



The Harvard Project on Climate Agreements

January 2014
Discussion Paper 14-63

The Optimal Energy Mix in Power Generation and the Contribution from Natural Gas in Reducing Carbon Emissions to 2030 and Beyond

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Prepared for

The Harvard Project on Climate Agreements

This paper has been previously released by Fondazione Eni Enrico Mattei (FEEM; www.feem.it). The Harvard Project on Climate Agreements is grateful to FEEM and the authors.

THE HARVARD PROJECT ON CLIMATE AGREEMENTS

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Acknowledgements

The Harvard Project on Climate Agreements would like to thank the Harvard University Center for the Environment for its generous support of the current series of publications.

The Harvard Project receives additional support from the James M. and Cathleen D. Stone Foundation and ClimateWorks Foundation. The Project is very grateful to the Doris Duke Charitable Foundation, which provided major funding during the period July 2007–December 2010. The Project receives ongoing support from the Belfer Center for Science and International Affairs at the Harvard Kennedy School.

The closely affiliated, University-wide Harvard Environmental Economics Program receives additional support from the Enel Endowment for Environmental Economics at Harvard University, the Enel Foundation, the Alfred P. Sloan Foundation, the Mossavar-Rahmani Center for Business and Government at the Harvard Kennedy School, Bank of America, BP, Chevron Services Company, Duke Energy Corporation, and Shell.

Citation Information

Carraro, Carlo, Massimo Tavoni, Thomas Longden, and Giacomo Marangoni. "The Optimal Energy Mix in Power Generation and the Contribution from Natural Gas in Reducing Carbon Emissions to 2030 and Beyond." Discussion Paper 2014-63. Cambridge, Mass.: Harvard Project on Climate Agreements, January 2014.

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Abstract

This paper analyses a set of new scenarios for energy markets in Europe to evaluate the consistency of economic incentives and climate objectives. It focuses in particular on the role of natural gas across a range of climate policy scenarios (including the Copenhagen Pledges and the EU Roadmap) to identify whether current trend and policies are leading to an economically efficient and, at the same time, climate friendly, energy mix. Economic costs and environmental objectives are balanced to identify the welfare-maximising development path, the related investment strategies in the energy sector, and the resulting optimal energy mix. Policy measures to support this balanced economic development are identified. A specific sensitivity analysis upon the role of the 2020 renewable targets and increased energy efficiency improvements is also carried out. We conclude that a suitable and sustained carbon price needs to be implemented to move energy markets in Europe closer to the optimal energy mix. We also highlight that an appropriate carbon pricing is sufficient to achieve both the emission target and the renewable target, without incurring in high economic costs if climate policy is not too ambitious and/or it is internationally coordinated. Finally, our results show that natural gas is the key transitional fuel within the cost-effective achievement of a range of climate policy targets.

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Keywords: EU Climate Policy, Energy Markets, Gas Share, Carbon Pricing, Renewables Target

JEL Codes: O33, O41, Q43, Q48, Q54.

First Draft: September 2013

The Authors are grateful to participants at the International Energy Workshop, IEW, Paris, June 2013 and the Sustainable Development Network Conference, Siena, July 2013 for helpful comments and suggestions. All remaining errors are ours. Correspondence address: Thomas Longden, Corso Magenta, 63, 20123 Milano – Italy. Email: thomas.longden@feem.it.

Section 1 – Introduction

The dynamics of energy markets in Europe are currently experiencing a paradoxical transition. On the one hand, a revival of coal imports and a reduction of gas consumption, with an associated negative impact upon greenhouse gas (GHG) emissions in some major European economies, have been observed in the past two years. On the other hand, the European Commission and most Member Countries are concerned about future climate change and have committed themselves in adopting actions to reduce GHG emissions in 2020 and beyond.

More specifically, gross inland consumption for 2012 shows a decline in natural gas consumption of 14%, a decline in oil consumption of 11% and an increase in coal consumption of 8% with respect to 2010 (Eurostat, 2013). In 2011, natural gas in the EU recorded its largest decline on record, a decrease of 9.9%, which has been identified as being driven by a weak economy, high gas prices compared to the U.S., warm weather and continued growth in renewable power generation (BP Statistical Review, 2012). But, no doubt, the explanation also lies in the incorrect policy mix adopted in the EU: excess subsidies on renewables and, partly as a consequence, a low level of carbon prices also played a relevant role (we will show in this study the close relationship between subsidies on renewables and carbon prices).

The European Commission itself has acknowledged the increased use of coal as a key issue for Europe, with increased CO₂ emissions being an increasing concern. The European Commission contribution to the European Council of 22 May 2013, titled ‘Energy challenges and policy’ notes that “EU consumption and imports of coal (hard coal and lignite) have increased by, respectively, 2% and almost 9% over the first 11 months of 2012, relative to the same period in 2011” (European Commission, 2013: 2). Policies to promote the transition towards a sustainable energy system – which are likely to favor natural gas, at least in the short and medium term – have not materialized to the extent expected only a few years ago. The role of natural gas as a transitional fuel within a joint Climate and Energy framework is an important issue and this was highlighted within the EU Energy

Roadmap 2050, which noted that the scenarios utilized within the Roadmap “are rather conservative with respect to the role of gas ... economic advantages of gas today provide reasonable certainty of returns to investors, as well as low risks and therefore incentives to invest in gas-fired power stations” (European Commission, 2011).

Hence, there is a need to conduct additional analysis on the role of natural gas within a joint Climate and Energy framework in Europe. Most importantly, there is scope for identifying cost effective policies which can alleviate the aforementioned paradox. The European Union cannot achieve its ambitious climate targets without relying heavily on gas rather than coal as a primary energy source. Therefore, appropriate measures need to be implemented to move energy markets in Europe closer to the optimal energy mix (where optimality obviously includes the internalization of the climate externality). In addition, gas is likely to play a relevant role in the optimal energy mix for at least four decades (as shown within the analysis below).

To address these issues, this paper focuses on three climate-related policy scenarios with two additional policy assumptions (two possible policy variations). In doing so, it reviews the role of natural gas within climate efforts which include the Copenhagen Pledges and the EU Roadmap – with specific sensitivity analysis upon the role of the 2020 renewable targets and increased energy efficiency improvements.

It should be noted that a range of studies have focused on the impact of climate targets upon Europe, e.g. refer to Böhringer et al. (2009), Blesi et al. (2010), Boeters and Koornneef (2011), Capros et al. (2012) and Bosello et al. (2013). However, this is the first study to specifically focus on the role of natural gas across different climate policy scenarios. Our focus on natural gas is due to the above statement within the Energy Roadmap 2050, the current debate concerning the additional sources of gas, and the potential role of gas as a transitional fuel within the shift towards a low carbon energy future as it provides a flexible power source which can counter the intermittency of renewables. While gas has been acknowledged to remain in the European primary energy mix within the long term

(Knopf et al., 2013), the extent to which natural gas plays a role has not been given sufficient attention.

This paper focuses upon the implications of different policy architectures for the optimal energy mix in Europe, and more broadly for the European economy. The analysis has been conducted using the WITCH (World Induced Technical Change Hybrid Model) integrated assessment model, a widely used model in the global assessment of climate and energy policies. Within the model, the main macroeconomic variables are represented through a top-down inter-temporal optimal growth economic framework. This is combined with a bottom-up compact modeling of the energy sector, which details energy production and provides the energy input for the economic module and the resulting emission input for the climate module. Further information about the model is available at the website www.witchmodel.org or can be sourced from Bosetti, Massetti et al. (2007), as well as in Bosetti, Carraro et al. (2006) and Bosetti, De Cian et al. (2009).

Underlying a review of the European energy market which focuses on 2020 are the issues of the impact of low economic growth and the influence of the renewable target. As a result, our scenarios make different assumptions about the stringency of climate policy across the globe and also capture real-world factors relevant to European policy such as sustained suppressed economic growth and post Fukushima apprehension concerning the safety of nuclear power. Modern renewables (such as solar and wind) are now becoming competitive due to the existing targets and incentives that the EU has put in place. The recent expansion of renewables has been forecast to continue, with UBS Investment Research (2013) predicting that up to 18% of electricity demand could be replaced by self-produced solar power in Germany, Italy and, eventually, Spain. Indeed, the same report discusses solar as being viable without subsidies within these same countries. Citi Research (2012) has also concluded that “renewables will reach cost parity with conventional fuels (including gas) in many parts of the world in the very near term” and that natural gas has a role to play as a transitional fuel within the progression towards a lower carbon world, as well as assisting in the balancing of the intermittency of renewables. Further reinforcing this point is a technical report by the National Renewable Energy Laboratory which notes that due to different risk profiles, natural gas and

renewable energy investments can be considered complementary portfolio options. In addition, the report notes that “the quick ramping ability of natural gas generators makes them ideal for complementing variable renewable generation” (NREL, 2012: 30).

The paper is compiled of four sections. An introduction appears before this point, while three sections follow. Section 2 provides a review of the WITCH model and an outline of the modelling framework and scenarios utilized within the analysis. Section 3 focuses on the main results of the project within three subsections, these being: - section 3.1 - which discusses the future of natural gas within Europe, - section 3.2 - which focuses upon the implications of following a climate policy target consistent with a 2°C Durban Action international agreement commencing in 2025, and - section 3.3 - which investigates the impact of an expanded availability of gas within Europe using a range of price sensitivity scenarios. Section 4 concludes with a discussion of the key findings of the paper.

As a prelude to the results of the paper, the conclusions have been separated into three key points. The first is the importance of setting a suitable carbon price which ensures that the right incentives are given to energy markets so that a consistent energy mix can be achieved, thus reducing the policy costs of all climate policy targets reviewed within the analysis. The second point is that natural gas is a key transitional fuel for a range of climate policy targets and therefore policy should be very careful in designing the right incentives to sustain gas consumption. And lastly, the importance of avoiding distortive policy instruments, e.g. subsidies, is highlighted. For example, in the near term (2020), the renewable target has been found to reduce carbon prices by about 10 \$/tCO₂, with clear negative impacts on incentives to adopt more energy efficient business strategies and to invest in climate-friendly technologies and production processes. What this study shows is that a correct carbon pricing can sustain gas consumption at while transitioning coal out of the power generation mix without damaging the development of renewables, even without subsidies. The policy mix inducing the welfare-maximising energy mix does not require subsidies on renewables and is therefore beneficial also for EU countries’ public budgets.

Section 2 – WITCH, the Modeling Framework and the Scenario Description

WITCH is a dynamic optimal growth general equilibrium model with a detailed (“bottom-up”) representation of the energy sector. Within the class of hybrid (both “top-down” and “bottom-up”) models, the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up representation of the energy sector. The top down component ensures a fully intertemporal allocation of investments, including those in the energy sector. The bottom up component guarantees an appropriate representation of substitution processes between different fuels. This framework is then utilized to model carbon mitigation options for the main greenhouse gases.

2.1 The model

A global model, WITCH is divided into 13 macro-regions, including Western and Eastern Europe which together are the main region focused upon within this paper (denoted as Europe throughout). The base year for calibration is 2005 and all monetary values are in constant 2005 USD. Amongst the distinguishing features of the model are the multiple channels of interactions between regions which include: technological spillovers, exhaustible common resources (coal, natural gas and uranium), trade of emission permits/credits, and the trade of oil, gas and coal. Environmental externalities in the form of climate damages can be activated within the model; however this analysis is conducted on the basis of a cost-effectiveness analysis of differing climate policies (namely, the study identifies the optimal strategy to achieve a given GHG concentration target). Hence, climate damages (still largely uncertain) are not accounted for within this study.

