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# Working Paper

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## **Assessing the Techno-economic Effects of the Delayed Deployment of CCS Power Plants**

**Samuel Carrara**

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### Assessing the Techno-economic Effects of the Delayed Deployment of CCS Power Plants

By Samuel Carrara, Fondazione Eni Enrico Mattei and Renewable and Appropriate Energy Laboratory (RAEL), University of California

#### Summary

Meeting the targets of climate change mitigation set by the Paris Agreement entails a huge transformation of the energy sector, as low- or no-carbon technologies must gradually substitute traditional, fossil-based technologies. In this perspective, the vast majority of energy analyses and scenarios project a fundamental role of Carbon Capture & Storage (CCS). However, uncertainty remains on the actual techno-economic feasibility of this technology: despite the considerable investment over the recent past, commercial maturity is yet to come. The main aim of this work is to evaluate the impacts of a progressively delayed deployment of CCS plants from a climate, energy, and economic perspective, focusing in particular on the power sector. This is carried out with the Integrated Assessment Model WITCH, exploring a wide set of long-term scenarios over mitigation targets ranging from 1.5°C to 4°C in terms of global temperature increase in 2100 with respect to the pre-industrial levels. The analysis shows that CCS will be a key mitigation option at a global level for carbon mitigation, achieving about 30% of the electricity mix in 2100 (with a homogeneous distribution across coal, gas, and biomass) if its deployment is unconstrained. If CCS deployment is delayed or forbidden, penetration cannot reach the optimal unconstrained level, resulting in a mix rearrangement, with a strong increase in renewables and, to a lesser extent, nuclear. The mitigation targets can be met, but policy costs without the implementation of CCS are from 35% to 72% higher than in the corresponding unconstrained scenarios.

**Keywords:** Carbon Capture and Storage, CCS, Power Generation, Climate Change Mitigation, Integrated Assessment Models

**JEL Classification:** Q42, Q43, Q54

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*Address for correspondence:*

Samuel Carrara  
European Commission, Joint Research Centre  
Directorate C Energy, Transport and Climate  
Westerduinweg 3  
1755 Le Petten  
The Netherlands  
Email: samuel.carrara@ec.europa.eu

# Assessing the techno-economic effects of the delayed deployment of CCS power plants

Samuel Carrara<sup>1,2\*</sup>

<sup>1</sup> Fondazione Eni Enrico Mattei (FEEM), Milan, Italy

<sup>2</sup> Renewable and Appropriate Energy Laboratory (RAEL), University of California, Berkeley, USA

## DRAFT COPY

### Abstract

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\* Currently at: European Commission, Joint Research Centre, Directorate C Energy, Transport and Climate, Westerduinweg 3 1755 LE Petten, The Netherlands. E-mail: samuel.carrara@ec.europa.eu  
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## 1. Introduction

Climate change mitigation is acknowledged as one of the major challenges that the mankind will have to face in the 21<sup>st</sup> century (IPCC, 2014). With the Paris Agreement, reached in 2015 during the Conference of Parties 21 (COP21), almost all countries of the world have committed to pursuing the ambitious target of limiting to 2°C the global temperature increase in 2100 with respect to the pre-industrial levels, making all the possible efforts to stay as close to 1.5°C as possible, in order to further limit detrimental climate impacts (Schellnhuber et al., 2016). However, these targets are very difficult to be reached, as they entail huge technological and economic transformations, as well as an internationally coordinated action.

Carbon Capture & Storage (CCS) has widely been recognized as one of the main technological solutions to decarbonize the energy sector and virtually all research studies project a considerable role in future mitigation pathways (see for instance Krey et al., 2014 and Koelbl et al., 2014), especially if the target is to stay below 2°C (Rogelj et al., 2015). This technology consists in capturing the carbon dioxide generated in plants fed with fossil fuels or biomass and storing it in proper underground deposits or marine aquifers (IEA, 2013). Its main advantage is the possibility to achieve a (theoretically) zero carbon energy generation adopting fossil fuels plants, i.e. without massively reconsidering the current generation paradigm that still dominates the energy sector (IEA, 2017). Indeed, even negative emissions can be achieved if CCS plants are fed with biomass which is replaced at a pace equal to consumption: in this case, the carbon neutrality related to the use of biomass (net of the emissions associated to the whole life cycle concerning harvesting, transport, etc.) is complemented by the CO<sub>2</sub> removal in the CCS plant. An additional advantage is related to the dispatchability of these plants, which is a fundamental aspect in a future energy scenario where non-dispatchable renewables (primarily wind and solar) will likely reach significant shares in the electricity mix. CCS availability would also entail economic savings in pursuing mitigation targets (Davidson et al., 2017).

However, large-scale CCS deployment is yet to come. Safety concerning the stability of storage sites, public acceptance, high technology costs, incomplete or unclear regulatory framework, the absence of business models, and a general uncertainty on the socio-economic impacts are major obstacles that still hinder the take-off of this technology (Creutzig et al., 2013 and Muratori et al., 2016). As a result, very few and small scale plants have been installed so far (GCCSI, 2017).

In this context, the main objective of this work is to investigate the role that CCS could play in carbon mitigation and in particular assess the techno-economic impacts that a progressively delayed deployment of this technology can have both in terms of rearrangement of the energy mix and in terms of policy costs. In other words, how urgent is it to start installing CCS plants for the feasibility and affordability of achieving more and more stringent climate targets?

This study has a global scope and focuses on the electricity sector. The research is carried out adopting the Integrated Assessment Model (IAM) WITCH.

The paper is structured as follows. Section 2 describes the WITCH model, and especially how the power sector and CCS technologies are modeled therein. Section 3 reports the scenario design. Section 4 reports and extensively discusses the most relevant results of the analysis. Finally, Section 5 concludes.

## 2. Methodology

### 2.1 The WITCH model

The tool adopted in this research is the World Induced Technical Change Hybrid (WITCH) model. WITCH is a dynamic optimization IAM designed to investigate the socio-economic impacts of climate change over the 21<sup>st</sup> century (Bosetti et al., 2006 and Emmerling et al., 2016) with time steps of five years. It combines a top-down, simplified representation of the global economy with a bottom-up, detailed description of the energy sector, nested in a Constant Elasticity of Substitution (CES) structure (Figure 1). The model is defined on a global scale: countries are grouped into thirteen aggregated regions, which strategically interact according to a non-cooperative Nash game. The thirteen economic regions are USA (United States), WEURO (Western EU and EFTA countries), EEURO (Eastern EU countries), KOSAU (South Korea, South Africa and Australia), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies, namely Russia and Former Soviet Union states and non-EU Eastern European countries), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa except South Africa), SASIA (South Asian countries except India), EASIA (South-East Asian countries), CHINA (People’s Democratic Republic of China and Taiwan), LACA (Latin America and Central America) and INDIA (India). As the model acronym suggests, technological change is endogenously modeled and it regards energy efficiency and the capital cost of specific clean technologies. The climate model MAGICC6 is soft-linked to WITCH (Meinshausen et al., 2011), which allows translating the greenhouse gas (GHG) emissions calculated by WITCH into concentration, radiative forcing, and finally atmospheric temperature increase.

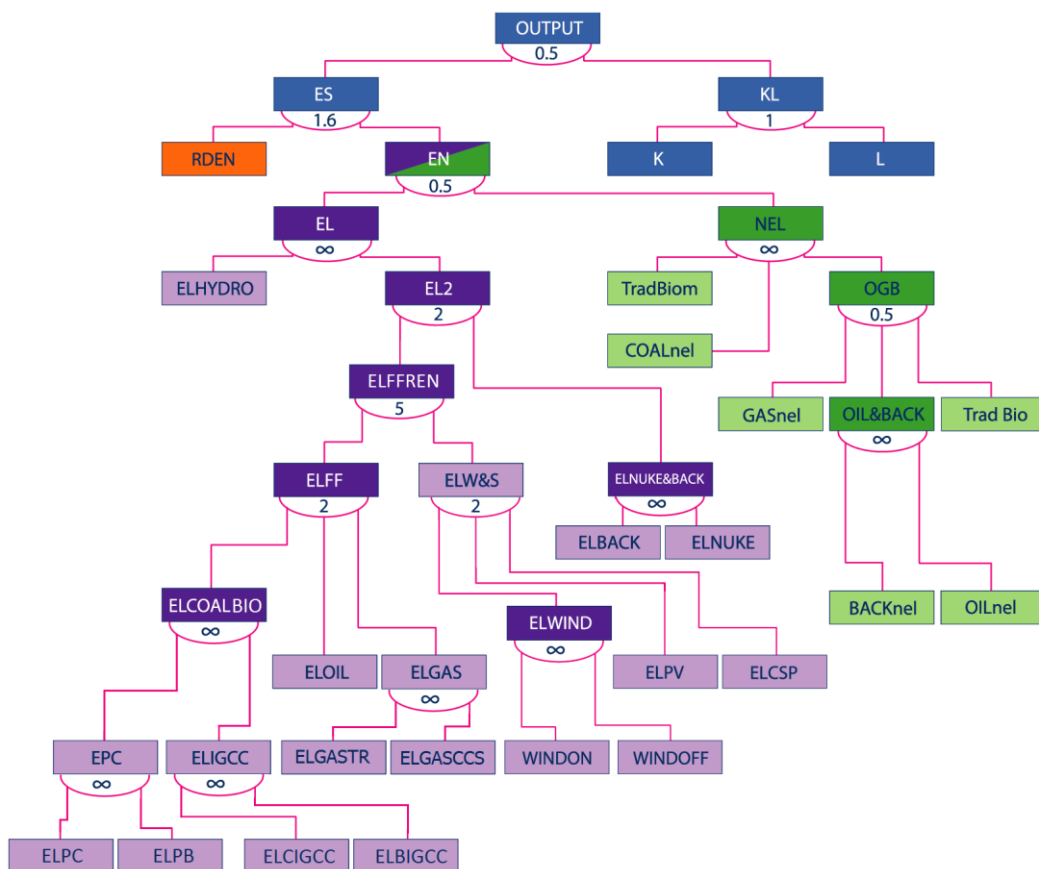


Figure 1 – The CES structure in WITCH.

