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MASTER THESIS

The Role of Direct Air Capture to Meet the Paris Climate Agreement: a Multi Model Assessment

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Omnia venenum sunt: nec sine veneno quicquam existit. Dosis sola facit, ut venenum non fit

Paracelsus

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Abstract

The overarching goal of the Paris Climate Agreement is to keep the world global temperature well below 2°C above pre-industrial level. In order to reach this target all the existing studies agree that Carbon Capture Sequestration (CCS) as well as globally net negative emissions will be needed. Among the most prominent candidate technologies to absorb CO_2 from the atmosphere and thus attain negative emissions are Bioenergy burning coupled with Carbon Capture (BECCS) and Direct Air Capture (DAC) of CO_2 from ambient air. If there are already several studies of the first, for the second very few are availble in the literature. The main advantage of DAC is being able to capture CO_2 directly from the atmosphere without the need of a concentrated flux of it. Nevertheless, there are several doubts about costs, plant design, energy consumption and the capacity to build industrially large scale DAC plants. Using two different Integrated Assessment Models (IAM) with different characteristics, I evaluate the role DAC could play in the climate change mitigation framework of the Paris Agreement -for the first time in a multi model setting. To do so, the thesis contributes the following: (1) Providing a brief overview of the state of the art (2) Implementing DAC in two IAM Models (3) Analysing of the role of DAC in 2°C and 1.5°C compatible scenarios. Both models show that DAC could have a significant impact in the mitigation scenarios analyzed. Compliance costs would be heavily reduced by the installation of this technology that would allow an extended usage of fossil fuels in the electric and non electric sector. The biggest beneficiaries of DAC are energy exporting countries that in a case without DAC would be forced to reduce drastically their fossil fuels production. Given DAC flexibility to deal with non concentrated sources, the production of oil is less affected by the climate policy while gas, instead, sees an increase in the production with respect to the current values. A sensitivity analysis to check the robustness of the results has been carried out on the following parameters: capital costs, learning rate, storage capacity and penetration rate. The most critical parameters appear to be the storage capacity and the penetration rate, while the results with respect to the other two are very robust.

Keywords: Direct Air Capture, Climate Change Mitigation, Negative Emissions, Integrated Assessment Models

Sommario

L'obiettivo globale dell'Accordo di Parigi sul Clima è quello di mantenere la temperatura terrestre ben al di sotto dei 2°C in più rispetto ai livelli preindustriali. Per raggiungere questo obiettivo tutti gli studi esistenti sono concordi nel dire che sia la Carbon Capture Sequestration (CCS) sia emissioni globali negative saranno necessarie. Tra tutte le possibili tecnologie che possono assorbire CO_2 dall'atmosfera e quindi ottenere queste emissioni negative ci sono la Bioenergia accopiata con la cattura di anidride carbonica (BECCS) e la Direct Air Capture (DAC) di CO_2 dall'ambiente. Se sulla prima parecchi studi sono già stati fatti, sulla seconda gli studi presenti in letteratura sono molto pochi. Il principale vantaggio di DAC è la capacità di catturare CO_2 direttamente dall'atmosfera senza la necessità di un flusso concentrato di anidride carbonica. Tuttavia esistono diversi dubbi riguardo specialmente costi, schema d'impianto, consumo di energia e capacità tecnica di costruire industrialmente su larga scala queste centrali. Usando due diversi Integrated Assessment Models (IAM) con diverse caratteristiche intrinseche, ho valutato il ruolo che DAC può avere nella mitigazione climatica e nell'accordo di Parigi - per la prima volta in un contesto multi-modello. Per fare questo, i contributi sono stati i seguenti: (1) Breve panoramica sulla letteratura e sullo stato dell'arte (2) Implementazione di DAC nei due modelli IAM (3) Analisi del ruolo di DAC nei due scenari: 2°C e 1.5°C. Entrambi i modelli mostrano che DAC può avere un ruolo importante nella mitigazione in entrambi gli scenari. Il costo per rispettare tali obiettivi sarebbbe molto diminuito dall'installazione di questa tecnologia che permetterebbe un uso prolungato di combustibili fossi sia nel settore elettrico che in quello non elettrico. I maggiori beneficiari di DAC sono i paesi esportatori di energia che senza DAC vedrebbero ridotte drasticamente le loro produzioni fossili. Per via della flessibilità che DAC garantisce nella gestione di fonti non concentrate di CO_2, la produzione di petrolio è meno influenzata dalle politiche climatiche mentre il gas, invece, vede addirittura un aumento della produzione rispetto al livello attuale. Un'analisi di sensitività è stata poi fatta per controllare la robustezza dei risultati facendo variare i seguenti parametetri: costi di investimento, tasso di apprendimento, capacità di stoccaggio e tasso di penetrazione. I parametri più critici si sono dimostrati essere la capacità di stoccaggio e il tasso di penetrazione mentre i risultati per gli altri parametri si sono dimostrati molto robusti.

Parole Chiave: Direct Air Capture, Mitigazione dei Cambiamenti Climatici, Emissioni Negative, Integrated Assessment Models

Extended Summary

Scope of the Work

The overarching goal of the Paris Climate Agreement is to keep the world global temperature well below 2°C above pre-industrial level. In order to reach this target all the existing studies agree that Carbon Capture Sequestration (CCS) as well as globally net negative emissions will be needed. Among the most prominent candidate technologies to absorb CO_2 from the atmosphere and thus attain negative emissions are Bioenergy burning coupled with Carbon Capture (BECCS) and Direct Air Capture (DAC) via chemical absorbers.

Using two different Integrated Assessment Models (IAM) with different characteristics I evaluate the role DAC could play in the climate change mitigation framework of the Paris Agreement. To do so, the thesis contributes the following: (1) Providing a brief overview of the state of the art (2) Implementing DAC in two IAM Models (3) Analysing of the role of DAC in 2°C and 1.5°C compatible scenarios.

Very few studies have tackled this topic from a IAMs perspective and this is, to the best of my knowledge, the first study ever to compare the role of DAC across different models.

Structure

The work is structured as follows. The first chapter provides an overview of the reason behind this study and how this study fits into the current climate change framework. Chapter 2 show all the possible designs DAC could have, with their costs and energy consumption charachteristics. Chapter 3 describes what an Integrated Assessment Model is, the characteristics of the two models used (WITCH and IMAGE) and how DAC has been implemented in those models. Chapter 4 and Chapter 5 provide the main analysis of the results, including the sensitivity analysis. Chapter 6 sums up all the results and puts forward ideas for new studies on this topic.

Methodology

Integrated Assessment Models (IAMs) are the main methodological tools used in this work. I use WITCH, an IAM developed at Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) as well as IMAGE, developed and mantained at PBL Netherlands Environmental Assessment Agency. The main characteristic of IAMs is to combine different sectors, like the energy, economy and climate ones, into a unified framework in order to account for the interconnectedness of the complex climate change problem.

The first step was to do a literature review in order to collect all the datas that are needed for the implementation. This step was complicated by the relative paucity of data on costs and energy consumption. The next step was to design the equations and write them in programming languages (GAMS and R). The equations governing DAC were written in dedicated modules and then linked to the main model. The final step was to run the models evaluating a range of climate policy scenarios and perform an extended sensitivity analysis.

Results and Conclusions

DAC appears to be a technology that could change the way the climate change is managed. Both models, despite the different charachteristics, heavily rely on this technology in the scenarios analyzed.

The total electricity demand does not present big variations with respect to the case without DAC. The electricity mix is influenced especially in the first half of the century where a more diffused presence of fossil fuels can be seen, coal and gas coupled with CCS are expected to have a bigger share with respect to the no-DAC case. In the second half of the century a switch to renewables is still needed since the fossil fueled power plants are expected to phase out almost completely.

Considering the non-electric sector oil and coal production is still expected to decrease in terms of total demand but at a slower rate with respect to the no-DAC case. Gas demand, instead is expected to grow with DAC expected to become the biggest source of demand of natural gas, accounting for almost half of the total. A big reduction in the policy costs is clearly evident in those countries that have economies that rely on fuel exports like the Middle East or Russia. Oil&Gas market size is expected to be significantly bigger during the whole century reducing, especially in the previously mentioned regions, the economic losses that a climate policy usually involve.

Due to the big diffusion of DAC and in general of CCS technologies, the amount of stored emissions is very high and so the CO_2 storage capacity becomes an important parameter. The penetration rate, that is the technical capacity to produce and install the amount of DAC required, appears to be most important input assumption. Future work should further explore it.

Sommario Esteso

Scopo del lavoro

L'obiettivo globale dell'Accordo di Parigi sul Clima è quello di mantenere la temperatura terrestre ben al di sotto dei 2°C in più rispetto ai livelli preindustriali. Per raggiungere questo obiettivo tutti gli studi esistenti sono concordi nel dire che sia la Carbon Capture Sequestration (CCS) sia emissioni globali negative saranno necessarie. Tra tutte le possibili tecnologie che possono assorbire CO_2 dall'atmosfera e quindi ottenere queste emissioni negative ci sono la Bioenergia accopiata con la cattura di anidride carbonica (BECCS) e la Direct Air Capture (DAC) di CO_2 dall'ambiente. Usando due diversi Integrated Assessment Models (IAM) con diverse caratteristiche intrinseche, ho valutato il ruolo che DAC può avere nella mitigazione climatica e nell'accordo di Parigi - per la prima volta in un contesto multi-modello. Per fare questo, i contributi sono stati i seguenti: (1) Breve panoramica sulla letteratura e sullo stato dell'arte (2) Implementazione di DAC nei due modelli IAM (3) Analisi del ruolo di DAC nei due scenari: 2°C e 1.5°C.

Gli studi fatti usando IAMs riguardo questo argomento sono molto pochi e questo lavoro dovrebbe essere il primo mai fatto che confronta gli effetti di DAC in due IAMs differenti.

Struttura

La tesi è strutturata come segue. Il primo capitolo fornisce il perché di questo studio e come questo studio si integra all'interno della discussione sul cambiamento climatico. Il Capitolo 2 mostra i vari possibili schemi di impianto di DAC con i loro costi di investimento e consumi energetici. Il capitolo 3 descrive cosa sia un Integrated Assessment Model e le caratteristiche tipiche di WITCH e IMAGE. Inoltre mostra come DAC è stato aggiunto a questi modelli. Nei capitoli 4 e 5 vengono analizzati i risultati, compresi dell'analisi di sensitività. Il capitolo 6 riassume i risultati e fornisce idee per futuri studi riguardanti questa stessa tematica.

Metodologia

IAMs sono il principale strumento usato in questo lavoro, in particolare sono stati usati WITCH e IMAGE. WITCH è un IAM sviluppato alla Fondazione Eni Enrico Mattei (FEEM) e al Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) mentre IMAGE è stato sviluppato alla PBL Netherlands Environmental Assessment Agency. La caratteristica principale degli IAMs è riunire sotto un'unica comune struttura diversi campi del sapere, come economia e scienza dei cambiamenti climatici, per fare in modo da avere una interpretazione più semplice di un problema così complesso.

Il primo passo verso l'implementazione è stato fare una ricerca bibliografica necessaria per raccogliere tutti i dati di input al modello. Questo passo ha presentato diverse difficoltà dovute all'incertezza dei dati che presentavano un intervallo di valori molto ampio e quindi trovare i dati giusti da inserire non è stato facile. Per questa ragione alcune semplificazioni sono state fatte per permettere un migliore inserimento nel modello. Il passo successivo è stato quello di pensare le equazioni da inserire e poi scriverle in linguaggio GAMS e M. Queste equazioni sono state inserite in moduli separati e poi collegati al modello principale. Il passo finale è stato quello di lanciare le simulazioni e fare le analisi di sensitività necessarie.

Risultati e Conclusioni

DAC sembra quindi essere una tecnologia che potrebbe cambiare il modo in cui il cambiamento climatico può essere affrontato. Entrambi i modelli, seppur iniziando le installazioni in diversi periodi, contano molto su questa tecnologia in entrambi gli scenari analizzati.

La domanda totale di energia elettrica non presenta grandi variazioni rispetto al caso senza DAC. Il mix energetico è influenzato in particolare nella prima metà del secolo dove una diffusa presenza di combustibili fossili può essere notata. Nella seconda metà del secolo invece un passaggio a fonti di energia rinnovabile è comunque necessario visto che le centrali a combustibile fossile spariscono quasi completamente dal mix energetico.

Riguardo il settore non elettrico, la produzione di carbone e petrolio vede un calo anche se ad una velocità minore rispetto al caso senza DAC. La produzione di gas invece vede un incremento con DAC che secondo le previsioni potrebbe essere la più grande fonte di domanda di natural gas, contando per almeno metà della domanda totale. Una grande riduzione dei costi della politica climatica è evidente in quelle regioni che basano le loro economie sull'esportazione di combustibili fossi come il Medio Oriente e la Russia. Le proiezioni riguardo il mercato dell'Oil&Gas dicono che nel caso di DAC questo risulta più grande riducendo quindi, specialmente nelle regioni prima menzionate, le perdite economiche che una politica economica solitamente comporta.

Per via della grande diffusione di DAC e in generale di tecnologie di CCS, la quantità di emissioni stoccata è molto alta e per questa ragione è importante essere sicuri di avere abbastanza capacità per stoccare tutta la CO_2 che il modello vuole stoccare. Il tasso di penetrazione, quindi la capacità tecnica di produrre e installare la quantità di DAC richiesta, deve essere studiato perché il suo valore può influenzare i valori in una maniera significativa.

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Introduction and Motivation

1.1 General Overview

One of the biggest problems humanity has to face in the 21st century is climate change. The correlation between increasing temperatures and greenhouse emissions caused by human actions has been recognized by the vast majority of the scientists. Intergovernmental Panel on Climate Change (IPCC) reports that the increasing of global mean temperatures will have several tragic consequences: rising sea level, ice melting, catastrophic events more likely to happen. The increase in temperature will be faster than the nature's adaptation velocity increasing the risk of extinction of 20-30% of plant and animal species. There will be problems for humans as well, it is expected that there will be an increase in malnutrition, diarrheal and cardio-respiratory diseases [35] [3]. But even if the evidences are very clear, the international political consensus on the need to reduce carbon dioxide emissions has been low in coming.

In the latest years, though, some steps forward have been made. In 2015 in Paris a conference of the parties (COP) has been held. The purpose of this COP21 was to set concrete targets of emission reduction and to set possible policies about mitigation and adaptation. These intentions were confirmed one year later in Marrakesh at the COP22 where the countries have ratified the Intended Nationally Determined Contributions (INDC).

1.2 Paris Agreement

During COP 21 the vast majority of the nations of the world agreed to face the common cause of climate change and undertake ambitious efforts to face it. The central aim is to keep the global temperature rise below the threshold of 2°C and to pursue efforts in order to limit the temperature even below 1.5°C. Another aim is to strengthen the ability of the countries to adapt to the impact of climate change.

In order to respect those limits it is necessary to cut the CO_2 emission production. For every particular rise in temperature there are some cumulative emission budgets in the period from 2011 to 2100 of greenhouse gasses (GHG) emissions that cannot be exceeded. The higher the budget, the lower the likelihood of restricting warming to a particular level. In order to reach the targets set by this agreement the INDC

Temperature Rise [°C]	**Carbon Budget** [$GtCO_2$]	**Radiative Forcing** [W/m^2]
1.5	400	1.9
2	1000-1600	2.6

Table 1.1: Carbon budgets and corresponding radiative forcing to respect the temperature threshold

countries have to limit their emissions in a way such that these budgets (Table 1.1) are respected. However limiting the emissions it is easier said than done, because of the challenges, both economical and technical, that have to be faced.

From a technical point of view the radical shift from a fossil fuel based system to an renewable powered system is complex and not ready to be implemented yet. This will also influence the economic point of view since the new possible options are more expensive with respect to the classical ones. Moreover spending more money in the present without seeing an actual profit, that will be seen only by future generations, will lead also to an ethical problem as well.