Optimization produces the optimal dynamic path of all endogenous variables (all kind of investments, GDP, emissions, etc.) subject to imposed constraints such as the model’s structure, emission targets and additional policy/technological assumptions. Accordingly, the WITCH model is a suitable tool for

an analysis of the optimal energy mix of power generation within Europe, where “optimal” is equivalent to “welfare maximising”.

Let us stress that our results should not be interpreted as forecasts, or how energy markets will develop in Europe, but rather how energy markets should evolve, were their dynamics consistent with the climate targets set out by the European Commission. It is precisely in this “normative” analysis that gas plays a crucial role. And this is why the model indicates that policies need to be designed to reconcile the present contradictory reality with the “ideal” situation for the European Commission and Member Countries.

The energy sector representation in WITCH is an aggregate of electric and non-electric energy sub-sectors with six fuels and over seven technologies for electricity generation. The electric sub-sector includes representations of oil, gas, coal, renewables (including biomass, off-shore/on-shore wind and PV/CSP solar) and nuclear power supply. With a range of fuels and energy types within the energy sector, the WITCH model uses a Constant Elasticity of Substitution (CES) function to aggregate the various forms of energy in a non-linear manner. This method of aggregation is common amongst economic models to ensure less than infinite substitution across factors. Within this framework, moving away from an established energy mix costs more than it would in a least cost minimization framework. Amongst the motives for the implementation of a CES function are econometric studies focusing on inter-fuel substitution which find an inelastic relationship between energy consumption and own/cross energy prices. The CES function allows for contemporaneous investments in different technologies which are consistent with base-year calibrated factor shares and the given elasticity of substitution framework. Hence the base year installed power generation capacity is calibrated for the year 2005 and this calibration influences the speed with which these technologies can be substituted with each other – refer to Bosetti, Massetti et al. (2007) for further details.

Within this analysis, the relationship between intermittent renewable and the other types of power generation is important. We account for the flexibility of natural gas and the intermittency of wind and solar with the implementation of the flexibility coefficients detailed within Sullivan et al. (2013).

Hence, the fraction of generation that is considered to be flexible for natural gas within WITCH is 0.5, while wind and solar require some additional flexible generation from another technology to account for intermittency. Wind requires an external fraction of 0.08 to satisfy changes and uncertainty in load, while solar requires 0.05. This in turn reflects the comparative advantage of natural gas to balance the intermittency of renewables as coal has a flexibility parameter of 0.15, although electricity storage would have a flexibility parameter of 1. In addition to the consideration of the energy system's ability to balance the intermittency of renewables, notably large shares are consistent with an additional need for storage devices. Accordingly, the need for storage of back up capacity and curtailment when the intermittent renewable share is relatively high is consistent with an additional penalty cost which has been imposed on top of the flexibility coefficients. The penalty cost is imposed within WITCH as a non linear function of the share of intermittent renewables within the power mix. Note that the calibration of this function has been based upon Hoogwijk et al. (2007). Indeed, DG Energy (2013) notes that “when these levels of 25% and above are reached, intermittent (renewable energy) RES need to be curtailed during the low consumption periods in order to avoid grid perturbation (frequency, voltage, reactive power) and grid congestion, unless the RES excess can be stored” (DG Energy, 2013: 5).

Upon discussing the future role and challenges of energy storage, DG ENER (2013) also makes the point that while storage may be considered an established technology; a sizable 99% of the current global large scale electricity storage capacity utilizes Pumped Hydro Storage systems. This working paper created by the European Commission's own Directorate-General for Energy also points out that demand for storage can also be covered by natural gas storage. In addition, natural gas is discussed as being an important fuel for electricity production as “natural gas power plants have a very high efficiency (above 60% for the best available technology), a very high flexibility and low CO₂ emissions (replacing an old coal fired power plant by a natural gas fired power plant reduces the CO₂ emissions per kWh up to 80%)” (DG ENER, 2013: 2). The same paper mentions that utilities are tending to rely on combined-cycle gas turbine systems as a range of factors have reduced the economic competitiveness of pumped hydro storage. The factors mentioned include: - increased

efficiency and reduced costs of flexible combined-cycle and simple-cycle natural gas turbines, - increased interconnection of the grid at the EU-level, and - decreased gas prices (DG ENER, 2013). Technological, market or regulatory issues and a holistic approach across borders are the main challenges for energy storage highlighted within DG ENER (2013). Within section 3.2 we further discuss the issue of storage and curtailment upon comparing the WITCH results to those of the PRIMES model. Differences in the results are partly related to the expansion of hydrogen as a means of storage of intermittent renewable power. The importance of a technological breakthrough in the production of hydrogen within the scenarios which accompany the EU 2050 Roadmap (produced by the PRIMES model) is highlighted by approximately 66% of net installed capacity in 2050 being sourced from renewables, with 80% of this capacity being from an intermittent source.

2.2 The scenarios

With a focus on the importance of climate policy for natural gas in Europe we have developed a range of scenarios which capture a realistic representation of the current conditions under which policy makers are operating. As part of this we have implemented the scenarios introduced below with underlying assumptions regarding economic growth and the expansion of nuclear power. For example, stagnant economic growth in Europe until 2020 is implemented by lowering labor productivity and within the baseline this results in a growth rate of approximately 0.4% per year for Europe between 2010 and 2020, increasing to be approximately 1.5% per year after 2020. Table 1 presents the population and GDP assumptions that are implemented within the baseline scenario, which is designated as the No Policy scenario within Table 2.

A gradual reduction of nuclear power in Western Europe is also implemented across all scenarios to reflect the post-Fukushima apprehension towards the technology. Within the baseline, this results in an 8% reduction in nuclear power generation in comparison to 2010 levels at the European level for 2020, increasing to a 14% reduction in 2030.

Table 1. Baseline Demographic and Economic Estimations

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (Billions)	0.513	0.520	0.525	0.528	0.530	0.530	0.530	0.528	0.526
GDP (Trillion 2005 USD MER)	15.17	15.67	16.15	17.39	18.86	20.33	21.96	23.67	25.52
GDP per Capita (2005 USD per person)	29,546	30,146	30,775	32,921	35,577	38,314	41,443	44,790	48,503

Table 2 reviews the full matrix of scenarios implemented within this analysis with two major dimensions being that of ‘climate policy stringency’ (i.e. No Policy, Moderate Policy, Stepped Up Policy and 2°C Policy) and a range of ‘additional policy assumptions’ (i.e. Base, No Renewable Target and High Energy Efficiency). Table 2 also provides the naming convention applied within the analysis and the next few paragraphs will provide descriptions of these scenarios based on the two dimensions specified.

Table 2. Policy Scenarios – Climate Policy, Renewable Target and Energy Efficiency

	a. Base	b. No Renewable Target	c. High Energy Efficiency	
			Energy Intensity	Energy Demand
1. No Policy	NoPol			
2. Moderate Policy	Pledge	Pledge/NoRET	Pledge/HEE_I	Pledge/HEE_D
3. Stepped up Policy	Pledge+	Pledge+/NoRET	Pledge+/HEE_I	Pledge+/HEE_D
4. 2°C Policy	2Deg	2Deg/NoRET	2Deg/HEE_I	2Deg/HEE_D

Climate policy stringency is reviewed across four different scenarios. The No Policy (No Pol) scenario is a comparative counterfactual state of the world in which no climate policy is implemented (not even in 2020) in any country in the world. As our focus is on Europe, the counterfactual nature of this scenario is clear as it does not include any of the existing policies which have already been implemented (such as the 2020 renewable and emissions target) and the main use of this scenario will be in providing a benchmark for the calculation of policy costs, including the costs of the 2020 renewable target.

The Moderate Policy (Pledge) scenario is a case where there is fragmented moderate action on climate and includes region specific policy objectives based on the Copenhagen Pledges. These region specific policy objectives include: - 2020 emission reduction targets, - technology specific policies (e.g. expansion of renewable and/or nuclear), and – post-2020 carbon intensity targets. Within the Moderate Policy scenario regions can trade carbon offsets internationally (for example, through a Clean Development Mechanism type of project or via a linkage of the ETS to other regions), however this is limited to be equivalent to 20% of abatement as at least 80% of emission reductions have to be conducted domestically. For Europe, this scenario includes the legislated 2020 targets (specifically emissions, renewables and energy efficiency) and a post 2020 extrapolation of the climate policies, with a 2030 and 2050 target of 25% and 45% emissions reductions with respect to 2005. Note that the Appendix contains an extended discussion of the specification of the policy scenarios with extensive detail for the major regions considered.

The Stepped up Policy (Pledge+) scenario replicates much of the settings of the Moderate Policy scenario, except that the level of ambition is stepped up in 2020 and beyond within all regions. For Europe, this results in a tightening of the supply of emission carbon offsets up to and including 2020 (or equivalently, this can be interpreted as having raised the ambition of emissions reductions in 2020 to 30% wrt to 1990). For 2030 and 2050, emission reductions would be 37% and 60% wrt 2005 respectively.

The 2°C Policy (2 Deg) scenario moves away from the fragmented representation of climate policy and captures a situation where the Durban Action Platform delivers a binding international climate treaty entering into force in 2025 with the aim of maintaining global temperature increase below 2C with sufficiently high probability. It is important to remark that since the model has a global scope, each policy scenario has a detailed formulation for all the native regions of the model (13 regions), and not just for Europe. The extent of regional climate policy effort is harmonized and based in the short term on national and international pledges. Full details of these policies for a set of major economies are reported in the Appendix of this paper.

The additional policy assumptions (the second dimension of the matrix) are then imposed on top of the implementation of the level of climate policy stringency with the Base case being the standard representation of policy. Note that for Europe, this means that the Base case includes the legislated 2020 targets (specifically emissions, renewables and energy efficiency) in all scenarios, except for NoPol. The first additional policy assumption that is implemented is the No Renewable Target (No RET) where the 20% renewable target (as a share of final energy) in Europe for the year 2020 and beyond is not activated. This allows disentangling the impact of the renewable target upon Europe – its cost for the EU in particular - in comparison to the alternative cases.

The second additional policy assumption is a case where Europe pursues energy efficiency policies in 2020 and beyond. This in turn stimulates High Energy Efficiency (HEE) where demand stays relatively flat between 2010 and 2050. The implementation of the HEE scenario has been separated into two potential options for policy design and implementation. The first of which is an energy intensity (HEE_I) based policy where technical change improves energy efficiency. The second is where the policy is imposed as a target on energy demand (HEE_D) and can be achieved by reducing energy demand, rather than through energy intensity. As will be discussed within section 3.1, the distinction is important with respect to policy design and policy costs, but is irrelevant with respect to the energy mix. Thus, the distinction will be retained only when presenting carbon prices and policy costs.

Section 3 – Main Results

Having briefly summarized the range of scenarios and assumptions that have been implemented within the analysis, the discussion within section 3 moves on to the scenario results with a focus on the role of natural gas within Europe (section 3.1), a review of how the fragmented policies differ in comparison to an international effort to achieve a 2°C Durban Action policy (section 3.2) and an analysis of different availability/prices of natural gas (section 3.3).

Before focusing upon Europe, it is also important to briefly review the overall climate policy framework that is being employed within other regions as part of the same scenarios. Figure 1 reviews the impact of the climate policy stringency scenarios upon global greenhouse gas emissions between 2010 and 2050. The Pledge and Pledge+ policies lead to a peak of global emissions by 2050 and 2040 respectively (and decline thereafter), whereas the 2Deg policy corresponds with global action which moves this peak forward to 2020 with immediate reductions corresponding with the international agreement implemented in 2025. The graph highlights the growing global gap in emissions between the case in which no action on climate is undertaken (NoPol) and the different climate policy scenarios. If emissions continued to grow unabated, in line with historical trends, the effects of climate change would be potentially significant, with a global increase in temperature increase by the end of the century estimated around a mean of 4 C. On the other hand, the 3 policies analyzed in the paper have the potential to reduce the temperature increase, depending on the stringency of emission reductions.

