2040 timeframe, in the extreme case of using bio-energy for achieving a 20% share of CO_2 free gas for power generation.[27,28] Naturally, this sensitivity analysis is not meant to suggest that this is the amount of bio-energy to be aimed for. With a view to possible negative consequences of a large use of bio-energy (land use, bio-diversity, etc.), it is recommendable to further consider synthetic gases such as hydrogen from electrolysis of water using solar and wind energy.

CARBON CAPTURE UTILISATION & SEQUESTRATION (CCUS)

Carbon Capture Utilisation & Sequestration (CCUS) is an important technology to contribute to a low carbon energy system. If not simply for restricting emissions from conventional energy use, CCUS could contribute to net-negative emissions by applying it to bio-energy use.

26 Building upon the scenarios sketched above.

27 In the WEO New Policies Scenario 2017, cumulative (2020-2040) primary energy production (TPED) of bio-energy is 34105 MTOE, to be used in all sectors of the energy system. 20% green gas being fed into gas-fired power plants from 2020 onwards requires an additional bio-energy demand of 10585 MTOE up to 2040. In this calculation, conversion efficiencies consistent with the NPS are applied. So, it would imply an increased cumulative requirement for bio-energy of 31% culminating in 44690 MTOE of bio-energy to be produced.

28 It is important to bear in mind that if bio-energy is not completely carbon neutral across the supply chain, then it does not qualify in full as a CO2 free gas; and use of it then leads to a smaller net reduction in CO2. Additionally, it should be noted that this is merely a sensitivity analysis and not a suggestion to only incorporate bio-energy. Rather, alternative gases such as green hydrogen from electrolysis of water using carbon free electricity should be considered.

While the theoretical/geological/technological CCUS potential may be enormous, it is challenging to develop and organise the required infrastructure, be it technologically, economically, or socially. In other words, building a CCUS-infrastructure from scratch is not an easy task, and available storage space could turn out to be scarce in coming years and decades, despite the enormous potential.

A range of CCUS technologies exist. One way of categorising these, is by thinking of a set of technologies that can be applied after the combustion of fuel, i.e. post-combustion, versus a set of technologies that can be applied before the combustion of fuel, i.e. pre-combustion. Post-combustion CCS is effectively an environmental technology applied to a smokestack, somewhat similar to other environmental technologies that are meant to limit environmental damage (sulphur scrubbers, NOx scrubbers, etc.). Pre-combustion CCS implies a pre-treatment of fuel before burning. For example, natural gas can be fed into an 'autothermal reformer' (ATR), which produces hydrogen, while the waste carbon is either used or sequestrated. Such hydrogen is frequently referred to as 'blue hydrogen'. The CO_2 free gases discussed in the previous section, could also include hydrogen, but in the analytical framework applied here, 'blue hydrogen' was not included in that section, since it requires CCUS. Rather, in the assessment presented in this publication, blue hydrogen is integrated in the CCUS scenario.

BOX 1. CCUS VERSUS CO_2 FREE GAS IN THE ANALYTICAL FRAMEWORK USED HERE

In the work presented here, 18 Gt of cumulative CO_2 storage is assumed, which is based on the contribution of CCS[29] in the scenarios of the WEO 2016 and the WEO 2017.[30] With a view to the level of emissions from the global power sector, not to mention the total emissions from the wider energy sector worldwide, an 18 Gt limit to CCUS should be regarded as a restrictive limit. Scarce storage potential must therefore be used wisely.

29 "CCS" (Carbon Capture and Storage) is used here as opposed to "CCUS" (Carbon Capture Utilisation and Storage) in reference to the work done by the IEA. That being said, this paper is of the opinion that the utilisation of carbon should not be excluded, and provides a layer of value to this whole process.