## 2.2 The CES structure

The CES structure reported in Figure 1 shows how the top-down aggregated economic model is linked with the disaggregated energy sector. In particular, energy services (ES) and the aggregated capital and labor node (KL) are combined to produce the final economic output of the model. Energy services are provided by the combination of the capital of energy R&D (RDEN), which is a proxy of energy efficiency, and the actual energy generation (EN). This node models the fact that the same energy services can be obtained through a lower level of energy input if there is higher energy efficiency. The EN node is divided between the electric (EL) and non-electric sector (NEL), with a progressive disaggregation to the single technologies. The electric sector has a higher detail, while the non-electric sector mostly reports nodes collecting consumption from all the non-electric usages of one specific energy source. Road passenger and road freight transport are the only demand sectors being explicitly modeled<sup>1</sup> (see Bosetti and Longden, 2013, and Carrara and Longden, 2017).

Focusing on the electric sector, the hydroelectric technology is found first (ELHYDRO), which is essentially exogenous in the model. The other technologies converge to the EL2 node, which is divided between two further nodes: EFLFFREN, i.e. the combination of fossils and renewables, and ELNUKE&BACK, i.e. the combination of nuclear and backstop. The fossil node (ELFF) has three groups of technologies: i) coal&biomass (ELCOALBIO), further divided into pulverized coal without CCS (ELPC), pulverized biomass without CCS (ELPB), integrated gasification coal with CCS (ELCIGCC), and integrated gasification biomass with CCS (ELBIGCC); ii) oil, only without CCS (ELOIL); iii) gas (ELGAS), with and without CCS (ELGASTR and ELGASCCS, respectively). Variable renewable energies (ELW&S) have i) wind (ELWIND), further divided between onshore (WINDON) and offshore (WINDOFF); ii) solar PV (ELPV); iii) solar CSP (ELCSP). Nuclear and backstop feature traditional fission nuclear (ELNUKE) and a backstop technology (ELBACK). The latter models a hypothetical future technology which generates electricity with no fuel costs and no carbon emissions, although characterized by high capital costs. It can be interpreted as an advanced nuclear technology, for instance nuclear fusion or advanced fast breeder fission reactors. However, this technology is not considered in the scenarios explored in this work. Concerning the non-electric sector, the first distinction is between traditional biomass (TradBiom), coal (COALnel) and the aggregated node formed by oil, gas, and modern biomass (OGB), which features gas (GASnel), traditional biofuels (Trad Bio), and the combination (OIL&BACK) between oil (OILnel) and a non-electric backstop technology, i.e. advanced biofuels (BACKnel).

The CES structure tries to capture from a modeling point of view the preference for heterogeneity that is experienced in the real world, where the choice of investing in energy technologies does not normally depend on economic considerations only. The numbers reported in the CES scheme under the specific nodes indicate the relevant elasticity of substitution. As suggested by the name, this value quantifies the level of substitutability between the sub-nodes that converge in the specific node. Zero elasticity means that the production factors are not substitutable and thus they are summed in fixed shares. Infinite elasticity means that the production factors are completely interchangeable and thus the competition between the two occurs on an economic basis only. Intermediate elasticities result in an intermediate behavior. More details concerning the CES structure can be found in Carrara and Marangoni, 2017.

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<sup>1</sup> These sectors are not shown in the CES scheme.

### 2.3 CCS modeling

WITCH models four CCS technologies, three in the electricity sector and one in the non-electric sector. The three electric technologies have been listed in the previous section and feature coal, gas, and biomass (the latter indicated with BECCS, in coherence with the literature). For all of them, the CCS technology directly competes with the relevant non-CCS technology, to which it is related through an infinite elasticity. The non-electric technology is applied to non-electric coal, even if it does not directly appear in the CES structure and it is not considered in this work<sup>2</sup>.

CCS modeling occurs on two levels, one regarding the power technologies and the other regarding the capture and storage costs.

Table 1 summarizes the main modeling assumptions for the three categories of CCS power plants<sup>3</sup>. In this respect, it should be noted that no further technological differentiation is considered in this work within each fuel category<sup>4</sup>. Concerning the data not reported in the table, O&M costs across regions are averagely 45 \$/kW for gas and 75 \$/kW for coal and biomass, respectively (only fixed O&M costs are considered). Efficiency of coal plants starts at 39% in 2015, linearly increases up to 43% in 2050, and then remains constant in the second part of the century. This is assumed to replicate the progress of the efficiency of non-CCS plants subtracting a 7%-efficiency loss related to the capture and storage process. Efficiency in biomass plants follows the same rationale, with a 10%-shift downwards. Efficiency in gas plants is regionally differentiated in 2015 (values are comprised between 39% and 51%), with a common convergence to 55% in 2050, which is held constant afterwards.

	<b>COAL CCS</b>	<b>GAS CCS</b>	<b>BECCS</b>
<b>Investment cost [\$/kW]</b>	3925	1856	5162
<b>Lifetime [years]</b>	40	25	25
<b>Capacity factor</b>	85%	70%	80%

*Table 1 – Modeling assumptions for the CCS power plants.*

<sup>2</sup> For the sake of coherence, the working hypotheses in terms of CCS deployment which will be described in Section 3 have been applied to the non-electric sector too. However, this work focuses on the power sector, therefore no further details are provided on the non-electric side.

<sup>3</sup> If not differently specified, values are held constant across regions and over the century. Costs are expressed in USD2015.

<sup>4</sup> Indeed, a more refined modeling solution for CCS in the WITCH model has been developed and described in Vinca et al., 2018, which includes a differentiation of the CCS power technologies (pre-combustion capture, post-combustion capture, oxyfuel technologies, etc.). However, such a detail has been deemed not to be necessary for the purposes of this work where the CCS technology as a whole is focused, also considering the computational effort required for the several scenarios developed.



CO<sub>2</sub> sequestration, transport, and storage are modeled via regional supply cost curves, which depend on site availability. The unit cost curve  $C_{CCS}(t,n)$  has a convex shape and is shown in Equation 1 (t and n refer to time step and region, respectively):

$$C_{CCS}(t,n) = a_{CCS}(n) \cdot \exp(\alpha_{CCS}(n) \cdot M_{CCS}(t,n)^{\beta_{CCS}(n)}) \quad (1)$$

where  $M_{CCS}(t,n)$  is the cumulated amount of CO<sub>2</sub> captured over the years (the capture rate is fixed to 90% for all the three power technologies), while  $a$ ,  $\alpha$ ,  $\beta$  are parameters calibrated on the storage capacities in the different regions as derived from IPCC, 2005, which estimates a global capacity between 1678 and 11100 GtCO<sub>2</sub>. The total CCS cost is finally computed by multiplying the unit cost  $C_{CCS}$  by the amount of fuel burnt in the relevant power plants.

Global prices of fossil fuels are endogenously calculated in WITCH, while the mean response functions produced by the Global Biosphere Management Model (GLOBIOM, see Havlík et al., 2014) are adopted to model land use. GLOBIOM provides biomass supply cost curves to WITCH for different economic and mitigation trajectories. This allows assessing woody biomass availability and cost.

### 3. Scenario design

The analysis considers a set of 25 scenarios where five climate targets are combined with five temporal options related to CCS deployment. The five climate targets refer to the temperature increase in 2100 with respect to the pre-industrial levels and are equal to 3.5°C, 3°C, 2.5°C, 2°C, and 1.5°C (the two latter are the most relevant in the Paris Agreement perspective<sup>5</sup>). The five temporal options refer to the starting year when investing in CCS is allowed. These years are 2020, 2040, 2060, and 2080, which are in addition to the case where CCS is not installed at all. As investment takes time to materialize, this framework implies that the first actual deployment year in the first four cases is 2025, 2045, 2065, and 2085, respectively (i.e. the following time step). Somehow, the no CCS case would correspond to fixing the starting year of investment in 2100, hence the first deployment year in 2105, i.e. after the temporal horizon of WITCH.

A complementary baseline or Business-as-Usual (BAU) scenario has also been run, where no carbon policy is applied. De facto this leads by construction to no CCS deployment: in the absence of a carbon signal, there is no reason to invest in a carbon-removal technology which is by definition more expensive than the corresponding non-CCS plants. The baseline scenario leads to a temperature increase in 2100 of about 4°C in WITCH (precisely 4.08°C), which explains why the explored climate change mitigation targets start at 3.5°C.

Table 2 summarizes the different options within the climate target and investment dimensions. In particular, the table provides the acronyms for the CCS deployment year which will be used in the graphs shown in Section 4 (“i” stands for investment). The scenario names are generated combining the target and the CCS year, e.g. 3.5C\_i20 or 3C\_i40.<sup>6</sup>

<sup>5</sup> The goal of the Paris Agreement is to “keep a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius” (UNFCCC, 2015).

<sup>6</sup> This naming scheme does not apply to the Business-as-Usual scenario, which is simply called “Baseline”.

<b>Climate target</b>	BAU, 3.5°C, 3°C, 2.5°C, 2°C, 1.5°C
<b>CCS first investment year</b>	2020 (i20), 2040 (i40), 2060 (i60), 2080 (i80), no CCS investment (ioff)

Table 2 – Scenario dimensions.

Figure 2 shows the temperature increase over the century in the 26 scenarios converging to the six climate targets described above. It can be noted that, whereas all scenarios from 2°C upwards converge uniformly towards the relevant target, the 1.5°C scenarios show a broader pattern. These scenarios, in fact, are at the frontier of technical feasibility in WITCH and with a delayed deployment of CCS the convergence can take place only slightly above 1.5°C (from exactly 1.5°C in the i20 case to 1.6°C in the ioff case), which negligibly affects the results.