Greenhouse gas emissions of selected major regions for the Pledge and Pledge+ policies, reflecting the commitments made within the Copenhagen Pledges, are shown in Figure 2. In these fragmented policy scenarios, OECD countries would reduce emissions, while emissions in China and India increase before 2030. In the case of China emissions level off in 2030 and decrease thereafter, reflecting a firm commitment towards climate and air pollution reduction objectives, while emissions in India continue to increase up until 2050, given the different stage of economic development. In the

case of China, CO2 emissions in 2010 were 22.7% of the global total and peak at 30.1% in the pledge case in 2030, decreasing to 26.7% in 2050. This is in comparison to 31.5% of global emissions in 2030 and 30.8% in 2050 within the no policy scenario.

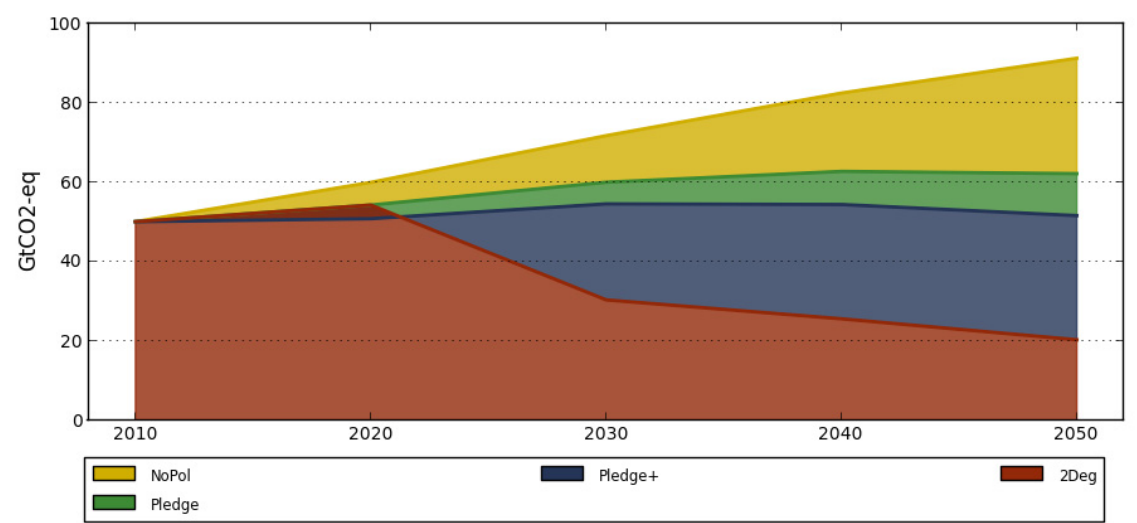


Figure 1. Global Greenhouse Gases by scenario

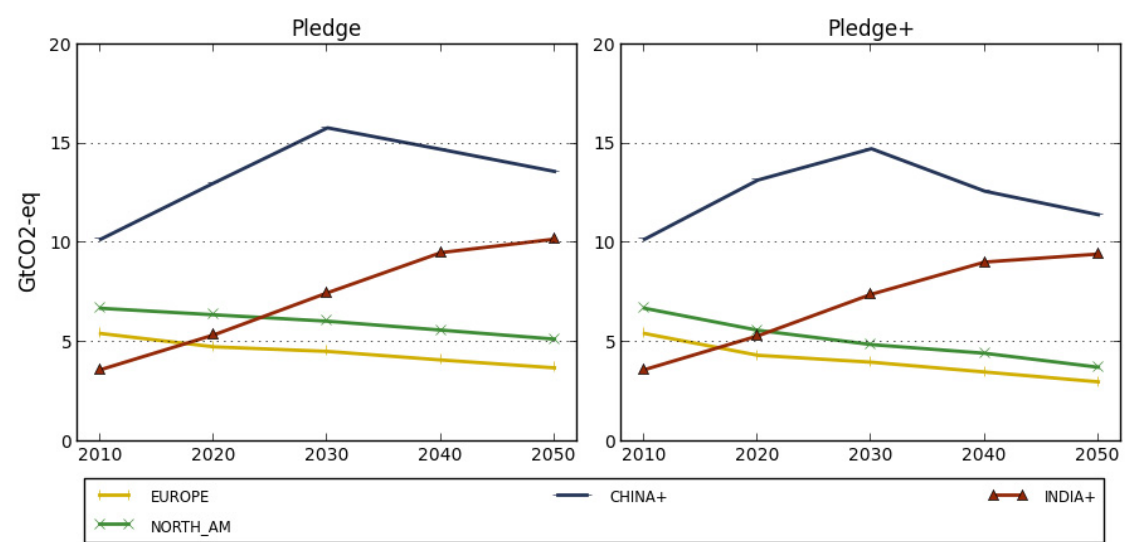


Figure 2. Greenhouse Gases by selected major region - Pledge and Pledge+

As Europe has a special focus within the paper and can be classified as a front runner on climate action, we will now pay attention to the level of action by Europe across the scenarios presented in Figure 2. CO₂ emissions associated to Europe were 12.1% of the global total in 2010 and under the Pledge scenario this would decrease to 6.6% in 2050 (in comparison to 8.7% in the no policy baseline). In terms of abatement, in 2050 Europe would be responsible for 13.6% of global emission reductions in the Pledge scenario, which decreases to 11.6% in Pledge+ and 8.4% with a unilateral focus on achieving 2Deg. Note that the percentage of emissions/abatement differs based on the level of commitment by regions outside Europe and the overall worldwide emissions total – refer to the discussion surrounding Figure 3 for specific details on the amount of abatement that Europe conducts with respect to 2010 levels.

3.1 – Implications for Europe

As noted within the introduction, the role of the power generation mix and especially gas within Europe is of interest for a range of reasons. These being: - the specific acknowledgement of a conservative representation of the role of gas within the scenarios utilized within the EU Energy Roadmap 2020, - the current debate about the impact of additional sources of gas, shale gas in particular, and - the role of gas as a transitional fuel that can also provide a flexible power source to counter the intermittency of renewables.

Before reviewing the role of natural gas, it is important to evaluate the climate policy stringency targets for Europe. Figure 3 reviews the European greenhouse gas targets for the Pledge and Pledge+ scenarios with a comparison between emissions with respect to the NoPol case. Note that Figure 3 makes a distinction between the allowance allocation of emissions and the total amount of emissions that occur within Europe, once international carbon offsets have been accounted for. As already implemented today, Europe is allowed to fulfill a fraction of its domestic emissions reductions targets by buying a certain amount of emission permits outside the region, most notably in the developing countries where abatement opportunities are cheaper.

As previously noted, the two policies considered foresee a gradual reduction in emissions in Europe, with emission reduction targets in 2030 of 25% and 45% (with respect to 2010) for the Pledge and Pledge+ policy scenarios respectively. These targets would increase to 45% and 60% by 2050, with a rather linear schedule.

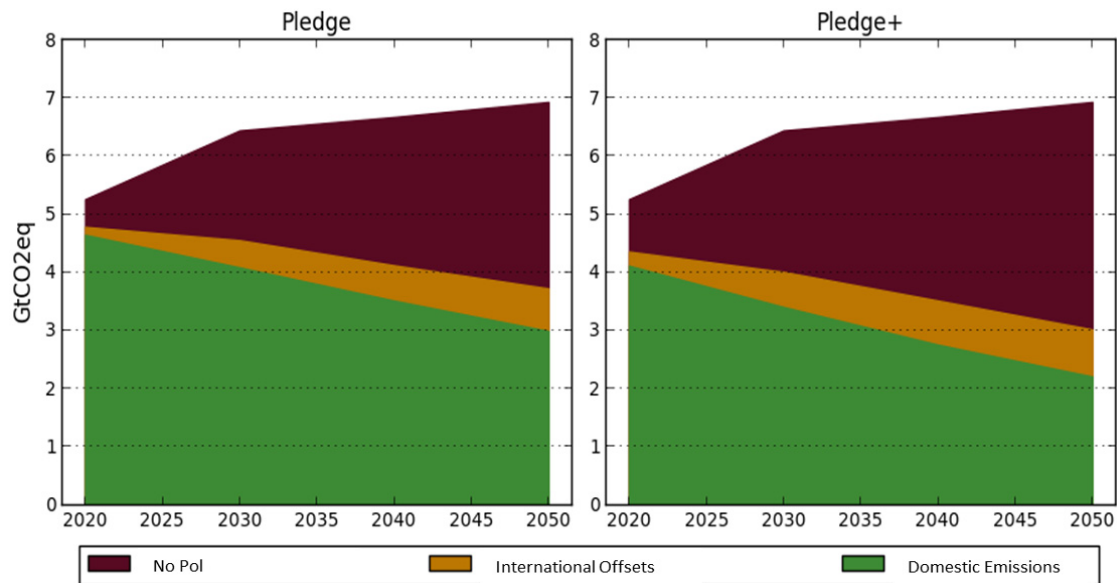


Figure 3. European Greenhouse Gas Targets - Pledge and Pledge+

3.1.1. Power generation within Europe

We start by providing an overview of the welfare maximizing power generation mix for coal, gas, nuclear and non-biomass renewables across the Pledge and Pledge+ scenarios and the additional policy assumptions. These are shown in Figures 4 and 5. The general trend in power generation for the Pledge and Pledge+ policy scenarios is a reduction in coal and an increase in gas and renewables, as well as a decreasing role for nuclear due to the inclusion of the potential impact of post-Fukushima apprehension within Western Europe. These trends are robust across the different policies.

In all scenarios, coals loses 10% of market share by 2030, recuperating slightly there after due to the deployment of CCS technology. Gas gains 10-15 percentage points, after an initial reduction in 2020 over 2010 due to the economic recession. Renewables show a fast growing pattern in the short term,

spurred to a large extent by existing incentives, but also a long term saturation, due to increase system integration costs.

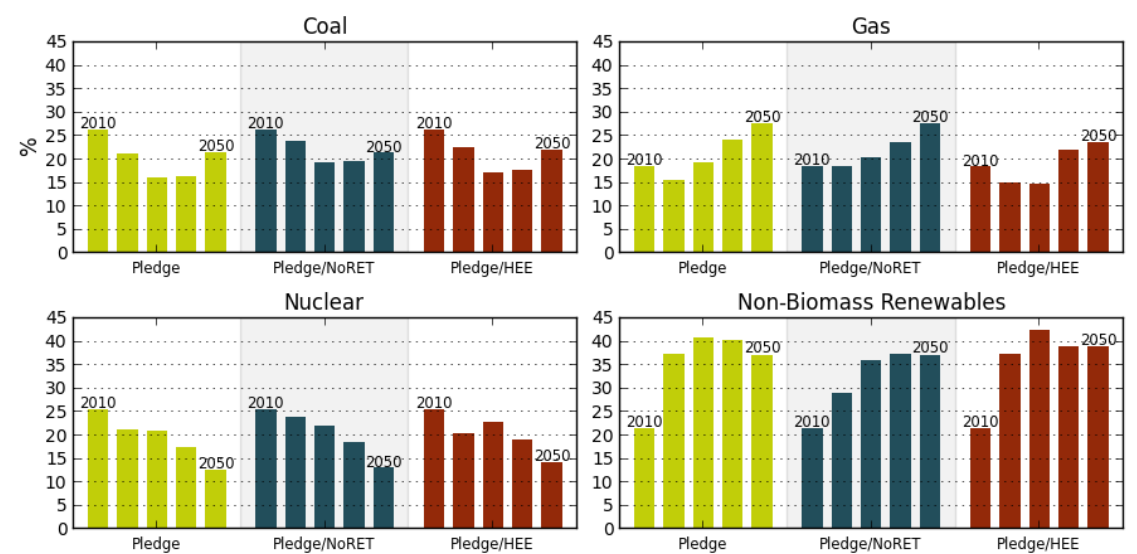


Figure 4. Power generation shares by fuel – Full range of Pledge scenarios, from 2010 to 2050.

