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Biomass Energy with Carbon Capture and Storage can reduce costs of EU's Energy Roadmap with 15-75%

Background document to CPB Policy Brief 2017/02

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1 Introduction[2]

At the UN climate change conference in Paris in 2015, world leaders reconfirmed that the increase of the global mean temperature compared to pre-industrial level should be limited to 2°C. In order to achieve this ambition, GreenHouse Gas (GHG) emissions need to decline by 2050 by 40-70%, compared to 2010 levels. Well-known mitigation options include wind-energy, solar-PV, energy savings technologies, and electrification of transport. Biomass may also play an important role in GHG abatement.

Biomass is already an important energy source. On the global level, with a share of 10% and 50EJ, it is the fourth most important source after oil, coal and natural gas, which includes enormous diversity in use. In developing countries, biomass is mainly used for domestic heating, lighting and cooking. In 2008, this traditional use of biomass, mainly in the form of wood, straw and manure, comprised around 80% of its total global use. The remaining 20% is made up of more industrial and modern uses of biomass. Modern uses typically involve conversion to make the combustion process more efficient. Examples include cars running on biodiesel from rapeseed and heating using biogas from manure and waste.

Global demand for biomass is expected to increase due to climate policy, because in many cases it is the only available zero-carbon option. Aeroplanes can fly on biofuel, but because of battery weight, not on electricity. Battery weight also limits the use of electricity as a fuel in heavy transport. Furthermore, biomass is the primary zero-carbon substitute for oil in the chemical industry. In total, projections of annual biomass demand for 2050 vary from 70 to 190 EJ, and may even be as high as 300 EJ.[1]

The EU also expects climate policy to induce a greater use of biomass. For example, in its Impact Assessment in support of its Energy Roadmap 2050, the European Commission (EC) projects the total use of biomass in Europe to increase from 5 EJ in 2010 to around 11 EJ by 2050.[3] Notably, the EC also predicts a threefold increase in biofuel use by 2050. Also at the global level a substantial amount of biomass for BECCS is necessary to keep the global mean temperature limited to 2°C (Turkenburg et al., 2016).

The large increase in biomass demand in Europe and other parts of the world could have negative impacts on food production or induce further deforestation. Although estimates of the sustainable biomass potential are uncertain, for 2050 a sustainable production of 150 EJ seems to be feasible.[4] At this production level the consequences for both food supply and forests will be limited.

If Europe were to apply biomass in power plants, would the advantages of doing so outweigh the disadvantages? Should power plants use CCS technology, thus creating the possibility of

[2] This section describes how the figures in Aalbers and Bollen (2017) are derived from model simulations presented here.
[3] EC (2011).
[4] IPCC (2011) and PBL (2012).

negative emissions? The answers hopefully contribute to the discussion on biomass. Next to the direct economic effects, the analysis here also considers possible negative impacts on the availability of resources for the chemical industry, the use of fossil fuels, air pollution, and assesses impacts on deforestation and food production.

This paper is organized as follows. We start by explaining the main elements of the MERGE-model used for our analysis. Next, we describe the scenarios that we designed to illustrate the size and the origin of the economic impacts of using BECCS. Then, we start the results section to analyze the changes of using BECCS on energy markets and the economy. Finally, we conclude the results section on discussing some indirect impacts of using biomass for BECCS, i.e. air pollution, food supply, availability of biomass for the chemical industry, and public safety.

2 MERGE-CPB

Our starting point is the MERGE model as applied and described in Blanford et al. (2015). MERGE represents the economy by a nested production function of capital, labor, and energy, with consumption defined as an aggregate of macro consumption and passenger vehicle services.

A bottom-up representation is used for the energy-supply sector, in which choices are made among specific activities for the generation of electricity and for the production of non-electric energy, including an option to produce electricity from bioenergy with carbon capture and storage (BECCS), thereby creating a negative emissions flow.

The cost of abatement of non-CO2 and non-energy-related emissions is handled by Marginal Abatement Cost Curves (MACC).[5,6] The model's time horizon extends to 2200, although the focus in this paper is on results in this century and in particular on the transition up till 2050. The regions of the model are Europe (covering EU27 plus EFTA countries), USA, Other OECD, China, and Rest of World (ROW).

Modeling Electricity

Outside Europe, MERGE assumes a conventional linear process model in which technologies are characterized by levelized costs and the production mix is subject to limits on expansion and decline rates and other share constraints.[7] But for Europe, a reduced-form capacity and dispatch formulation is used. Instead of specifying, for technology *i* in region *r* in year *t*, one decision variable for total electric energy supplied, MERGE specifies for each technology *i* one variable for installed electric capacity and a separate set of variables for dispatch of installed capacity to meet demand for electricity in twenty segments of approximately 5% of

[5] The MACC is a function that relates emission abatement to marginal cost of abatement.
[6] The accumulation of gases in the atmosphere and the subsequent effects on radiative forcing and temperature are described in a simple climate module. This part of the model is not used in this paper.
[7] Levelized costs is defined as the costs to install a technology divided by its expected life-time energy output.

timespan of a year and one peak-segment. For more details, we refer to Blanford et al. (2015).

For the European region the model tracks the variation of electricity demand both diurnally and seasonally, which - given the relatively high cost of electricity storage - is a fundamental driver of the economics of power generation investments.

Electricity is generated in MERGE by several fossil technologies (with or without CCS), by nuclear power, or by renewable energy technologies. On renewable energy, the model distinguishes biomass (with or without CCS), solar, and wind. There are three classes of wind: one series describing standard continental European on-shore wind, one for premium on-shore locations bordering the North Sea, and one for off-shore locations in both the North Sea and Baltic Sea. We consider a single solar series, based mainly on Southern European weather characteristics. Table 2.1 summarizes our default assumptions for electric generation technologies within the European section of MERGE, which are based on (though not identical to) assumptions in the World Energy Outlook (IEA, 2012). Levelized electricity production costs for other regions are based on these figures. [8]

Table 2.1 Default Scenario Technology Capital Cost Assumptions ($/kW)

	2020	2030	2040	2050+
Coal (Pulverized)	$2,100	$2,100	$2,100	$2,100
Coal Integr. Gasification Comb. Cycle (IGCC)	$2,400	$2,300	$2,200	$2,200
Coal+CCS (IGCC+CCS)	$3,500	$3,000	$2,700	$2,700
Gas Single Cycle	$625	$625	$625	$625
Natural Gas Combined Cycle (NGCC)	$900	$900	$900	$900
NGCC with CCS	$1,620	$1,500	$1,350	$1,350
Nuclear (Gen III)	$4,000	$4,000	$4,000	$4,000
Nuclear (Gen IV)	N/A	N/A	N/A	$5,600
Biomass	$2,300	$2,200	$2,100	$2,100
Biomass with CCS[9]	$3,400	$3,200	$3,000	$3,000
Wind On-shore[10]	$1,700	$1,700	$1,700	$1,700
Wind Off-shore	$2,500	$2,200	$2,100	$2,000
Solar PV	$2,000	$1,600	$1,200	$1,000
Note: costs are expressed in year 2005 USD.				