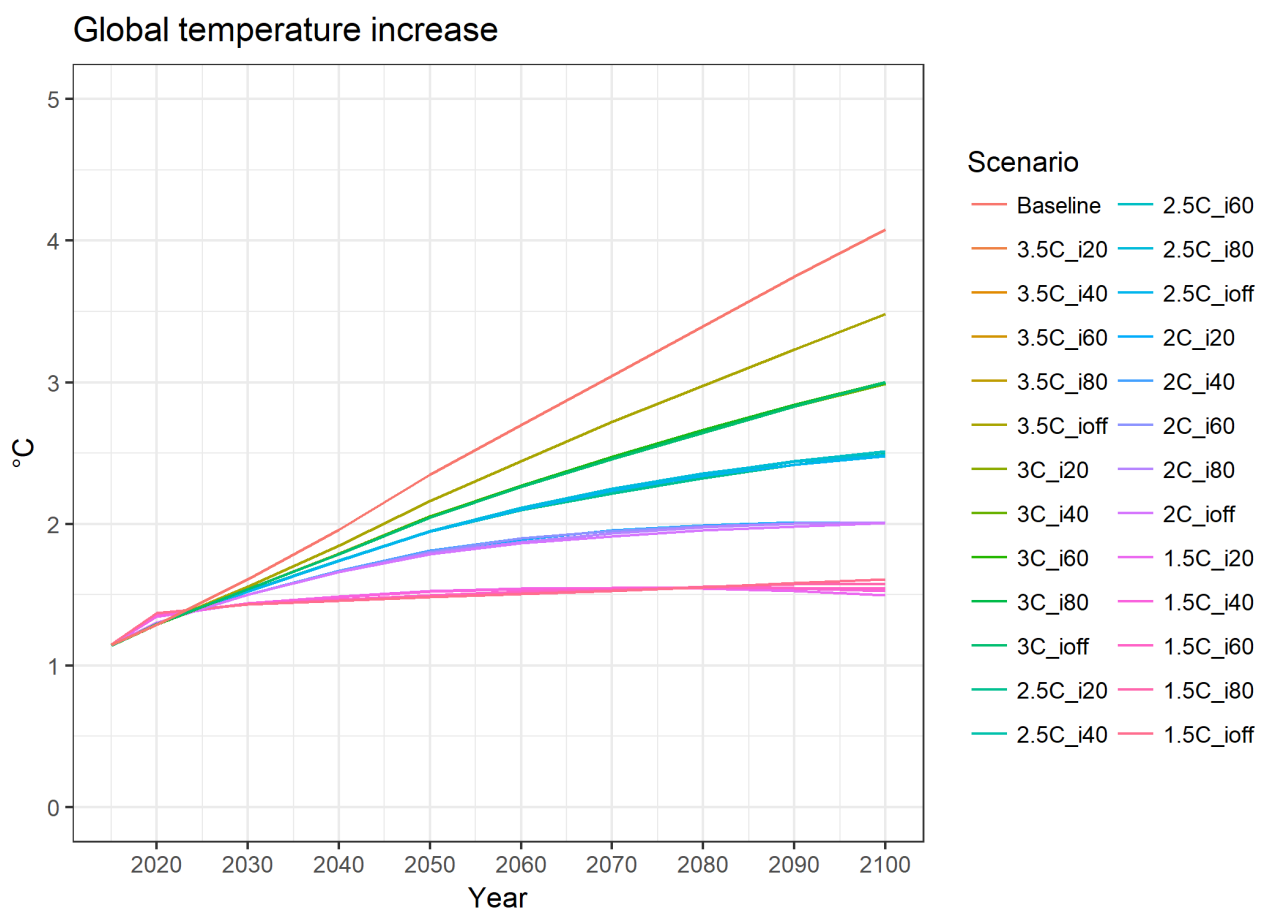


Figure 2 – Global temperature increase with respect to the pre-industrial levels.

The climate targets are reached via the application of a carbon tax on GHG emissions. The tax starts in 2020 and grows exponentially in order to yield the desired temperature increase. As will be shown in the next section, the delayed or forbidden deployment of CCS plants causes by definition an increase in the mitigation costs, as it hinders a technology option which would be otherwise used. This implies an increase in the carbon tax if the same climate target is to be reached. Operatively, a common starting value has been fixed for the different climate targets (referring to the database of similar optimized scenarios) and then the growth rate has been recursively adjusted in order to reach the relevant temperature. No details

are provided on the actual values implemented, as the economic focus will be put on the overall policy cost (shown in Section 4) rather than on the specific carbon tax values, which are not within the interests of this work.

Figure 3 shows the resulting GHG emission patterns in the different scenarios. In particular, Kyoto gases are considered, i.e. carbon dioxide, methane, nitrous oxide, and fluorinated gases.<sup>7</sup>

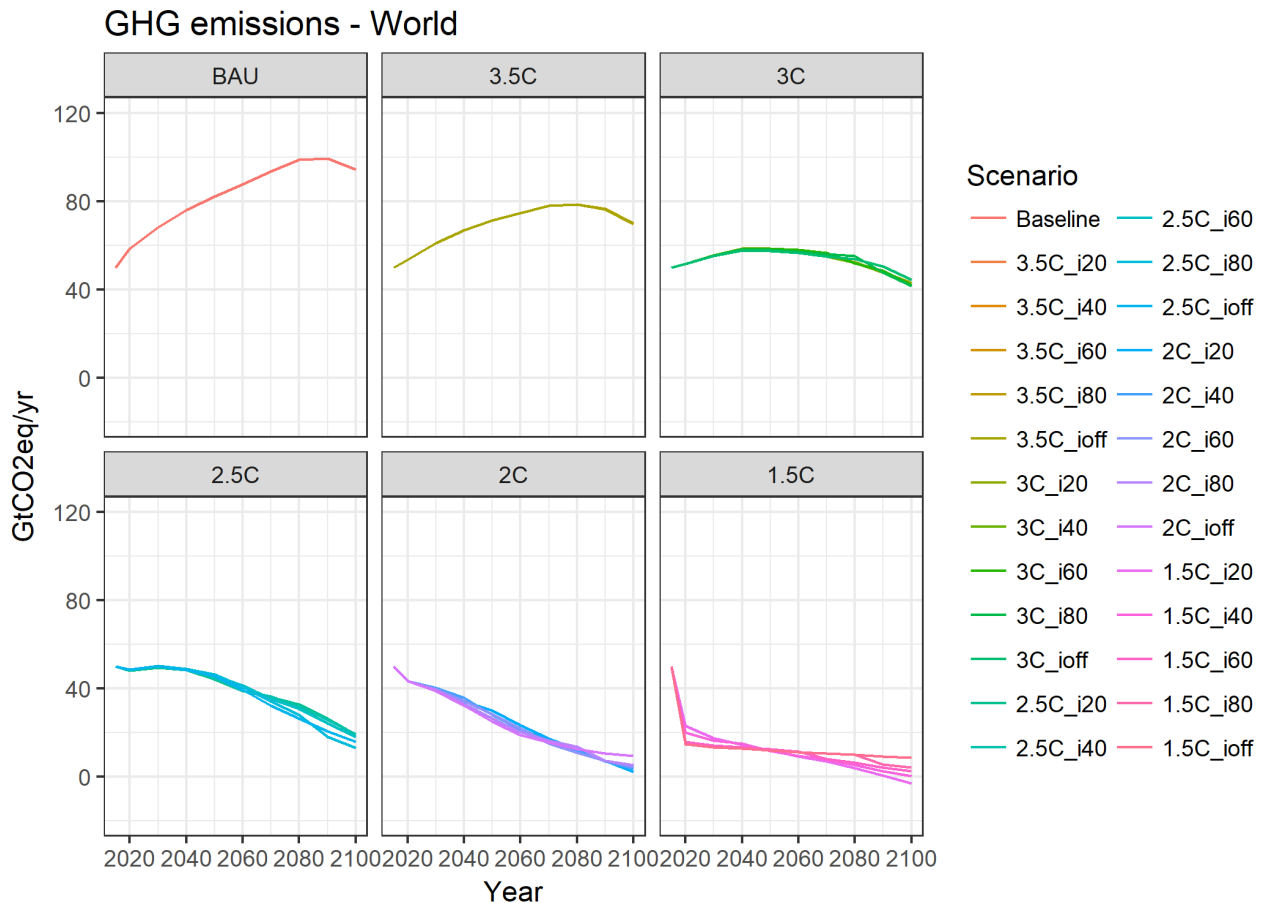


Figure 3 – Global GHG emissions.

In 2015 global GHG emissions accounted for 50 GtCO<sub>2</sub>eq. In the baseline scenario GHG emissions grow up to about 100 GtCO<sub>2</sub>eq in 2080/2090, with a slight decrease towards the end of the century (94 GtCO<sub>2</sub>eq in 2100). The same pattern is found in the 3.5°C scenarios, where emissions peak at 78 GtCO<sub>2</sub>eq in 2070/2080 and then decrease to 70 GtCO<sub>2</sub>eq in 2100. The 3°C target entails that emissions remain substantially constant all over the century, with a peak at 58 GtCO<sub>2</sub>eq in 2040 and a smooth decrease down to around 42 GtCO<sub>2</sub>eq in 2100. The 2.5°C target, instead, implies a constant emission decrease to about 15-20 GtCO<sub>2</sub>eq starting in 2030/2040 after a few decades of relative constancy. The 2°C target requires an immediate and constant decrease, achieving a total net emission amount of few thousands of GtCO<sub>2</sub>eq in

<sup>7</sup> The impact of non-CO<sub>2</sub> gases is assessed via the Global Warming Potential technique. According to this scheme, each GHG is associated to a coefficient which quantifies its relative greenhouse power with respect to carbon dioxide. According to the last IPCC report (IPCC, 2014) the 100-year GWP is 28 for methane and 265 for nitrous oxide, while fluorinated gases have a GWP in the order of hundreds or thousands.

2100. Finally, the 1.5°C target would entail a sudden and dramatic cut of emissions by two or three times in the very first years, with a constant decrease down to zero or even net negative emissions in 2100. As will be discussed in the next section, the extraordinary fall in emissions after 2015 makes this set of scenarios practically infeasible in this design. However, it is not within the scope of this work to discuss about the feasibility of this emission pattern and the policy that would make it possible. Here the focus is on understanding what role can be played by CCS in achieving these long-term targets and its technical and economic impacts with a multi-decadal perspective.

## 4. Results

It is interesting to start by observing how CCS deployment evolves at a global level in the scenario set, see Figure 4. In general, the progressively more and more ambitious emission targets imply a progressively more and more substantial rearrangement of the energy sector, and in particular of the power sector that is focused in this work. In particular, the role of low-carbon or no-carbon power technologies, among which CCS, progressively grows, until these technologies dominate the sector in the more stringent scenarios.