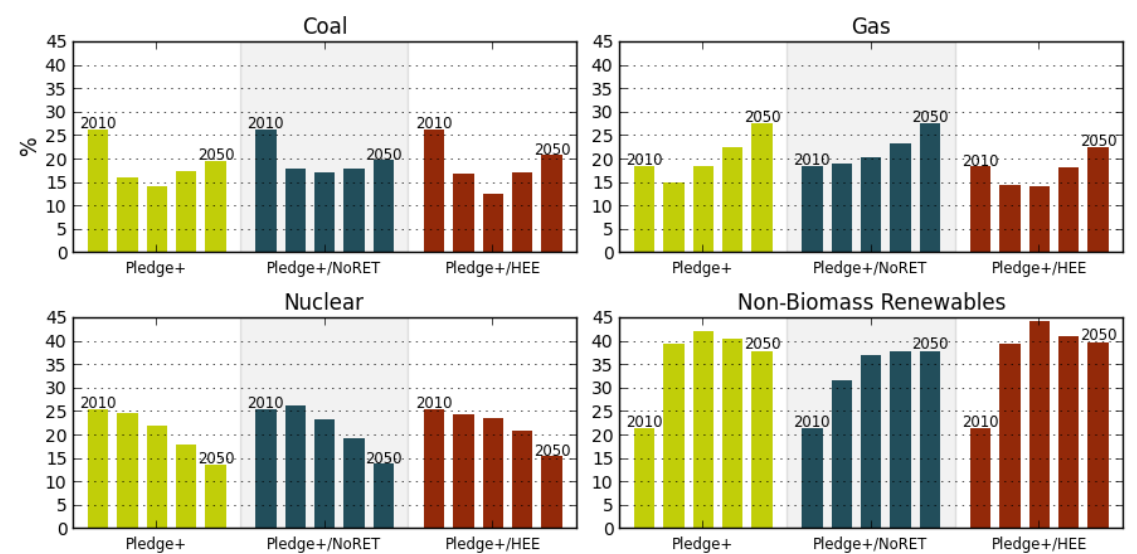


Figure 5. Power generation shares by fuel – Full range of Pledge+ scenarios, from 2010 to 2050

Specifically, the power generation shares for Europe within Pledge in 2020 are 21% for coal, 16% for natural gas, 37% for non-biomass renewable and 21% for nuclear, in comparison to shares of 25%, 17%, 27% and 25% in 2015. The removal of the renewable target for 2020 results in power generation

shares for Europe within Pledge/NoRET in 2020 of 24% for coal, 18% for natural gas, 29% for non-biomass renewable and 24% for nuclear, with an additional 5% decrease in total electricity demand.

In the case of Pledge+, the power generation shares for Europe in 2020 are 16% for coal, 15% for natural gas, 39% for non-biomass renewable and 23% for nuclear, in comparison to shares of 25%, 17%, 27% and 25% in 2015. The removal of the renewable target for 2020 results in power generation shares for Europe within Pledge+/NoRET in 2020 of 18% for coal, 19% for natural gas, 32% for non-biomass renewable and 26% for nuclear, as well as a 6% decrease in total electricity demand.

Underlying a review of Europe which focuses on 2020, as done above, are the issues of low economic growth and the impact of the renewable target. Figure 4 and Figure 5 show indeed that natural gas within Pledge and Pledge+ is expected to slightly decline in 2020 wrt 2010 and this is related to the slow demand growth in total electricity. However, the impact of the renewable target is notable with no contraction in the share of natural gas occurring within the NoRET cases.

Irrespective of the impact of the renewable target, after 2020 both the Pledge and Pledge+ climate policies induce gas to increase significantly and coal to continue decreasing (until it is somewhat revived when coupled to CCS by mid century). Figure 6 provides the changes in natural gas from electricity in terms of the level of production. The chart indicates that natural gas would eventually increase its contribution to the power mix in a significant way, with an expected generation by mid century of 1000-1200 TWH, which roughly corresponds to a doubling from today's levels.

The exact timing of the increase in the use of gas depends on assumptions about the economic recovery and the set of policies in place after 2020. As evident from Figure 6, the impact of the renewable target upon the amount of gas within power generation is visible only in 2020. The impact of the renewable target in 2020 vanishes after that due to an increased role played by renewable energy sources in the long term across all of the additional policy assumptions due to the level of carbon prices in the market. On the other hand, strong post 2020 legislation on energy efficiency is shown to have a sizeable impact on the prospects of natural gas, as a result of lower electricity demand due to increased savings.

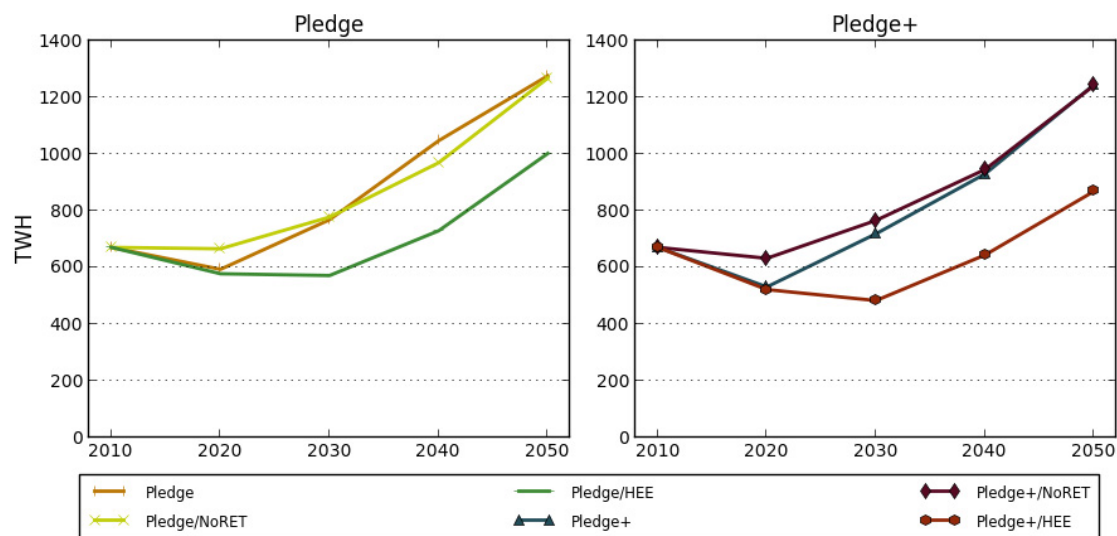


Figure 6. Natural gas electricity – level of power generation

Underlying the results that have been discussed within this section are changes in the investments related to providing the capacity for the power generation options reviewed. Focusing on the Pledge and Pledge/NoRET scenarios within Figure 7 allows for a focus on the impact of the renewable target on investments across coal, natural gas and modern renewables.

The chart shows two contrasting trends for coal and gas on one side, and renewables on the other. Investments in both coal and gas are expected to grow over time, in the range of 100-300 USD Billions per decade, but only after the post 2020 economic recovery. Despite its decreasing role in the power mix, investments in coal remain substantial, due to the higher overnight capital costs of coal power, and the fact that after 2030 the majority of coal is equipped with Carbon Capture and Storage (CCS) technology. Indeed, for coal to remain in the optimal energy mix, and still enable the achievement of emissions consistent with Copenhagen Pledges, coal needs to be equipped with CCS after 2030. As a comparison, natural gas is also coupled with CCS, however this occurs after 2040 within the Pledge scenario. Despite providing a much larger electricity share, investments in gas are smaller, due to the low overnight capital costs assumed for CCGT technologies.

For renewables, investments on the other hand slightly decrease after 2020, due to the improved economics of renewables, as well as a saturation of their contribution due to the already highlighted system integration constraints. In 2020, policies supporting renewables increase investments by about 50%. Between 2010 and 2030, the Pledge scenario corresponds with investments in modern renewables being 55% of total investments related to the supply of electricity. In terms of capacity, this equates to 65% of new power capacity between 2015 and 2030. Note that projections completed by Bloomberg New Energy Finance forecast that renewables will account for between 69% and 74% of new power capacity added between 2012 and 2030 at the global level. (BNEF, 2013)

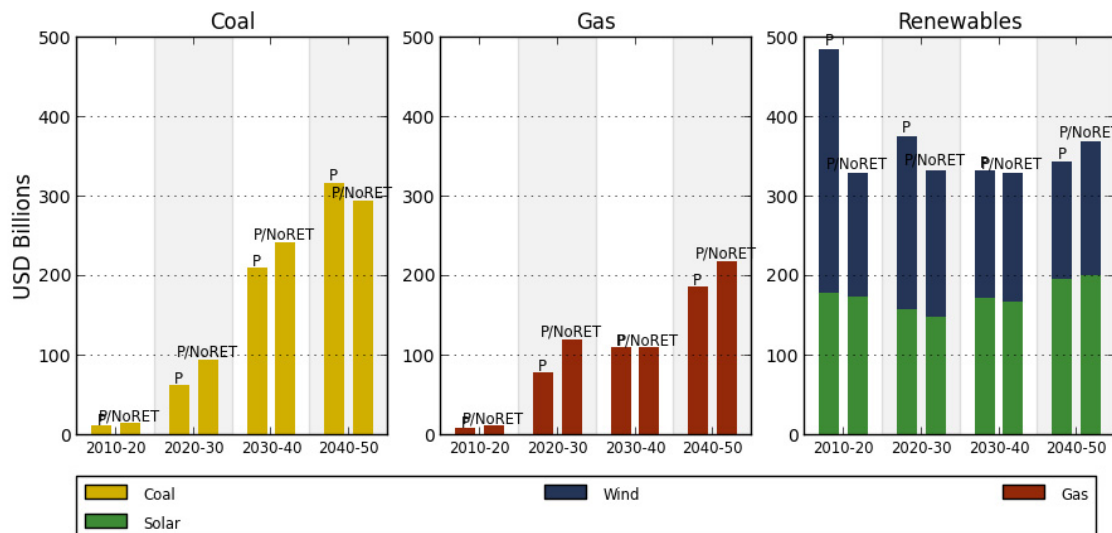


Figure 7. Decadal investments across key power generators

3.1.2 Carbon Market and Policy Costs

We now turn to the economic implications of the economic, energy and climate scenarios analyzed within this paper. We begin by looking at an important indicator, namely the carbon prices which emerge from the EU carbon market, see Figure 8. The chart highlights the expected fact that carbon prices grow in the stringency of the emissions reduction target, both over time (by about 5\$/tCO₂ each year) and across the policies (with Pledge+ adding 10-15\$/tCO₂ to the Pledge case).