1.3 Current CO_2 Emissions Situation

In 1750, according to a study of Joos and Sphani [21], the concentration of CO_2 in the air was 277 part per millions (ppm). During the three centuries after that date the concentration has constantly increased and in May 2013, for the first time, it has gone over 400 ppm. If at the beginning the rise in concentration has been due to land-use-change activities, after the industrial revolution the main source of emissions have been fossil fuels and they still are the major contributor.

As it can be seen in Figure 1.2 in 2015 fossil fuels produced 9.6±0.6 GtC/year which corresponds to 35.2±2.2 $GtCO_2$/year. There are also natural sinks as ocean and land that are able to capture around 15 $GtCO_2$/year. Considering emissions and sinks, the amount of carbon dioxide remaining per year in the atmosphere is 16.5 $GtCO_2$. These values are not constant, they are constantly increasing. It is easy to understand that with the current emissions' pace the budgets, for both the targets, would not be respected.

The main source of emissions is the power generation sector, that accounts for nearly half of the total emissions, other significant emitting sectors are the transport and the residential sector. Coal fueled plants are still today the main source of electric energy accounting 40% of the total electricity produced in the world. If we add the other fossil fuels, gas and oil, this percentage reaches 65%. Fossil fuels are also the main source of energy for the transport sector that is expected to constantly increase in terms of emissions as more and more vehicles are being bought in the developing countries.

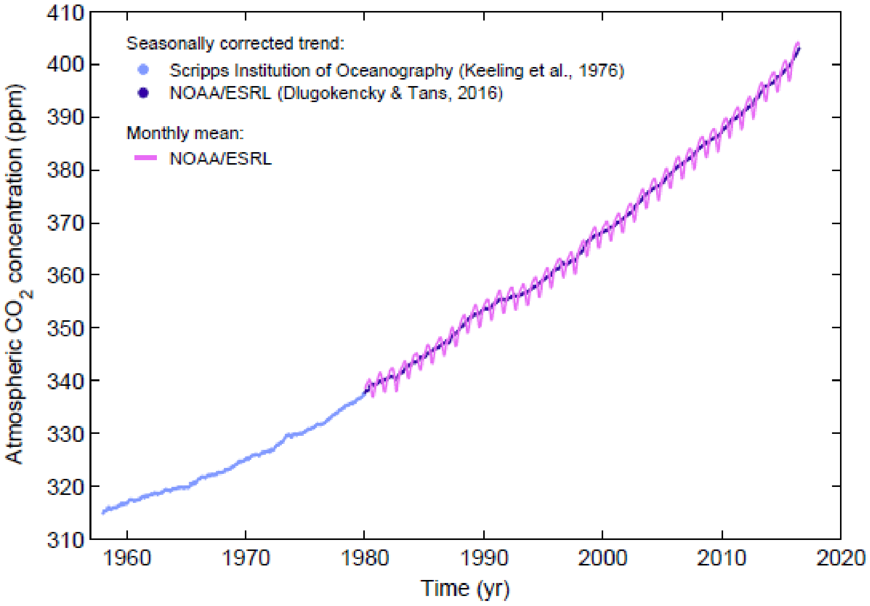


Figure 1.1: Historical and present concentration of CO_2 in atmosphere

1.4 How to Reduce Emissions

There are several ways to reduce emissions, some are general and some are more sector-related. The most general way is to increase efficiency of plants or vehicles. In this way for the same amount of output produced, whether it is electricity or km driven, the amount of emissions will decrease. While doing this it is also important to take into consideration the Jevon paradox that states that when there is an increase in efficiency in the usage of a resource the rate of consumption of the same resources tends to increase because of an increase in the demand reducing so the benefits of the increase in the efficiency.

In the electricity sector it is easy to think about switching to renewable sources as wind, solar or to nuclear power. However there are very well known issues related to both these solutions. Nuclear, even if it is a cheap alternative to fossil fuels, is badly seen by people and in some countries of the world it is forbidden and for these reasons its possibility to be a valid alternative is reduced. Solar and wind (and in general renewables) are very well seen by the population but they have drawbacks mainly linked to their costs and their dispatchability. The investments costs are high but have decreased a lot and under certain circumstances can become competitive with standard technologies. Dispatchability is still a problem, renewables are in general intermittent and this means that their presence requires the grid to be flexible. Having priority of dispatchability the electricity they produce is always put into the market forcing the grid to balance the production from all the other sources of energy in order to supply the amount of electricity needed. This means that they cannot give a base load as nuclear or fossil can. This problem can be resolved by the use of batteries in order to stock the excess of electricity and use it when it needed, but batteries have not reached a techno-economic level that will

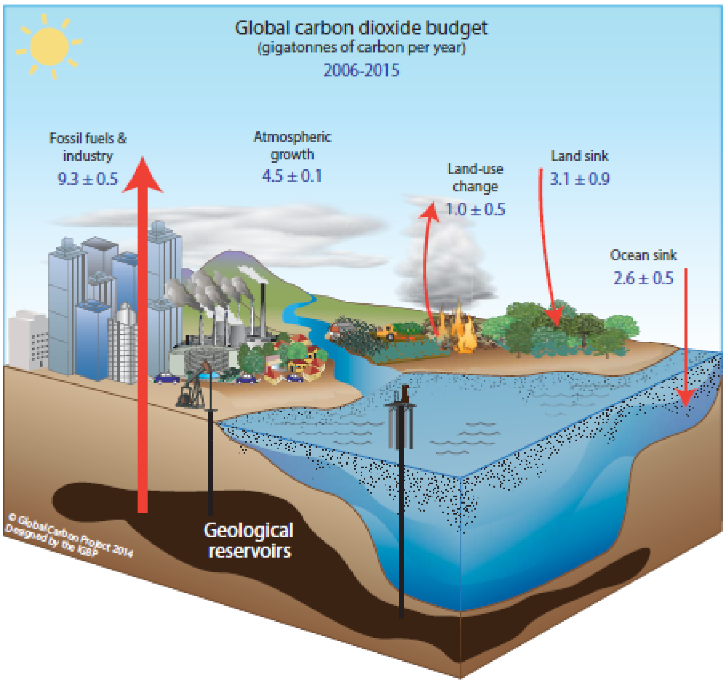


Figure 1.2: Schematic representation of current emissions and sinks

allow to do this in a competitive way.

1.5 Why Do We Need Negative Emissions

Reducing the emissions may not be enough if the objective is to respect Paris' targets. Several studies have shown that the possibility of achieving the 2°C target, and so the 1.5°C target, is linked to the cumulative amount of CO_2 emissions. On average the budget, across the century, needed to respect the 2°C target goes from 1600 $GtCO_2$ to 1000 $GtCO_2$, respectively with a probability of 50% and 66%. The budget shrinks to 400 $GtCO_2$ if we want to reach the 1.5°C target with probability of 50%. To have an idea of the challenges those budgets set it is enough to calculate the budget in the business as usual (BAU) case. This budget overcomes the 5000 $GtCO_2$, so more than 3 times the allowed emissions for the least strict target. Knowing all these numbers is "conventional" mitigation, so just the reduction in CO_2 emissions, enough? Or do we need something more than just reducing like capturing the CO_2 we produce?

In a study by Gasser et al [14]., reduction of emissions through conventional mitigation has been taken into account. In particular emissions start to decrease in various points of time 2015,2020,2025 or 2030 at a various exponential decarbonization rates from -5% to -1%. The exponential shape of the decrease comes from the assumption that the most effective actions will be taken first, leaving the least effective at last. The rates were chosen taking into considerations historical datas, like the -4.6% yearly reduction in French emissions during the nuclear program of 1980-1985, and the pledges by USA and EU. Even in the best case scenario, -5%

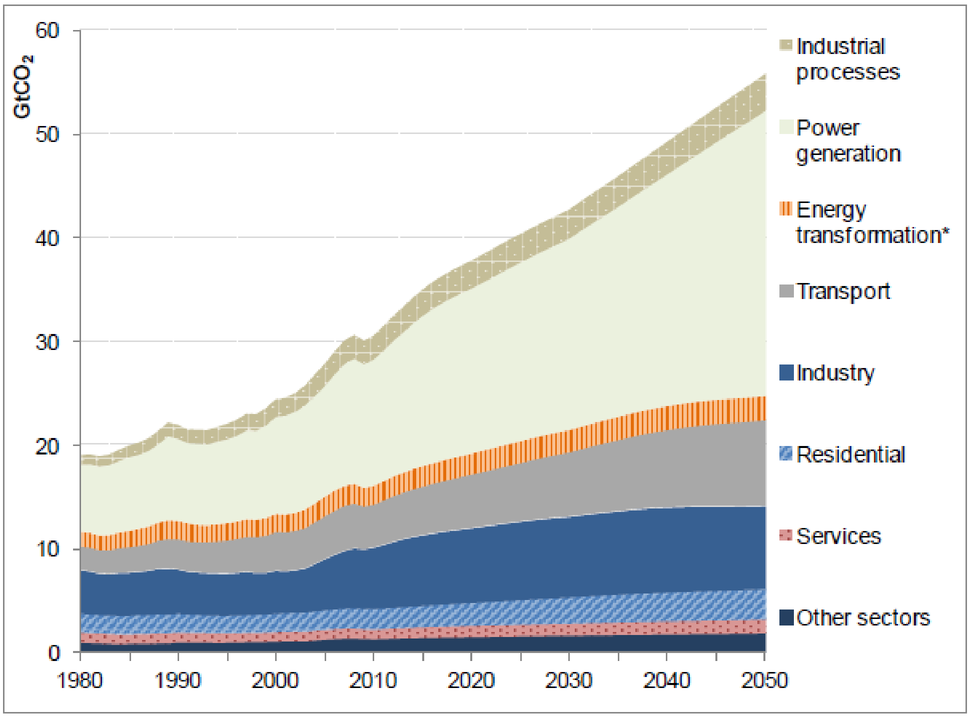


Figure 1.3: Global CO_2 emissions by source 1980-2050

yearly starting in 2015, there is the need of capturing from 1.8 to 11 $GtCO_2$ per year to respect the target. What are the ways to capture CO_2?

The most common idea of doing so is to capture carbon dioxide directly where a CO_2 rich-air is produced, at the exhausts of fossil fuel power plants. This technology is called Carbon Capture Sequestration (CCS). This will allow to have a fossil fuel power plant that can virtually be considered carbon neutral because almost all the CO_2 normally produced will be captured and stored underground. Power plants can actually be considered carbon negative in some cases. If we consider a CCS power plant fueled by biofuel, we can say that the overall process actually captures more carbon dioxide than the one produced. Biofuel per se is considered carbon neutral since plants, from which it is produced from, during their lifetime absorb an amount of CO_2 that is similar to the amount of CO_2 produced by the burning of the biofuel. So powering a power plant with biofuel and then capturing the emissions is actually carbon negative.

This type of power plant is called Bio Energy Carbon Capture Sequestration (BECCS). All that glitters ain't gold, BECCS have several issues linked specially to the fact that the harvesting of the crops needed to produce biofuel is in direct competition with food, moreover the amount of water needed can be a problem. For these reasons a lot of studies have been made to calculate the potential of BECCS such that there is not a competition with food crops which is estimated to be around 10 $GtCO_2/y$. This is a way to deal with emissions that are produced in a specified area, and for this reason they are called centralized. So CCS is a good way to tackle point source emissions but it is definetely not suitable for decentralized emitters like vehicles. Their emissions can not be captured by any type of "traditional" CCS.

What it can be done instead is to try to capture CO_2 directly from air, so treating air in order to reduce its carbon content. The main issue related to this type of technology is well explained by the Sherwood plot.

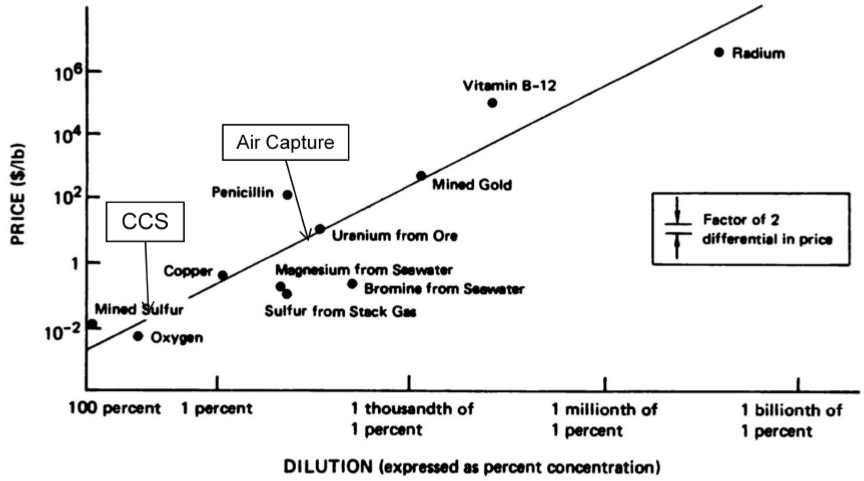


Figure 1.4: Sherwood plot

At the end of the 50's, it was originally plotted to show the empirical relationship between the price of a metal and the concentration of that metal in the ore it was extracted from, plotted on a log-scale. Later it has been seen that this relationship can be extended to several other substances. Being the concentration of CO_2 in flue gasses in a range that goes from 3% to 15% while the concentration of CO_2 in atmospheric air in the range of 400 ppm it is easily seen that the costs will be much higher. The plants that are able to capture CO_2 directly from air don't have a proper name yet and they are simply called Direct Air Capture (DAC) plants. This is not sci-fi, in fact the first DAC plant, able to capture 900 tonnes of CO_2 per year, has been installed on the 31^{st} of May 2017 in Zurich by the Swiss Company Climeworks. Their projections is that, by the time of 2025, they would be able to capture 1% of global CO_2.

1.6 Questions and Methodology

1.6.1 Questions

DAC is a reality and probably closer to a large scale deployment than what we expect. In a climate change perspective carbon dioxide removals are one of the hottest topics in last years. Some questions naturally pop up and the objective of this thesis is to give, or at least try, an answer to these questions:

1. What are the DAC plant designs that exist? What is their energy consumption? What are their costs?

2. What impact could DAC have on climate change policies if there is the possibilty to use it?

3. What impact could DAC have on the electricity production and on the fossil fuel usage?

4. How the uncertainties on costs, storage, learning rate, installation rate could influence the impact of DAC?

1.6.2 Methodology

Integrated Assessment Models (IAM) are the base of this thesis. IAMs are the main instrument used to face the problem of global warming. They are a type of scientific modelling able to make the interpretation of dependent phenomena, such as climate, energy and economy, easier. In this thesis two different IAMs have been used are WITCH (World Induced Technical Change Hybrid) and IMAGE (Integrated Model to Assess the Global Environment). Both the IAMs used are designed to analyze climate mitigation and adaptation policies taking into consideration economy, energy and climate change. In order to implement DAC technology in those models and have an answer to the previous questions these are the steps that has been followed:

1. Literature Review: collecting informations and datas on the possible DAC technologies with their present and estimated future costs, electric and thermal consumptions. The scarcity of technical papers has made this part very challenging and critical because good datas are the base for a good implementation

2. Equation Design and Implementation: after the review the datas collected had to be processed in order to use them into equations. These equations then had to been implemented according to the language of the models: GAMS (General Algebraic Modeling System) for WITCH and M for IMAGE

3. Scenario Runs: when the implementation was completed, different runs with different targets have been done to see the impact of DAC

4. Parameter Sensitivity Analysis: being the range of datas obtained in the first step very wide an analysis on the boundaries was necessary. So the new runs have been made changing every time a data in order to see the effect of that on the final result.

1.6.3 Thesis Structure

The rest of the thesis is divided as follow:

Chapter 2: DAC is described under a technical point of view proposing several designs

Chapter 3: A description of IAMs has been given, with a focus on WITCH and IMAGE. Then it is described how DAC has been modelled

Chapter 4: An analysis of the results obtained for the 2°C scenario

Chapter 5: An analysis of the results obtained for the 1.5°C scenario

Chapter 6: Conclusions and further possible studies

Chapter 2

Technical Design of Direct Air Capture (DAC) of CO_2 from Ambient Air

2.1 Introduction

Direct Air Capture is not a fully mature technology, for this reason there are several proposed designs for capturing CO_2. In this chapter I will describe the most likely to be implemented in the future.