Recent developments indicate that our cost assumptions on wind-energy and solar are somewhat outdated, so we ran our main scenarios also with costs assumptions of $1500 for all types of wind energy.[11] But this confirms again Blanford et al. (2015), which showed that the share of onshore and offshore wind-energy is stable over a wide range of cost

[8] A 4.5% discount rate leads for `Wind Off-shore` to a price of 6 ct/kWh.
[9] The negative carbon emissions of BECCS arises as biomass production extracts carbon from the atmosphere, while the embedded CO2 in the biomass used in the plant is not released back to the atmosphere, but captured and stored in a reservoir. Thus, the net emissions of BECCS are negative. The emission coefficient (tCO2 per kWh delivered) of BECCS is negative. The carbon emission coefficient is, for example, 250% lower than the coefficient for pulverized coal-fired power plants. For comparison, biomass-fired power plants without CCS have a zero emission coefficient, which is 100% lower than emission coefficient of pulverized coal-fired power plants. Alternatively, biomass can be used for liquid fuel blending, but then carbon emissions from the burning process in small mobile sources are not captured, and add again to the carbon stock in the atmosphere. Thus, the use of biomass as biofuels has a zero impact on emissions.
[10] Off-shore wind comes with a cost premium for both initial investment and ongoing maintenance and a shorter lifetime. Integration costs of renewable energy reaches $15/MWh at high penetration levels.
[11] Results of these simulations can be sent upon request.

assumptions of technologies, suggesting that variable renewable technologies mainly compete with other variable renewable technologies and to a much lesser extent with controllable technologies.[12] Thus, for the electricity sector a well-composed mix of both variable renewable and controllable production technologies appears to be the most efficient way of reducing emissions within the electricity sector. In the end, it is not the cost of a technology that determines its' importance, but the value it can generate in the entire energy system. For example, although solar-pv will become much cheaper in terms of costs, and it could even become one of the cheaper technologies in the long run. Still, Blanford et al. (2015) show that solar-pv's economic value will be limited in Europe. The reason is that storage related solar-pv makes it less favorable to other clean technologies, because storage is necessary as little electricity can be produced by solar in the winter to meet demand in that same period.

Modeling Hydrogen (only Europe)

This version of MERGE also - for the EU - integrates hydrogen production with electricity generation. There are five conversion technologies for hydrogen: coal gasification with and without CCS, natural gas steam-reforming with and without CCS, and electrolysis. These technologies have two close links with electricity production. First, the coal-gasification plant can achieve a higher capacity factor by also producing hydrogen when the price of electricity falls below its dispatch cost. The second link is that the model chooses the segments to use electricity for the production of hydrogen and weighs capital costs against the endogenous capacity factor of the electrolysis plant.

Hydrogen can either be used in the non-electric sector to offset liquids and gas or as a fuel in passenger transportation. To reflect infrastructure needs, expansion constraints are placed on the penetration of hydrogen as an end-use fuel and a cost premium is added for non-electric use. Additionally, we assume that it cannot supply more than half of non-electric, non-passenger-transport energy demand.

Defining ETS and non-ETS (only Europe)

The current setup of MERGE distinguishes electricity, non-electricity, small transport, and other emissions. Although the emissions simulated by MERGE cover all sources, the model does not explicitly cover the ETS sector. To be able to closely match EU climate policy, we map each emission source in MERGE-CPB to either the ETS or the non-ETS sector.

Related to this mapping procedure it is important to realize that ETS includes electricity generators, energy-intensive industries, and aviation, see EEA (2015). Calculations show that for the year 2010 that 58% of the direct coal use represents the demand by energy-intensive industries and 13% of total liquid demand the energy use of aviation sector. For future years we take the electricity related emissions and add emissions related to the direct use of coal and total liquid demand multiplied by the shares as derived for the year 2010. The non-ETS emissions for future years are calculated as the sum of the emissions from the transport sector plus 42% of the emissions of direct coal use and 87% of emissions of liquid fuel

[12] For Solar PV a similar line of reasoning applies, and the maximal market share we observed was 7% from a simulation in which the investment cost of Solar-PV was $500 per kW by 2050.

demand plus emissions related to all other non-electric energy use. This enables MERGE to closely simulate the ETS and non-ETS emissions for future years.

Finally, we allow for banking of emission allowances in both the ETS and non-ETS sector in Europe.[13] As a result, emissions in any particular year need not be equal to the number of issued emission allowances. In particular, emission allowances may be saved in early years to be consumed in later years to avoid high costs of abatement in subsequent years. In this way, we connect to Hotelling's rule which states that the optimal extraction path of a non-renewable resource (the carbon budget) is one along which the price of the resource (the CO_2-price) increases at the rate of interest (Hotelling, 1931).

3 Scenarios

We want to understand both the size and the origin of BECCS' economic advantages, and under which polices these advantages are realized. To that end, we introduce two scenarios, "Road" and "Integrated Carbon Markets (ICM)". The "Road" scenario captures the main features of current EU climate policy. In this scenario, the EU carbon market is split in two submarkets, the ETS and the non-ETS. The ETS emissions follow the trajectory as described in the EU energy Roadmap (see EC, 2011a), so the allowances in ETS are in 2050 equal to 35% of the total EU-cap on carbon.[14] The cap in non-ETS is equal to the total EU cap on emissions minus ETS allowances. Consequently, (future) carbon prices in the ETS and non-ETS may diverge. In addition, in line with the ETS directive, BECCS is not rewarded for producing negative emissions. This directive states that companies do not have to hand in any emission allowances if they capture and store CO_2. Unfortunately, this emission-trade exemption does not reward BECCS for capturing and storing CO2, as the use of biomass, in contrast to that of fossil fuel, is already exempt from the emission trade.

On the other hand, the "ICM" scenario assumes that there is a single EU carbon market. Small emitters, such as households and small business companies, could either participate directly and trade themselves or could indirectly be 'represented' by their energy suppliers, such as distribution companies and refineries. The latter option has the advantage of limiting transaction costs (Koutstaal, 1996). In addition, in this scenario, the ETS directive is amended such that negative emission technologies are rewarded for producing negative emissions, thus establishing a level-playing field between mitigation options. Initially, for both scenarios we assume that imports of biomass into the EU are not allowed, an assumption that we will relax later on. This assumption enables us to disentangle the advantages of using biomass differently (by using BECCS) from the advantages of using more biomass (by increasing imports). It also addresses concerns about deforestation and lower food production in non-EU countries.

[13] Emissions allowances of the aviation sector are constant over time, while those of all other ETS operators annually reduce with 1,7% till 2020, and with 2.2% in the years after 2020.
[14] The EU emission allowances in 2050 are equal to either 80%, 85%, 90%, or 95% below the 1990 emission level.

By comparing the simulated GDP trajectories with the MERGE-model of the “ICM” and the “Road” scenarios, we get to understand the size of the macro-economic GDP gain from using BECCS. Recall that the “ICM” scenario assumes negative emission contributions by BECCS are rewarded and that there will be a uniform carbon price or integration of the ETS and non-ETS carbon markets. Contrary, the “Road” scenario assumes that BECCS negative emissions are not rewarded and that there is no integration of the two carbon markets. Also, we will better understand the origin of the gains by analyzing the outcomes for specific variables of the “ICM and “Road” scenarios. The most relevant variables are emissions, emission prices in both ETS and non-ETS, the use of electricity generation technologies, and fuels consumed for non-electric energy.

Table 3.1 Climate Policy Scenarios

Name	Label	Description
Business-As-Usual	BAU	No Climate Policy
Roadmap	Road	EU Roadmap; BECCS not eligible to receive emission allowances
Integrated Carbon Market	ICM	BECCS eligible to receive emission allowances

Note: Emission allowances in 2050 in all scenarios are 80, 85, 90, or 95% lower than the emissions in 1990.[15]

The mitigation costs also depend on the prices of biomass. For example, a cap on biomass production will make biomass as one of the ingredients for liquid fuels for transport or for BECCS more expensive. And if biomass becomes more expensive, then this also holds for abatement. Regarding biomass supply, we assume that the sustainable production of biomass is capped at 150 EJ per year (see PBL, 2012). In the EU, the production of sustainable biomass is capped by the demand for biomass in the Business-As-Usual (BAU), which is equal to 9.6 EJ per year. For comparison, in EU (2016) the total demand for biomass increases up to around 11 EJ per year in 2050.