Carbon prices in 2020 for the cases where the renewable target is implemented are 9-14 $\text{\$/tCO}_2$ in the Pledge policy and 22-28 $\text{\$/tCO}_2$ in the Pledge+ policy scenario, depending on the impact of high energy efficiency. However, the carbon price without the renewable target imposed would be 22 $\text{\$/tCO}_2$ in Pledge/NoRET and 38 $\text{\$/tCO}_2$ in the Pledge+/NoRET. This indicates that the renewable target suppresses carbon prices in 2020 by approximately 10 $\text{\$/tCO}_2$. The importance of the differences in carbon prices lies in the need to provide clear incentives to energy markets – indeed, a stable and long-term signal which increases over time would prevent the recent expansion of coal within Europe which was noted within the introduction.

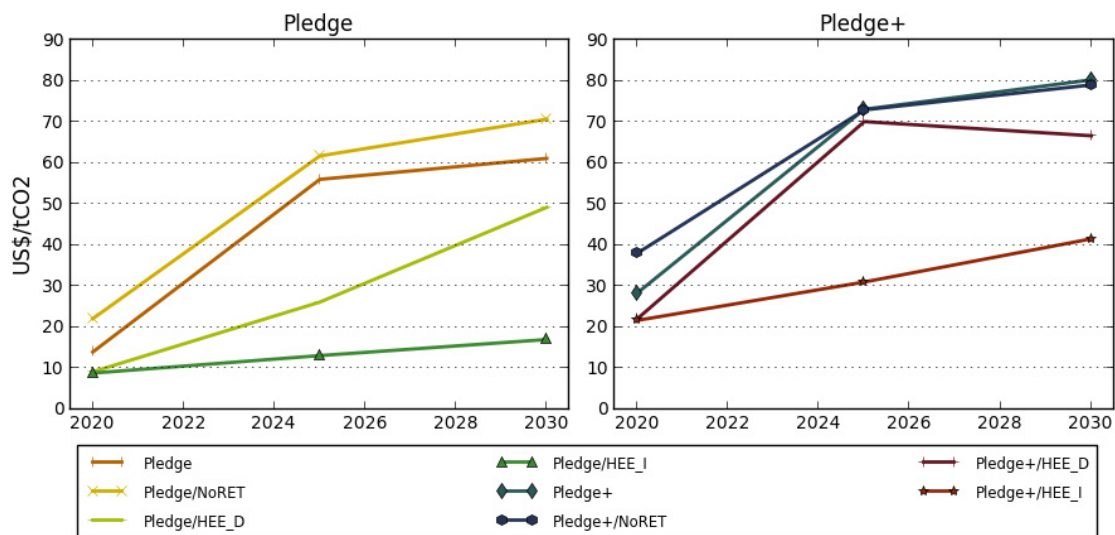


Figure 8. Carbon prices – Full range of Pledge and Pledge+ scenarios

In addition, if full auctioned, the sales of permits has the potential to generate significant fiscal revenues, which are important at times of consolidation of public debt. We estimate that public revenues with Pledge and Pledge+ are associated with potential revenues of 65 to 166 Billion USD, and exceed 200 USD Billions after 2030 (refer to Figure 9). In 2020, the renewable target would reduce revenues by almost 40 Billion USD irrespective of whether Pledge or Pledge+ is followed. This highlights that subsidies and/or incentives for modern renewables, in addition to being costly, also reduce the revenues from issuing emission permits.

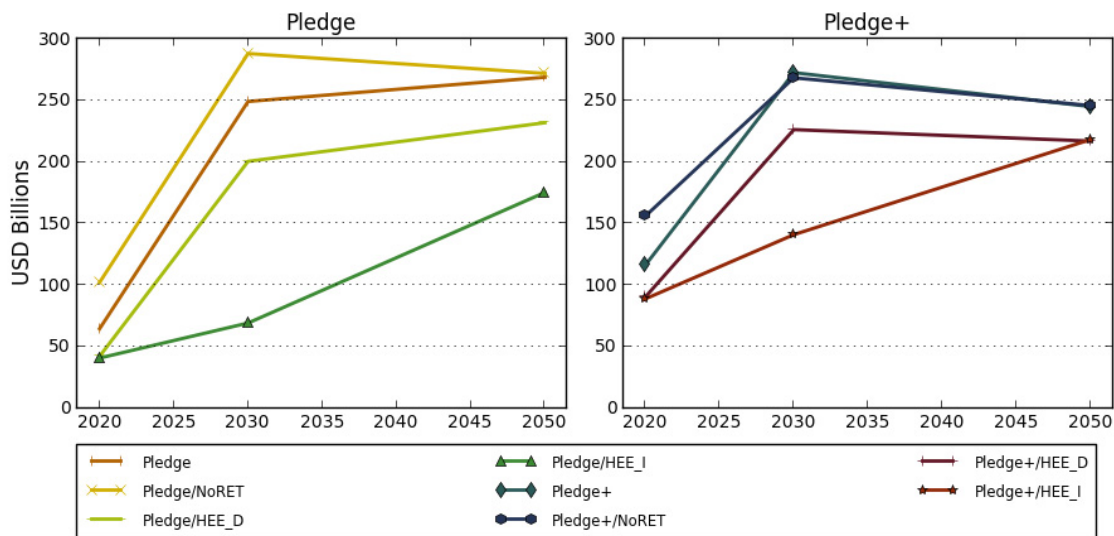


Figure 9. Fiscal revenues from the carbon market

Figure 8 and Figure 9 also review the carbon prices and permit revenue associated with two different approaches to implementing the same energy efficiency improvements – that being either through energy intensity improvements with technical change (HEE_I) or energy demand reductions (HEE_D). Between these two scenarios the differing impact of the imposition of the energy efficiency improvements are highlighted with energy intensity improvements through technical change reducing the burden of emission reductions which occur within the economy and hence have a downward impact upon the amount of carbon offsets which are sourced by Europe from abroad.

Carbon prices are imperfect indicators of macro-economic costs, as a result we assess these costs –as measured by GDP losses- separately in Figure 10 and 11. Policy costs in the Pledge scenario are found to be in the order of 0.5% GDP loss in 2020, growing to 1.5% by the mid century. The renewable target is responsible for a considerable fraction of short term costs, more than doubling 2020 policy costs; however these converge over time once the impact of the 2020 renewable target disappears. The Pledge+ policy induces moderately higher costs – 0.6% and 0.3% for the base case and NoRET respectively. Note that upon adjusting their analysis for an economic recession, Bosello et al. (2013) find a similar level of policy costs for a scenario similar to Pledge using the ICES model

(another integrated assessment model developed and used at CMCC), with a policy cost of 0.5% for the EU when implementing its energy and climate policy unilaterally.

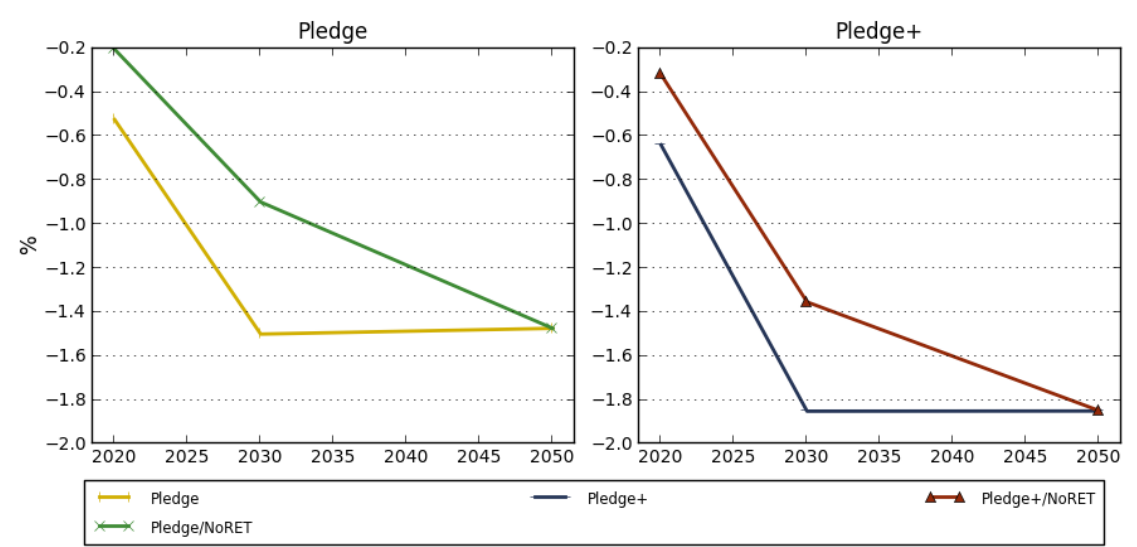


Figure 10. Policy costs in comparison to the no policy scenario – Selection of Pledge and Pledge+ scenarios

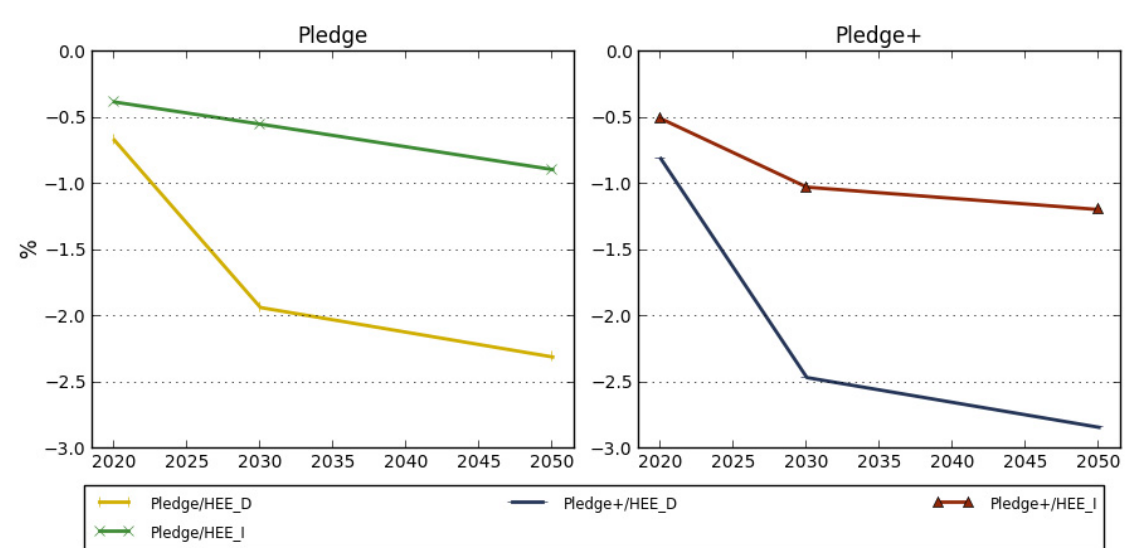


Figure 11. Policy costs in comparison to the no policy scenario – Focus on High Energy Efficiency (HEE) Pledge and Pledge+ scenarios

Figure 11 also reviews policy costs associated with the two different approaches to implementing the same energy efficiency improvements – that being either through energy intensity improvements (HEE_I) or energy demand reductions (HEE_D). In 2020, the difference in policy cost is limited as

the difference in energy demand with respect to the baseline is small due to the assumption of suppressed economic growth. However, over time the level of electricity demand within both of these scenarios is notable (20% lower in 2050) with policy costs between HEE_I and HEE_D differing by approximately 1.5% of GDP. Indeed, the changes over time show that the costs of the HEE scenarios crucially depend on policy design and implementation. If the energy efficiency target is designed as energy intensity improvements and implemented as increased technological change, then costs are lower than in the other scenarios.