2.2 Sodium Hydroxide and Calcium Hydroxide Cycles Based Plant

This can be considered the standard design plant. The majority of the possible designs of DAC plants is based on the design here descripted with some changes in the components but still relying on the same chemical elements and reactions.

2.2.1 Plant Design

These types of plants are mainly based on a scheme proposed by Baciocchi [1]. All the companies that work in this field rely heavily on this design, with only few variations with respect to the standard plant. In his paper Baciocchi proposed two different schemes.

The first step, in both the proposed designs, is to absorb the CO_2 where an aqueous solution of sodium hydroxide will absorb carbon dioxide converting it into sodium carbonate.

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \tag{2.1}$$

So carbon dioxide in air is conveyed into an absorption column where it will react with a sodium hydroxide solution forming a stream containing that carbon dioxide in form of carbonate ions. The main issue about this absorption column is the very low concentration of CO_2. To solve this problem what is needed is a column able to work with low pressure drops and a high throughput and there are some absorption

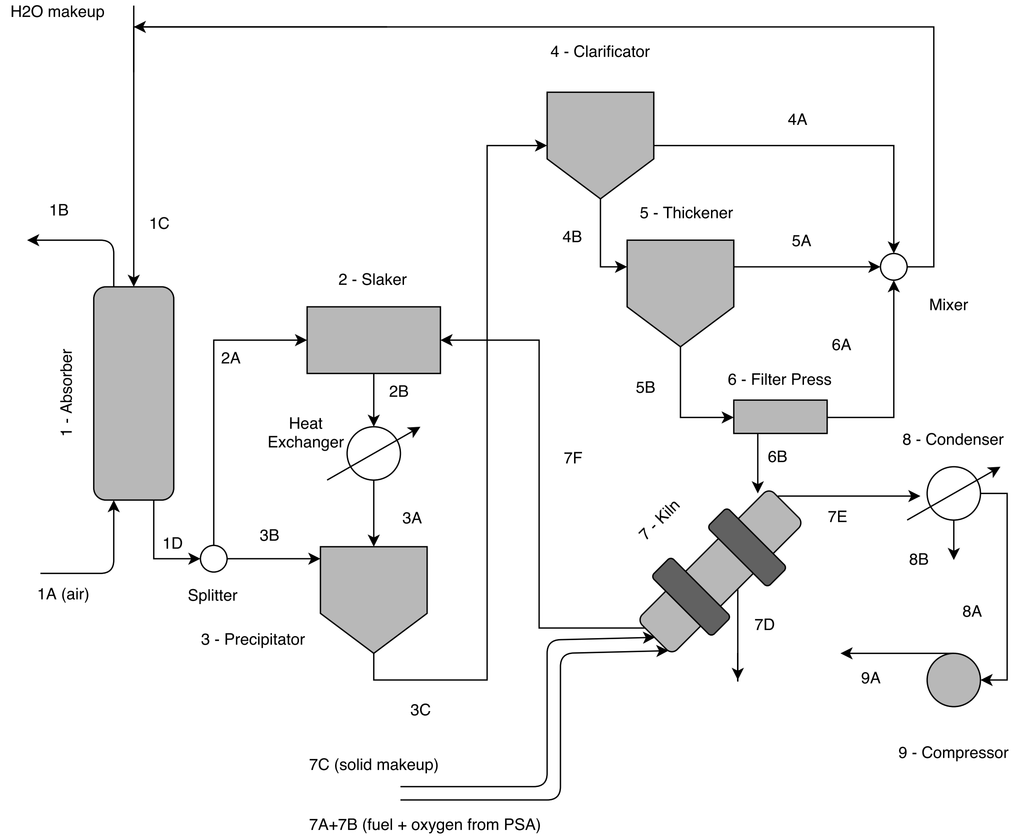


Figure 2.1: Scheme of the plant for CO$_2$ capture from air, process option A

columns in the market able to fulfill the requirements. Nevertheless it is also useful to move air in order to increase the volume of it passing through the contactor, this may be done using large surfaces or fans, but this of course requires energy. After having captured the CO$_2$, it has to be concentrated in order to store it and to make the recovery of the reactants maximized. This regeneration to release the carbon dioxide and restore the reactive sodium hydroxide is not trivial. The most straight forward solution would be to evaporate water from the absorption solution and the to isolate a solid sodium carbonate, but the thermal energy to make all the water evaporate would be too high making the process impractical. So what is done is to add to the sodium cycle a calcium hydroxide cycle. Calcium carbonate it is added to the sodium carbonate solution forming calcium carbonate and regenerating the sodium hydroxide.

$$Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH \tag{2.2}$$

This is based on existing processes used in the paper industries, as the Kraft process, and the lime-soda softening in water treatment systems. The lime used in this reaction is formed through quicklime hydration. This reaction happens in the slaker.

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{2.3}$$

The slaker has to be designed selecting the correct water-quicklime ratio in order to control better the temperature. The optimal temperature to get high quality

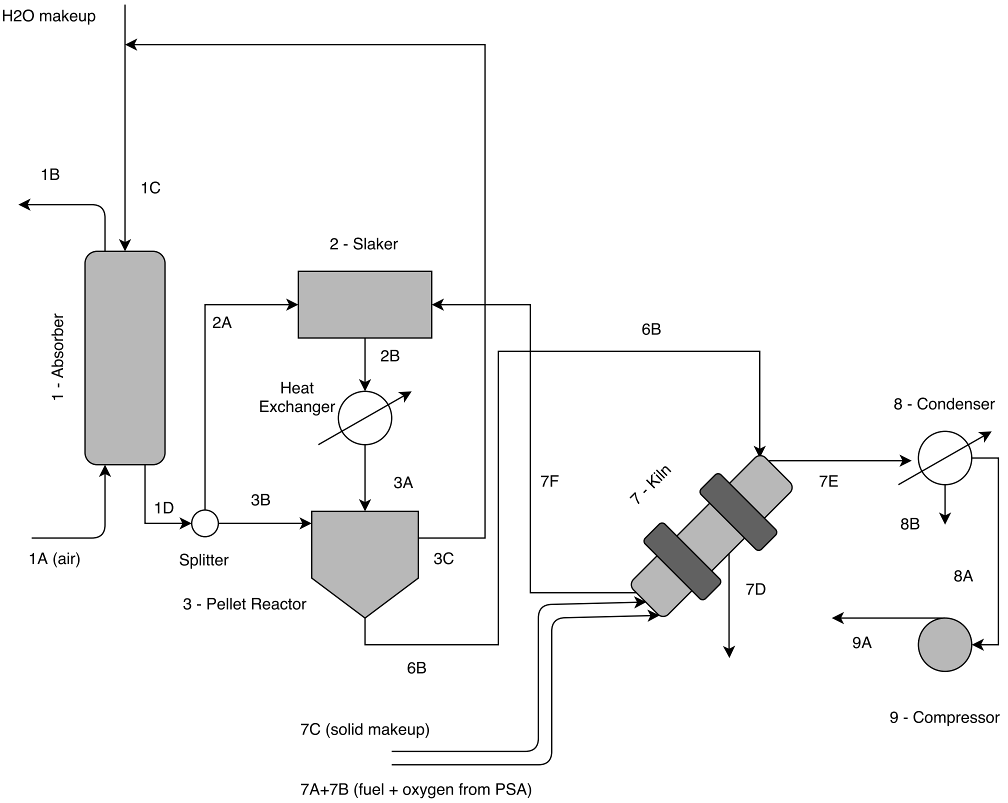


Figure 2.2: Scheme of the plant for CO_2 capture from air, process option B

product for this type of process is 95°C. The water required is provided or by an external source or by the outlet stream of the absorption column. The calcium carbonate is then calcined into quicklime, tha is used for the regeneration process, and carbon dioxide, that is going to be stored. If this takes place in a pure oxygen kiln the separation of carbon dioxide would be much easier. The oxygen is supposed to be given by an air separation unit. Depending on the design chosen the calcium carbonate can be carried in two different ways. The first option is to cool down the calcium hydroxide and mix it with the sodium carbonate to form the calcium carbonate precipitate. This precipitate has to pass through clarification, separation and thickening of the sludge that contains it. This will lead to a solid composition with around the 30-35% of water. If the percentage of water is still to high it is possible to dry the composition using hot air. The second approach uses a pellet reactor that consists in a cylindrical vessel partially filled with seed material like sand or calcium carbonate itself. Water is pumped into this cylinder in order to have a pellet bed that is in a fluidized state so the supernatant and the bed are clearly separated. The bed have a large crystallization surface that makes the pellets grow. Growing, the pellets become heavier and so they move to the bottom of the reactor. Periodically part of the largest pellets is discharged and new pellet material can so be added. In both cases the calcium carbonate, or in a sludge form or pellet form, is brought to the kiln.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2.4}$$

This is what happen also in the cement industry but the difference between that case and this one is the fact that the temperature needed are way lower. If cement needs a temperature of 1500°C, here 900-1000°C should be enough so reducing the thermal needs that still stay relevant since the percentage of water is around 30%. The flue gases need more processing to obtain pure CO_2. Water vapour has to be removed in a condenser and then gas stream is brought to a compression unit where carbon dioxide reaches 58 bar becoming liquid and ready to be stored.

2.2.2 Mass and Energy Balance

The overall process can be divided into two different sections. The first one absorbs the CO_2 and the second one aims to extract and concentrate the CO_2. Of course the second section is totally dependent on how the first one, so the absorption column, is designed. Every component will be analyzed now.

Absorption Column The column is chosen in order to absorb CO_2 from air at a concentration of 500 ppm and having an outlet value of 250 ppm. The chosen capture rate of this plant is 0.42 $MtCO_2/y$, the same order of magnitude of the largest CCS plants that were active at the time of the publication of the paper. To obtain such a capture rate a cross section area of 20,000 m^2 would be needed. For practical reasons the dimensions of the column will not exceed 12 m in diameter and 2.8 m in height. Other parameters chosen are the molarity of the NaOH solution, 2 M, and the air velocity at the absorber, 2 m/s.

Precipitation and Dewatering section The two processes here have different components. The first option uses more standard technologies used in the water management systems, while the second one uses a rather innovative pellet reactor. Of course being different components, the mass balances and energy requirements will be different as reported in the tables.

Process A It is consisted of four units: a precipitator, a clarification unit, a thickener and a filter press. It has been calculated that the energy requirements of these steps are negligible with respect to the other contributions. The final wet calcium carbonate steam will have a 35% of water that will have to be evaporated in the calciner.

Process B The pellet reactor is the only unit needed here. The input is the same but the outlet is solid pellets with a 10% of residual water content and the clarified NaOH can be recicled to the absorber.

Kiln Calcium carbonate has to be calcined and, being an endothermic reaction, it requires to be heated.

$$CaCO_3 \rightarrow CaO + CO_2 \quad \Delta H = 179kJ/mol \tag{2.5}$$

The unit where this reaction happens is a oxy-fuelled kiln fired by a stream of pure CH_4. The CO_2 can then be easily separated from water, recovered and

Figure 2.3: Sulzer Mellapak 500 Y, example of packing material needed by the absorption column to deal with low concentration

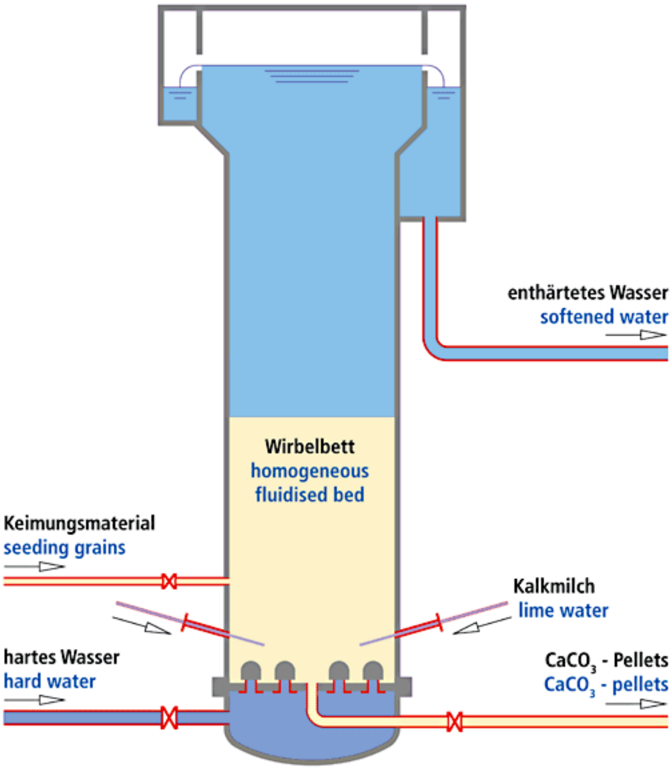


Figure 2.4: Pellet reactor scheme

compressed. The second output of the kiln, calcium oxide, is recycled to the slaker. To compensate losses the flow of the calcium carbonate flow is 10% higher with respect to the stoichiometric one. The temperature needed has been calculated to be 900°C. The process B requires a lower heat since the $CaCO_3$ is dryer with respect to process A. Being the temperature so high, two heat recovery terms have been considered.

Slaker The quicklime that exits from the kiln here is hydrated to have calcium hydroxide. This reaction is exothermic.

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad \Delta H = -65.7 kJ/mol \tag{2.6}$$

So choosing a slaking temperature of 95°C and a 4 to 1 weight ratio between water and quicklime, the heat generated by the reaction is used to theat the solution to the slaking temperature. The stream leaving the slaking could be used to heat another component of the plant but being the temperature low this would be very difficult. The residence time is considered to be of 10 minutes and the volume of 0.33 m^3, this would require a power of 0.5 kW which is negligible with respect to the other components of the plant

Water Condenser The outlet gaseous stream of the kiln is cooled from 200°C to 30°C and becomes water. A low-grade heat flow is release with this reaction but it would be very hard to recover, so this option is not taken into account.

Compressor To have liquid CO$_2$ at ambient temperature the pressure has to be of 58 bar. This pressure is obtained thanks to a multistage compressor. The literature provides the consumptions needed. Since the flue gas flow rate is smaller in process B than A, the energy requirements will be smaller as well.

Oxygen Purifier PSA manufacturer provides the consumptions of this unit which are 0.4kWh/Nm^3. For the same reason of the compressor process B will require less energy.

The overall energy requirements can be seen in Figure 2.5. The biggest amount of energy requirements come from the calcination accounting for 4.5 GJ/tCO$_2$ captured. The heating of calcium carbonate and of air also play a significant role, their contribution can be avoided using method B. Total contribution for process A is 10.6 GJ/tCO$_2$ captured, where 8.8 GJ/tCO$_2$ comes from thermal needs and 1.8 GJ/tCO$_2$ from mechanical needs. Process B will drastically reduce the consumptions going to 7.6 GJ/tCO$_2$ (6.0 GJ/tCO$_2$ thermal and 1.6 GJ/tCO$_2$ mechanical).