Another crucial set of variables to understand the size of the mitigation costs are carbon prices in the rest-of-the-world (ROW) and international fuel supply prices. For example, a high level of the oil price makes it easier to substitute away from oil. In MERGE, the supply price of coal is constant as its supply is unlimited, while oil and gas supply prices increase as producers move from cheaper to more expensive “varieties” of gas and oil.[16] At the same time, carbon prices and energy prices interact with each other. For example, high carbon prices lower the global oil supply price. We assume carbon policies in the rest of the world generate a similar carbon price in the rest-of-the world as for Europe. Outside Europe, the emissions are fixed to the level as simulated in a scenario with a long-run target for atmospheric GHG concentrations of 550 ppm CO2 and a uniform carbon price in the world.[17]

[15] As we move to more stringent emission reduction schemes in Europe, we also increase in those cases the emission reductions in the rest of the world. The percentage reduction from 80% to 95% reduces the cumulative budget in the rest of the world with 1-(100-95)/(100-80)% = 75%.

[16] The cost of using non-crop biomass is constant, while crop-based-biomass is derived from a quadratic demand function.

[17] Switching from an 80% emission reduction in Europe to a 95% emission reduction also leads to an extra emission reduction in ROW. The extra emissions reduction in 2050 in ROW in the 95% case is 5%. In this way, the marginal abatement cost difference in the “ICM” scenarios from 2050 onwards between Europe and ROW is kept to a minimum.

4 ETS reform lowers costs

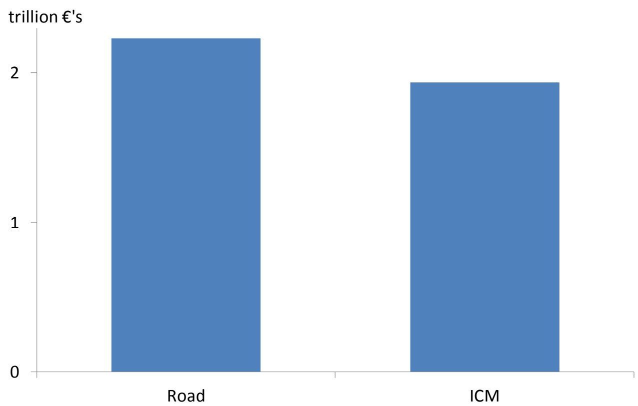
Section 4.1 illustrates the main point of the efficiency gains of the EU Energy Roadmap for the 80% emission reduction target when using BECCS. The negative emissions of BECCS alleviate the burden of expensive abatement options outside the ETS, which is illustrated to be more pronounced for emission reductions of 95%. Also is explained how much BECCS capacity is needed and how this affects electricity and non-electricity energy markets.

Section 4.2 argues that the substitution of bio-energy from non-ETS (biofuel blending of oil) to ETS (BECCS) generates efficiency gains of the EU energy Road map, and hardly impacts food prices or unsustainable land-use changes elsewhere in world. Also, this substitution leads to more fossil energy use in the non-ETS sectors, thus increasing air pollution. However, the deterioration of air pollution can be easily reduced by spending a small part of the economic gains of this substitution to catalytic filters.

4.1 ETS reform can avoid high-cost carbon measures in non-ETS

We now start with trying to understand the size of the efficiency gains of BECCS. The GDP gain is summarized in Figure 4.1, which compares the total discounted GDP losses in the EU till 2050 of the two policy scenarios: "Road" and "ICM".[18]

Figure 4.1 Discounted Abatement Costs (in trillions) in 80% case in two climate policy scenarios



Source: MERGE simulations.

The climate policy costs in the "ICM" scenario can be seen to be lower than in the "Road" scenario by an amount of 273 bn euros according to the MERGE model. Intuitively, climate policy costs decline as BECCS' negative emissions enable the EU to defer some of the

[18] GDP losses are compared to the GDP of a scenario without any climate policy. The average discount rate is 3%.

expensive carbon mitigation options while sticking to the climate budget of the 80% emission reduction case.[19]

To better understand where this cost reduction comes from, Table 4.1 contains a detailed break-down of the contributing factors. Firstly, there are variables like the emissions in the BAU, and in the climate policy scenarios "Road" and "ICM". Secondly, there are variables explaining the discounted cost numbers, which are derived from estimating the yearly costs from the surface below a MACC, which can be approximated from the simulated data in the climate policy scenarios. For more details on the formulas used, we refer to Appendix A. Finally, there are variables transforming yearly costs to approximate the discounted costs of climate policy scenarios. These latter discounted costs turn out to be close to the simulated MERGE numbers for GDP.

Table 4.1 **Comparing direct costs and GDP losses till 2050**

	Levels									Changes (ICM – Road)			
	Emissions in Gt CO_2						Prices $/t$CO_2$			Emissions in Gt CO_2		Prices in $/t$CO_2$	
	BAU		ROAD		ICM		Road		ICM				
	ETS	NETS[1]	ETS	NETS	ETS	NETS	ETS	NETS		ETS	NETS	ETS	NETS
2020	0,64	0,81	0,34	0,70	0,43	0,73	31	90	38	0,09	0,03	8	-52
2030	0,95	0,70	0,16	0,50	0,25	0,58	48	143	61	0,09	0,08	12	-82
2040	1,18	0,64	0,16	0,30	-0,01	0,49	75	222	94	-0,16	0,19	19	-127
2050	1,53	0,68	0,10	0,20	-0,06	0,51	114	337	144	-0,16	0,32	29	-194

Changes in Cost (ICM – Road)

	Yearly in bn €		over 10 years in bn €[4]					bn €		
	ETS[2]	NETS[3]	Period	ETS	NETS	Sum	DF[5]	Discounted	Period	Cumulated
2020	-0,6	-2,4	2010-2020	-3	-12	-15	0,87	-13	2010-2020	-13
2030	2,2	-9,2	2020-2030	8	-58	-50	0,67	-34	2010-2030	-47
2040	17,6	-32,5	2030-2040	99	-209	-109	0,51	-58	2010-2040	-105
2050	32,4	-84,0	2040-2050	250	-582	-332	0,39	-134	2010-2050	-239

Note: [1] NETS = non-ETS
[2] Yearly costs are equal to $P_{ICM}*(EM_{BAU} - EM_{ICM})/2 - P_{ROAD}*(EM_{BAU} - EM_{ROAD})/2$, see Appendix A illustrating this formula
[3] Yearly costs are equal to $P_{ROAD}*(EM_{ICM} - EM_{ROAD}) + (P_{ICM}-P_{ROAD})*(EM_{ICM} - EM_{ROAD})/2$, see Appendix A illustrating this formula
[4] 10 years costs are equal to $(Costs + Costs_{-1})/2*10$
[5] DF = $(2-(1+mpc)/(1+g))$^10 $*DF_{-1}$.[20] For 2010-2050, the average annual discount factor approximates 3%

[19] There are little economic gains involved when BECCS operators can only trade emission allowances with other ETS operators (thus no trading in emission rights between ETS and non-ETS operators). The reason is that BECCS cannot compete with, for example, wind-energy in ETS, but it can with many expensive abatement technologies in non-ETS.
[20] With g the growth of the economy, mpc the marginal productivity of capital, and $DF_{2015}=1$;

The BAU we employ here characterizes EU's emissions and energy trends. The ETS emissions increase from 0,6 Gt C in 2020 to 1,5 Gt C in 2050, while the non-ETS emissions rise till 2030 but stabilize beyond 2030 at around 0,7 Gt C.[21] Emissions of the "Road" scenario decline steadily in non-ETS and rapidly in the ETS, hence the overall emissions decline rapidly till 2030 and more moderately in 2030-2050. The "Road" scenario is an early abatement scenario because of banking.

Contrary to the "Road" scenario, we see in the "ICM" scenario that ETS postpones early (costs of) abatement. Recall that the "ICM" scenario assumes one binding carbon budget applicable to the entire EU economy instead of two separate carbon budgets to the ETS and the non-ETS sectors. The negative ETS emissions induced by employing BECCS allows to more than double the non-ETS emissions in 2050 compared to the "Road" scenario, which makes very expensive abatement in non-ETS redundant.