However, if the energy efficiency target is designed as a target on energy demand reduction (as done in the EU Energy Efficiency Directive), then costs and the demand for offsets are notably higher. In reality, the response to a target would likely be made up of a mixture of energy efficiency improvements and reduced energy demand, however the policy costs shown within Figure 11 highlight the importance of providing an incentive for a mixed response to a given target. Whether the current European target within the Energy Directive is based on energy demand is suitable will be contingent on the response of industry and consumers, rather than being driven by policy design.

3.2 – 2°C Durban Action policy

Having reviewed the role of natural gas within Europe for two fragmented policy scenarios, the analysis now turns to how these scenarios differ to a situation where the Durban Action Platform delivers a binding international climate treaty entering into force in 2025 with the aim of ensuring that the 2100 global temperature increase is below 2°C with sufficiently high probability.

Figure 12 updates the European Greenhouse Gas targets for the Pledge, Pledge+ scenarios, including also the case of 2Deg. Under the 2Deg policy, emissions in Europe would need to be cut significantly more than in the Pledge and Pledge+ policies, by 60% in 2030 and 80% in 2050. This result is consistent with the emission reductions specified within the EU 2050 Roadmap.

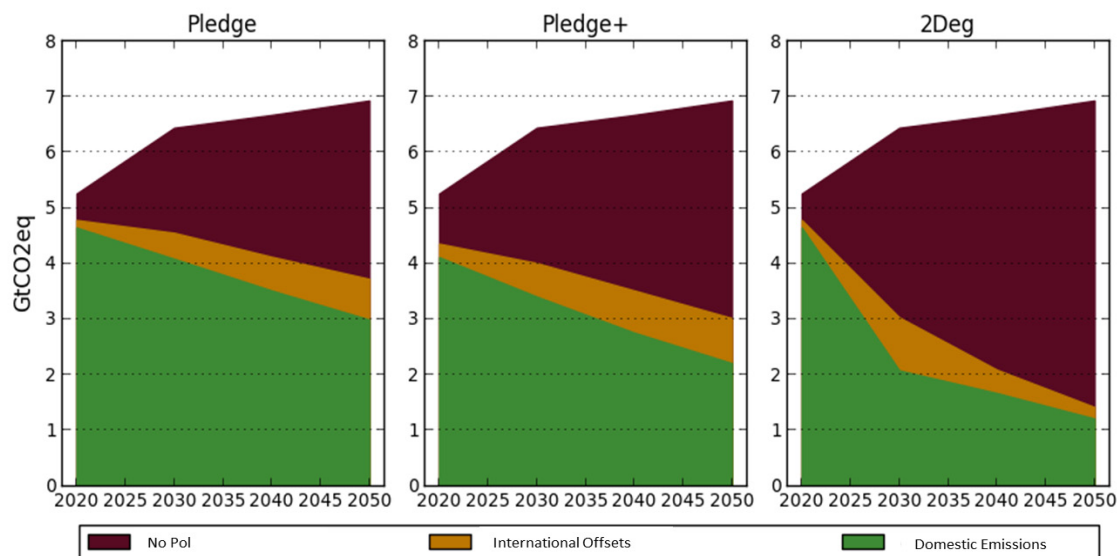


Figure 12. European Greenhouse Gas Targets – Pledge, Pledge+ and 2Deg scenarios

Within Table 3 we compare our results for Europe in the 2Deg scenario to those in Capros et al. (2012a) which focuses on the EU27. Capros et al. (2012a) details the impact assessment study conducted using the PRIMES model, which accompanied the impact assessment of the EU 2050 Roadmap.

A comparison of the two models shows that WITCH allows for substantially more gas within the energy mix than PRIMES, which instead has a preference for zero carbon technologies such as renewables and nuclear. However, WITCH foresees a more marked contraction in the overall electricity demand, as well as an important role for Gas with CCS. In comparison the PRIMES results show a notable expansion in wind and other renewable energy sources with a corresponding contraction in Gas without CCS and relatively delayed CCS deployment until after 2030. With respect to renewables the PRIMES model has a 46% share of power generation in the ‘decarbonisation under effective technologies and global climate action’ (ET_GCA) scenario, in comparison to a notable 42% share in the Reference scenario. After 2030 Gas with CCS does have strong deployment within PRIMES with a power generation share of 0.5% for Gas without CCS and 13.3% for Gas with CCS reported for 2050. This is in comparison to a 0.1% share of Gas with CCS in 2030.

Table 3. Comparison to EU27 Estimates associated with the EU Roadmap 2050

% Share Power Generation	PRIMES - EU27 - Roadmap 2050			WITCH - Europe - 2Deg		
	2020	2030	2050	2020	2030	2050
Nuclear	25.2	29.0	26.4	21.3	26.4	18.2
Fossil Fuels	39.6	24.9	22.2	39.4	32.3	34.7
<i>Coal/Solids</i>	18.0	7.0	8.3	21.3	11.3	8.8
<i>Gas</i>	20.2	16.8	13.8	15.6	19.5	25.7
Renewables (including biomass)	35.2	46.1	51.4	39.3	41.3	47.1
<i>Wind</i>	16.1	24.1	27.4	16.3	13.6	13.6
<i>Solar and other</i>	2.3	4.9	8.8	5.2	6.7	11.1

Indeed, with such stringent emission targets there is a need to notably curb emissions and underlying modeling/assumptions concerning the expansion of renewables and/or CCS will be important factors during a comparison of model results. Note that with respect to WITCH, the modeling of system integration through flexibility constraints and a penalty cost are of importance upon reviewing the expansion of modern and intermittent renewables. Capros et al. (2012b) is dedicated to the issue of intermittency and focuses on the impact of large-scale energy storage and optimal transmission grid expansion. In doing so, they find that enhancement of the transmission system is preferred for lower renewable penetration and as the penetration levels increase energy storage becomes more and more important. This conclusion is accompanied by the caveat that “the related technologies have not reached a fully commercialized level, hence cost data used in the models are rather an anticipation of what level of maturity is the related technology expected to reach” (Capros et al., 2012b: 9). It should be noted at this point that Capros et al. (2012a) also states that “hydrogen is shown to emerge in the long term as a means of storage of intermittent renewable power” (Capros et al., 2012a: 96) and that this coincides with a situation where the EU 2050 Roadmap has approximately 66% of net installed capacity in 2050 sourced from renewables and 80% of this is from an intermittent source. Capros et al

(2012a) also notes that in order “to avoid curtailment of RES the model develops endogenously hydro pumping and hydrogen, the latter being used for mixing with natural gas” (Capros et al., 2012a: 88). Indeed, the introduction of hydrogen production from excess electricity is a crucial feature of the PRIMES model with respect to intermittent renewables and has a direct impact upon the demand for natural gas.

Having discussed the EU 2050 Roadmap scenarios from the PRIMES model, we now return to an analysis of the results for a 2Deg policy. The power generation shares for Europe are shown within Figure 13. In 2030, the power generation shares are 11% for coal, 19% for natural gas, 38% for non-biomass renewable and 26% for nuclear, in comparison to Pledge shares of 16%, 19%, 41% and 21%, respectively. Natural gas maintains a similar (albeit slightly lower) share in the power mix than in the moderate and stepped up policies (i.e. Pledge and Pledge+). Underlying these numbers are strong energy efficiency improvements with 2Deg in 2030 having a 10% reduction of total electricity demand in comparison to the Pledge case which is almost equivalent to the high energy efficiency scenarios reviewed within the fragmented policies. The strength of the reduction in energy demand results in the spike for nuclear within Figure 13 in 2030 as the capacity of nuclear has been fixed to reflect a partial phase out nuclear of within Western Europe.

Having reviewed gas as a percentage share, we now review the amount of natural gas based electricity in terms of TWh across the 2Deg additional policy scenarios and show that increased demand for gas wrt 2010 tends to occur in all but the HEE scenario and when the renewable target has an impact (i.e. 2020 within 2Deg, but not within 2Deg/NoRET). In comparison to the Pledge and Pledge+ cases there is a lower demand for natural gas with the 2050 amount in 2Deg being 976 TWh in comparison to 1276 TWh in Pledge and 1245 TWh in Pledge+. However, this is in line with only a slight difference in the power generation share and is driven by the reduced electricity demand. Policy costs within the 2Deg scenario are significant irrespective of global action and in 2050 costs are over three times larger than in the other policies considered (6.27% in comparison to 1.47% in Pledge and 1.85% in Pledge+).

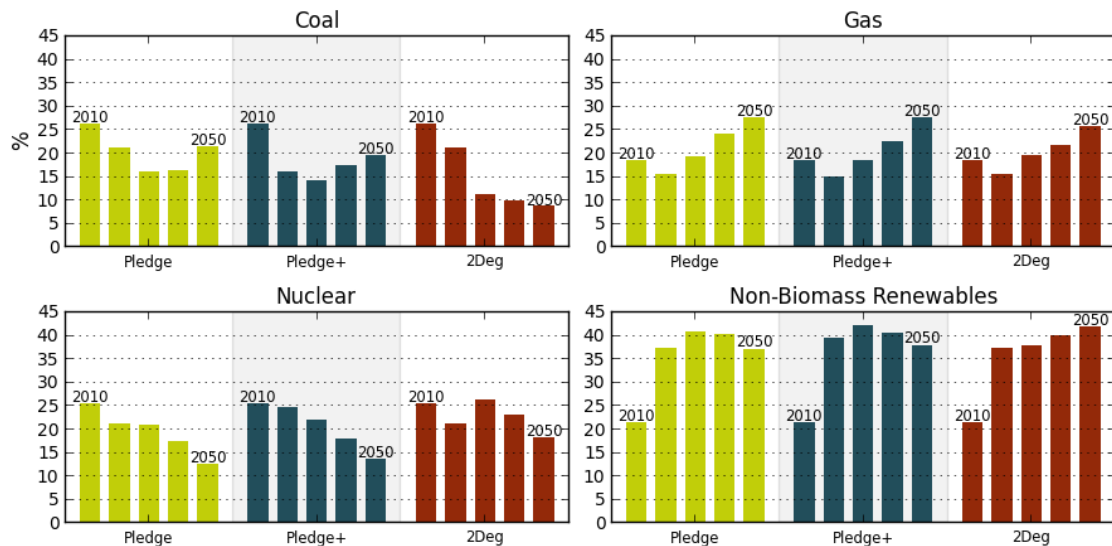


Figure 13. Power generation shares by fuel – Pledge, Pledge+ and 2Deg scenarios

3.3 – Focus on the availability and price of gas

The European Commission contribution to the European Council of 22 May 2013, titled ‘Energy challenges and policy’ notes that the US shale gas boom has led to a situation where “while Europe's dependence on fossil fuel imports is increasing, the US is on its way from being a gas importer to a net exporter” (European Commission, 2013: 2). The impacts of this include industry gas prices which are at least four times lower in the US than they were in Europe during 2012. In the same period there was also increased use of coal within Europe. Indeed, the impacts of lower gas prices are an important factor which needs to be considered. A lower price of natural gas may be achieved through a variety of channels, including but not limited to European shale gas production and/or imports of LNG. It should be noted that for Europe the potential impact of expanded shale gas production in other regions across the World will hinge upon the potential for imports of LNG (including the establishment of notable re-gasification capacity), competition from other regions/nations and the development of a fully functioning market within Europe. (Teusch, 2012)

Within this section, we review the potential of more abundant natural gas within Europe by utilizing four price sensitivity scenarios which have been formulated as decreases based on the 2010 price due

to additional supply. Before focusing upon the price sensitivity scenarios, it should be acknowledged that these price levels are not directly related to certain levels of increased shale gas production or the expansion of LNG imports. Nonetheless, the changes of prices analyzed in this section could be consistent with expanded supply of natural gas induced by more shale gas in Europe or LNG imports.