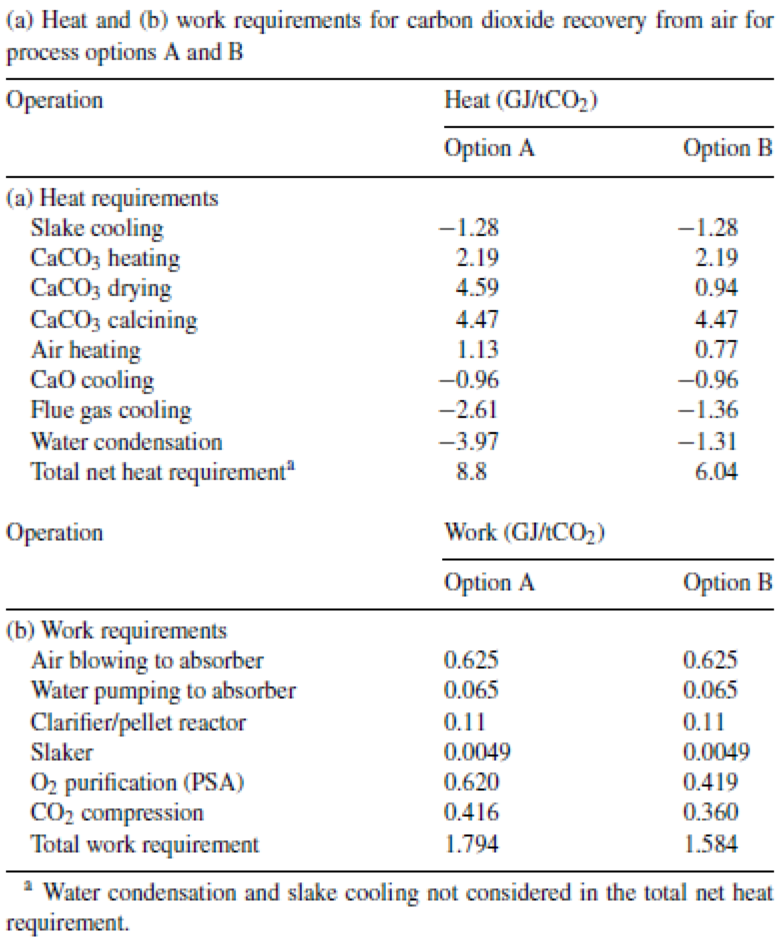
2.3 Solar Powered Calcium Hydroxide Plant

These plants share a common part with the plants described before but they have the advantage of not relying on fossil fuels to receive the energy they need, in particular what they use is power coming from concentrated solar plants. This design is proposed in a paper by Nikulshina et al. [33]

2.3.1 Plant Design

Closed Material Cycle

The closed-material cycle relies on three chemical reactors (a carbonator, a slaker and a calciner) and two heat exchangers. Ambient air is sucked from atmosphere



(a) Heat and (b) work requirements for carbon dioxide recovery from air for process options A and B

Operation	Heat (GJ/tCO_2)	
	Option A	Option B
(a) Heat requirements		
Slake cooling	−1.28	−1.28
$CaCO_3$ heating	2.19	2.19
$CaCO_3$ drying	4.59	0.94
$CaCO_3$ calcining	4.47	4.47
Air heating	1.13	0.77
CaO cooling	−0.96	−0.96
Flue gas cooling	−2.61	−1.36
Water condensation	−3.97	−1.31
Total net heat requirement[a]	8.8	6.04

Operation	Work (GJ/tCO_2)	
	Option A	Option B
(b) Work requirements		
Air blowing to absorber	0.625	0.625
Water pumping to absorber	0.065	0.065
Clarifier/pellet reactor	0.11	0.11
Slaker	0.0049	0.0049
O_2 purification (PSA)	0.620	0.419
CO_2 compression	0.416	0.360
Total work requirement	1.794	1.584

[a] Water condensation and slake cooling not considered in the total net heat requirement.

Figure 2.5: Overall energy requirements for Process A and Process B [1]

at a ambient temperature, then it passes through the first heat exchanger where it is preheated by the high temperature CO_2 free air. The preheated air reaches the carbonator and carbon dioxide is separated from it forming $CaCO_3$ and water. CO2 depleted air before being released to the atmosphere is cooled down in the heat exchanger previously described. Calcium Carbonate goes itself into another heat exchanger to be preheated before going to the calciner where thermally decomposes to CO_2 and CaO. The high temperature heat needed in this reaction is supplied by concentrated solar power. CaO is sent to the slaker where it reacts with water to regenerate $Ca(OH)_2$. After being cooled down CO_2 is sent to the storage site.

Open Cycle with Co-Production of H_2

The open cycle has the same components of the closed one beside the calciner that produces quicklime and syngas having as input the calcium carbonate and the CH_4 reforming. Syngas is then processed through water-gas shift and separation into two streams of H_2 and CO_2. The benefit of the open cycle is, of course the decrease in emissions, the separate production of these two commodities which make everything economically more desiderable.

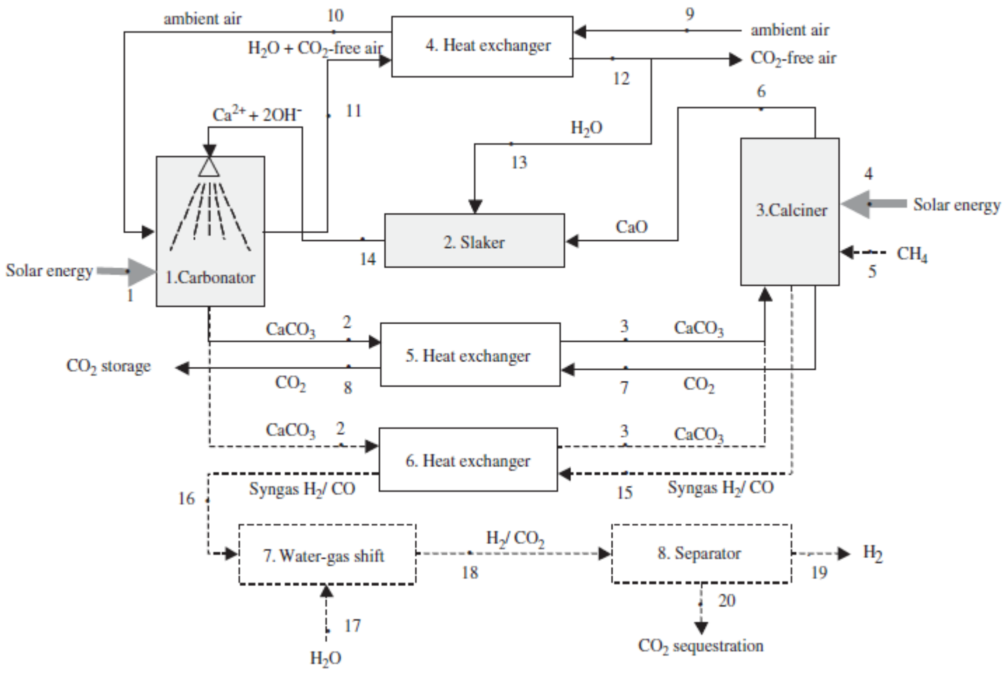


Figure 2.6: Scheme of CO_2 capture process using solar energy, the solid lines represents the closed cycle while the dotted lines represents the open cycle with H_2 production

2.3.2 Thermodynamic Analysis

The baseline design has a capture capacity of 1 mol/s of CO_2. The main assumptions of this analysis are: slaking heat lost to environment, carbonator works adiabatically, carbonator products separates naturally without any work input, heat exchanges are ideal, substances are pure and all reactions reach the chemical equilibrium. One important parameter is the temperature of the carbonator. The forming of $CaCO_3$ to have an acceptable kinetic rate has to happen at least at a T_1=500 K but this means that a significant amount of thermal energy is needed to heat up 57.9 kg_{air} per mole of CO_2 as shown in Figure (2.7). The graph also shows the importance of the heat exchangers that reduce but a factor 10 the energy needs in case of a high carbonation temperature.

Assuming a overall heat transfer coefficient of 8 W/m^2K the area needed would be around 30,000 m^2 and the heat recovered about 9.5 MW. The slaker operates at 353 K with a H_2O/CaO molar ratio of 4:1 producing 266.7 kg/h of $Ca(OH)_2$ releasing to the atmosphere 124 kW of low temperature heat power. The calciner needs a temperature of 1500 K and a thermal input of 163 kW, supplied by the solar power. The cool down of CO_2 from 1500 K to 832 K preheats the $CaCO_3$ and then it is stored at a rate of 1 mol/s. The total thermal energy needed is, considering the presence of the heat exchangers, 2485 kJ/molCO_2 captured. Considering instead the open cycle the calciner input rise to 498 kW. The syngas, after being cooled to 700 K, is brought to the hydrogen plant where the water-gas shift reaction is carried out in an auto-thermal reactor so there is no necessity of preheating the

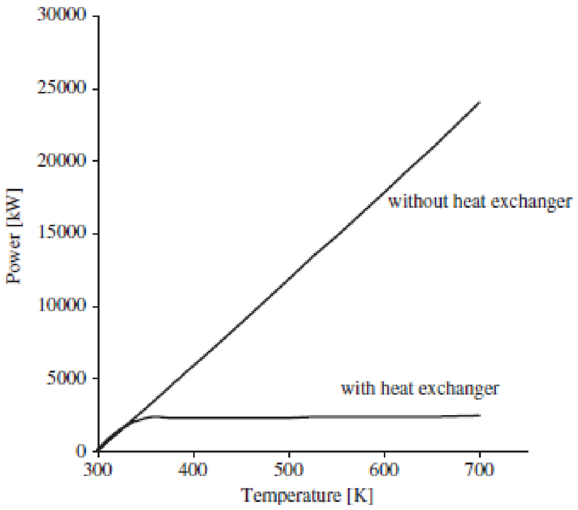


Figure 2.7: Power requirement for heating the reactants to the carbonation reaction temperature, with and without the use of a countercurrent-flow heat exchanger

reactants. A separation unit based on pressure swing adsorption separates H_2 and CO_2 consuming 9.17 kJ/molH_2. CO_2 at a rate of 2 mol/s (1 mol coming from air, 1 from the use of methane) is then stored. The total energy requirement here is 2809 kJ/molCO_2 captured and per 4 molH_2 produced.

2.3.3 Solar Reactor

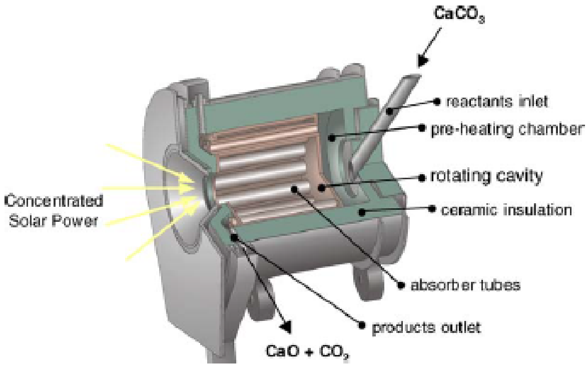


Figure 2.8: Solar thermal reactor for $CaCO_3$ thermal decomposition

The technology to perform a calcination with solar power has been demonstrated. It consists in a rotary kiln containing a multitube SiC absorber and a SiC preheating chamber. The costs of the CaO produced in this way is about 140 $/ton, roughly the double with respect to lime selling price, but the emissions are cut by 95%. Considering CO_2 captured using the CaO produced in this way, the cost of capturing a ton of CO$_2$ would be in the range of 160-200 $. The costs of the solar field would account for half of that costs. The technical scheme for the open cycle reactor is slightly different since it features a vortex flow of methane laden with calcium carbonate particles kept in a cavity receiver directly exposed to the high-flux solar radiation.

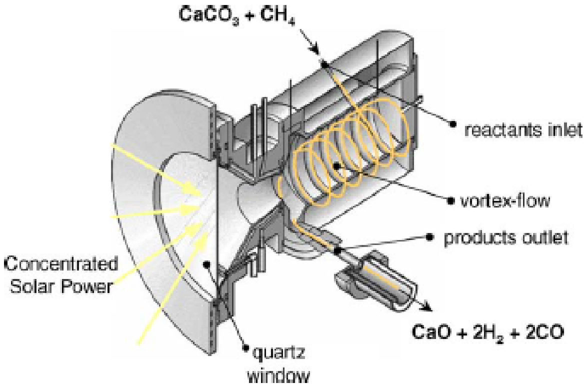


Figure 2.9: Solar thermal reactor for CaCO$_3$ thermal decomposition and CH$_4$ reforming process and the production of CaO and syngas

2.4 K$_2$CO$_3$/Alumina Composite Sorbent Plant

Veselovskaya et al. [50] thought to use potassium carbonate which, in presence of water vapour, reacts with CO$_2$ forming potassium bicarbonate. The main idea behind this design proposed by Veselovskaya is to incorporate direct air capture into the energy system in order to exploit the fluctuation of renewable energy making DAC a new type of storage. The CO$_2$ captured in this way can be considered a valuable feedstock to produce renewable methane which can be utilized for heating purposes and transportation. The starting point was to notice that the regeneration cycles are multistage and generally energy intensive. To solve this issue the use of potassium carbonate has been thought since just in presence of water vapour is able to react with CO$_2$

$$K_2CO_3 + H_2O + CO_2 \rightarrow 2KHCO_3 \tag{2.7}$$

$2KHCO_3$ is a very well known inorganic chemisorbent but if used bulkly the carbonation rate is very low. To overcome this problem $2KHCO_3$ particles are dispersed on a porous support material. These types of composite materials are well known to be very effective for capturing carbon dioxide from flue gases. In particular the composite which seems to be mostly effective is $2KHCO_3/\gamma - Al_2O_3$. This design has been tested in a cyclic mode with the apparatus shown in figure. This absorbent is considered to be the most promising because it does not need any pretreatment and can absorb CO$_2$ directly from ambient and also is thermally stable in multiple temperature swing absorption (TSA) cycles. Moreover this material will be perfectly suitable for a methanation process that will help the regeneration

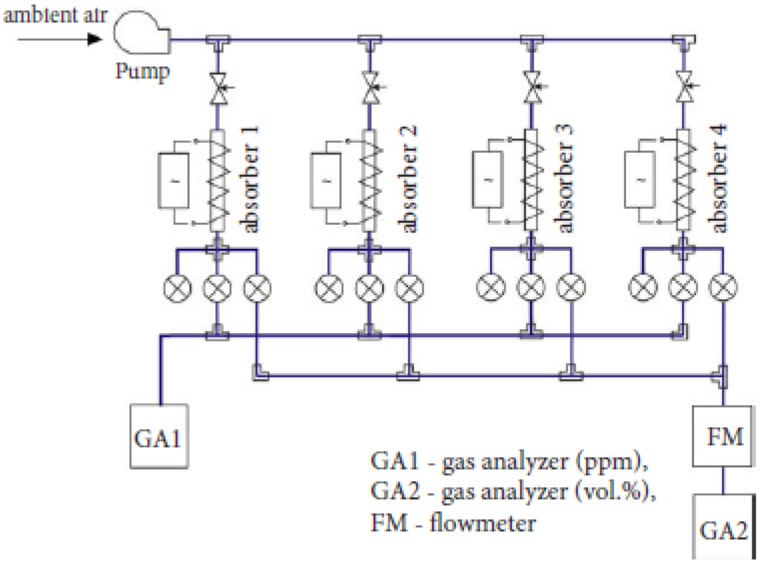


Figure 2.10: Test design of the Veselovsakaya capture process

process of the sorbent itself. This process will take place at a temperature around 250-300°C. These temperatures are more easily reachable than the previous design and so they do not require the use of fossil fuel or extremely expansive solar reactors. What the tests have also shown is that the smaller the grain size the less capable of absorbing CO_2 the material will be, this means that the process is likely to be limited by the mass transfer. An actual design plant based on this has not been proposed yet but for all the mentioned reasons this composite material should be considered in the discussion on how the future DAC plants should be.

2.5 Artificial Trees

Artificial trees are devices that mimic the process of capturing CO_2 from the ambient that regular trees do. What Lackner proposes is a wind-moved passive device that presents a large surface area of absorbing material where mass transfer can happen [27].

2.5.1 Air Capture Collector

The collector is a large filter covered with a sorbent that is able to capture CO_2. Being a filter, a good compromise between large surface areas, pressure drops, air flow speed and carbon dioxide depletion has to be found. It has also to be taken into account that a collector that creates turbolent waves wastes pressure drops in favour of kinetic energy and so there is no contribute in terms of CO_2 transported to the sorbent surfaces. If it is not dominated by the air side, CO_2 absorption can of course being limited by the chemical ability of the surfaces to absorb it.