The findings on emissions are also confirmed by the emission prices. The carbon price in ETS in the "Road" scenario equals 31 €/tCO2 in 2020 and rises to 114 €/tCO2 in 2050.[22] The relatively high level of 31 €/tCO2 in 2020 confirms the above mentioned early action and banking. Likewise, the non-ETS carbon price in the "Road" scenario already starts at a relatively high level 90 €/tCO2 in 2020, while it increases to 337 €/tCO2 in 2050. So, the difference between the ETS and the non-ETS price in "Road" widens over time. The reason is that mitigation is (increasingly) scarce and expensive in non-ETS.[23] In the "ICM" scenario, the carbon price is uniform in all sectors by assumption. The uniform carbon price of the "ICM" scenario is higher than the ETS price of the "Road" scenario and lower than the non-ETS price of the "Road" scenario, because from all abatement options in ETS, BECCS is a relatively expensive abatement option, but it is much cheaper than the even more expensive abatement options in the non-ETS sector.[24]

The economic gains from BECCS depend on the changes in emissions and emission prices in ETS and non-ETS in the two policy scenarios. The direct annual change in yearly costs can be estimated for the "ICM" compared to the "Road" scenario, and is measured by the surfaces below a MACC. Appendix A explains in more details how these differences in yearly costs are calculated. These yearly cost differences are transformed to decadal costs, which can be discounted and accumulated over the entire 2020-2050 period.

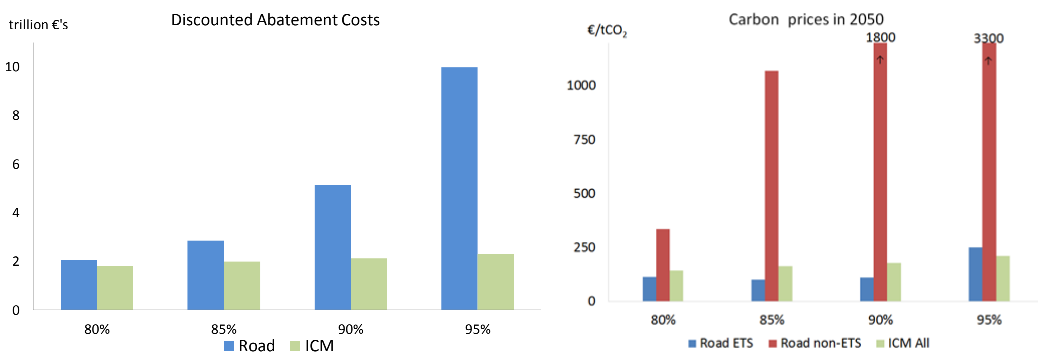
So for ETS, we can see in 2020 in the "ICM" scenario that the costs decrease with 0.6 bn €, while after 2020 the costs increase to 32 bn € per year in 2050. Likewise, we see that the

[21] The simulated BAU emissions are based on a 'no climate policy' scenario that serves as a regional benchmark when measuring the costs of carbon abatement in a climate policy scenario (Blanford et al., 2015). It makes the regional cost estimates comparable as opposed to BAU's including region-specific climate ambitions or current policy plans.
[22] All CO_2 prices in this paper are based on the HCIP inflation index, converted into 2015 prices.
[23] Non-ETS mitigation is limited to biofuel-blending, fuel switching, CCS, and energy savings. On the other end, in ETS there are much more large-scale (near)-zero-carbon producing cheaper technologies such as wind-energy, biomass, solar-energy, and fossil-fuel based power plants with CCS.
[24] A sensitivity case to the "ICM" scenario confirms that BECCS is the abatement option to compete with non-ETS abatement measures. The sensitivity case does not grant BECCS negative emissions. Not surprisingly, the reallocation of resources compared to the "Road" scenario is very modest, and hence the uniform carbon price is only slightly lower than the non-ETS price of the "Road" scenario. The reason for the modest change is that ETS emissions in the "Road" scenario are almost zero by 2050, and therefore only little additional abatement is feasible.

abatement costs in non-ETS in 2050 decline to 84 bn € per year. The next three columns show the decadal costs for ETS and non-ETS and the sum of the two sectors. It can be seen that for the entire 2040-2050 period the cost reductions are equal to 332 bn €, which translates to a discounted flow of 134 bn €. The accumulated discounted gain accrues to 239 bn €, which is slightly lower than the accumulated GDP gains of 273 bn € simulated by MERGE (Figure 4.1).

We continue with the simulated GDP results of MERGE. The advantage of BECCS becomes much greater at more ambitious targets, because those targets require much more (expensive) measures in the "Road" scenario. The carbon price in non-ETS in the "Road" scenario can be seen to increase to 1000 €/tCO_2eq. in the 85% case and more than 1800 €/tCO_2eq. in the stricter cases (right-panel of Figure 2). BECCS allows to avoid these more expensive non-ETS measures. The opportunity to avoid the really high long-term carbon prices at more ambitious emission targets of 85%, 90%, and 95% explains the much higher GDP gains of 1, 3, and 8 bn € (left panel of Figure 4.2). Finally, the ETS carbon prices in the "ICM" scenarios are only moderately affected by the stringency of the emission target.[25]

Figure 4.2 Discounted Abatement Costs (GDP in trillion €'s) and Carbon Prices (€/t CO_2) in 2050 in four emission reduction cases for two scenarios



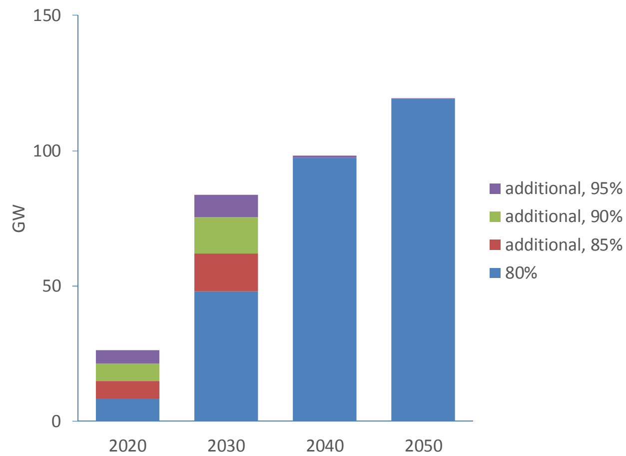
Source: MERGE simulations

The advantage of BECCS is much lower if there are two separate prices on the non-ETS and ETS carbon markets. If two separate carbon prices remain, then the economic gains from allowing the negative emissions of BECCS to be used only in ETS in the 80%, 85%, 90%, and 95% case are only a fraction of the earlier (standard) gain (less than 1%).[26]
However, if we want to realize the advantages of BECCS in the "ICM" scenario, it is important that investments in BECCS start immediately (Figure 4.3).[27] For example, in the 80% case, it

[25] The economy-wide carbon price in 2050 in the "ICM" scenario in the 95% case is 50% higher than in the 85% case. However, This price increase would be 14% higher in a scenario with trade in biomass for BECCS.
[26] The discounted GDP losses in the "Road" scenario are equal to 0.28% and 1,33% in the 80% and 95% case, respectively. In the "ICM" scenarios these losses decline to 0,24% and 0,31%. In the "ICM" variants in which we also restrict air pollution of the "Road" scenario as an upperbound, then the discounted GDP losses increase a little compared to the "ICM" scenario. These losses are equal 0,24% and 0,32% in the 80% case and the 95% case, respectively. Thus, these extra losses incurred from air pollution policy are less than 1% of the gain when switching from the "Road" scenario to the standard "ICM" scenario.
[27] This does not rely on whether or not there is trade in biomass for BECCS. Later we will show that the global demand for biomass declines. Partly this is driven by the argument that in Europe biofuels (lower emissions of fossil fuels in non-electric energy markets) become obsolete once it is reallocated to BECCS.