In the baseline case, no CCS deployment is observed. As already discussed in the previous section, if there is no carbon signal, there is no need to install low-carbon technologies which are by far more expensive than the corresponding non-CCS ones. The carbon signal is too low in the 3.5°C scenarios as well, except for a negligible deployment in the last years of the century. From the 3°C target downwards, instead, CCS is regularly installed. Figure 4 clearly shows that the delayed trigger to CCS deployment does have a considerable effect: in all cases, as soon as CCS installation is permitted, it actually starts, with a constant growth over the following decades. It is interesting to note that under no cases can CCS capacity reach the level that is achieved if it can be deployed 20 years in advance. This is mostly due to the constraints affecting the capacity growth that can physically take place over a five-year period, but it also highlights that CCS is an option that is fully exploited in the unconstrained scenarios, if available. It can also be noted that the CCS generation has a similar pattern across the scenario set, especially from 2.5°C to 1.5°C: in 2100, CCS generation reaches 113-134 EJ/yr in the i20 scenarios, 61-72 EJ/yr in the i40 scenarios, 29-35 EJ/yr in the i60 scenarios, and 8-10 EJ/yr in the i80 scenarios, respectively (by definition, it is zero in the ioff scenarios).

Figure 5 provides a detail on the CCS generation in 2100. In addition to stressing that a late CCS deployment leads to a lower CCS generation, the graph shows that the three CCS power technologies (coal, gas, and biomass) provide quite a homogeneous contribution, even if late deployment seems to favor the BECCS technologies. The ioff scenarios are not shown here for the reasons explained above.

### Electricity generation from CCS plants - World

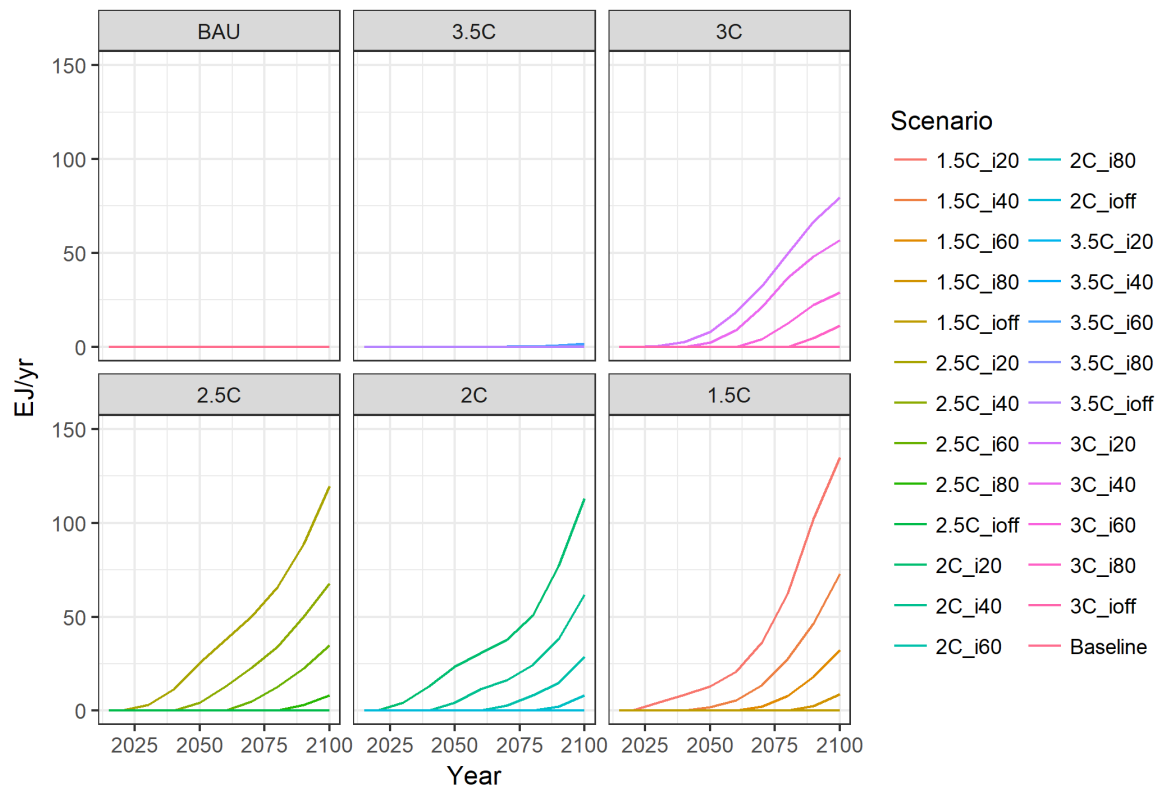


Figure 4 – Global CCS generation over time.

### Electricity generation from CCS plants in 2100 - World

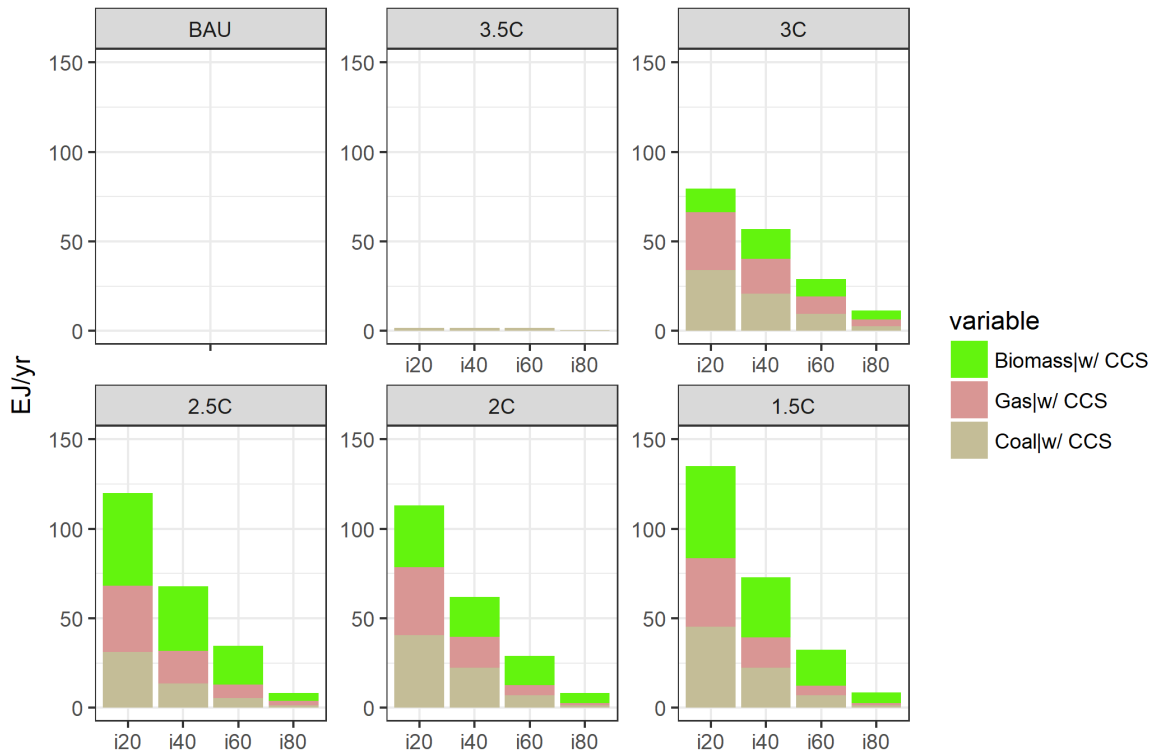


Figure 5 – Global CCS generation in 2100 by source.

## Electricity generation over time across scenarios - World

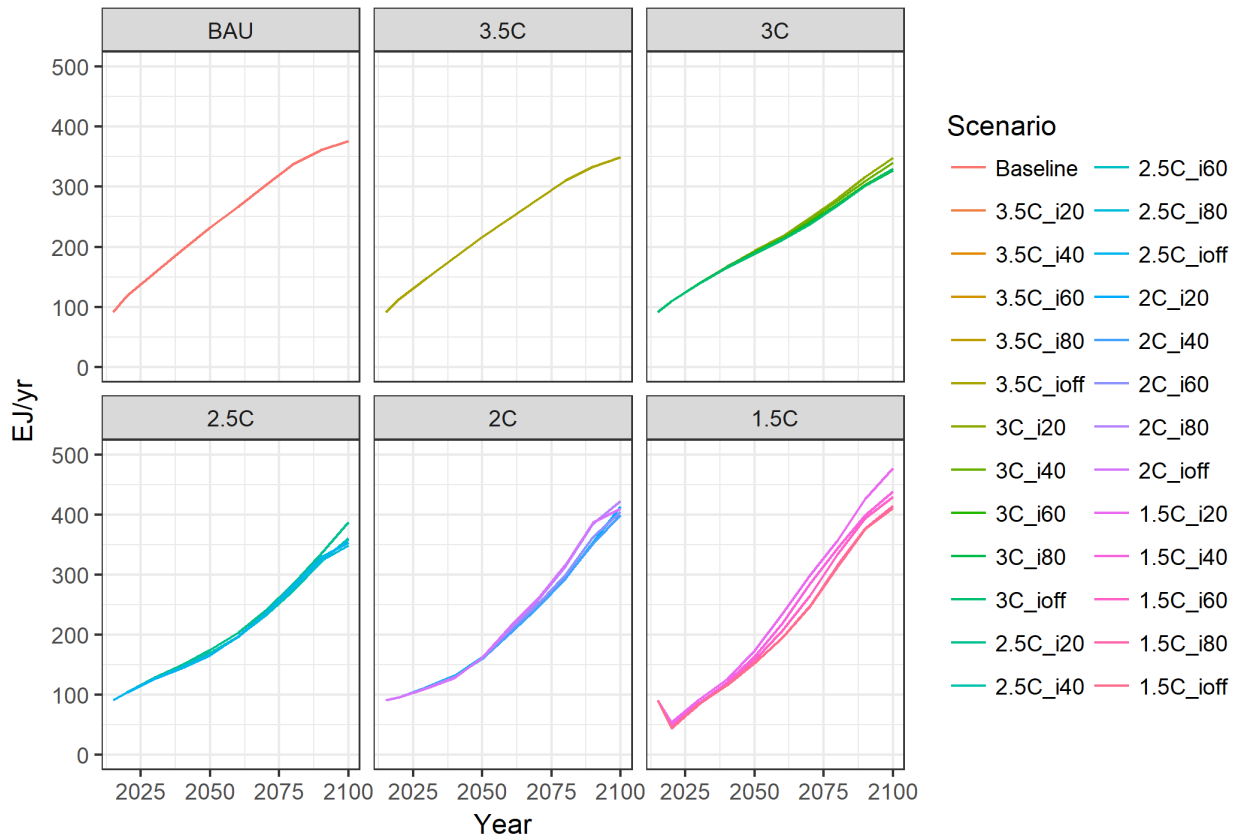


Figure 6 – Global curtailed energy conversion.