Many designs involve non-turbolent flows, a very conservative one is capable of operating at speeds of the order of 1 m/s. In this case, due to the loss of kinetic energy and the momentum caused by the drag resistance of the filter, only a small fraction of CO_2 can be captured. Assuming an efficiency of 30%, 0.25 g/s of CO_2 per square meter of frontal area can be captured. This means that 50 m^2 of frontal area are needed to capture a ton per day. This is a large absorbing area but due to the fact that exploits low speeds it can be installed where the wind velocity is too slow for windmills. The surface area has to be covered with sorbent materials, at a concentration of 400 ppm sorbents are able to capture between 10 and 100 $\mu mol/m^2 s$ which means between 2500 and 25000 m^2 for a ton per day device. This is not hardly achievable with flat sheets that are one meter deep, spaced one centimeter apart and forming parallel channel to the air flow.

2.5.2 Chemical Sorbent

The resin material which seems to be the better for this application is a composite material with a resin similar to Marathon A (Dow Chemicals) as active ingredient. The material is composed by 60% of this resin and for the rest by an inert polypropylene sheet. The resin is composed of a poystyrend backbone with quaternary amine ligands attached to the polymer that carry a permanent positive charge. Usually the resin is bought in its chloride form to provide the negative countercharge. Washing the resin in sodium hydroxide will replace the chloride ions with hydrogen ions resulting in a material very similar to a solidified sodium hydroxide solution. The concentration of CO_2 in air is not a problem because these resins can capture CO_2 even for way less concentrated streams. The absorption rate is rapid, in the order of 10 to 500 $\mu mol/m^2 s$, and exceeds that one of a molar sodium hydroxide film of equal nominal area. To saturate the resin it has to be loaded with one mole of CO_2 per mole of positive charge attached to the surfaces. For this reason CO_2 has the same charge ratio of sodium bicarbonate. The fundamentals reaction that occurs are the direct formation of the bicarbonate:

$$OH^- + CO_2 \rightarrow HCO_3^- \tag{2.8}$$

The formation of the carbonate:

$$2OH^- + CO_2 \rightarrow CO_3^{2-} + H_2O \tag{2.9}$$

The formation of bicarbonate from carbonate:

$$CO_3^{2-} + CO_2 + H_2O \rightarrow 2HCO_3^- \tag{2.10}$$

It has been tested that is possible to absorb 0.85 mol of CO_2 per kg of resin. This resin can be regenerated easily, in fact if it is exposed to water CO_2 will be released. A water vapor of 45°C is enough to release most of the CO_2 off the resin and have it revert to the carbonate state and so when the resin is dry can start absorbing carbon dioxide again. So it is possible to have a cycle of loading carbon dioxide into the resin, clean it with moisture, dry it and the absorbing CO_2 again.

2.5.3 Prototype Design

The design has been thought to respect two simple parameters: has to be based on the current state of the art and could be easily transportated without the needs of special shipping cargoes. The plan involves a modular design involving a set of air filter 2.5 m tall, 1 m wide and 40 cm thick. 30 units would collect 1 ton of CO_2 per day, but considering recovery time and drying time the entire system will be composed by 60 units. If the total volume is calculated it can be found that the whole set of 60 units can be packed in a standard 12 m x 2.5 m x 3 m shipping container.

A single filter will take one hour to be full of CO_2, when full it will be moved to a chamber where low grade vacuum will be created. Then moisture will be injected and so the filter will be cleaned up. In this cleaning process the partial pressure of CO_2 will increase up to a pressure between 5 and 10 kPa, this carbon dioxide will be pumped out of the chamber and compress it into the pipeline.

The system can be driven just by mechanical energy since the heat needed will be produced as part of the compression. The energy demands come from:

- Air removal from regeneration chamber: 100 kJ of energy are needed to evacuate a volume containing 100 kg of resin and about 25 mol of CO_2. So considering a volume fill of 10% and a CO_2 loading of 0.25 mol/kg we need 4kJ/molCO_2

- Carbon dioxide compression: the pipeline pressure is about 6.7 MPa so we need to compress from 5 kPa to that value. At this pressure and a temperature of 300 K CO_2 is liquid so the amount of energy needed is small. The amount is theoretically 19 kJ/molCO_2

- Water vapour compression against constant partial pressure: the condensation of water requires 2.5 kJ/molH_2O. Considering that the ratio of water vapour to CO_2 gas is 1/1 there is an addition of 2.5 kJ/mol

The total amount of energy consumption so is nearly 50 kJ/molCO_2 or 1.1 GJ/tonCO_2. Considering all the pumps, filters, resins and everything needed to make the design work, the current design costs approximatevely 200000$ and the author expects to drop the price to 20000$.

Chapter 3

Models Description and Implementation

In the previous chapters the potential impact of DAC on the climate change issue has been stated. Climate change is a very complex problem that requires to know the interactions between different fields of knowledge like climate, energy and economy. A tool to understand this problem better is an Integrated Assessment Model (IAM). In this chapter the main features of IAMs and the implementations of DAC will be described.

3.1 Integrated Assessment Models

In order to describe the relations between human development and environment Integrated Assessment Models(IAMs) have been developed. Weyant et al. [53] [54] states the purposes of IAMs in:

- Assess climate change policies
- Force different fields of knowledge, for example the economic and the scientific dimensions of the climate change problem, into a common framework
- Understand the influence of climate change on the other problems mankind is facing

Nowadays models can take into consideration a very large number of impacts such air and water quality, water scarcity, depletion of non-renewable energy sources and overexploitation of renewable resources. Being the problems IAMs try to solve so complex, the output will not be a perfect prediction of the future. There are some intrinsic sources of uncertainties:

- Parameter uncertainty: it is impossible to know every aspect of the problem, some parameters, like R&D, can be supposed but not known
- Stochasticity uncertainty: some phenomena that affects the economic and physical processes can simply not be modeled. Eruptions, sunspots and other phenomena influence the global mean temperature in a way that can only be approximated with a auto-regressive process.

3.2 WITCH

WITCH (World Induced Technical Change Hybrid) is an IAM developed at Fondazione Eni Enrico Mattei (FEEM) and at Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) aimed at analyzing mitigation and adaptation to climate change. WITCH is a dynamic global model that collects the most important element of climate change into a united framework. The economy is modelled through an inter-temporal optimal growth that takes into consideration the long term economic growth dynamics. Moreover economy is modelled through a top-down approach, while the energy sector is bottom-up. The energy sector is hard linked with economy so energy investments and resources are chosen optimally considering the trend of macroeconomic variables. Instead land use mitigation and future climate are soft linked, so they are available through GLOBIOM and MAGICC that are respectively a land use and forestry model and a climate model. All these elements allow to have a complete dynamic view of climate change mitigation and adaptation. The model has a time horizon that goes from 2005 to 2150 with a time step of 5 years. The world is divided into 13 regions (see Figure 3.1) . Each region includes countries with similar economy, energy sector and also political situation.

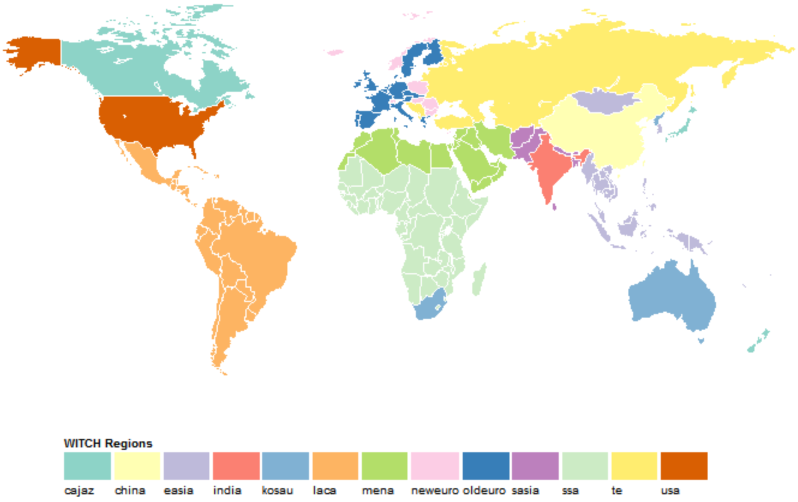


Figure 3.1: WITCH regions

Regions can cooperate or behave independently, the model will maximize the welfare of each region, or coalition, simultaneously and strategically.

3.2.1 Economy

The objective of WITCH is to maximize the discounted utility sum over time for every region. The utility function has as output a final good that derives from capital and labour, according to a Cobb-Douglas productivity law, combined with energy services through a CES (Constant elasticity of substitution). The regional utility function is also influenced by other parameters such as population, time preference discount factor and consumption of the final goods.

3.2.2 Energy Sector

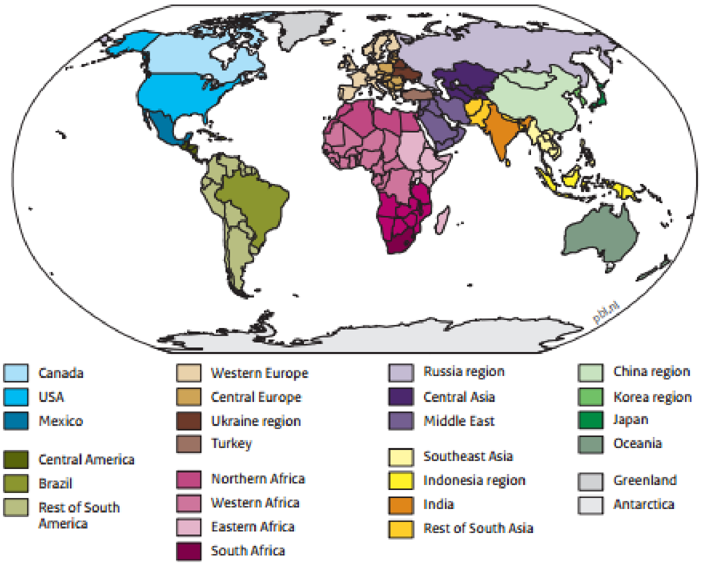
WITCH includes several technologies in order to describe the energy sector. Every technology can participate to the energy mix production thanks to a CES structure, so there is the possibility to switch from a technology to the other according to their elasticity of substitution. Electricity can be generated by traditional fossil fuel plants and newer technologies. Fossil fuel-based plants include coal, oil and natural gas plants while low carbon solution includes hydro, nuclear and renewables such wind, solar and biomass. The cost of production is endogenous and combines investment costs, O&M and costs of fuel. This cost includes a technological improvement as well, there are three types of learning in WITCH:

- Learning by doing: the reduction in the costs of a technology is based on the amount of the capacity installed of that technology, this means it is an endogenous reduction of costs. The technologies that rely on this type of learning are solar, wind and advanced biofuels
- Learning by research: this is as well an endogenous improvement but it is based on the amount of investments spent in a technology. This is used in the model to improve general energy efficiency and new technologies as batteries
- Performance improvements: this is determined exogenously and it is linked to a better usage of resources and a reduction in the consumptions. Plant efficiency, capital and labour productivity rely on this type of learning

It is present also a system integration module that guarantees flexibility and capacity contraints on variable renewables energies (VRE). The flexibility constraint is built in order to have the grid able to follow the load, while the capacity constraint is needed in order to satisfy sudden electricity demand peaks.

3.3 IMAGE

IMAGE (Integrated Model to Assess the Global Environment) is a comprehensive integrated modelling framework of interacting human and natural systems developed at the PBL Netherlands Environmental Assessment Agency. This model is used to analyze interactions between human development and natural environment. With respect to other IAMs, that have as primary focus only the climate change, IMAGE covers a broad range of dimensions as water availability and quality, air quality, biodiversity, resource depletion. To cover so many dimensions IMAGE is divided into different models that are specific to a single field of interest. There are two main systems linked one to the other, the *Human system* that describes the long-term development of human activities relevant for sustainable development and the *Earth system* that describes the change in the natural environment. Each system has several model inside. Models in the Earth system are hardly linked on a daily or annual base, while model in the Human system are linked through a soft link and they can be run independently. The main soft linked models in IMAGE are MAGNET (agro-economic model), FAIR (climate policy), GLOBIO (biodiversity), GLOFRIS (flood risk) and GISMO (human-development). IMAGE is used on a global scale and the world is divided into 26 regions according to a criteria similar to WITCH. The time scale can be annual or a five-year time steps if the focus is on long term issues, it is also possible, if needed, to run shorter time steps. IMAGE first year of run is 1971 so it is possible to test model dynamics against key historical trends



Source: PBL 2014

Figure 3.2: IMAGE regions

3.3.1 Economy

In IMAGE economic variables are model drivers for the other models, in particular the energy demand one. GDP per capita, Sector value added and private consumption are all used to indicate economic activity. In particular GDP per capita is broken into rural and urban and divided in quintile of salary according to the GINI index . The model linked to the economy is MAGNET, a model that also has a big focus on agriculture.

3.3.2 Energy Sector

TIMER (The IMage Energy Regional model) is the soft link model developed to study the energy system in the IMAGE framework and is the model in which DAC has been implemented. The model simulates long-term trends in energy-use, considering depletion of resources, greenhouse gases, air pollution and land-use demand for agriculture. The objective of TIMER is to understand the dynamic relationship inside the energy system, like inertia, learning by doing, depletion of resources and trade. TIMER is a simulation model, this means that the results depend on a set of deterministic algorithms, according to which the system in a certain year depends entirely from a previous system state and so it is not the result of an optimization process [51]. TIMER could be compared to energy simulation models as POLES[10] and GCAM [48]. The model has three components as it is

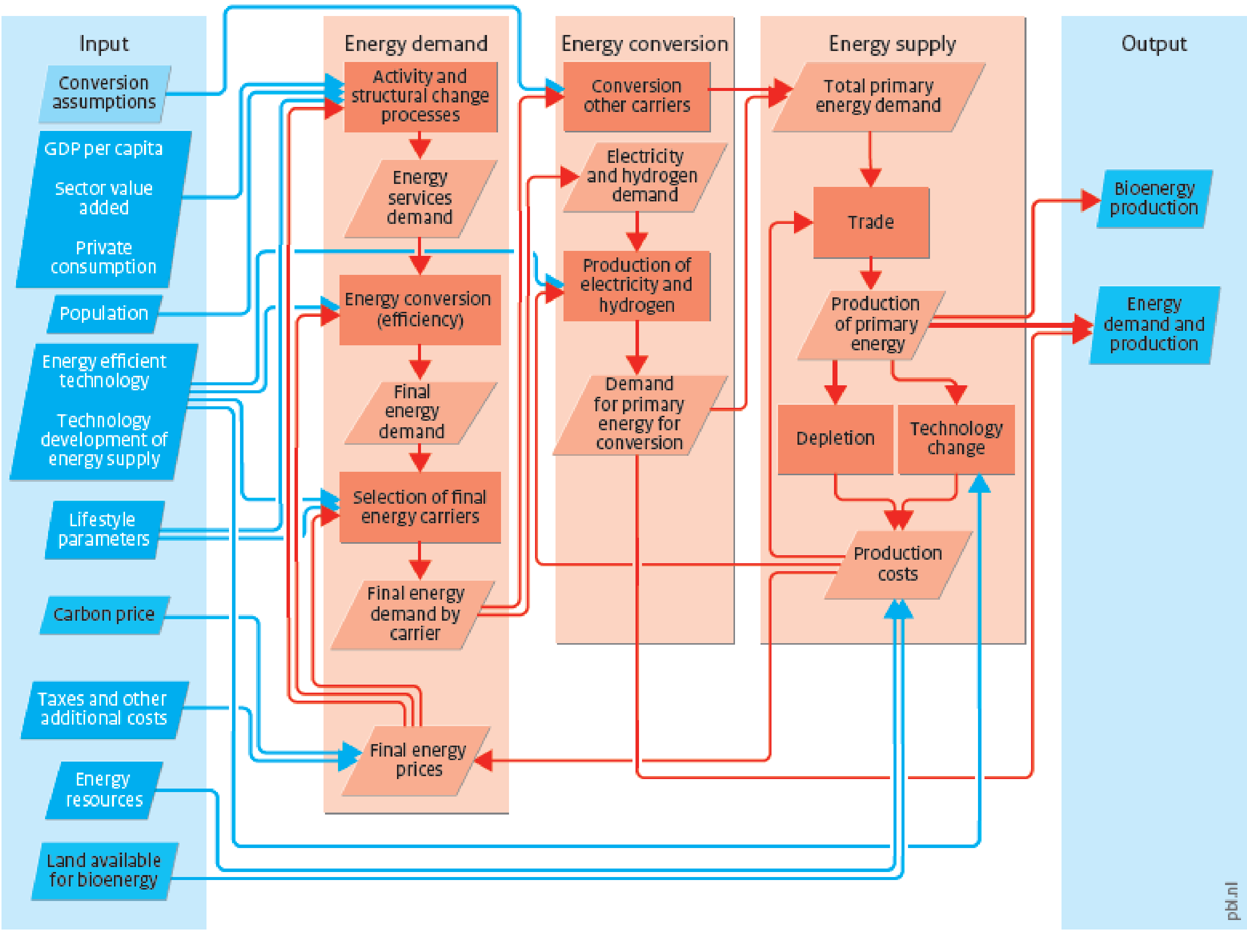


Figure 3.3: TIMER input output table

possible to see in Figure (3.3):

- Energy demand: the demand of energy is determined for five economic sectors (industry, transport, residential, services and other sectors)
- Energy conversion: the modules describes how energy carriers, like electricity and hydrogen, are produced
- Energy supply: the modules describe the production of primary energy carriers, calculate prices endogenously for both primary and secondary energy carriers that drive investments in the technologies associated with the carriers.