would require a European production capacity of close to 10 GW by 2020 and nearly 50 GW by 2030. And for a target of 95%, this would be 25 and 85 GW, respectively. In our simulations, BECCS' optimal capacity is independent of the emission target and increases to around 120 GW by 2050.[28]

Figure 4.3 BECCS capacity investments in four emission reduction variants in the "ICM" scenario



Source: MERGE simulations

Investments in BECCS are needed in 2020 and 2030, because it will take some time for the infrastructure around those plants to be completed. This, for example, concerns the local supply of biomass, the time required to obtain permits, construction of the plants, development of local expertise, and the infrastructure for the CO_2 storage itself. If the initial investments are not made until 2040 or 2050, it would take until 2070 or 2080 before capacity levels would be sufficient.[29]

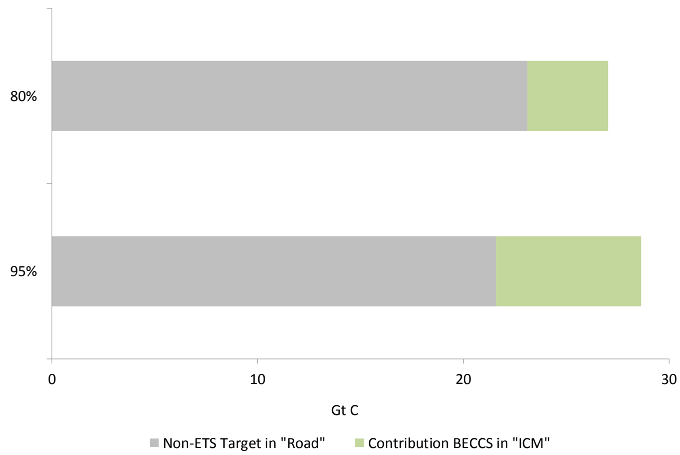
We stress that these figures are not based on our assumptions regarding the cost of expensive measures, such as electric vehicles and energy-neutral housing. For the costs of these expensive measures lie far above the 'strike price' of 115 €/tCO_2 at which BECCS becomes interesting. This strike price is also considerably lower than the 2050 CO_2-prices published by the EC for their 80%-reduction target, which stand at 265 and 350 €/tCO_2 (see Table 37 in EC, 2011b). According to these prices, it would pay to invest in BECCS.

Now, we will further deepen our understanding of the effects of BECCS by linking the changes brought about by BECCS to the energy system in terms of its inputs (biomass) and outputs (electricity, increased carbon budget). First, BECCS increases the carbon budget, as its negative emissions may offset additional carbon emissions from fossil fuels without jeopardizing the overall emission target. For example, BECCS' negative emissions may offset emissions from coal-fired power plants (with or without CCS), from the direct use of gas for heating and industrial purposes, and from the use of fossil liquids in transport. We will refer to this as the 'carbon effect'. Secondly, the biomass used by BECCS is no longer available as an

[28] This is 12% of the EU electricity production. In a scenario that also assumes trade in biomass for BECCS the capacity of BECCS in 2050 increases to 200GW (20% of total electricity production).
[29] The same argument also applies to investments in other new technologies, such as wind and solar energy.

input in the production of liquid fuels (biofuels). Hence, the users of these biofuels must switch to alternative energy sources. We will refer to this as the 'input effect'. Finally, increases in the electricity produced by BECCS will decrease the electricity production from other technologies, such as wind, IGCC-CCS and nuclear. We will refer to this as the 'substitution effect'.

Figure 4.4 Carbon effect in 2010-2050 in the "ICM" scenarios for the 80% and the 95% emission reduction case



Source: MERGE simulations.9

Figure 4.4 summarizes the 'carbon effect' in the period 2010-2050 by comparing the issued emission rights (in GtC) in that period to non-ETS in the "Road" scenario and the negative emissions produced by BECCS in the "ICM" scenario for the two emission reduction cases.[30] Indeed, we can see that the 'carbon effect' substantially increases the carbon budget for non-electric energy, i.e. with about 15% and one third in the 80% and 95% case, respectively.[31]

Next, we move to the impact from BECCS on non-electric energy markets. We illustrate the 'input effect' on non-electric energy use (Figure 4.5) by showing the main fuels used here in 2050 in both the 80% and 95% cases in the "Road" and "ICM" scenarios.[32]

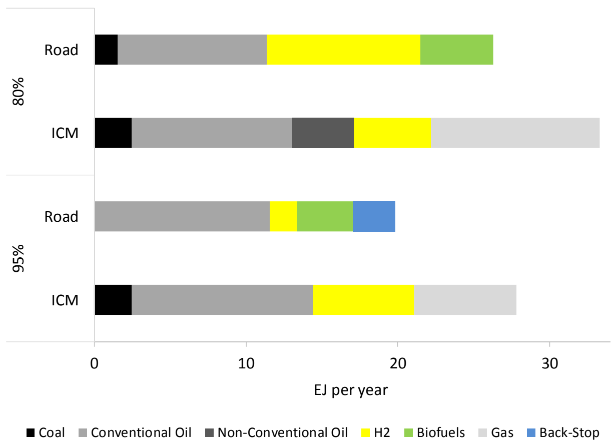
Recall that in "Road" in the 80% case, the non-ETS carbon price increases to 337 €/tCO_2 in 2050. This price also increases the price of consumption, which in turn reduces demand.[33] But next to these savings, the carbon price decarbonizes non-electric fuel demand. Firstly, the biofuels penetrate the non-ETS market as they combine with Conventional Oil on the liquid fuel market. Secondly, the carbon-free gaseous fuel hydrogen gets a market share,

---

[30] There are two changes in the assumptions of the "ICM" scenario compared to the "Road" scenario. BECCS negative emission contributions are granted and there is one uniform carbon price. Nevertheless, we can still compare the targets of the "Road" scenario and the negative emissions of BECCS in the "ICM" scenario, because separately changing these assumptions does have a little impact in addition to the "Road" scenario, see footnote 22 and the remark below Figure 2.
[31] However, it most likely pays to use this expansion of the carbon budget of the whole 2010-2050 period to avoid the most expensive measures in 2050, because in that year carbon price is extremely high. The not cumulated carbon effect in the 80% case in 2050 is twice the non-ETS carbon budget in 2050 and increases eightfold in the 95% case.
[32] The MERGE model does not explicitly model heating. In this paper, non-electric energy includes the direct energy use for transport, industrial production, and heating.
[33] in the next 40 years energy savings are approximately 35%.

which is produced by the gasification turbines of "Coal-CCS". Finally, the direct use of coal - for heating and industrial processes- is tackled with CCS.
However, the carbon price in the "ICM" scenario is more than 50% lower (144 €/tCO_2) than in the "Road" scenario. The consequence is that the need to implement energy savings becomes less important, which in turn increases the total non-electric energy consumption with 25%. Also, there are no biofuels, as BECCS now absorbs the demand for biomass. The supply gap – the total non-electric energy demand increase plus the reduction in biofuels in the "ICM" compared to the "Road" scenario - equals 11,8 EJ. The increase in the demand in non-electric energy contributes for 59% to this supply gap while the rest comes from the reduction in biofuels. This supply gap is filled by gas, non-conventional oil (coal-to-liquids), and an increase of the demand for coal and conventional oil.[34]

Figure 4.5 Non-Electric Energy demand in 2050 in two emission reduction scenarios



Source: MERGE simulations

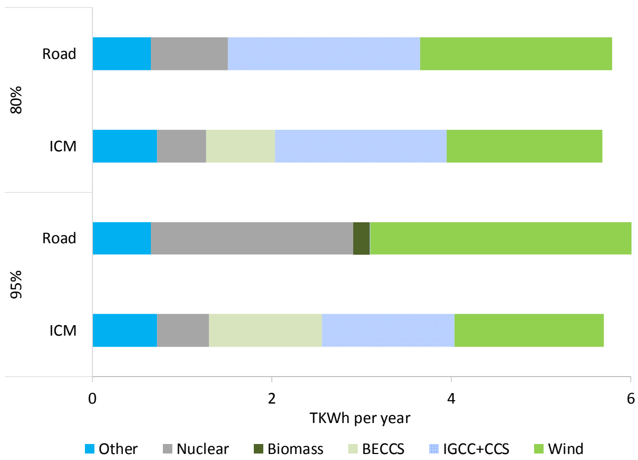
In the "Road" scenario of the more restrictive 95% case there is even more need for energy savings and decarbonisation as non-ETS carbon prices increases to more than 3000 €/tCO_2. Now the very expensive backstop enters the market. Also there is much less hydrogen (compared to the 80% case), which is now produced by electrolysis as the alternative to IGCC-CCS, which produces too much emissions that do not fit with the stringent carbon budget.