The impacts on the overall electricity generation are shown in Figure 6. Electricity generation starts from 90 EJ/yr in 2015 and progressively grows over time in all scenarios, with the partial exception of the 1.5°C scenarios, which show a dramatic (and unlikely) decrease in the electricity generation associated to the emission pattern discussed in the previous section: in these scenarios, it is not possible to massively rearrange the power sector in such a short period to meet with the mitigation requirement, therefore the only solution is to cut the overall generation. In the BAU scenarios, the final value in 2100 is 376 EJ/yr. As a progressively increasing carbon tax is applied, the demand growth slightly slows down, at least until the 2.5°C scenarios: the 2°C scenarios show an opposite behavior, with a convergence in 2100 at around 400 EJ/yr, and even more so in the 1.5°C scenarios, which spread between 410 and 480 EJ/yr.

These results highlight the two possible and contrasting patterns to achieve carbon mitigation. On the one hand, emissions can be reduced simply by reducing energy demand. On the other hand, emissions can be reduced by shifting energy demand from highly emitting to low emitting fuels or carriers. As the power sector shows more viable routes for decarbonization than other sectors, mitigation futures can arguably entail an electrification of the energy sector with a parallel decarbonization of the power sector (Capros et al., 2012 and Wei et al., 2013). The first tendency prevails in the milder scenarios, while the opposite occurs in the more stringent scenarios.

Figure 7 shows the CCS relative penetration in the electricity mix as resulting from the previous two figures: it can be noted that in the absence of deployment constraints, i.e. if investment is allowed from 2020, CCS technologies can reach about 30% in the electricity mix in 2100.

## CCS shares in the electricity mix in 2100 - World

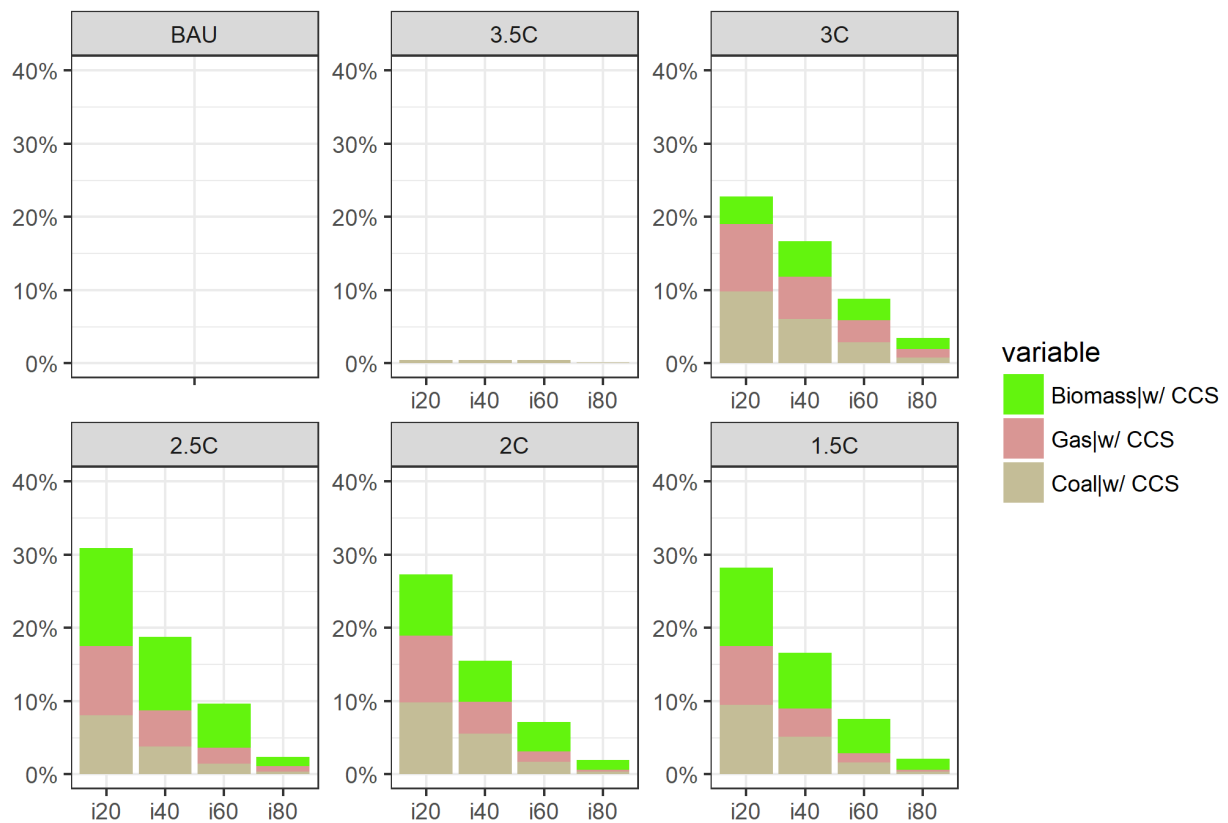


Figure 7 – Global CCS relative penetration in the electricity mix in 2100 by source.

Figures 8 and 9 provide a more general view on the overall electricity mix in 2100. The former shows the absolute generation, while the latter focuses on the relative shares.

In the baseline scenario, fossil fuels (without CCS) dominate the electricity mix, accounting for 50% of the total (coal 30%, gas 18%, and oil 2%). Nuclear accounts for 12% (substantially the same level as today), hydro decreases to 7% (the hydro potential is not sufficient to maintain the current 16% share), while variable renewables (wind and solar) account for 30%, approximately two thirds from wind and one third from solar.

The 3.5°C scenarios are characterized by a very similar electricity mix, simply with a 10%-shift from fossils to wind and solar. More impacts can be seen in the 3°C scenarios, i.e. where CCS technologies appear in a non-negligible amount. As already noted, the delayed deployment of CCS implies lower and lower shares for this technology in 2100. Its contribution is mostly compensated by renewables, nuclear, and also gas without CCS, which is still a viable technology for this mild climate target. This no longer happens in the more stringent climate targets. Figure 7 has already shown that in all these cases, CCS accounts for about 30% of the electricity mix in 2100 if its deployment is allowed starting from 2020. If CCS is constrained, as there is no more room for non-CCS fossil technologies (apart from a negligible gas contribution in the 2.5°C scenarios), the electricity mix tends to converge to a solution dominated by renewables (with about 35% wind onshore, 10% wind offshore, 30% solar PV, and 5% solar CSP, i.e. 80% in total), with a complementary contribution of nuclear (12%) and hydro (8%).

### Electricity mix in 2100 - World - Absolute generation

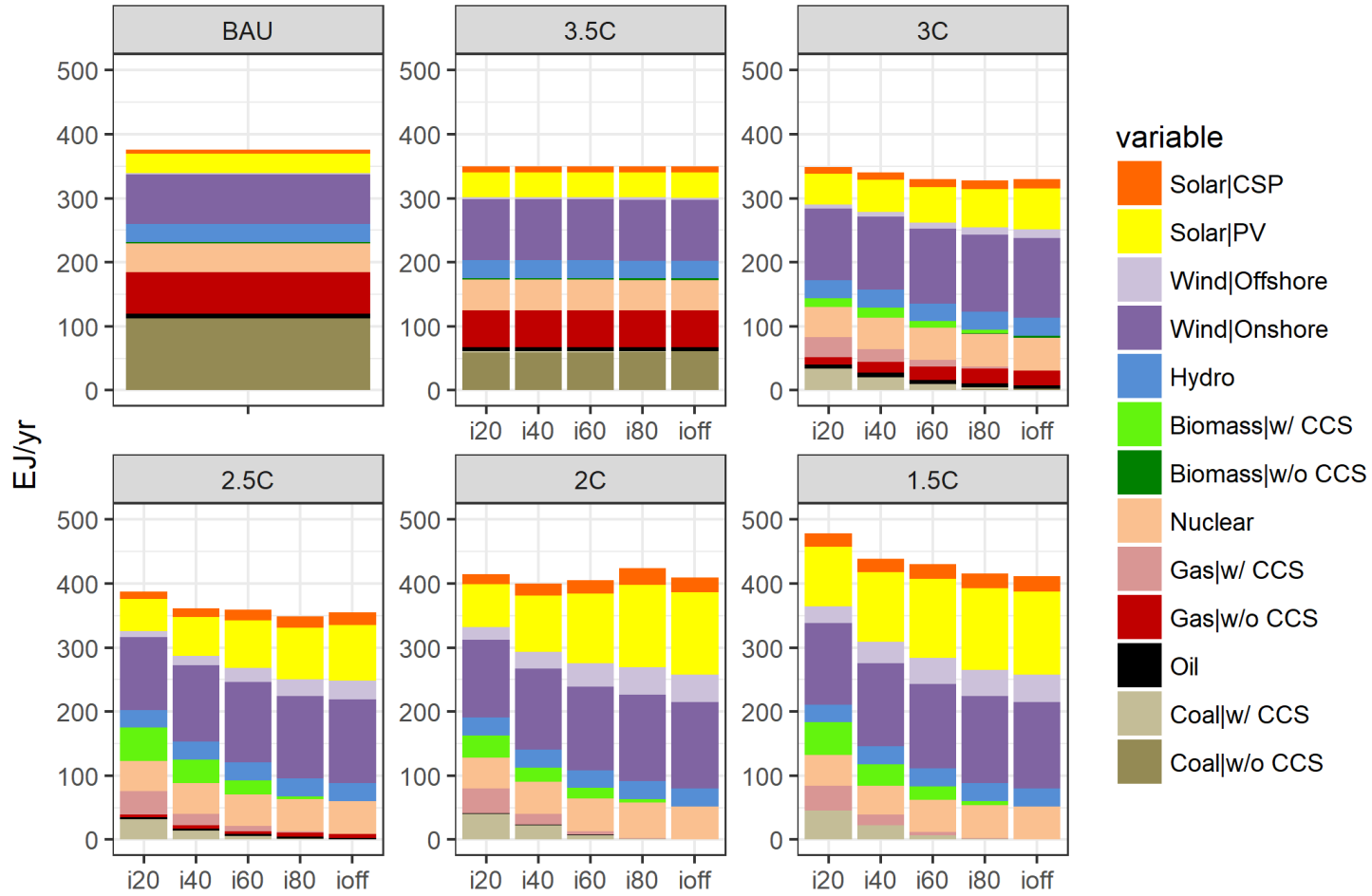


Figure 8 – Global electricity mix in 2100: absolute generation.