The output of these three components allows a calculation of the emissions.

	WITCH	IMAGE/TIMER
Category	Global equilibrium	Partial Equilibrium
Solution Algorithm	Intertemporal Optimization with perfect foresight	Recursive Dynamic
Objective	Evaluation of the impacts of climate policies on global and regional economic systms providing informations on the optimal responses of these economies to climate change. Positive externalities are taken into consideration from learning-by-doing and learning-by researching in the technological change	Analysis of large-scale and long-term interactions between human development and the natural environment to gain better insight into the processes of global environmental change. Identification of response strategies to global environmental change based on mitigation and adaptation
Policy implementation	Quantitative climate targets (carbon budgets, radiative forcing, carbon dioxide concentrations) are reached through carbon tax, allocation of emission permits, subsidies, taxes or other penalties on energy sources	Quantitative climate targets (carbon budgets, radiative forcing, carbon dioxide concentrations) are reached through carbon tax, allocation of emission permits, subsidies, taxes or other penalties on energy sources
Time Horizon and Step	2005-2150, 5 years step	1971-2100, 1 year step
Regions	13	26
Language	GAMS	M

Table 3.1: Differences between WITCH and IMAGE [4][45]

	Optimistic [million \$]	**Realistic** [million \$]	**Pessimistic** [million \$]
Near Term	300	1600	3000
Long Term	20	100	200

Table 3.2: Near term and long term capital costs for 1 $MtCO_2$ captured per year [5].

3.4 Implementation

In this section a detailed explanation of how DAC has been implementend in WITCH and TIMER is given. Having worked at both the implementations in the same period they were made as similar as possible and with the same starting datas in order to make a comparison between the models meaningful.

The reference plant taken into consideration in the implementation is a variation on the Baciocchi's design B [1] and it is proposed in a report of the APS (American Physical Society) [43]. In particolar a plant capable of capturing 1 $MtCO_2$/y at the absorber is considered. It has been decided to consider this type of plants as reference because it is the most studied design so far and the one which seems to be the most likely to be implemented on a large scale. Costs and energy consumptions of this plants were average with respect to the several designs proposed, so this middle position made this design the most suitable to an implementation in IAMs. Broehm et al. [5] did a bibliographic review and taking different designes provided ranges of costs and energetic demand for the other designs. The input numbers of the models have been accurately taken from all the papers.

3.4.1 Investment and O&M Costs

Assessing the costs of DAC can be complicated because all the difference sources of costs should be considered: investment, O&M, storage, electricity and fuel. In this section only investment and O&M would be considered since the others costs will be linked to the model making the total costs dependending on the models themselves. Estimates are scaled on a 1 $MtCO_2$/year, even if some systems refer to different size plants. The near term costs ranges from 300 million \$ to 3 billion \$, this big uncertainty is due to the possible different designs and costs of material and is a symptom of the relative immaturity of the technology. This range makes reasonable to assume as middle value an estimation of 1.6 billion \$. For this last value, considering some economic factors as capital depreciation (5% of the capital) and return on investment (7% of capital), the annualized capital cost is around 185 million \$ per year which translate into 185 \$/tCO_2. There is only one estimation for long term costs and is given at 20 million \$. This value will be considered the most optimistic value for the costs. In order to have a range it seems reasonable to assume that the order of magnitude will remain the same having so an upper value of 200 million \$ and a middle one of 100 million \$. The considered operational costs include only maintenance, labor and consumables, such chemicals and water. They are estimated to be in the order of 10 to 120 \$/tCO_2 and do not include electricity and fuel costs. Long term estimates are used as capital floor costs [5] [43] [27].

In the literature also total costs of DAC are present, so with electricity and fuel costs included. In the implementation these values were not taken into considerations since in both the models electricity price and fuel costs are calculated by the models themselves so there were no reasons to use them as starting datas.

3.4.2 Technological Learning

Investment costs are supposed to decline over time so a possible path of this decreasing has to be designed. A combination of learning by research and learning by doing has been used. The learning by research has been assumed taking into consideration that there is already a market for CO_2 streams. In 2015 the demand was about 6 billion \$ and is expected to grow at a average growth rate of 3.7% reaching 8.6 billion \$ in 2025. The main uses for carbon dioxide are in the food industry, from preservation and packaging of food to carbonation of beverage, and agriculture where it is used to produce urea. The main user is the fossil fuel industry that injects CO_2 into depleted oil fields to perform the so called enhanced oil recovery (EOR). The presence of this market makes reasonable to assume a decrease in costs in order to stay competitive. In particular a decrease in the investment cost of 1% per year has been decided. After the first plants are installed a decrease based on the amount of capacity installed has been used. The estimates for long term total costs have been used as floor costs, in order to avoid having an irrealistic cost that may happen in case of a massive installation of DAC. The learning by doing has been implemented in both the models in a way that it was as similar as possible to how that was already implemented for other technologies.

WITCH The closest technologies to DAC present in the model are carbon capture and sequestrations technologies(CCS) and so they have been used as example and so a one factor learning curve has been used:

$$\frac{InvCost(t,n)}{InvCost_0(t,n)} = \left(\frac{CCS_{stored}(t,n)}{CCS_{stored0}(t,n)}\right)^{(-b)} \tag{3.1}$$

The numerator is the total amount of CO_2 stored, so it is the sum of carbon dioxide captured by "traditional" CCS and DAC. The denumerator, that should represent the initial capacity in a normal learning curve, is the amount of CO_2 captured by traditional technology when DAC become competitive. b is a parameter that usually depends on the technology, the value chosen here is the one used in the model for Natural Gas + CCS power plants.

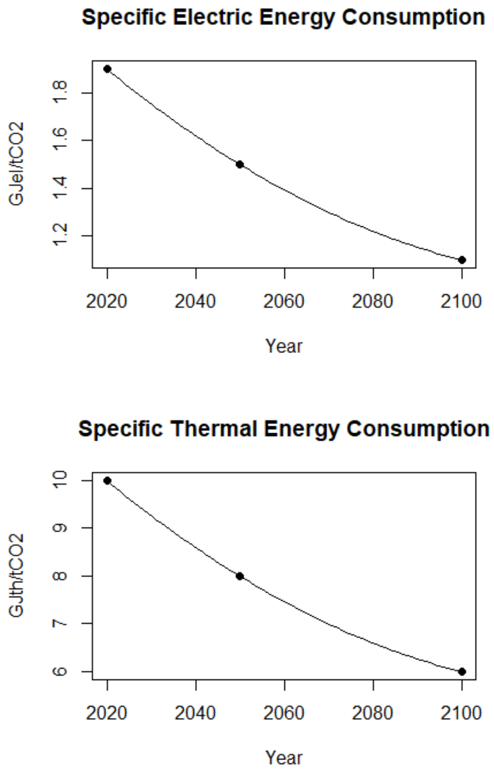
TIMER-IMAGE New technologies in this model have different learning by doing formulas since there is not a pre-existent capacity of DAC, so the approach used in the model for electric vehicles has been followed:

$$InvCost(t,n) = Inv_{Floor} + (InvCost(t_{inst},n) - Inv_{Floor}) * DAC_{units}(t,n)^{\left(\frac{Log_{10}(1-b)}{Log_{10}2}\right)} \tag{3.2}$$

Inv_{Floor} is the floor cost for capital investments. $InvCost(t_{inst},n)$ is the investment cost DAC has when the first plants are installed, it's different with respect to the initial cost because of the exogenous reduction explained before. b is chosen as in the WITCH case.

3.4.3 Energy Consumption

Every report assesses different electricity and thermal demands for their plants, but it is possible to find the ranges and use those values for the implementation (Table 3.3). Being this technology in its very early stage it is possible to assume that the specific consumption of both electricity and thermal energy will decrease over time so what has been done is taking the upper value as starting value of specific consumption in 2020 and decrease it to reach the lower limit at the end of the simulation in 2100 (Figure 3.4). It is important to underline that all the electricity used to power DAC is considered to come from low CO_2 sources in order to avoid the controversial situation of having a carbon capture technology powered by CO_2 emitters.



Specific Electric Energy Consumption

Specific Thermal Energy Consumption

Figure 3.4: Specific Electric and Thermal consumption over time

3.4.4 Expansion constraints

One of the problems linked to the implementation of this technology into IAMs is that DAC can be easily considered as a backstop technology, so a technology

Source	**Mechanical Energy** [GJ/tCO_2]	**Thermal Energy** [GJ/tCO_2]
(Baciocchi et al.,2006 [1])	1.58 - 1.79	6.04 - 8.8
(Socolow et al., 2011 [43])	1.78	8.1
(Keith et al., 2006 [22])	0.71 - 0.77	10.9
(Lackner, 2009 [27])	1.14	-
(Veselovskaya et al. 2013 [49])	-	7.3
Upper Value	1.9	10
Middle Value	1.5	8
Lower Value	1.1	6

Table 3.3: Thermal and Electrical Energy Required for DAC [5].

that, if becomes economically competitive, is seen by the model as the solution to completely solve the problem of climate change. Thanks to its characteristics, as soon as DAC becomes economically competitive, the models will tend to overinstall it creating problems in the simulation/optimization mechanisms that rule the model itself and so making impossible to find a solution. This behaviour is called bang-bang solution and it has to be avoided. In order not to have that type of solution some limits in the rate of installation have to be thought and used. The best solution thought was to use a limit on the amount of $GtCO_2$ of nominal capacity installed per year globally. Then this limit has been implemented according to the various characteristics of the different regions. It has been decided that the installation would follow a logistic function shape since it has been noticed in several occasions that new technologies often follow this type of diffusion.

$$f(x) = \frac{L}{1 + e^{(-k(x-x_0))}} \tag{3.3}$$

L is the maximum value the curve can have, k is the steepness of the curve while x_0 is the value of sigmoid's mid-point.

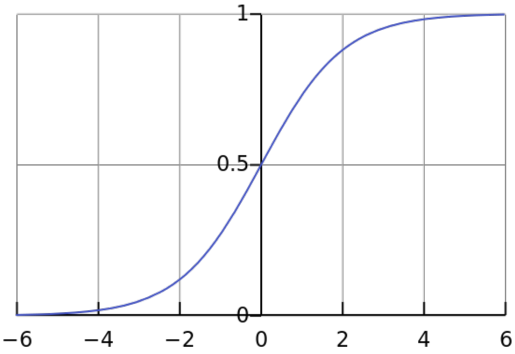


Figure 3.5: Logistic function

After having considered the various components of the model that logistic function has been changed in this way:

$$NewD(t,n) = D_{max} * \frac{Stor_{av}(t,n)}{StorGlob_{av}(t)} * \frac{1}{1 + e^{(-(r(t,n)-1))}} \tag{3.4}$$

NewD(t,n) is the amount of DAC that is possible to install every year, D_{max} is the maximum amount installable globally and the amount chosen is 1 $GtCO_2$/year so 1000 plants having the size of the one used as reference in the American Physical Report [43], the reference system captures up to 1 $MtCO_2$/year which corresponds roughly to the amount of CO_2 emitted in one year by a 300 MW natural gas combined cycle power plant or a 150 MW supercritical coal power plant. To understand if 1 $GtCO_2$/year is a reasonable number the money needed to install that amount of DAC has been considered. Considering the highest total cost estimates, which are 550 \$/tonCO_2, installing 1 $GtCO_2$ corresponds to an investment of 550 billion dollars which is a very big number but still lower than the amount of money invested every year in the oil and gas sector in the past years [1] . The specific cost per ton of CO_2 will decline over time making the total investement needed to install the max amount of capacity lower year after year. For these reasons that threshold has to be considered acceptable. $Stor_{av}(t,n)$ is the amount of CO_2 storage available in every region while $StorGlob_{av}(t)$ is the total amount of storage available in the world. The last term is $r(t,n)$ which represents the ratio between the carbon tax and the DAC cost per $GtCO_2$ captured, this varies over the regions due to the difference in costs of storage, fuel, electricity and installing between the regions. This equation, with the appropriate corrections, is implemented in both the models as limiting equation.

WITCH The total amount of DAC installed has also to take into consideration the depreciation of this technology. The depreciation is based on a depreciation rate based on the lifetime according to how it is already implemented in the model:

$$D(t+1,n) = D(t,n) * (1 - deltaDAC)^{tstep} + tstep * \frac{I_{DAC}(t+1,n)}{InvCost(t,n)} \tag{3.5}$$

$D(t,n)$ is the total capacity installed, I_{DAC} is the amount of money spent for installing new direct air capture plants. The value of $deltaDAC$ is calculated as follow:

$$deltaDAC = \frac{1}{lftm - \frac{1}{200} * lftm^2} \tag{3.6}$$

Being the lifetime of a DAC plant of 20 years, the results is a $deltaDAC$=0.055

TIMER-IMAGE Also in TIMER-IMAGE the depreciation has been taken into account:

$$DeprDac(t,n) = \sum_{j=0}^{10} \frac{1}{11} NewDac(lftm + j - 5, n) \tag{3.7}$$

DeprDac is the amount of DAC installed not working anymore due to the depreciation, this quantity has to be subtracted to the total amount of dac installed. *NewDac* is the amount of DAC installed in that year and *lftm* is the technical lifetime of the plant which is equal to 20 years as in WITCH of course.

This is not the only limit used in TIMER because here, according to what happens in the model, a limit on the installation based on the availability of storage has been implemented. If the amount of DAC the model want to install is bigger than 5% of the available storage then the quantity installed will be this percentage of the available storage so limiting the amount of DAC installable every year.

$$NewDAC(t,n) = min(MaxGrowth(t,n), \sum_{stor} StorCap(t,n,stor) * maxepl) \tag{3.8}$$

MaxGrowth is the maximum growth the model will allow, *StorCap* is the storage available and *stor* is the type of storage.

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[1] The value of this parameter will be discussed in detail in the Sensitivity Analysis section (4.9.4)

3.4.5 CO_2 captured

There is a difference between capacity installed and total amount of CO_2 captured. In fact it is important to take into consideration also the carbon dioxide that comes from the gas used to fuel DAC. For this reason the amount of CO_2 stored is bigger with respect to the nominal capacity, this is important in terms of cost of storage and commitment of the storage capacity. So this consideration has been implemented as follows:

$$TotCO_2capt(t,n) = D(t,n) + CO_{2gas} * \eta_{ccs} \tag{3.9}$$

CO_{2gas} is the amount of emission produced by burning the necessary amount of CH_4 and η_{ccs} is the average ccs efficiency of a NGCC plant. Being the efficiency different from 100% there is a part of CO_2, coming from the gas, that still is emitted and this has been taken into consideration as well.