However, if we consider the "ICM" scenario, then we observe that BECCS creates a supply gap by lowering energy savings and the biomass reallocation to BECCS . The supply gap is now equal to 11,7 EJ, of which 68% can be attributed to the increase of demand of non-electric energy while 32% comes from the demand reduction of biofuels. This supply gap is filled with coal and gas, while there is also even more hydrogen demand (substitute of the carbon-intensive non-conventional oil). The hydrogen can increase as BECCS provides sufficient negative emissions to compensate the emissions by IGCC-CCS.

[34] We will show later that there are some air pollutions damages involved with the expansion of fossil fuels, which can be cheaply tackled through air policies.

Subsequently, we move to the ‘substitution effect’. This comprises the penetration of BECCS in electricity generation substituting all other technologies, including IGCC-CCS (Figure 4.6).

Figure 4.6 Production of Electric Energy in 2050 in the “Road” and the “ICM” scenarios for both the 80% and the 95% emission reduction case



Source: MERGE simulations.

In 2050, in the 80% emission reduction case in the “Road” scenario, wind-energy accounts for approximately 30% of the electricity production. Wind contributes mainly to low-load hours and there are some spills (see Appendix B for more details on dispatch). IGCC-CCS serves as a back-up for wind-energy, while it produces hydrogen when wind turbines do produce electricity. There is a direct advantage producing hydrogen, because it substantially improves the load factor of this type of power plant (see also Blanford et al., 2015). Moreover, producing hydrogen is economically attractive as this zero-carbon fuel substitutes the non-zero-carbon liquid fuels, while it also avoids the cost of importing oil and biofuels on liquid fuel markets. Nuclear accounts for 10% of production while also serving as back-up to wind-energy options. Finally, “other” is almost fixed.

In the “ICM” scenario in the 80% emission reduction case, BECCS accounts for around 10%, thus driving down the ETS emissions while allowing to expand on non-ETS emissions. BECCS substitutes zero or near-zero carbon technologies such as wind-energy, “IGCC-CCS” and nuclear power.[35] BECCS substitutes in the 80% case both for nuclear and IGCC-CCS, which also lowers their back-up role to the high penetration of wind-energy capacity.

However, in the 95% emission reduction case the extra abatement requirement. i.e. 15 percentage points less emission allowances in 2050 - reduces also the potential of IGCC-CCS because of its residual emissions.[36] In the “Road” scenario, nuclear and wind-energy then account for 85% of the electricity production. Wind dominates not just the low-load hour time segments (with 20% spills in the lowest-load time segment), but also the medium-load hour time segments. The excess supply of wind-electricity is now used for electrolysis to produce hydrogen (see Appendix B). The extra “Generation III” nuclear capacity already

[35] Also, BECCS lowers electricity demand, because electric transport vanishes as BECCS enables to expand the emissions from other half sources. In 2050, in the “Road” scenarios, electric driving accounts for 3% of the total electricity generation. In the “ICM” scenarios, the demand for electric energy by private transport declines with 75%.
[36] The IGCC-CCS technology exhibits a 90% lower emission coefficient than the current coal-fired power plants.

kicks in by 2020. In this case a small portion of electric production comes from biomass without CCS, because it is cheaper than BECCS and the negative emission contributions are not granted in this scenario.

In the 95% emission reduction case in the "ICM" scenario, we see BECCS increase up to 20% of production, which is twice as much as in the 80% emission reduction case. IGCC-CCS can exist next to BECCS and can also serve again as back-up to wind-energy. The electricity production by IGCC-CCS is less than compared to the 80% emission reduction case because the small amount of emissions still absorbs large bulks of the very small carbon budget.

4.2 Other concerns of BECCS

Above, we demonstrated that from an economic point of view the use of BECCS has great advantages. As a result, biomass demand might increase substantially in order to supply BECCS. This might, in turn, increase imports of biomass into Europe, thus restricting the availability of land for food production outside Europe. Poorer countries may be particularly affected, and the increase in the demand for biomass may also lead to further deforestation.[37]

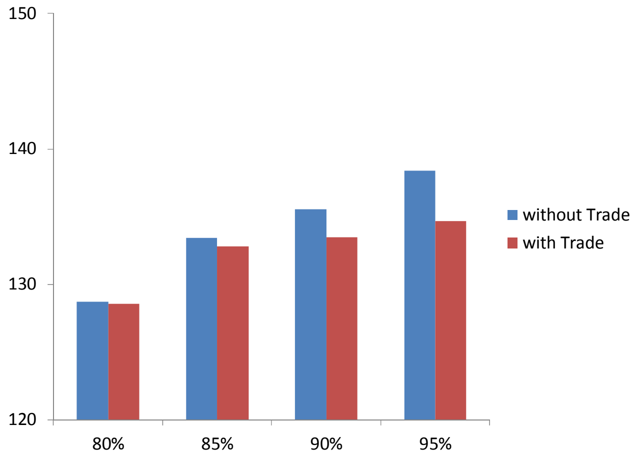
But in the "Road" scenario, total biomass production in the EU will be around 9.6 EJ of biomass by 2050.[38] If the EU allows BECCS as in the "ICM" scenarios, the total import of biomass will be around 0.8 EJ under an 80% reduction target and 7.6 EJ under a 95% target. Depending on the required target, this would bring total biomass use by 2050 to 10.4 EJ and 17.2 EJ, respectively.

Rather surprisingly, the imported biomass by the EU would cause global demand for biomass to decrease, instead of increase (Figure 4.7).[39] The reason is that the demand for biomass in BECCS makes energy less scarce, because it increases the carbon budget. On the one hand, the demand for biomass increases because of BECCS. But on the other hand, the increase of the carbon budget allows for more fossil energy use, which in turn lowers the demand for renewable energy, and thus also for biomass. The net impact is a decline in the demand for biomass.

Roughly speaking, the use of 1 EJ of unconverted biomass in a BECCS power plant results in around 0.3 EJ of electricity. Additionally, the storage of 0.9 billion tonnes of CO_2 allows the use of fossil fuels and resources in the petrochemical industry to increase by 0.7-1.1 EJ, respectively.[40] Thus, in total, using 1 EJ of biomass in BECCS power plants, results in 1.0-1.4 EJ of energy.

[37] See the Dutch Sustainable Biomass Commission (2015), Dutch House of Representatives (2014).
[38] If the EU does not allow biomass-imports, then land-use patterns in Asia, Africa and South America are unaffected.
[39] This also holds for a scenario in which the annual global availability of sustainable biomass is limited to 100 EJ instead of 150 EJ. Also, the global demand of global biomass in "100" lowers by using BECCS. Thus, no additional agricultural land is required when using BECCS.
[40] Indirect emissions released during the production of fossil fuel strongly determine the additional amount of fossil fuel that can be used on the basis of additional emission allowances. Unconventional oil (e.g. shale oil, tar sands and gas to liquids) and synthetic oil (e.g. gas to liquids and coal to liquids) have more indirect emissions than the currently more common light crude oil (Brandt and Farell, 2007). A certain amount of these indirect emissions, however, could be captured by using CCS technology during the production process.