30 In the WEO 2016, CCS plays a role in the 450 scenario and in the WEO 2017 it plays a role in the SDS scenario. In both cases, these are back-casting scenarios, consistent with meeting longer term climate objectives. The order of magnitude of CCS is similar in both cases and is not large, in relation to global greenhouse gas emissions. This is for good reasons. Realistic assumptions on the contribution of CCS do not only depend on geological and technological potential. Also, the challenging organisation of supply chains requires major efforts, and success depends on political (and societal) support. So, notwithstanding larger geological and technical potential, the order of magnitude for CCS is set at 18 Gt in this study, which is in the same range as the amounts in the aforementioned IEA scenarios. See figure 10.16 in IEA (2016: 429) and see Figure 3.15 in IEA (2017: 139). t

In the assessment presented here, CCUS is applied to gas-fired power generation, rather than to coal-fired power generation. Applying CCUS to coal-fired facilities would provide half the amount of energy, given 18 Gt of limited CCUS potential included in the assessment, while the other half of the required energy would have to be produced using other technologies, potentially resulting in new emissions. Alternatively, one could argue that the 18 Gt must be used not for power generation, but for industrial energy emissions. However, then the argument that it is more logical to use the least-carbon intense fuel for doing so still holds.

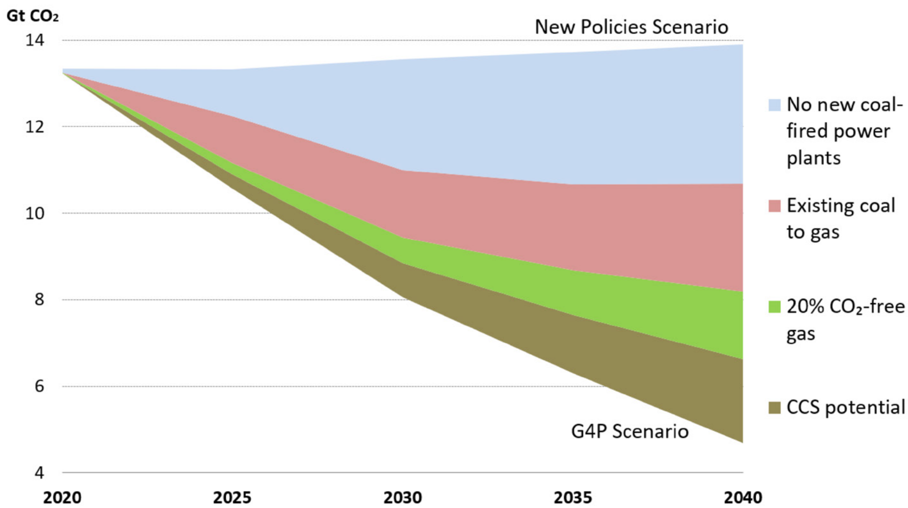

FIGURE 6. CO2 SAVINGS IN THE G4P DECARBONISATION SCENARIO OVER THE 2020-2040 HORIZON

Figure 6 illustrates the combined result of (1) preventing the development of new coal-fired power plants; (2) gradually phasing out existing coal-fired power plants along an efficient pathway; (3) increasing the role of CO_2 free gas used for power generation; and (4) embracing CCS to an extent similar to the IEA's SDS, exclusively applied on gas-fired power plants. Cumulative savings in energy-related CO_2 emissions would reach 107 Gt in the 20 years from 2020 to 2040. Power sector emissions in 2040 would go down by 66.3% from 13.9 Gt per year in the NPS, to 4.7 Gt per year in the G4P decarbonisation scenario. It is important to stress, once again, that this is the result of changes in the power sector only, since other sectors are responsible for approximately another 22 Gt of emissions in 2040 according to the NPS. Additional policies and measures, such as promoting clean energy use in the industrial sector, energy efficiency in the transportation sector and the heating of buildings, etc. are indispensable for bending the curve of the entire global energy sector further downwards.

6 ENERGY PER CARBON MATTERS

According to the NPS, global energy needs are on the rise as the world population grows and economic development lifts millions of people out of poverty, and new middle classes emerge. With a view to the very limited carbon budget available for the coming decades, the challenge is to increase the (energy and) carbon efficiency of the energy system.

The world needs a large and growing amount of energy, while the carbon budget in coming decades is limited. As was argued in the CIEP Publication *Energy Per Carbon Matters*, the remaining carbon budget must therefore be used wisely.[31] To the extent that conventional fuels are used for power generation, squeezing as much electricity as possible out of every ton of carbon in the budget is vital.