Chapter 4

2°C Scenario

The first scenario analyzed is the 2°C scenario. Both the models have run using the radiative forcing as target in particular aiming at a value of 2.6 W/m^2 as it is possible to see in the Figure 4.1. Having used the radiative forcing, because of the intrinsic uncertainties linked to the climate change calculations, the temperature may be slightly different from the 2°C. In this case for example the reached temperature is even lower with respect to what expected.

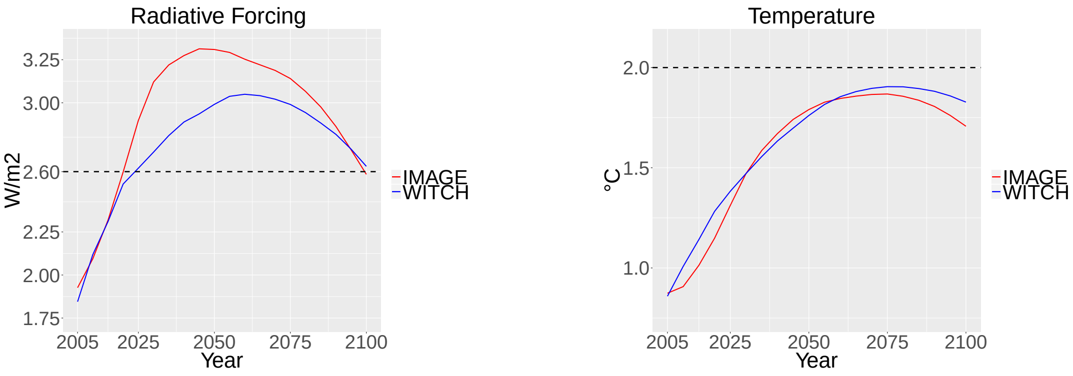

Figure 4.1: Radiative Forcing and Temperature Profile for the 2°C Scenario

In this chapter the results of the runs will be shown and the differences between the DAC case and the non DAC case will be highlighted. At the end of the chapter a parameter uncertainty analysis will be shown to check the robustness of the models.

4.1 CO$_2$ emissions path

Figure 4.2 represents the global annual industrial emissions. As it is possible to see there are some differences between the two models but the influence of DAC in both cases is the same. The difference of about 1 GtCO$_2$ in the first years are caused by different calibration datas. The main effect of DAC is to allow an overshoot in emissions, basically it allows to postpone the mitigation effort. In IMAGE it is possible to produce roughly 5 GtCO$_2$/year more than the non DAC case until around 2075 when there is the intersection of the curves. WITCH shows the same

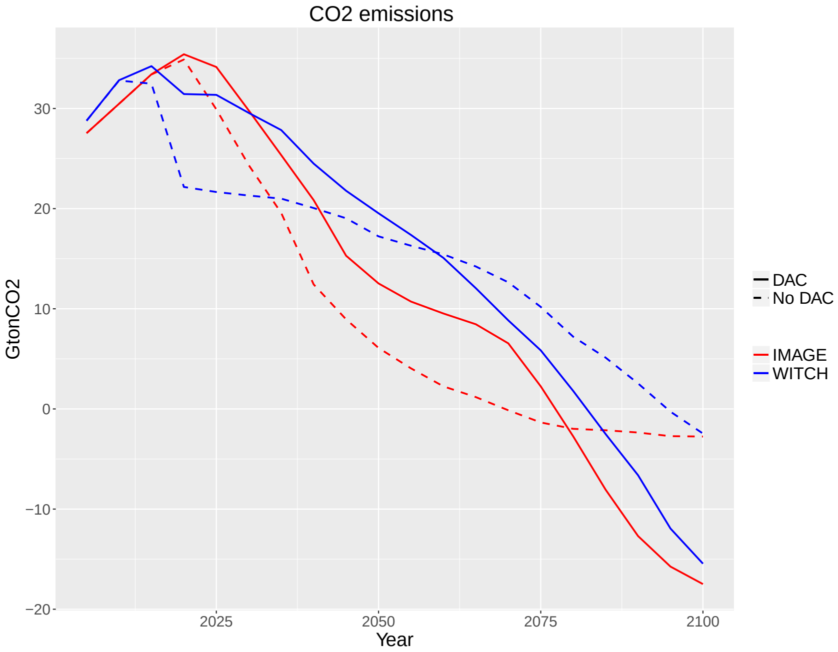

Figure 4.2: World Industrial CO_2 emission paths in the 2°C scenario

behaviour especially in the first years. The year in which there is the intersection is between 2055 and 2060. Final emissions for both the models are similar in the DAC case and in the no-DAC case as well reaching 15 $GtCO_2$/year of negative emissions in the DAC case while in the base one negative 2.5 $GtCO_2$/year. This means that, even without DAC, there is the necessity to have negative emissions at the end of the century and this is possible only thanks to Biomass with CCS (BECCS). So DAC gives a boost to the possibility of reaching negative emissions. Moreover it is interesting to note that in the no-DAC case IMAGE reaches negative emissions in 2070 while WITCH reaches them only in the 90s, this is possible because WITCH prefers to reduce drastically emissions in the first years of the simulation and have a smoother decrease in emissions during the rest of the century, IMAGE instead prefers to post pone the emissions reduction after 2025 and this implies a faster decrease since everything is postponed.

One of the main point of the Paris Agreement is the ratification of the INDC. Their purpose is to reduce emissions by 2030 in order to have the possibility to reach the final goals. In the DAC case the amount of emissions allowed is roughly 10 $GtCO_2$ more with respect to the base case. This will allow to make all the political issues, about the responsabilities on who should decrease the emissions more, easier to solve, taking still in consideration that these efforts are only postponed.

4.2 Carbon Tax profile

All the IAMs used in climate policies use a carbon tax as mean to reach the climate goals. This tax is applied to every region in the models with the same value everywhere. Its aim is to make less attractive fossil fuel energy sourcing taxing the

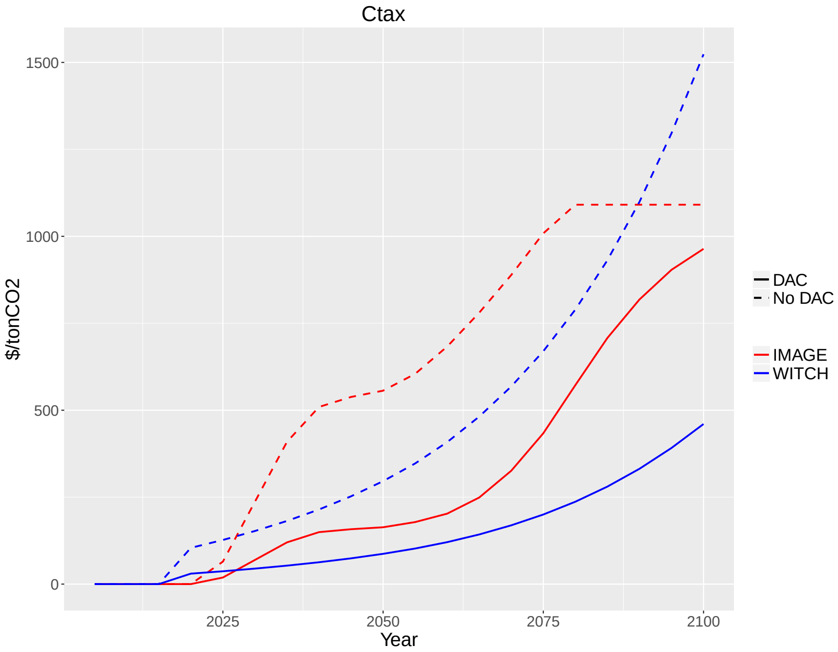

Figure 4.3: Carbon Tax profiles in the 2°C scenario

amount of CO_2 they produce. IMAGE and WITCH present two different carbon tax profiles. WITCH follows an exponential curve that starts from a starting value in 2020 and grows smoothly until 2100. IMAGE's profile instead is determinated by the climate policy model FAIR. As it is possible to see from the non-DAC case there is a plateau at around 1100 $\$/tonCO_2$ that corresponds to 4000 $/tonC. This is an upper limit that PBL has decided to use, historically it was 1000 $/tonC but with stricter and stricter policies the limit has been brought to the current one.

Without DAC WITCH reaches 1500 $\$/tonCO_2$ while IMAGE reaches its top limit just after 2075. The influence of DAC is very clear, WITCH's ctax is roughly one third with respect to before, with a starting value in 2020 of 30 $\$/tonCO_2$ instead of 105 $\$/tonCO_2$, while IMAGE's ctax never reaches the plateau and the path followed is very different.

4.3 DAC installed

The amount of DAC installed varies a lot between the different models (Figure 4.4). WITCH starts installing it in 2020 with the first plants built in Canada and USA, the final amount of capacity installed is 27 $GtCO_2/year$. IMAGE waits until 2065 to start installing it, this delay allows the model to have 17 $GtCO_2/year$ in 2100. One of the main reason for such a big difference is the foresight capability WITCH has while IMAGE doesn't. IMAGE starts installing DAC only when the total costs of installation, so including storage, electricity and thermal needs and so on, are smaller with respect to the carbon tax. In the first years WITCH instead installs DAC, even if it would not be economically convenient, in order to build capacity, reducing so the costs and have the possibility to install more DAC when it will be economically convenient, thanks to an higher carbon tax. The countries where this tecnology is installed the most are Canada and United States in WITCH where in 2100 there are about 10 $GtCO_2$ and 8.5 $GtCO_2$, these numbers are much bigger with respect to the other regions. Middle East and North Africa (MENA) countries are the third installer with 2.5 $GtCO_2$. WITCH storage capacity database allocates the vast majority of the storage to those two North American countries and so the storage costs will be lower and so the installation in these regions is more convenient and fostered[1]. In IMAGE instead, aggregating the regions as in WITCH, DAC is mostly installed in the energy exporting regions as the Russian one, the MENAs countries and Sub-Saharian Africa with 3, 2.5 and 2 $GtCO_2$ respectively.

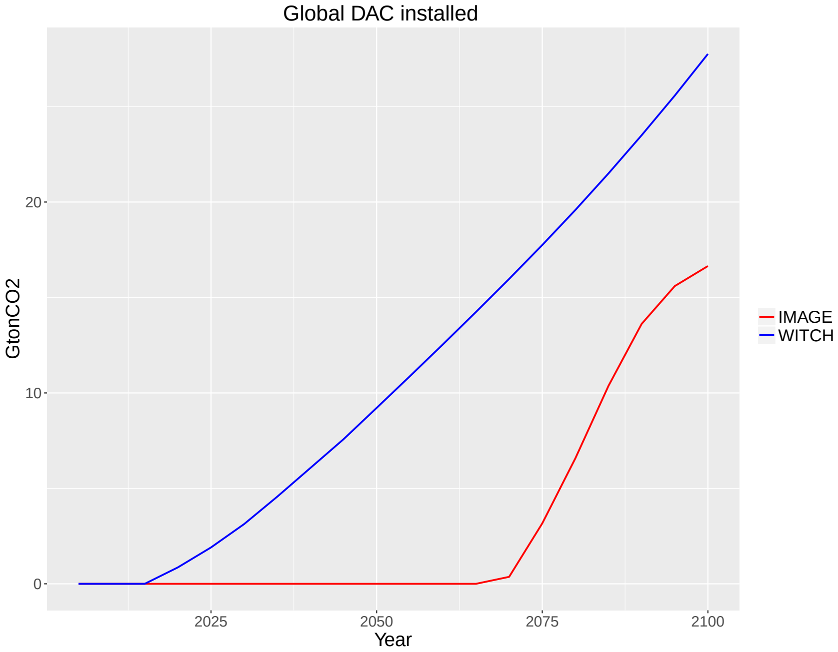

Figure 4.4: Amount of DAC installed globally in the 2°C scenario

4.3.1 CO_2 stored

The presence of DAC will influence the total amount of emissions stored (Figure 4.5). In both the cases, as it was easy to assume after having seen the emission paths, the amount of stored CO_2 is greatly increased. In IMAGE we have an increase of 22 $GtCO_2$/year, from 20 to 42 $GtCO_2$/year. In WITCH, due to the bigger amount of DAC installed, there is an increase of more than 30 $GtCO_2$/year, from 25 to 57 $GtCO_2$/year. In IMAGE the presence of DAC is not phasing out traditional CCS, in fact the amount of emissions stored per year by CCS is almost the same in the DAC and no-DAC case being close to 20 $GtCO_2$, also for WITCH CCS is still heavily used even if there is a small decrease but still being above 20 $GtCO_2$ and the reason will be clear as soon as the electricity mix will be analyzed

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[1] Storage capacity differences between the models will be explained in the "Australian Case" sub-chapter 4.8.1

in the following sections. The amount of total emissions stored by DAC is 21 $GtCO_2$/year for IMAGE and 37 $GtCO_2$/year for WITCH, these values are different with respect to the nominal capacity of DAC installed because it takes into account also the emissions produced, and then captured, by the burning of the natural gas used to fuel the plants. The total amount of stored CO_2 in the models is very big, especially in WITCH. In this model the cumulative carbon dioxide stored by traditional CCS is equal to 932 $GtCO_2$, while DAC stores 1400 $GtCO_2$ in the whole centuries making it the biggest source of capture. In IMAGE instead, because of the late adoption of DAC, the biggest capturer is still the traditional CCS with 777 $GtCO_2$ while DAC captures "only" 400 $GtCO_2$. This big difference can be attributed again to the foresight ability of the model as explained before. This ability makes DAC to be installed already in 2020 and so the cumulative has to be significantly higher with respect to a model that begins to install in 2060.

4.4 Total Primary Energy Supply

In a global point of view Total Primary Energy Supply (TPES) represents the sum of electricity and thermal energy production (Figure 4.6). Also in the no-DAC case, the two models show a big difference in the total value. WITCH results are significantly higher with respect to IMAGE, but this is due to the different hypotesis the two models rely on. What it is important is to see if the effect of DAC is the same on both the models and this is exactly what happens. DAC technology increases a lot the demand and so the supply, that goes from 275000 TWh to 350000 TWh in WITCH and from 175000 TWh to 220000 TWh in IMAGE. Since this represents electricity and non-electricity combined supply it is important to divide these two components in order to see if this increase is due to an increase in the electricity supply or if it is linked to thermal needs, so the non-electricity production.