Figure 4.7 Global Demand for Biomass in 2050 in the "ICM" scenario with and without trade in Biomass for Electricity Generation



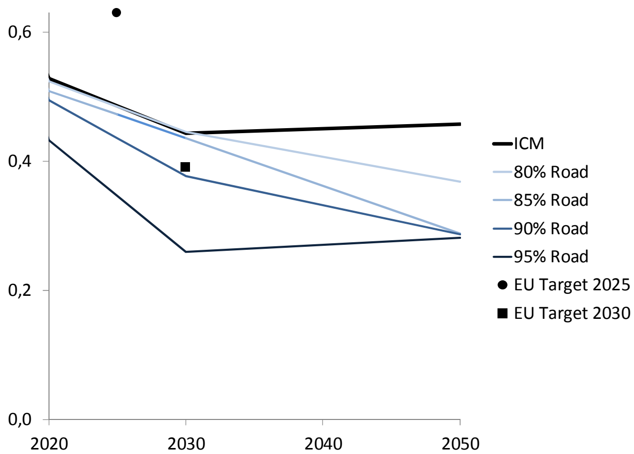
Source: MERGE simulations

In contrast, in the "Road" scenario without BECCS, the use of 1 EJ of unconverted biomass provides about 0.5 EJ of biofuel or resources for the petrochemical industry. Thus, the use of BECCS in the "ICM" scenario results in a net energy gain of around 0.5 to 0.8 EJ. Note that the increased use of fossil energy will not lead to higher CO_2 emissions since the increased emissions from fossil energy are counterbalanced by lower (negative) emissions from biomass. On balance, this would make CO_2 emission levels more or less constant, by 2050.[41] The increased availability of fossil energy also means that the use of BECCS will not lead to shortages in high-value resources and fuels in the petrochemical, aviation and heavy transport industries. Quite the contrary, it would alleviate such shortages.

Another concern on BECCS is that the negative emissions from BECCS will decrease the need to reduce the use of fossil fuels, which may have a negative impact on air quality. Thus, in the "Road" scenario without BECCS, the average exposure of humans to particulate matter in the EU would decline by approximately 60% by 2050 under an 80% emission reduction target and by 70% under a 95% emission reduction target (Figure 4.8).[42] And indeed, in the "ICM" scenario with BECCS this decrease is limited to about 50%. This would mean that the air quality in 2050 would even not comply with the EU air quality target for 2030.[43] However, the EU can quite easily comply with the 2030 air quality standards by taking additional measures.[44] The costs of such measures would be less than 1% of the increase in welfare created by using BECCS. Therefore, using biomass in this way remains a very attractive option, also from a societal perspective.

[41] Using BECCS even slightly increases the CO_2 emissions by 2050 due to banking.
[42] This is the average exposure of the total EU population over an entire year, in both rural and urban areas. It is lower than the measured concentration levels in so-called hotspot areas. In 2010, this average exposure was equal to 10 μg/m^3. The 2030 EU target equals approximately 4 μg/m^3. For futher details, see Bollen (2016).
[43] For 2030 onwards, EU policy is assumed to limit the average exposure to particulate matter to around 4 μg/m^3, due to the national emission ceilings for SO_2 (sulfur), NO_x (nitrogen), NH_3 (ammonia), and $PM_{2.5}$ (particular matter).
[44] This, among other things, concerns end-of-pipe measures, such as filters, but also shifts in the use of fossil energy.

Figure 4.8 Average Annual Exposure of EU Citizens to PM_{25} concentrations (in 10 µg/m3) in different scenarios in relation to the EU targets



Source: MERGE simulations

Finally, there is resistance within society to storing CO_2 underground due to safety issues.[45,46] If the application of biomass in power plants were to increase the underground storage of CO_2, this may affect public safety.[47] This may be true, but the simplest way of accommodating those concerns is to prohibit CO_2 storage on land. This would not affect the use of BECCS, as it remains extremely profitable, both from a private and societal perspective. Moreover, most of EU's storage capacity is offshore.

[45] See also, link.

[46] Survey results, incidentally, indicate that the Dutch are far more positive about storing CO_2 from biomass than from fossil fuel (Mastop et al., 2014).

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Appendix A

We illustrate here two formulas:

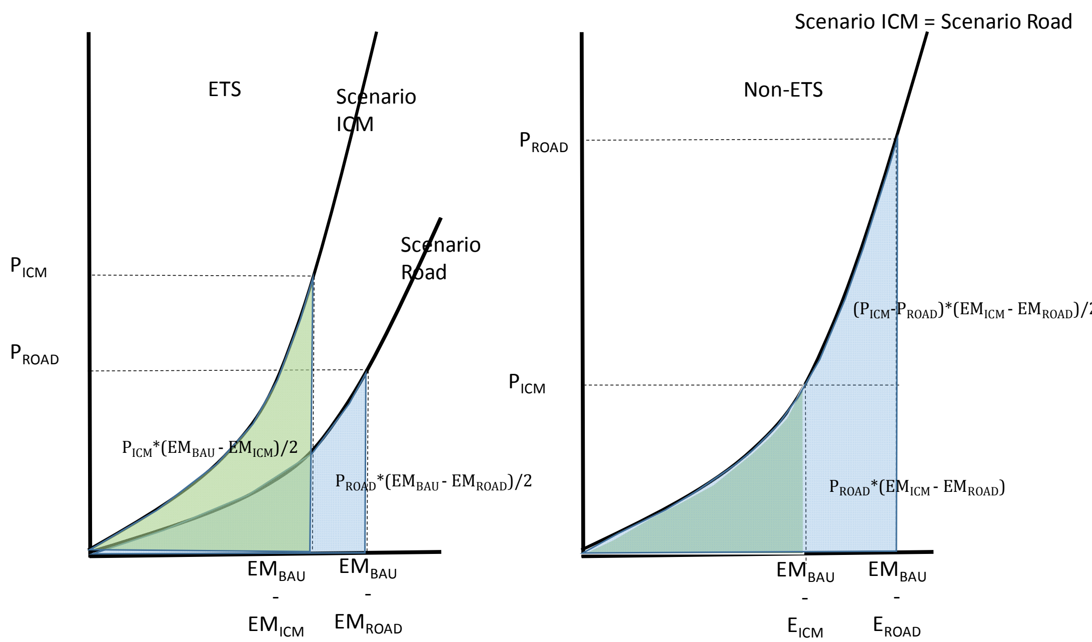
1. Yearly costs in ETS=P_{ICM}*(EM_{BAU} - EM_{ICM})/2 - P_{ROAD}*(EM_{BAU} - EM_{ROAD})/2

The ETS formula compares two MACCs.[48] The reason for this approximation is that ETS can "pay" for non-ETS abatement through hydrogen production by a gasification plant, which runs on coal, gas, or biomass. The hydrogen production changes significantly, which in turn changes the MACC. On the one hand, more hydrogen production calls for more abatement and pushes the MACC to the right, while banking (here before 2050) allows for less abatement (and options) and pushes the MACC to the left. The overall impact is unclear, and hence we approximate the costs by the point estimates in the two contrasting scenarios as if there are two different MACC's.

2. Yearly costs in non-ETS=P_{ROAD}*(EM_{ICM} - EM_{ROAD}) + (P_{ICM}-P_{ROAD})*(EM_{ICM} - EM_{ROAD})/2

For non-ETS, costs are derived more easily by using only one MACC. The reason is that fuel switching (even hydro) is already part of the MACC simulated in the "Road" scenario. In other words, we use the formulae as mentioned in note 3, i.e. costs advantages in "ICM" is estimated as moving along the MACC curve derived from the "Road" scenario and estimate the surface below this MACC as emission reductions are reduced.

Figure A.1 Approximating the direct cost of abatement of Table 4.1 with a MACC for ETS and non-ETS



[48] The number 2 enters the formulae if we assume the MACC to be linear.