Figure 14 presents the four price scenarios which have been implemented within the Pledge and Pledge+ scenarios to reflect more abundant gas within Europe. These price/gas abundance scenarios are composed of a decrease in the price of primary gas supply of approximately 15% (P1), 30% (P2), 50% (P3) and 70% (P4) in 2020, with respect to the 2010 level. In all cases where the lower price/more abundant gas is applied, the gas contraction seen in the Pledge scenario disappears irrespective of continued suppressed demand from low economic growth and the renewable target being in place.

With respect to the Pledge scenario without the price changed, Pledge_P1 has an increased utilization of gas of 12.55% (75 TWh) in 2020. Figure 15 presents this percentage change as the actual power generation share achieved by natural gas – approximately 17.5% in 2020 in comparison to 15.6% when there was no change in the price. Price levels P2, P3 and P4 are associated with natural gas power generation shares of 17.8%, 19.1% and 22.1%, respectively. As expected, removing the renewable target results in larger increases in natural gas and results in Pledge/NoRET_P1 having an increase in generation of 13.73% (81 TWh) or the achievement of a 19% power generation share. A policy consistent with the Pledge+ scenario shows similar natural gas power generation shares in comparison to the Pledge case with 17.7% (P1), 18.8% (P2), 19.1% (P3) and 21.6% (P4). The removal of the renewable target makes a sizable difference, with Pledge+/NoRET_P1 associated with a power generation share of 20.3%, increasing to 20.7% (P2), 22.0% (P3) and 24.7% (P4).

Focusing on the lowest price change, a decrease in the price of gas by 15% with respect to 2010, results in a change in power generation share of approximately 1.4-2.6 percentage points when the renewable target is removed (depending on whether the policy focused upon is Pledge or Pledge+).

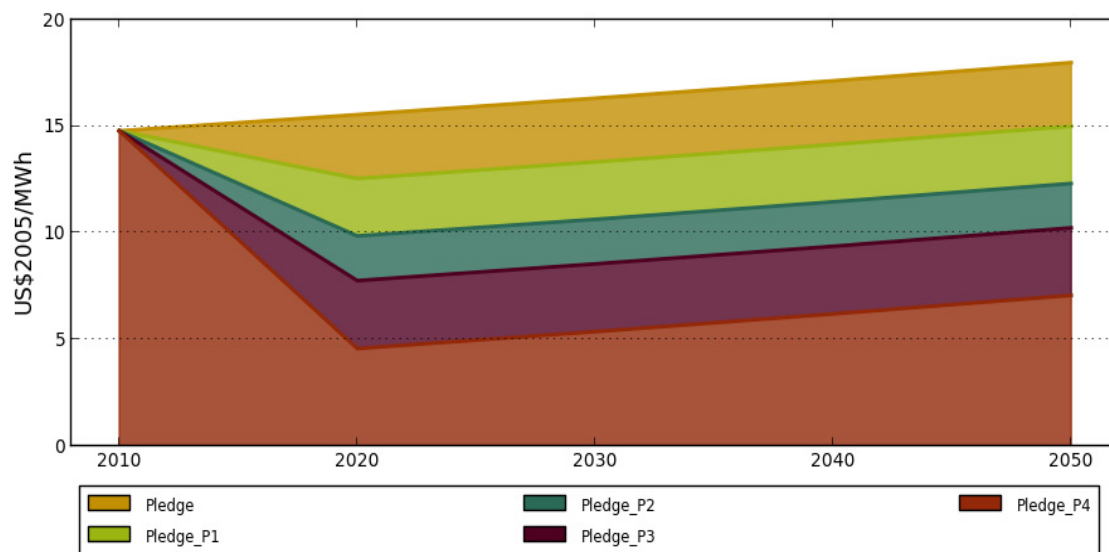


Figure 14. Price scenarios imposed (P1 to P4) in comparison to the gas price in the Pledge scenario

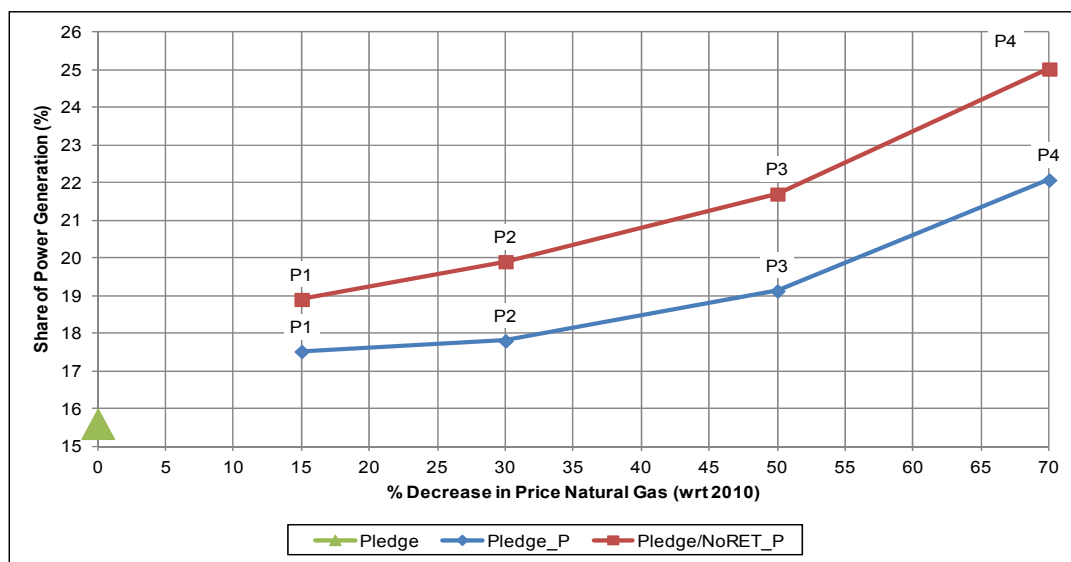


Figure 15. Share of power generation using gas in comparison to the percentage decrease in the price of natural gas

While the above discussion shows that changes in the energy mix do occur in response to the different natural gas price levels, an increase in the natural gas power generation share to a level above 18% in 2020 tends to occur when the renewable target is removed and the price of gas is decreased by 15% or greater (i.e. Pledge/NoRET_P1). Alternatively with the renewable target in place, the same only

occurs when the price of gas has decreased by almost 50% (i.e. Pledge_P3), hence the impact of the renewable target on the potential expansion of natural gas is shown to be significant.

Section 4 – Conclusions

This paper has used WITCH, an integrated assessment energy-economic model to assess a range of energy and climate policy scenarios, as a way to pin down the prospects for natural gas within the welfare-maximising energy mix in Europe for the next four decades. In doing so, it reviewed the role of natural gas within climate efforts, which include the Copenhagen Pledges and the EU Roadmap – with specific sensitivity analysis upon the role of the 2020 renewable targets and increased energy efficiency improvements.

Section 3.1 reviewed the implications for Europe by focusing on power generation shares and policy costs across a range of scenarios which were defined with section 2. Section 3.2 then focused on the achievement of a 2°C Durban Action policy with our results compared to those conducted using the PRIMES model, which accompanied the impact assessment of the EU 2050 Roadmap. Section 3.3 closed the analysis with a focus on the potential of more abundant natural gas within Europe and utilized four price sensitivity scenarios which have been formulated as decreases based on the 2010 price due to additional supply.

Having conducted this analysis we can now summarize the large body of results into three key points. The first is the importance of setting a suitable and sustained carbon price which ensures that the right incentives are given to energy markets so that the welfare-maximising energy mix can be achieved. This would also reduce the policy costs related to all of the climate policy targets reviewed within the analysis. The second point is that natural gas is very likely to be the key transitional fuel within the cost-effective achievement of a range of climate policy targets. And lastly, the importance of avoiding distortive policy instruments, e.g. subsidies, is highlighted. The next three sub-sections provide further detail on these points with respect to the analysis conducted within section 3.

4.1 Setting the right carbon price

Even a moderate and fragmented climate policy is sufficient to provide the appropriate incentives for re-aligning energy markets dynamics with climate objectives. This would require a carbon price of above 15 \$/tCO₂ which grows to 60-70 \$/tCO₂ over time. This can be achieved at moderate economic cost by a 2030 emission reduction target in the range of 25%-35%, and a 2050 target of 40-60% (all relative to 2005).

The 2050 Energy Roadmap (reduction targets of 60% in 2030 and 80% in 2050 which are consistent with a global objective of 2°C in 2100) would have a significantly higher economic impact (much higher GDP losses) than the fragmented carbon policy scenarios identified as Pledge and Pledge+, even with global action consistent with the Durban Action Platform. In light of the current levels of international effort and emission abatement within key economies, much more international coordination and/or carbon market integration worldwide is needed for emission targets to be both cost effective and in line with the results for the 2Deg scenario.¹ Our results show indeed that costs for Europe in the 2Deg scenarios would be too high in the absence of a fully coordinated global policy.

In relation to providing appropriate incentives for energy markets via a carbon price, it is important to note that modern renewables, such as solar and wind, are becoming competitive due to the existing targets and incentives. Modern renewables would continue to play an important role after 2020 as long as carbon prices are sufficiently high (e.g. 20-50\$/tCO₂) and this will occur even without additional incentives or subsidies.

Energy efficiency regulation could play an important role by reducing overall electricity demand: however, the policy design will matter with a notable impact in terms of policy costs, depending on whether it is implemented through improved intensity or reduced demand. Indeed, if the energy efficiency target is designed as a target on energy demand reduction (as done in the EU Energy Efficiency Directive), then costs and the demand for offsets are notably higher.

¹ Let us recall that a global carbon market would achieve the same outcomes in terms of emissions and costs as a fully and globally coordinated policy.

4.2 Gas as a transition technology

Due to slow growth in demand and the growing role of renewables which has been induced by the EU target and related incentives/subsidies, natural gas use in power generation is expected to slightly decline until 2020 (unless important changes in gas supply related to share gas production occur). The impact of the renewable target is notable, with no contraction in the share of natural gas occurring within the target is removed (the NoRET cases).

Irrespective of a decrease in the share of natural gas until 2020 due to the renewable target, the share of natural gas rises after 2020 and an increase in gas is consistent with the cost-effective achievement of a range of climate targets – refer to the discussion surrounding Figure 6 for further details. In other words, although natural gas's share falls through 2020, it will rise after 2020 if climate targets are to be met cost-effectively.

After 2020, both the Pledge and Pledge+ climate policies would induce an increase in gas consumption, while the use of coal decreases. After 2020, increases in gas consumption and a phase out of coal would be enhanced by promoting climate policies which sustain carbon prices above 15\$/tCO₂ and up to 50-70\$/tCO₂ in the following decades.

Gas demand would increase after 2020 in all simulated policy scenarios, including the 2Deg scenario through linkages to CCS. The growth of renewables is likely to slow down after 2020 due to limitations of system integration. This will enhance the role of gas as a transition fuel. However, to achieve the 2°C target a further development of renewables is required, even at high costs, which explains the high policy cost of the 2Deg scenario.

4.3 Policy instrument mix

Carbon prices in 2020 should be in the range of 10-15 \$/tCO₂ for standard policies, and 20-30 \$/tCO₂ if the supply of permits is tightened. The renewable target has been found to deflate the carbon price by about 10 \$/tCO₂, with negative consequences on climate friendly investments, business strategies and public revenues.