### Electricity mix in 2100 - World - Relative shares

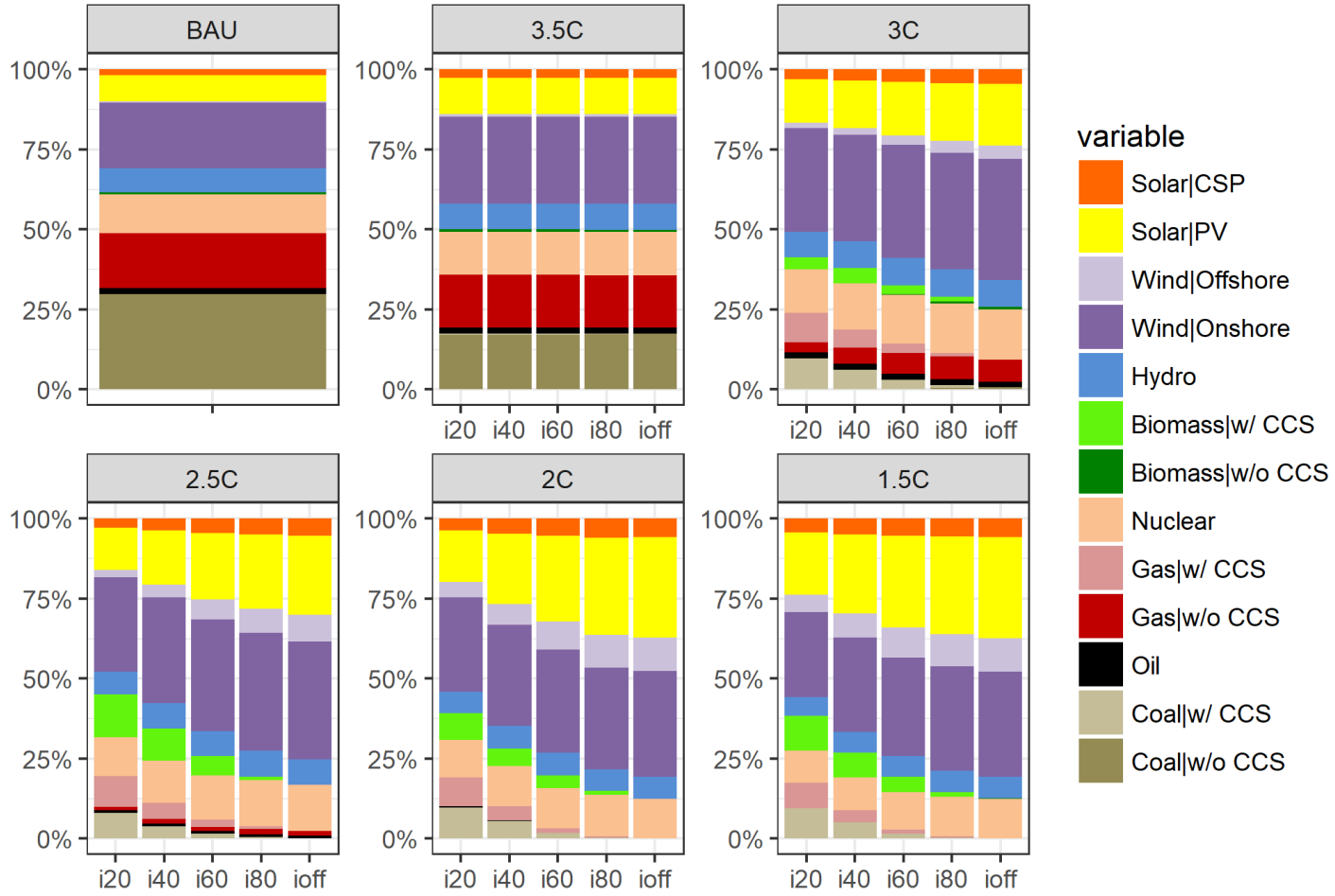


Figure 9 – Global electricity mix in 2100: relative shares.

Concerning the latter result, it should be noted that such a huge penetration of renewables would imply a profound re-structuring of the electricity system. From a modeling point of view, it is not easy to cope with the system integration issues in IAMs, as the low temporal and spatial scales which characterize these aspects are in contrast with the need of providing long-term projections over an horizon of decades, considering aggregated annual quantities and focusing on large regions. However, it is not within the scope of this paper to discuss these topics: here it is sufficient to underline that the model considers huge investment in storage capacity and grid expansion to comply with this renewable deployment. The reader is referred to Carrara and Marangoni, 2017 for further details on the WITCH model and to Pietzcker et al., 2017 for an overview of IAMs.

In order to have a more dynamic view of the electricity mix without focusing on 2100 only, Figures from 10 to 13 show the evolution of the electricity mix over time in selected years (2025, 2050, 2075, and 2100) for the two boundary groups of CCS deployment options, i.e. i20 (thus, the unconstrained CCS scenarios) and ioff (thus, the no CCS scenarios), for all the climate targets. BAU results are always reported for benchmarking purposes. In particular, Figures 10 (i20) and 12 (ioff) report the absolute generations, while Figures 11 (i20) and 13 (ioff) report the relative shares.

These figures help visualize how coal, and then gas, are progressively phased-out in the mitigation scenarios. This happens smoothly over the decades in the milder mitigation scenarios, quite strongly after 2025 in the more stringent scenarios. Naturally, the phase-out is more urgent for coal than for gas, as the former is characterized by specific emissions which are about twice as those of the latter. In the i20 scenarios, fossil phase-out is compensated by the progressive CCS penetration, in addition to the massive deployment of renewables.

Furthermore, Figures 8 and 9 highlighted that biomass without CCS is barely present in the electricity mix in 2100. Indeed, Figures 10 to 13 show that this technological solution does have a non-negligible penetration in the first decades, but then it is phased out, underlining that in the long run biomass is appealing only if coupled with CCS technologies in order to allow negative emissions.

Finally, it has already been noted that the 1.5°C scenarios would imply a huge cut in the electric generation immediately after 2015 in order to meet with the carbon mitigation requirements. Indeed, this implies an immediate retirement of most (i20) or all (ioff) fossil plants. As a result, the 2025 electricity mixes are (almost) completely characterized by a carbon-free generation deriving from hydro, nuclear, and variable renewables. It has already been discussed that this scenario is really extreme, but it is interesting to explore these barely-feasible conditions for comparison purposes.

### Electricity mix over time - World - Absolute generation - i20 scenarios

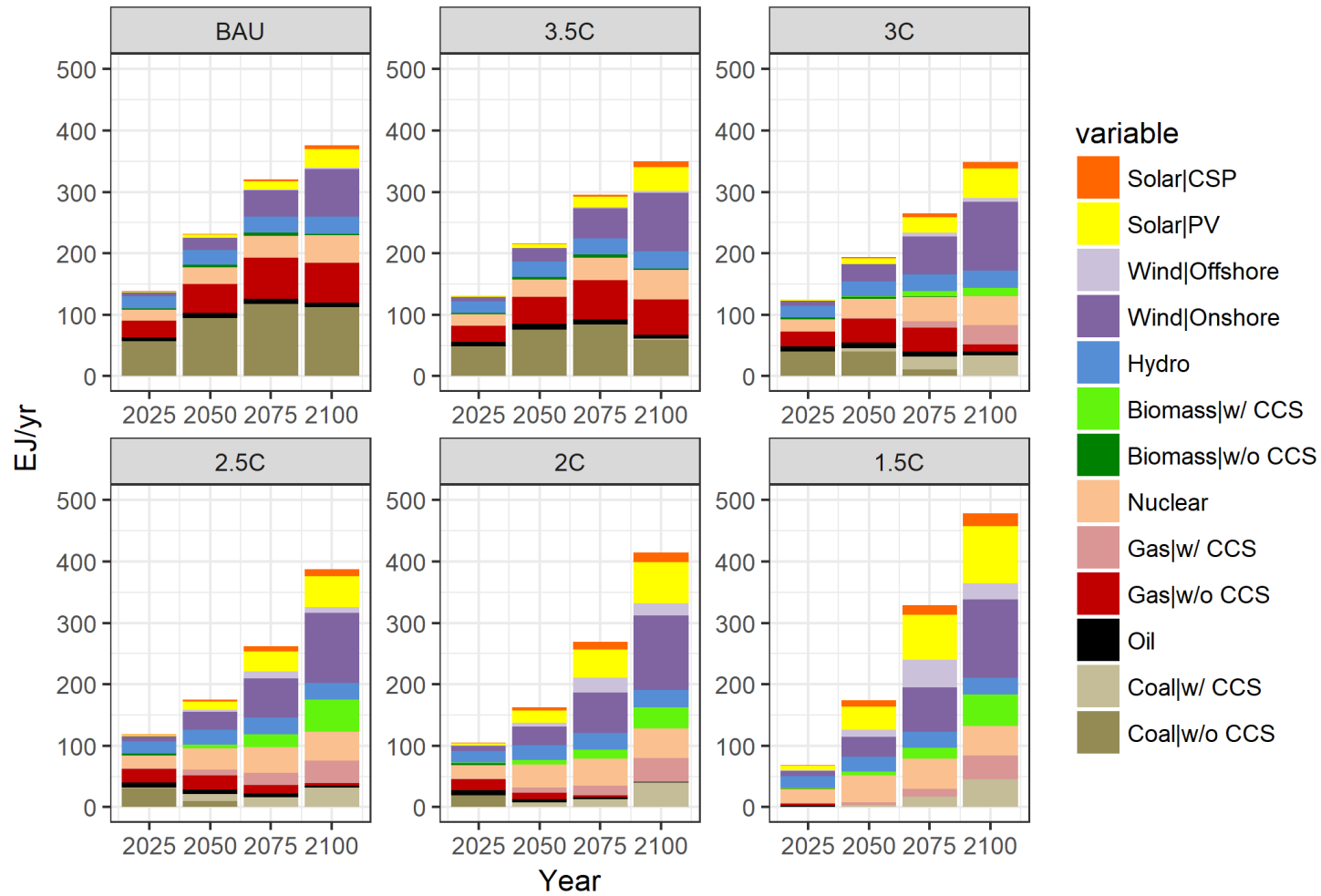


Figure 10 – Global electricity mix over time in the i20 scenarios (unconstrained CCS): absolute generation.