Appendix B

We illustrate here the dispatch of different electricity technologies over different time segments for the year 2050 in the "Road" and "ICM" scenarios for both the 80% and 95% reduction cases (Figure B.1). Be aware that the width of the peak segment is exaggerated for illustrative purposes. In the model it is only weighted with a single hour.[49] Electric generation above the black dotted line, excluding the "spill" quantities in low-load hours (due to electricity generation from renewable sources), is used for hydrogen production via electrolysis.[50]

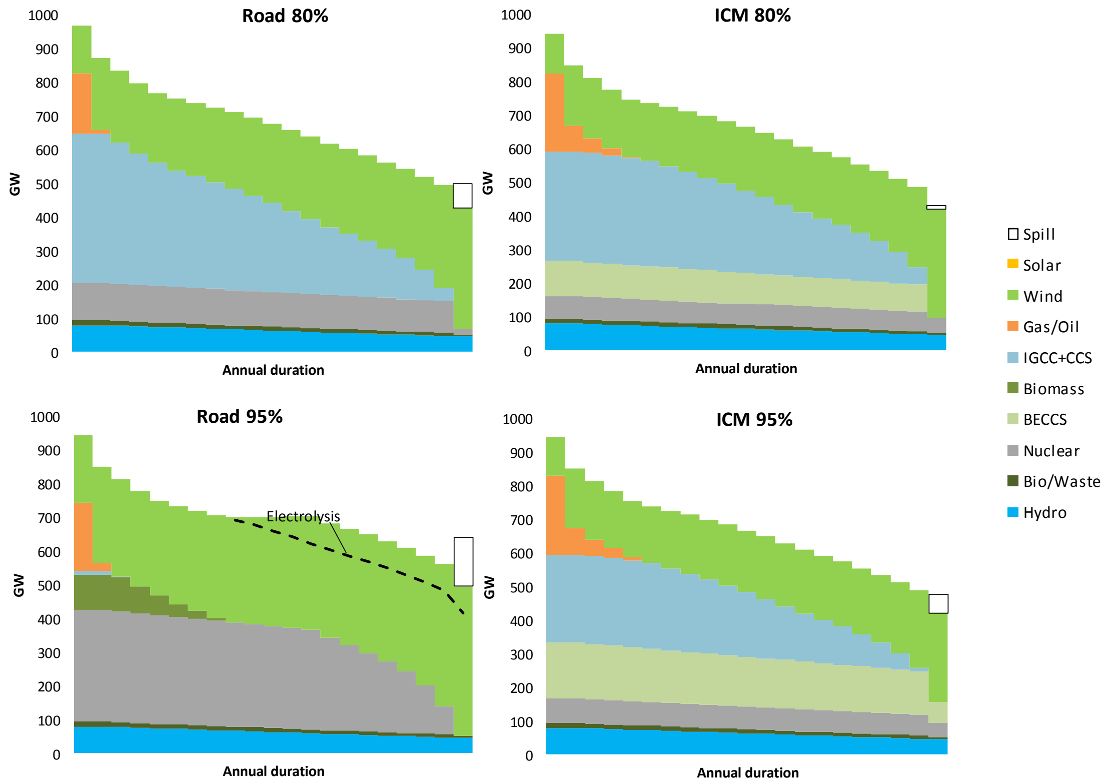
The left-top panel is the 80% emission reduction case in the "Road" scenario. It can be seen that wind-energy (30% of production) is the main contributor to low-load hours, forcing dispatchable technologies to operate at lower capacity factors and lowering the value of energy when they are operating. On the other hand, the low contribution of wind-energy to peak ensures that sufficient dispatchable or "back-up" capacity is present (either retained from the extant endowment or added in future time steps). But it pays if this "back-up" can quickly start or stop producing electricity, or produce another valuable product such as hydrogen. There are two options. First, we have the IGCC plant running on coal, which can produce a steady stream of syngas to create a flow of hydrogen that can be stored relatively cheaply, or alternatively use this syngas in a second stage turbine to produce electricity. Secondly, we have NGCC-plants running on gas, which can be used to produce either electricity or hydrogen. In stringent climate policy scenarios it pays to combine these plants with CCS to have them generate near-zero carbon emissions. The main question is then whether the plant is to run on gas or coal. The price of coal is significantly lower than gas, and therefore 'IGCC-CCS' takes a 35% production share. This technology can easily produce electricity when wind-energy is not available and hydrogen when wind turbines produce electricity. The less flexible nuclear option accounts for only 10% of the electricity production. Solar capacity is not "in the money" with the default cost trajectory as reported in Table 2.1.[51]

The rest of the electric production ("other" in Figure 6) concerns "Gas/Oil", "Hydro" and Bio/Waste". The "Gas/Oil" option refers in 2050 only to the current vintages of flexible "single gas cycle" powerplant, which can be seen to only operate at peak load hours. Note that "Hydro" and Bio/Waste" are options that are fixed and almost equally spread across the different time segments. By assumptions there is no variation in the dispatch of these technologies.

[49] The peak load segment is weighted by a single hour, with the second-highest segment weighted by 437 hours. The remaining 19 segments are weighted by 438 hours each for a total of 8760. Thus the graphics in Figure B.1are slightly mis-scaled as the width of the peak segment is exaggerated for illustrative purposes.
[50] The "spill" in segments with surplus output is possible, because the contribution from wind-energy is incorporated as an inequality constraint.
[51] But even with a more rapid decline in the unit investments costs in solar to 700$ per kW by 2050, zero-use of CCS, and a restriction on onshore wind-energy to 400 GW, then still only 7% of the electricity production in 2050 will come from solar. For more details we refer to Blanford et al., (2015).

Finally, we can see in this scenario also some "spill" of renewable technologies (only wind-energy) In this case excess electricity produced at the lower end of the residual load curve is spilled, as it is not cost-effective to over-build electrolysis capacity to absorb large amounts of excess energy for a small number of hours.

Figure B.1 Dispatch of Electric Energy in 2050 in the "Road" and the "ICM" scenarios for both the 80% and the 95% emission reduction case[52]



Source: MERGE simulations.

As said before, in the 80% emission reduction case in the "ICM" scenario (top right panel), BECCS accounts for around 10% of the electricity production, and substitutes wind-energy, "IGCC-CCS" and nuclear power. Adding this negative emission technology to the portfolio increases the number of clean electricity technologies, and thus also increases the load factor of for example nuclear power, while it reduces on the spills in the low-load segments. BECCS can indeed serve as a back-up to large bulk of wind-energy capacities for electricity generation.

However, returning to the "Road" scenario in the 95% emission reduction case (lower left panel), the extra abatement requirement. i.e. 15 percentage points less emission allowances in 2050 – does not fit with the residual emissions of IGCC-CCS. This coal-option no longer can

[52] Electric dispatch above the black dotted line, excluding the "spill" quantities, is used for hydrogen production via electrolysis. Note that the width of the peak segment is exaggerated for illustrative purposes. The peak load segment represents a single hour, with the second-highest segment accounts for 437 hours, while the remaining 19 segments are weighted by 438 hours each for a total of 8760.

produce electricity. It pays to rely on nuclear and wind-energy (85% of production), and the excess capacity of wind in ow-load hours accounts for 30% of demand. The excess electricity produced at the lower end of the residual load curve is now used for hydrogen production via electrolysis. Despite electrolysis, also some energy is still spilled, as it is not cost-effective to over-build electrolysis capacity to absorb large amounts of excess energy for a small number of hours. Electrolysis also changes the shape of electricity demand (flat profile of mid-load segments). Finally, biomass-power without CCS (gasification plant) extends on gas to produce electricity in peak-hours.

Finally, the “ICM” variant (lower right panel) looks similar to the 80% emission reduction case, although BECCS doubles compared to the 80% emission reduction case. The reason is that there is more need for BECCS’ negative emission contributions to relax on the increased burden of abatement elsewhere in the economy. The increased need for BECCS reduces also the need for “IGCC-CCS” in the electric sector.

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