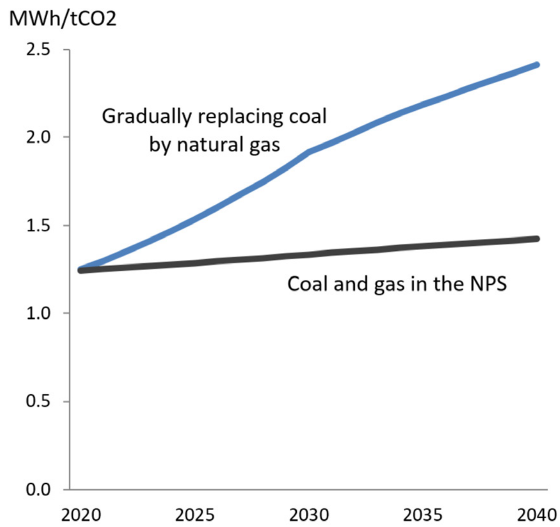

FIGURE 7. ELECTRICITY PER CARBON MATTERS

31 CIEP (2015), Why Energy per Carbon Matters, available at www.clingendaelenergy.com/publications/publication/why-energy-per-carbon-matters.

In previous sections, advanced measures such as the use of CO_2 free gas and the application of CCS to gas-fired power plants are included in the assessment. However, the gradual shift from conventional coal use to conventional gas use in itself, a central part of the G4P scenario, already yields significant benefits. In Figure 7 the amount of electricity produced from coal and gas is shown, per ton of carbon emitted for every year in the 2020-2040 period.[32] It demonstrates that electricity per carbon produced increases substantially as the role of coal starts to diminish towards 2040.

32 For reasons of simplicity, supply chain emission effects are not considered here. As indicated, the calculations in the previous chapter suggest that the effects are limited, and in case the pledge for a 50 % reduction of upstream emissions in the gas supply chain were to materialise, upstream emissions in the gas supply chain would be in the same order of magnitude (per kWh electricity produced) as upstream emissions in the coal supply chain. Even when accounting for upstream emissions in the gas supply chain and coal supply chain, as reported by the IPCC (2014) per kWh electricity produced, a very significant advantage for gas over coal would continue to exist.

7 EMISSION PATHWAYS TOWARDS 2040

The WEO 2017 included three main scenarios. As indicated, the New Policies Scenario (NPS) was used as a starting point for the analysis presented here, as a baseline from which a G4P scenario was developed. In addition to the NPS, the IEA included the Current Policies Scenario (CPS). In the words of the IEA, the CPS *"assumes no changes in policies from the mid-point of the year of publication (previously called the Reference Scenario)"*.[33]

While the NPS and CPS are forward-looking, taking "today" as a starting point, the WEO also put forward the Sustainable Development Scenario (SDS), which is back-cast in nature. The SDS "*offers an integrated way to achieve a range of energy-related goals crucial for sustainable economic development: climate stabilisation, cleaner air and universal access to modern energy, while also reducing energy security risks*".[34]

The ultimate (long term, towards the year 2100) global warming effect of the CO_2 related energy emissions in the period up to 2040 cannot be understood properly without making assumptions on global carbon emissions in the post-2040 period. Such analysis, however, is clearly beyond the scope of the research presented here. Rather, a comparison is made, with emission pathways put forward by the IEA in the WEO 2017, in order to understand the significance of the emission pathway that comes with the G4P scenario.