### Electricity mix over time - World - Relative share - i20 scenarios

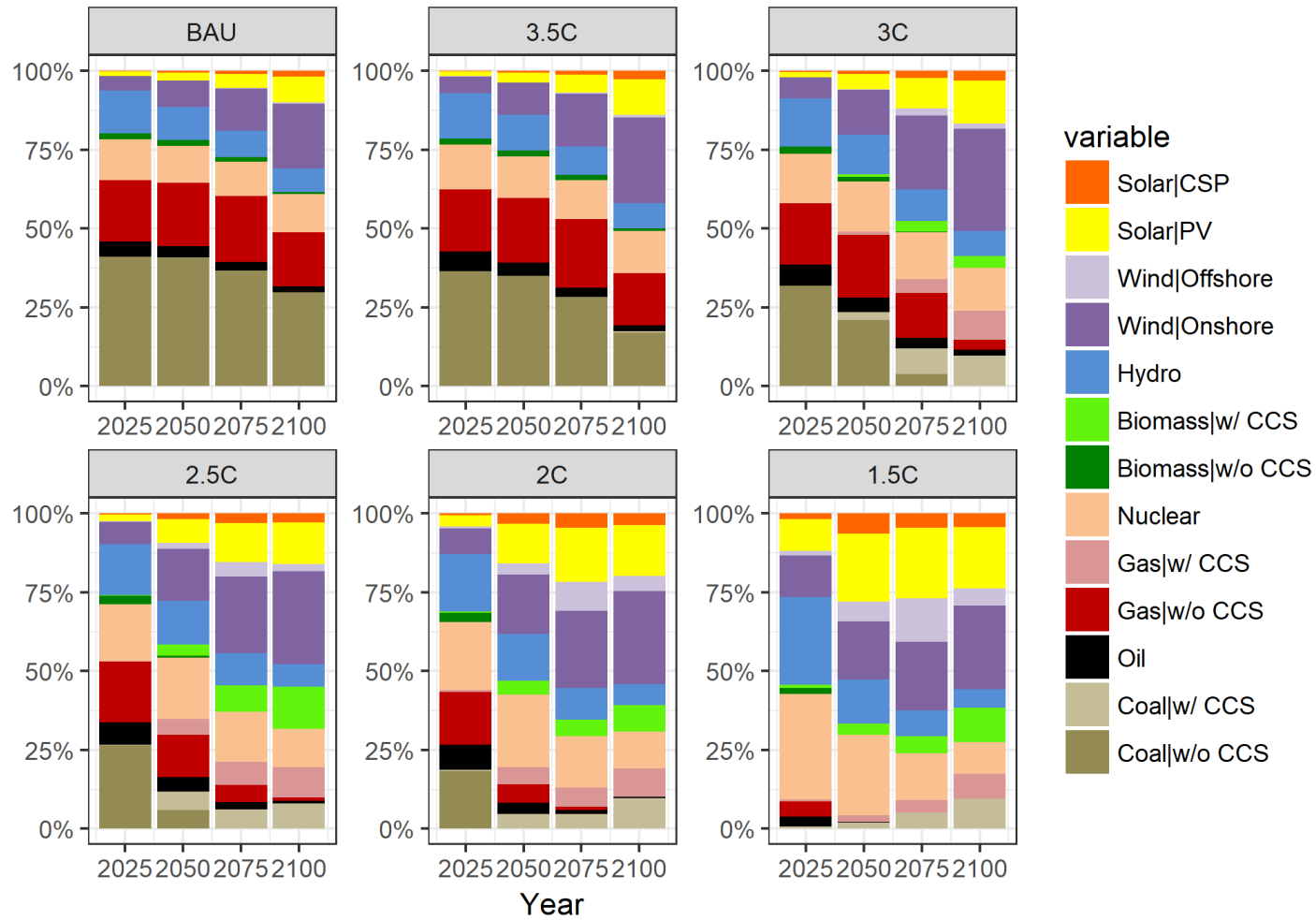


Figure 11 – Global electricity mix over time in the i20 scenarios (unconstrained CCS): relative shares.

### Electricity mix over time - World - Absolute generation - ioff scenarios

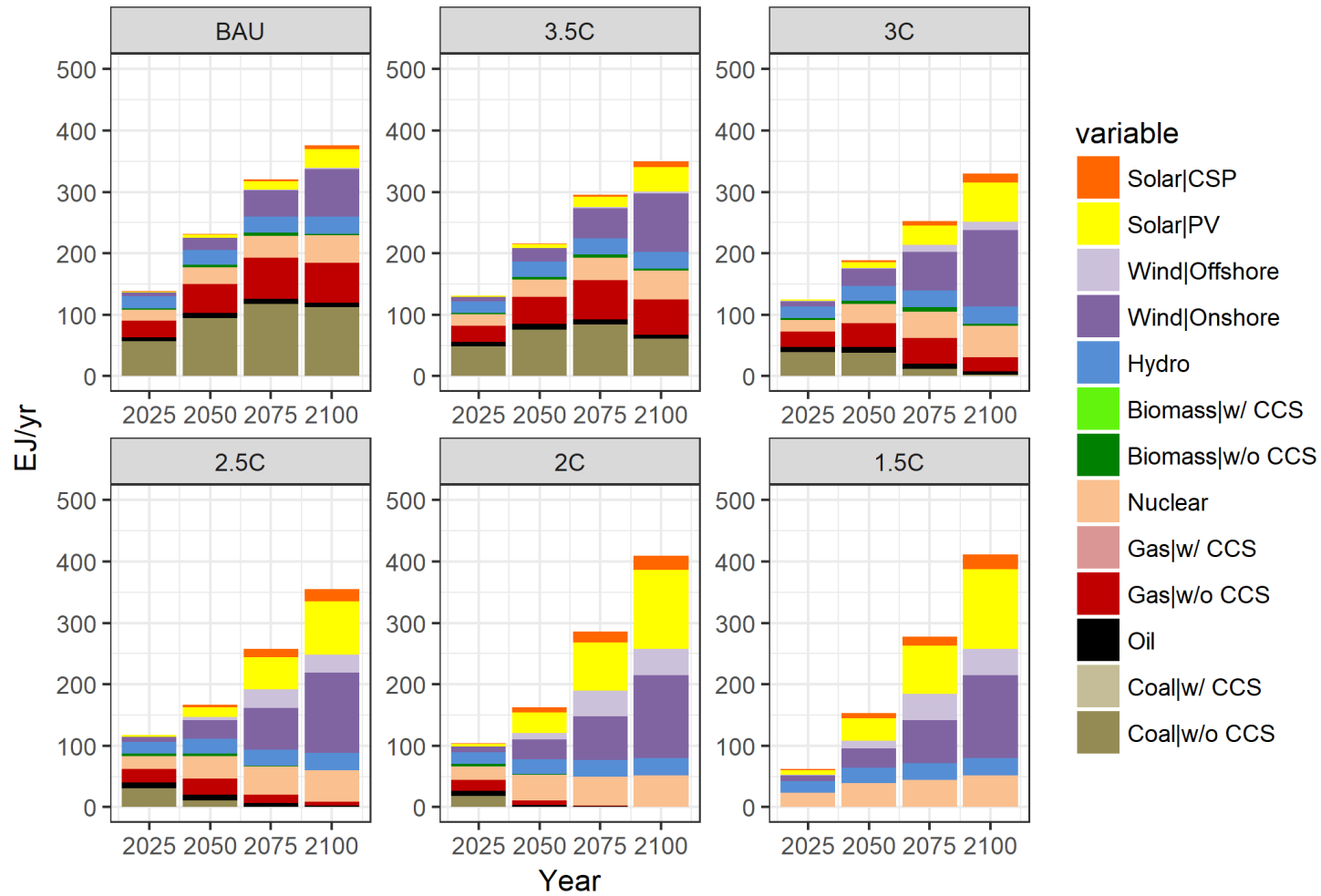


Figure 12 – Global electricity mix over time in the ioff scenarios (no CCS): absolute generation.