Subsidies and incentives to renewables are not needed beyond 2020, provided that the carbon price is sufficiently high (above 15-20 \$/tCO₂ and increasing over time). This would also have the co-benefit of increasing the potential revenues from issuing emission permits, with important implications for the stretched domestic public finances in many EU countries.

Hence a single instrument, carbon pricing, is preferable for post 2020 policymaking for a range of reasons: - it is effective in achieving the optimal energy mix, - it reduces emissions, - it contributes to improved public budgets, and - it avoids distortions in the market.

In order to avoid reductions of the carbon price that would undermine the effectiveness of the policy scenario just outlined, an active policy to monitor the supply of permits and therefore the carbon price is necessary (similar to, but more effective than, the recent backloading proposal of the European Commission and similarly to the role played by a central bank with respect to their mandate to monitor money supply and interest rates).

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Appendix

Specification of policy scenarios

This Appendix reviews the policy specific specifications of the climate policy scenarios utilised within this paper.

The definition of policies in the moderate and stepped up scenarios are in line with the AMPERE (<http://ampere-project.eu/web/>) and LIMITS (<http://www.feem-project.net/limits/>) projects, funded by the European Commission under the 7th framework programme.

For some countries, the carbon intensity or emissions reductions targets represent the lower end of their Copenhagen pledges. For other countries, plausibility considerations lead to the specification of emissions reductions targets that are weaker than their Copenhagen pledges. In cases where Copenhagen pledges appeared to be ambitious (mostly developing country emissions reductions relative to baseline), the level of stringency was halved. For the U.S., the 2020 reduction target was taken from an assessment of the impact of existing US regulations². Country targets were extrapolated to larger regions under the assumption that neighboring countries follow the regional leaders.

Moderate Policy

Fragmented moderate action on climate, with region specific policy objectives based on 2020 emission reduction targets, technology specific policies (e.g. renewables, nuclear) and post 2020 carbon intensity targets.

Regions can trade carbon offsets internationally (e.g. CDM type of project), but at most 20% of abatement can be attained on the market, and 80% has to be done domestically. For Europe, this entails the legislated 2020 targets (emissions, renewables and efficiency), and a post 2020 extrapolation of the climate policies, with a 2030 and 2050 target of 25% and 45% emissions reductions with respect to 2005 respectively.

Full details of emission targets and specific capacity settings for key regions are provided in the table below.

² Source: N. Bianco, F. Litz, Reducing Greenhouse Gas Emissions in the United States Using Existing Federal Authorities and State Action, Report World Resources Institute, 2010.

Region	Across the board GHG emissions reductions target in 2020 (relative to 2005 ³ or no policy baseline (BAU) as specified in brackets; use your model baseline in the latter case; excl. LULUCF if not indicated differently)	Carbon intensity reductions (relative to 2005. Intensity improvements measured relative to GDP PPP scenario.)	Modern Renewable share (incl. hydro, excl. non-commercialized biomass) (Reference quantity PE, FE, or electricity in brackets. Targets formulated in terms of PE shares of renewable energy are calculated using the substitution method.)	Installed renewable energy capacity (Capacity targets are minimum levels; target year in brackets)	Installed nuclear power capacity (Capacity targets are minimum levels; target year in brackets)	Average GHG emissions intensity improvements after 2020 (% / year; Kyoto GHG equivalent emissions excluding LULUCF. Intensity improvements measured relative to GDP PPP scenario.)
EU27	-15% (2005)	N/A	20% (of Final Energy, by 2020) Also the Energy Efficiency target of 20% reduction in primary energy consumption by 2020	-	A gradual reduction in nuclear capacity (from 120GW to 100GW in 2030, 70GW in 2050)	Emissions reduction targets of 25% in 2030 and 45% in 2050 wrt to 2005 (compatible with GHG emission intensity improvement of about 3% per year)
CHN	N/A	-40%	15% (of Primary Energy, by 2020)	Wind: 100 GW (grid connected, 5GW off shore); Solar PV: 10GW; Hydro: 270 GW (all by 2015)	41 GW (2020)	3.3%
IND	N/A	-20%	-	Wind: 20 GW; Solar: 10 GW; Small hydro: 3.25 GW, Biopower: 3.75 GW (all by 2022)	20 GW (2020)	3.3%
JPN	-11% (2005)	N/A	-	Wind: 5 GW; Solar: 28 GW (all by 2020)	N/A	2.2%
USA	-5% (2005)	N/A	13% (of electricity production, by 2020);	-	N/A	2.5%
RUS	+27% (2005) ⁴	N/A	2.5% (of electricity production, by 2015); 4.5% (of electricity production, by 2020)	-	34 GW (2030)	2.6%

³ Source GHG emissions: European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2.

<http://edgar.jrc.ec.europa.eu>, 2011

⁴ Including LULUCF

AUNZ	-13% (2005)	N/A	10% (of electricity production, by 2020)	-	N/A	3%
BRA	-18% (BAU) ⁵	N/A	-	Wind: 1.805 GW (by 2020) (Use only as calibration)	N/A	2.7%
MEX	-15% (BAU) ⁶	N/A	17% (of electricity production, by 2024)	-	N/A	2.8%
LAM	-15% (BAU) ⁷	N/A	8% (of electricity production, by 2016);	-	N/A	2.1%
CAS	+25% (2005)	N/A	N/A	N/A	N/A	2.6%
KOR	-15% (BAU)	N/A	3% (of Primary Energy, by 2020)	Wind: 8 GW (by 2022)	N/A	3.3%
IDN	-13% (BAU) ⁸	N/A	7.5% (of electricity production, by 2025)	-	N/A	2.1%
SSA	N/A	N/A	20% (of Primary Energy, by 2020); 2.5% (of electricity production, by 2020)	-	N/A	2.3%
CAN	-5% (2005)	N/A	13% (of electricity production, by 2020)	-	N/A	2.4%
EEU	+64% (2005)	N/A	N/A	N/A	N/A	2.6%
EFTA	-21% (2005)	N/A	24% (of Primary Energy, by 2020)	-	N/A	3.7%
MEA	-10% (BAU)	N/A	15% (of Primary Energy, by 2020); 5% (of electricity production, by 2020)	-	N/A	3.5%
NAF	N/A	N/A	20% (of electricity production, by 2020)	-	N/A	3.5%
PAK	N/A	N/A	10% (of electricity production, by 2012)	-	N/A	1.9%
SAF	-17% (BAU)	N/A	N/A	N/A	N/A	2.8%
SAS	N/A	N/A	10% (of electricity production, by 2020)	-	N/A	2.9%
SEA	N/A	N/A	15% (of electricity production, by 2020)	-	N/A	2.1%
TUR	N/A	N/A	-	Wind: 20 GW (by 2023); Solar 0.6 GW	N/A	2.3%

⁵ Including LULUCF

⁶ Including LULUCF

⁷ Including LULUCF

⁸ Including LULUCF

				(by 2013); Geothermal 0.6 GW (by 2013)		
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Stepped up Policy

Level of policy ambition is stepped up in 2020 and beyond across all regions.

For Europe, this means tightening the supply of emission permits to 2020 (or equivalently, raising the ambition of emissions reductions in 2020 to 30% wrt to 1990). For 2030 and 2050, this implies emission reductions would be 37% and 60% wrt 2005 respectively.

Full details of emission targets and specific capacity settings for key regions are provided in the table below.

Region	Across the board GHG emissions reductions target in 2020 (relative to 2005 ⁹ or no policy baseline (BAU) as specified in brackets; use your model baseline in the latter case; excl. LULUCF if not indicated differently)	Carbon intensity reductions (relative to 2005. Intensity improvements measured relative to GDP PPP scenario.)	Modern Renewable share (incl. hydro, excl. non-commercialized biomass) (Reference quantity PE, FE, or electricity in brackets. Targets formulated in terms of PE shares of renewable energy are calculated using the substitution method.)	Installed renewable energy capacity (Capacity targets are minimum levels; target year in brackets)	Installed nuclear power capacity (Capacity targets are minimum levels; target year in brackets)	Average GHG emissions intensity improvements after 2020 (% / year; Kyoto GHG equivalent emissions excluding LULUCF. Intensity improvements measured relative to GDP PPP scenario.)
EU27	-25% (2005)	N/A	20% (of Final Energy, by 2020). Also the Energy Efficiency target of 20% reduction in primary energy consumption by 2020	-	A gradual reduction in nuclear capacity (from 120GW to 100GW in 2030, 70GW in 2050)	Emissions reduction targets of 37% in 2030 and 60% in 2050 wrt to 2005 (compatible with GHG emission intensity improvement of about 3.6% per year)
CHN	N/A	-45%	25% (by 2020)	Wind: 300 GW. Solar	80 GW (2020)	3.9%

⁹ Source GHG emissions: European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. <http://edgar.jrc.ec.europa.eu>, 2011

				PV: 80 GW (all by 2020)		
IND	N/A	-25%	-	Wind: 40 GW; Solar: 20 GW; (all by 2020s)	20 GW (2020)	3.5%
JPN	-12% (2005)	N/A	-	Wind: 5 GW; Solar: 28 GW (all by 2020))	N/A	2.5%
USA	-17%	N/A	25% (by 2020);	-	N/A	3%
RUS	+12% (2005) ¹⁰	N/A	4.5% (by 2020)	-	44 GW (2030)	3.4%
AUNZ	-22% (2005)	N/A	20% (by 2020)	-	N/A	3.6%
BRA	-36% (BAU) ¹¹	N/A	-	Wind: 1.805 GW (by 2020) (Use only as calibration)	N/A	3.7%
MEX	-30% (BAU) ¹²	N/A	35% (by 2020)	-	N/A	4%
LAM	-30% (BAU) ¹³	N/A	35% (by 2020)	-	N/A	3.3%
CAS	N/A	N/A		N/A	N/A	3.4%
KOR	-30% (BAU)	N/A		Wind: 16 GW (by 2020 ₁₁)	N/A	3.9%
IDN	-26% (BAU) ¹⁴	N/A	15% (of electricity production, by	-	N/A	3.3%

¹⁰ Including LULUCF

¹¹ Including LULUCF

¹² Including LULUCF

¹³ Including LULUCF

¹⁴ Including LULUCF

			2025)			
SSA	N/A	N/A		-	N/A	2.7%
CAN	-17% (2005)	N/A	25% (of electricity production, by 2020)	-	N/A	3.3%
EEU	N/A	N/A		N/A	N/A	3.4%
EFTA	N/A	N/A		-	N/A	3.6%
MEA	N/A	N/A		-	N/A	2.0%
NAF	N/A	N/A	20% (by 2020)	-	N/A	2.0%
PAK	N/A	N/A		-	N/A	2.9%
SAF	-34% (BAU)	N/A		N/A	N/A	3.6%
SAS	N/A	N/A		-	N/A	3.3%
SEA	N/A	N/A	15% (by 2020)	-	N/A	3.3%
TUR	N/A	N/A	-	20 GW wind by 2020	N/A	3.6%

Two Degree Policy Scenario

The Durban Action Platform delivers a binding international climate treaty entering into force in 2025 with the aim of maintaining the global temperature increase below 2C in 2100 with sufficiently high probability. This policy is consistent with the UNFCCC objective of stabilizing GHG concentrations at a level which prevents dangerous interference with the climate system.

Emission targets are calculated by the WITCH model assuming that the probability to exceed 2C over the century has to be lower than 30-40%. Formally, this is imposed a constraint on CO2 concentrations at around 450 ppm-eq in 2100. The target can be exceeded before 2100. Global cooperation is imposed from 2025 onwards, and till then everything is equivalent to the moderate policy.