33 IEA website, see https://www.iea.org/about/glossary/s, retrieved 7th October 2019.

34 IEA (2017: 29), World Energy Outlook 2017, available at https://www.iea.org/weo2017.

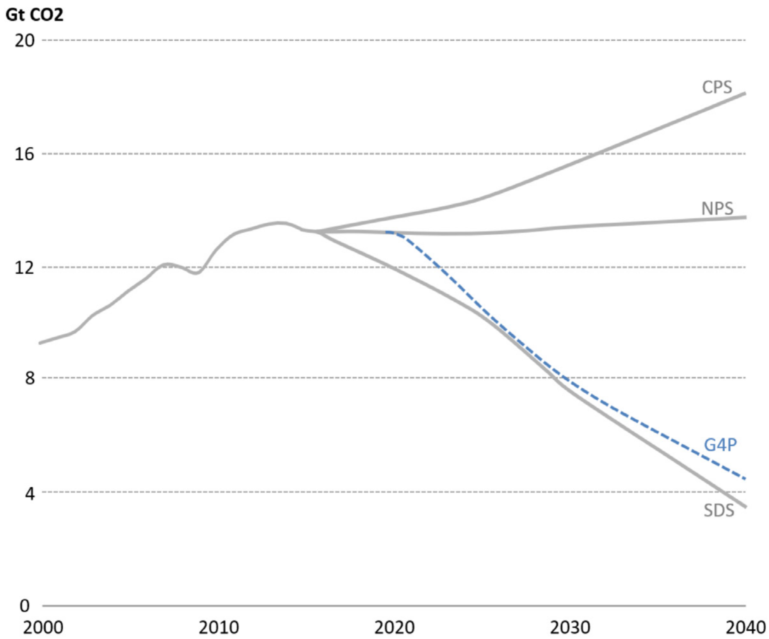

FIGURE 8. GLOBAL POWER SECTOR EMISSIONS IN THE WEO CPS, NPS, AND SDS, VERSUS THE G4P DECARBONISATION SCENARIO

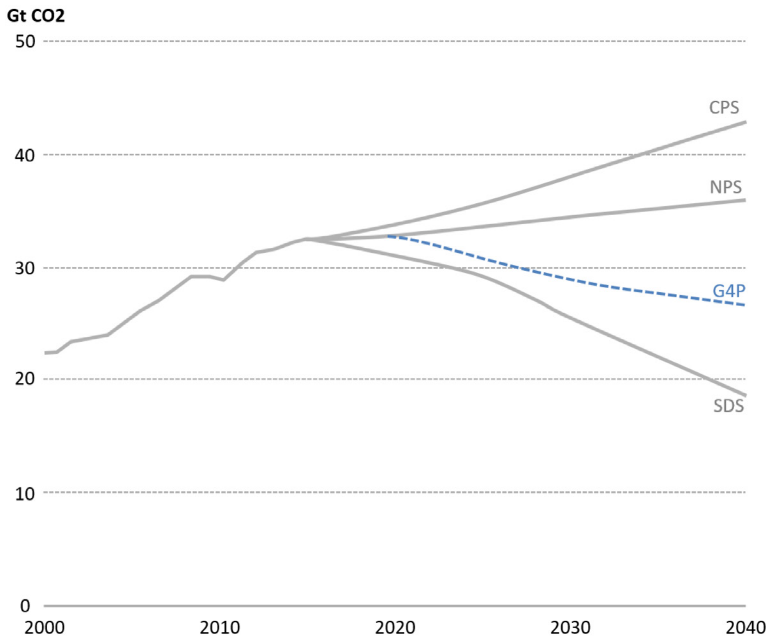

FIGURE 9. COMPLETE GLOBAL ENERGY SECTOR EMISSION REDUCTION PER SCENARIO, INCLUDING THE G4P SCENARIO. LOWER POWER SECTOR EMISSIONS SIGNIFICANT IMPACTS THE COMPLETE GLOBAL ENERGY SECTOR CO_2 EMISSIONS

Figure 8 illustrates *global power sector emissions* in the G4P decarbonisation scenario. It also shows the pathways in the three scenarios that were put forward by the IEA in the WEO 2017. The figure demonstrates that the emission pathway achieved for the power sector towards 2040, is approximately the pathway set out in the IEA Sustainable Development Scenario until 2040.

Moreover, Figure 9 shows how the G4P scenario performs, if the *entire global energy system* is considered. As indicated, the G4P scenario only includes power sector measures. A true comparison between the SDS and G4P scenarios can only be made, if measures and policies would also be proposed for sectors other than the power sector. One could think of policies encouraging energy efficiency in all sectors, electrification and efficient combustion engines in the transport sector, the use of clean fuels in industries, energy efficiency measures to reduce energy consumption for the heating of buildings, etc.