### Electricity mix over time - World - Relative share - ioff scenarios

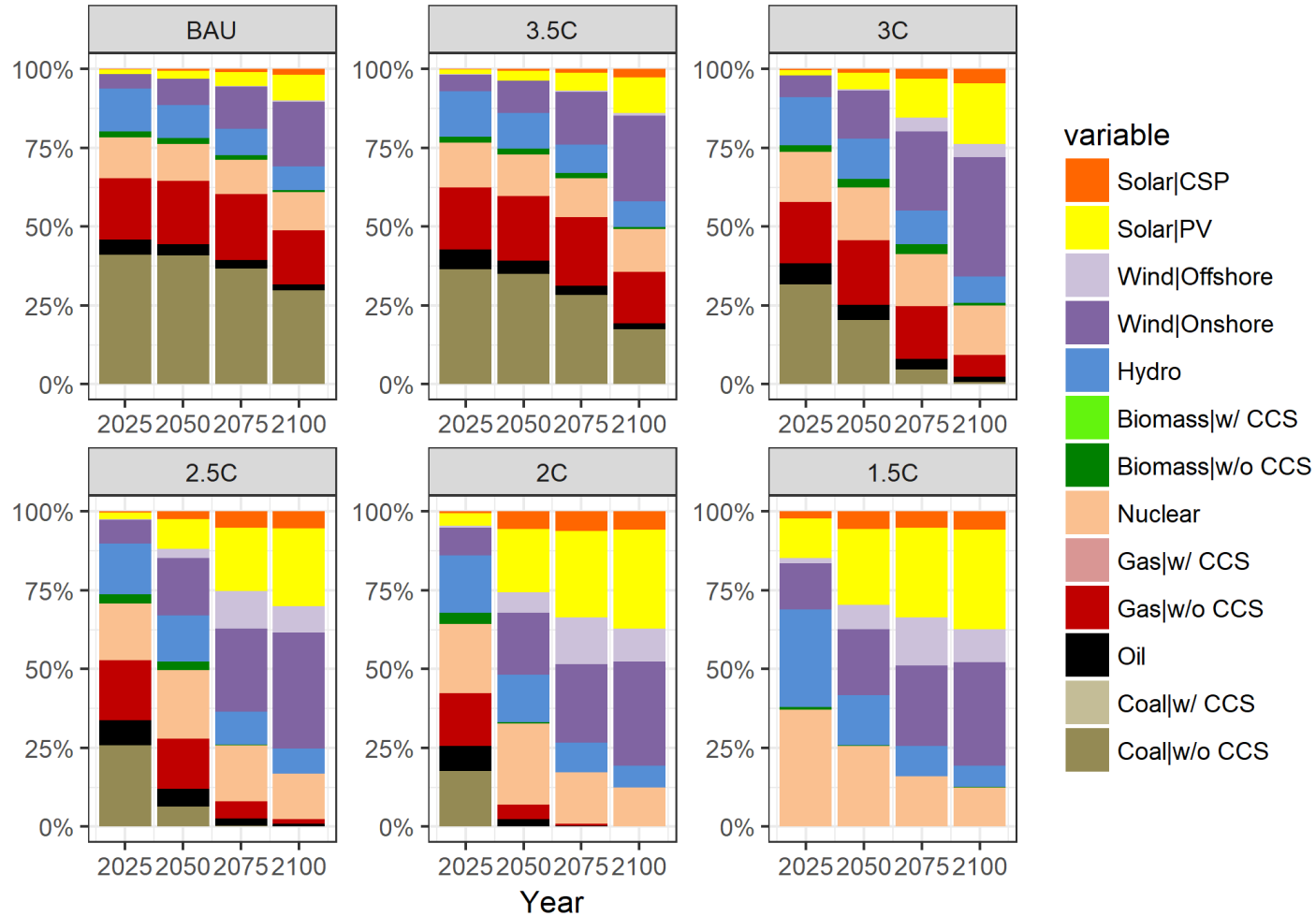


Figure 13 – Global electricity mix over time in the ioff scenarios (no CCS): relative shares.

Figure 14 shows the policy costs in the different scenarios. Policy costs are evaluated as the cumulative GDP loss over the century with respect to the cumulative GDP in the baseline case, considering an annual discount factor of 2.5%. Values are shown on the same scale, in order to facilitate a comparison of the orders of magnitude across the different scenarios.

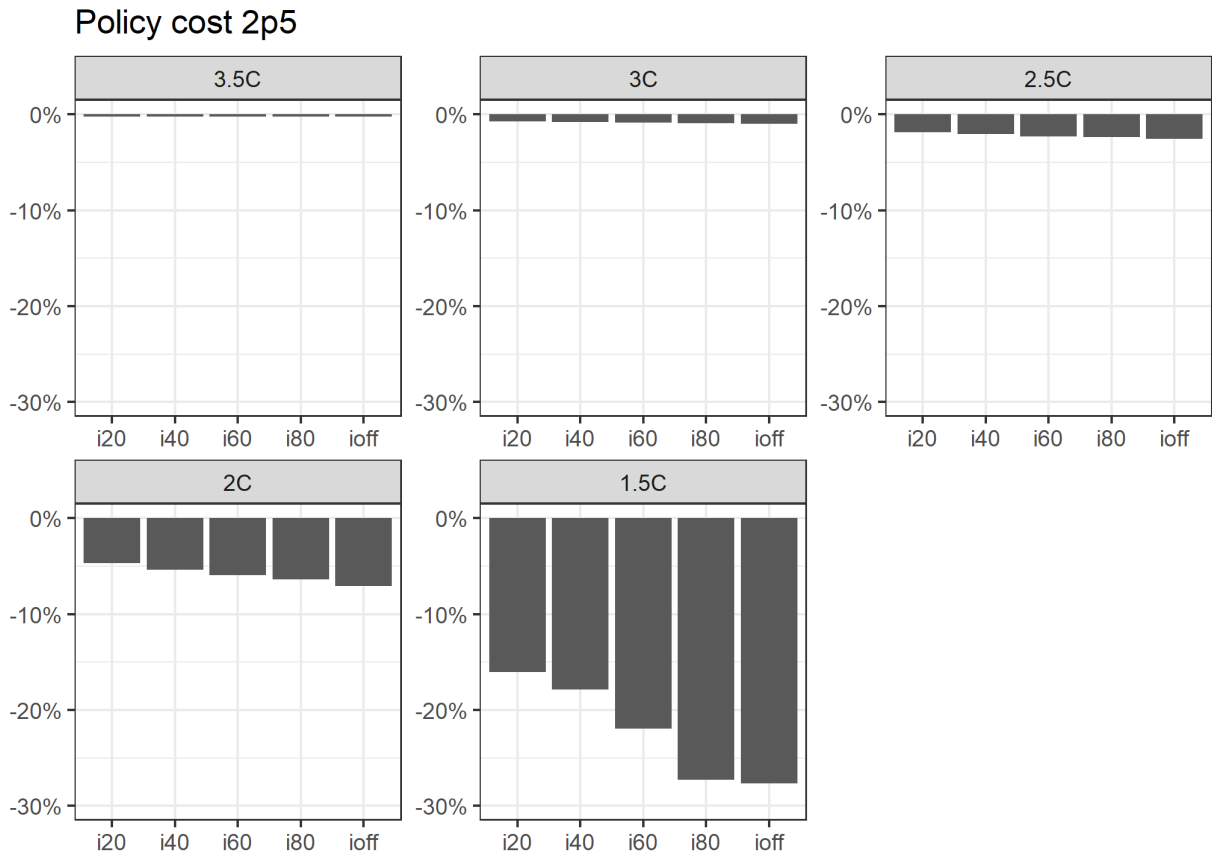


Figure 14 – Policy costs (global GDP loss with respect to the baseline scenario).

Policy costs in the 3.5°C scenarios are negligible, around 0.2%: after all, the stringency of the target is very mild, so the required changes to the economic and energy systems are almost null. As discussed in the previous pages, CCS is not deployed in these scenarios, so results are not differentiated per CCS deployment year within this target. A moderate difference emerges in the 3°C scenarios, where policy costs are around 0.7-1%. In particular the ioff scenario has a policy cost which is 35% higher than the i20 scenario. In the 2.5°C scenarios, policy costs range between 1.9% and 2.7%, with the no CCS case costing 38% more than the unconstrained CCS scenario. If reaching 2.5°C entails relatively moderate costs, achieving the Paris-compatible 2°C target implies much higher expenses. If CCS can be deployed with no constraints, the aggregated GDP loss is 4.7%. This values increases with a progressively delayed CCS deployment, up to 7.1% in the no CCS case, i.e. 51% more than the former. Finally, the profound revolution which is required to achieve the 1.5°C target has inevitable enormous effects on the policy costs: with a fully unconstrained technology portfolio the policy cost is about 16.1%, while it rises up to 27.6% in the corresponding ioff case, i.e. 72% more than the unconstrained case. Therefore, not only is the delayed deployment of CCS impacting on the policy cost, but this impact increases in relative terms with the policy stringency.

## 5. Conclusions

CCS is considered one of the key technologies for climate change mitigation, and in particular for the decarbonization of the power sector. Its main advantage consists in eliminating carbon dioxide emissions without shifting away from the fossil-based paradigm which still characterizes this sector. However, in reality many issues still hinder its diffusion, such as safety concerns about storage sites, public acceptance, high technology costs, and the absence of a common regulatory framework and of business models.

The main aim of this work is to explore the effects that a delayed deployment of CCS can have on the power system and on the economy. Five deployment options have been considered, based on the starting year from which CCS installation is allowed: 2020 (i.e. the unconstrained scenario, as global CCS capacity is practically negligible as of today), 2040, 2060, and 2080, in addition to the no CCS scenario. These five scenarios have been explored over a wide set of policy targets, ranging from the no policy or Business-as-Usual scenario, which leads to 4°C as a temperature increase in 2100 with respect to the pre-industrial levels, to 1.5°C.

Scenarios confirm the consolidated result in the literature that CCS is likely to play a major role in the decarbonization of the electricity sector at a global level, as it is installed in all scenarios with a policy target equal to 3°C or less. In all these cases, as soon as the investment in CCS is allowed, this option is immediately activated by the optimization model. Due to expansion constraints, the delayed installation prevents CCS from reaching the optimal level which would be achieved in the unconstrained scenarios.

This implies a progressively lower penetration in the electricity mix as the deployment is delayed: global CCS penetration is around 25-30% in 2100 in all scenarios from 1.5°C to 3°C, gradually decreasing to zero as the deployment is delayed or not allowed. The contribution from coal, gas, and biomass is quite well balanced. The overall electricity demand diminishes with the progressively delayed CCS deployment. This decrease is indeed quite little if the mitigation effort is limited to 2°C (the difference is lower than 5% in across scenarios), while it is more marked in the 1.5°C scenarios, where the difference in 2100 between the i20 and ioff scenarios is around 15%. The absence of CCS is mostly compensated by renewables (notably wind and solar), with also a moderate increase in nuclear.

Removing (partially or totally) CCS from the optimal electricity mix has significant effects on the overall economic performance. The analysis on the changes in policy costs shows that, within the specific policy targets, the no CCS scenario is characterized by a relative cumulative GDP loss which is from 35% to 72% higher than the corresponding unconstrained CCS scenarios, thus highlighting the strong economic impact of the delayed CCS deployment. Lower differences are found for the more moderate mitigation scenarios (35% is the result obtained if the climate target is 3°C), while the distance broadens as the policy objective becomes more stringent (72% is the relative difference across the 1.5°C scenarios).



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**Fondazione Eni Enrico Mattei**

Corso Magenta 63, Milano - Italia

Tel. +39 02.520.36934

Fax. +39.02.520.36946

E-mail: [letter@feem.it](mailto:letter@feem.it)

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