The carbon budget in the case of a 50% chance of 2 degrees Celsius warming is 1080 Gt, as mentioned before. The budget is smaller in the case of a 66% chance, and amounts to 830 Gt. In either case, the budget is very restrictive, with a view to expected future energy demand. Energy-related CO_2 emissions up to 2040 in the WEO NPS are roughly equal to the entire budget for the period up to 2100, in the 50% probability case. In the 66% probability case, NPS emissions already exceed that budget before 2040.

In both the 50% probability and the 66% probability case, emissions up to 2040 in the G4P scenario fit within the budget. A small amount of emission space remains for the years after 2040. It is highly questionable, however, if emissions from the energy sector post-2040 would fit that budget, and it is very unlikely to do so if no 'negative emissions' materialise, for instance by combining the use of bio-energy with CCUS technologies. In none of these scenarios is the entire energy system carbon neutral by 2040, implying that there will still be carbon emissions post-2040. From a CO_2 pathway perspective, this illustrates the challenge that lies ahead.

8 CONCLUSION & DISCUSSION

Global energy needs are on the rise. The world's population is growing, millions are being lifted out of poverty, and a new energy intensive middle class is emerging. With a view to the limited carbon budget for the coming decades, as agreed upon in the Paris Climate agreement, we are challenged to improve the energy efficiency and the carbon efficiency (i.e. to lower the carbon intensity) of the entire energy system. By increasing the use of natural gas, phasing out coal, promoting the use of CO_2 free gases, and adopting CCUS, emissions from the power sector can be decreased substantially. The G4P scenario demonstrates how the use of natural gas and new clean gases can contribute to reducing energy-related CO_2 emissions.

The calculations presented in this paper are based on the assumptions made in the IEA's WEO 2017. Following the subsequent 2018 WEO presentation in November 2018, the urgency to put the right policy framework in place became clear once more. It showed that emissions from existing coal-fired power plants represent about one-third of all CO_2 emission in the world, with half of these coal-fired power plants being less than 15 years old. In any decarbonisation scenario, a rapid growth in renewable energy is essential, but it is highly questionable whether future greenhouse gas emissions can follow a pathway that is consistent to the objectives laid out in Paris, especially if renewables are supplemented by an unnecessarily high carbon intensive mix of power generation technologies. The G4P scenario demonstrates an alternative to the continued use of coal as a supplement to the rapid expansion of renewable energy production, in a dynamic decarbonising fashion.

The G4P decarbonisation scenario shows the potential in replacing coal-fired power plants with natural gas and new clean gases alone. It is crucial to stress, however, that the use of gas together with an *accelerated* expansion of renewable energy technologies, such as solar and wind, results in much more positive carbon reduction gains. The relatively low cost of constructing gas-fired power plants, combined with the flexible nature of such facilities, can in fact support a rapid decarbonisation of the power sector. At the same time, it still leaves other sectors, such as industry (with its high temperature heat requirements), the buildings (demand for low temperature heat), as well as the transportation sector (encompassing not only passenger vehicles, but also heavy-duty vehicles, marine traffic, rail and aviation), with a substantial but not insurmountable task of closing the gap further.

In the publication 'Why energy per carbon matters' we already pointed out that climate and energy policies should focus on energy and carbon efficiency. They should also avoid replicating a coal-intense phase of economic development in upcoming regions such as large parts of the African continent, and large parts of developing Asia, including India. While we should be allowing these economies to grow and their people to prosper, policies should therefore opt for an energy and carbon-efficient mix of fuels and technologies. Alongside the positive impact on global greenhouse gas emissions, this certainly also benefits local air quality and therefore public health.

Although volumes of coal are internationally traded, most coal is produced and consumed within the borders of nations. Abundance of the resource, its cheap availability, and the high level of employability around the industry in geographies where often few other jobs are available, creates large political-economic dilemmas in the short term, both in emerging economies and OECD countries. The vast availability of natural gas at competitive prices is perhaps the best policy support for halting the trend of the continued expansion of coal-fired power plants.

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