4.5 Electricity Mix

Direct Air Capture is a electric energy source of demand so the expectations are of an increased electric production in order to satisfy this new demand. This is what happen in IMAGE where there is a small increase in the demand. In WITCH the situation is different because there is a small decrease in the total electricity. In particular the source of energy that sees the most significant reduction is BECCS. This may be explained by the fact that, in order to reach negative emissions, BECCS was essential being the only technology capable to do so. Nevertheless saying that DAC in this case appears as an alternative to BECCS would not be correct since the reduction in BECCS is very limited. It is possible to say that this small reduction in BECCS can be considered a little help to the solving of the problems linked to land use and land for food competition BECCS usually has. It is interesting to see what happens in the first half of the century. In both the models the usage of fossil fuel, with and without Carbon Capture and Storage, is definetely bigger in the DAC case than in the no-DAC case. The phasing out of traditional coal is delayed

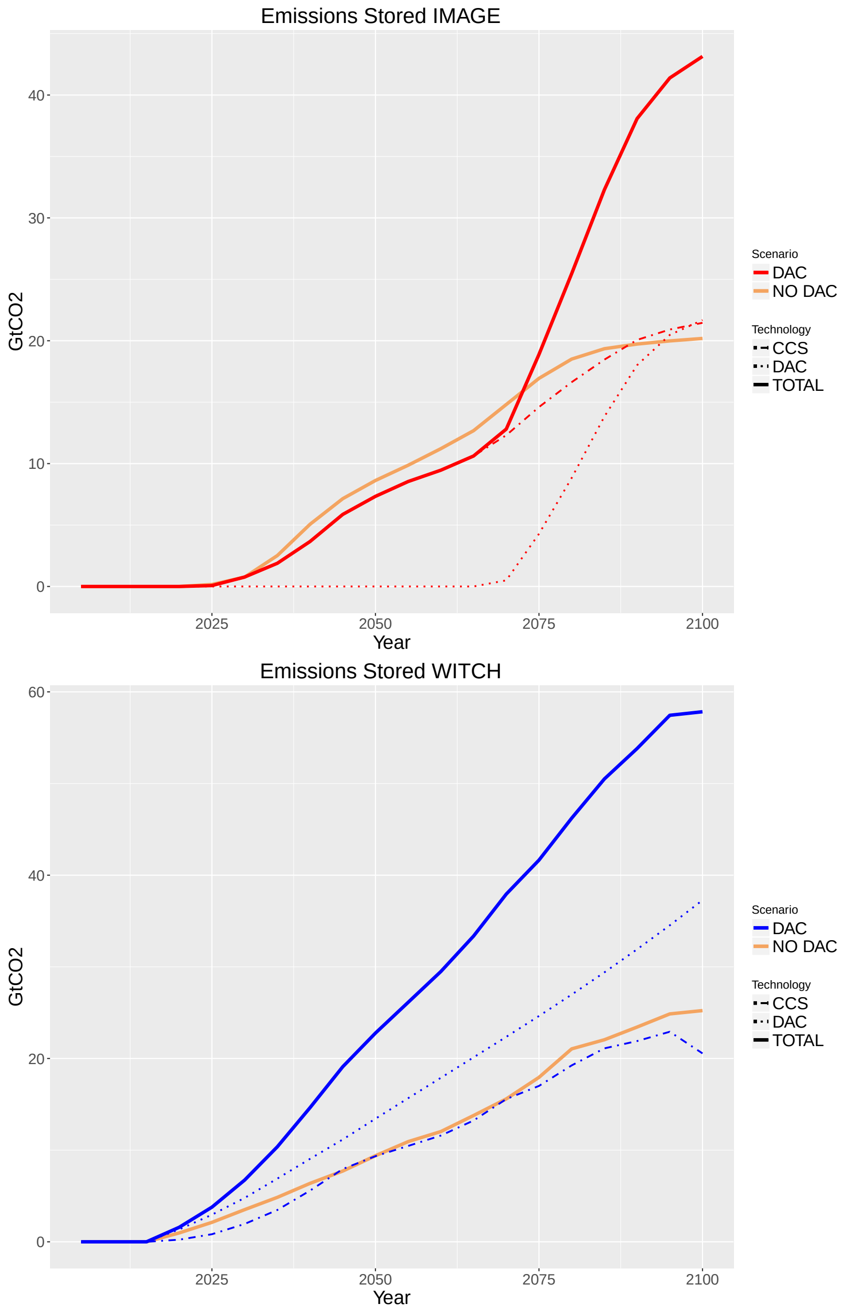

Figure 4.5: Total amount of CO_2 stored per year in the 2°C scenario divided into traditional CCS (dot-dashed line) and DAC (dotted line). In the No-DAC case all the emissions stored come from CCS

Figure 4.6: Total Primary Energy Supply in the 2°C scenario

until around 2050 in both the models. IMAGE still uses coal, coupled with CCS, also in 2100. Gas is widely used in both models, without CCS in the first half of the century and with CCS in the second half. BECCS is widely used in both the models as the only other negative emission technology, beside DAC.

With DAC, it will be possible to reach the climate target of Paris even if some fossil fuels will still be used in the power production sector in the first half of the century. But even with DAC a transition to low carbon energy sources is still needed. Renewables are the main source of electricity in both the models along with nuclear power.

4.5.1 Electricity Dedicated to DAC

As it is easy to notice the total amount electricity required has a shape that is very similar to the amount of DAC totally installed. This is due to the fact that, even if the specific electricity consumptions is decreasing over time, the amount of DAC installed every year is always growing making so the total consumption grow. The total amount of electricity DAC requires with respect to the total is small, about 6% in both the models. Of course the total consumptions in WITCH are higher with respect to IMAGE because of the $GtCO_2$ of DAC installed.

It is important to check that the electricity that powers DAC must come from low carbon sources, otherwise we will fall into the paradox of emitting CO_2 emissions to capture them afterwards. In WITCH it is possible to force the model to use certain sources to give the electricity to DAC, the sources that can be used are the one shown in the legend of Figure 4.8. As in the total electricity demand, wind is by far the source where electricity is taken from accounting for almost the 90% of the demand, the rest of the electricity is given by BECCS. In IMAGE-TIMER

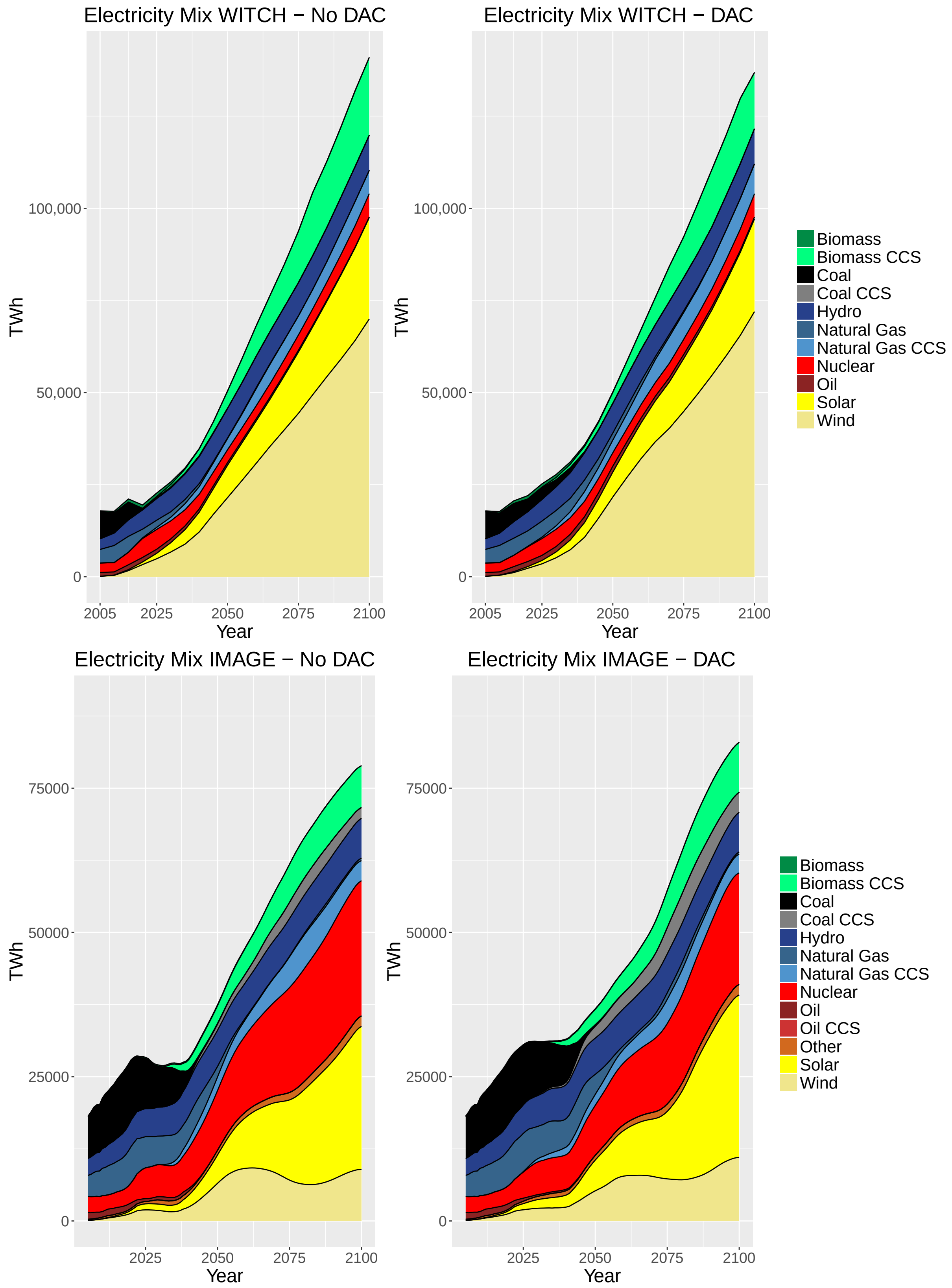

Figure 4.7: Electricity Mix in WITCH and IMAGE in the 2°C scenario

Figure 4.8: World total electricity consumption of DAC in the 2°C scenario and the electricity sources powering DAC (WITCH)

it is not possible to force the model to select certain technologies to satisfy part of the demand, but DAC is not installed until 2060 and at that period of time the electricity demand is satisfied only by low carbon sources, whether renewable sources or CCS plants, so it is possible to say that also in this case the paradox introduced before is not a problem.

4.6 Fossil Fuels Consumption

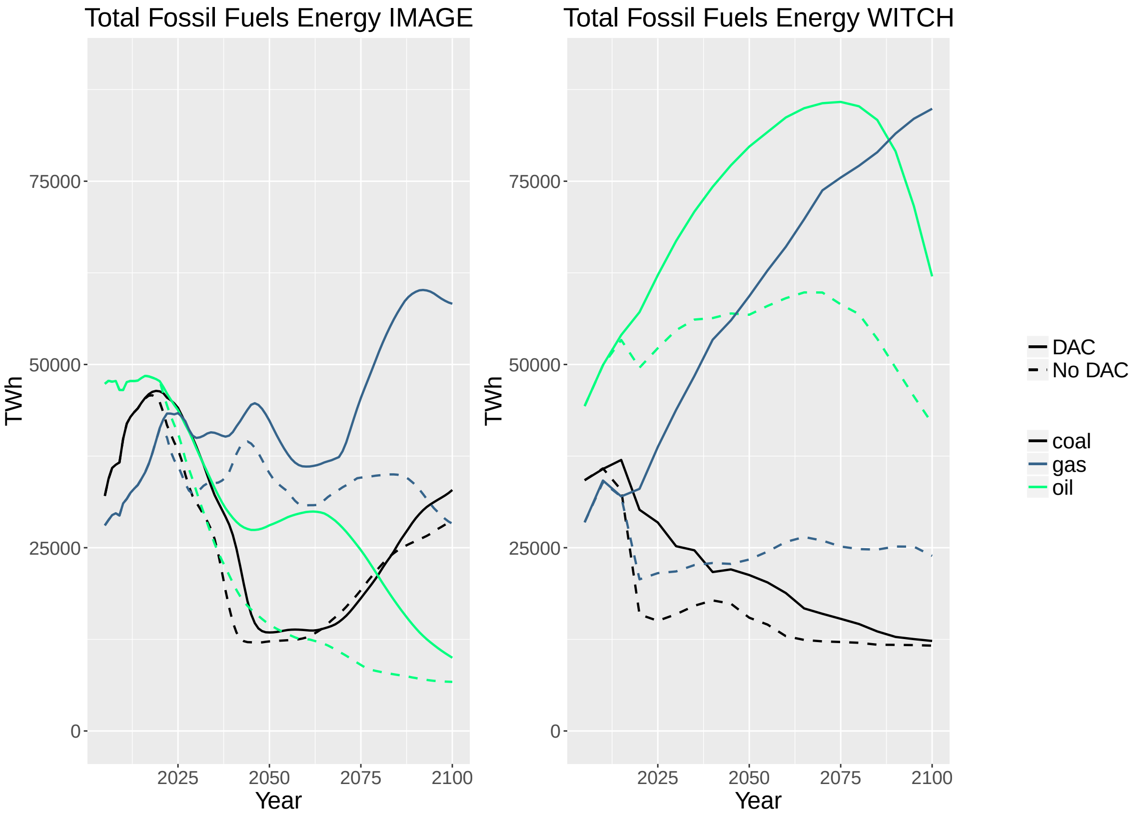

Figure 4.9: Fossil fuels production/consumption in the 2°C scenario

Both the models are more focused on the electric sector, while the non-electric sector is not as detailed. The fossil fuels usage, though, takes into consideration this sector as well. As seen before, especially later in the future, the fossil fuels will be mainly used in the non-electric sector and not in the electric sector so it is reasonable to assume that all the big changes that are possible to see in the graph are linked to the non-electric demand, that comprehends travels, thermal demand and so on.

Coal in both the models and in both the scenarios is going to be reduceed, in WITCH the reduction is very important while in IMAGE this reduction is smaller due to the fact that Coal CCS is still a technology used later in the century.

Oil shows different behaviours. In IMAGE shows a reduction so important that the amount of energy produced by it will be lower with respect to coal. In this case DAC will allow a longer use in the middle of the century. In WITCH instead the presence of oil, even in the no-DAC, is important during the whole century. The presence of DAC will allow a even more consistent use of it. This difference between the models is given by the presence in IMAGE of a very detailed module about biofuels and electric vehicles that also WITCH has but it is not included in the main model and, for now, it is only an optional module. This will allow IMAGE to switch from conventional cars to electric cars reducing the amount of oil needed, this transiction is not possible in WITCH yet but this module is under implementation.

The main differences between the DAC and no-DAC scenarios, for both the models, are in the gas production/consumption and this is mainly due to the gas used to power the DAC plants and this will be analyzed in the following subchapter.

Considering the electricity mix and the fossil fuel consumption just shown it is clear that DAC is not seen as a technology used to decarbonize the electric sector, this is something that can be done using different strategies that are very well known, but it can be considered a technology able to tackle all the emissions that are harder to decrease. It is evident that the amount of CO_2 captured comes from the non-electric sector, that includes transport and heavy-industry. These emissions, being mobile in the case of transport and being in the case of heavy-industry linked to very high temperatures not easy to reach, have a higher cost of reduction and so DAC is expected to tackle these type of emissions

4.6.1 Gas Dedicated to DAC

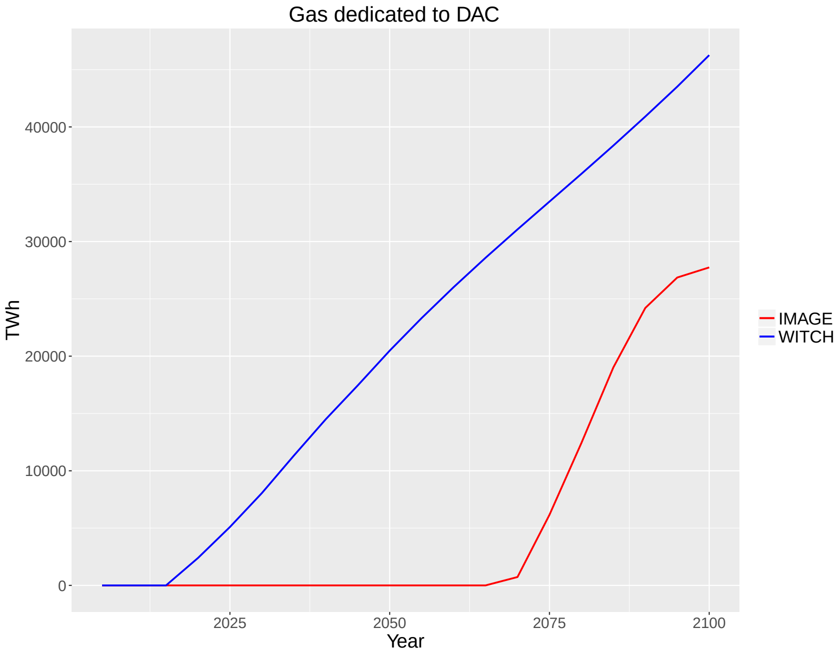

Figure 4.10: Gas consumption of DAC in the 2°C scenario

As in the electricity case, the total amount of gas used has a very similar shape to the total DAC installed curve. In 2100 the TWh required by DAC is 45000 TWh and 27500 TWh for WITCH and IMAGE respectevely. This amount of energy produced by burning gas is basically the difference between the no-DAC and the DAC case of the previous paragraph. These values corresponds roughly to half of the total gas demand in both the models. So after all the considerations done before it is possible to say that the increase shown in the TPES is mostly due to the thermal needs of direct air capture plants.

4.7 Investment in Energy System

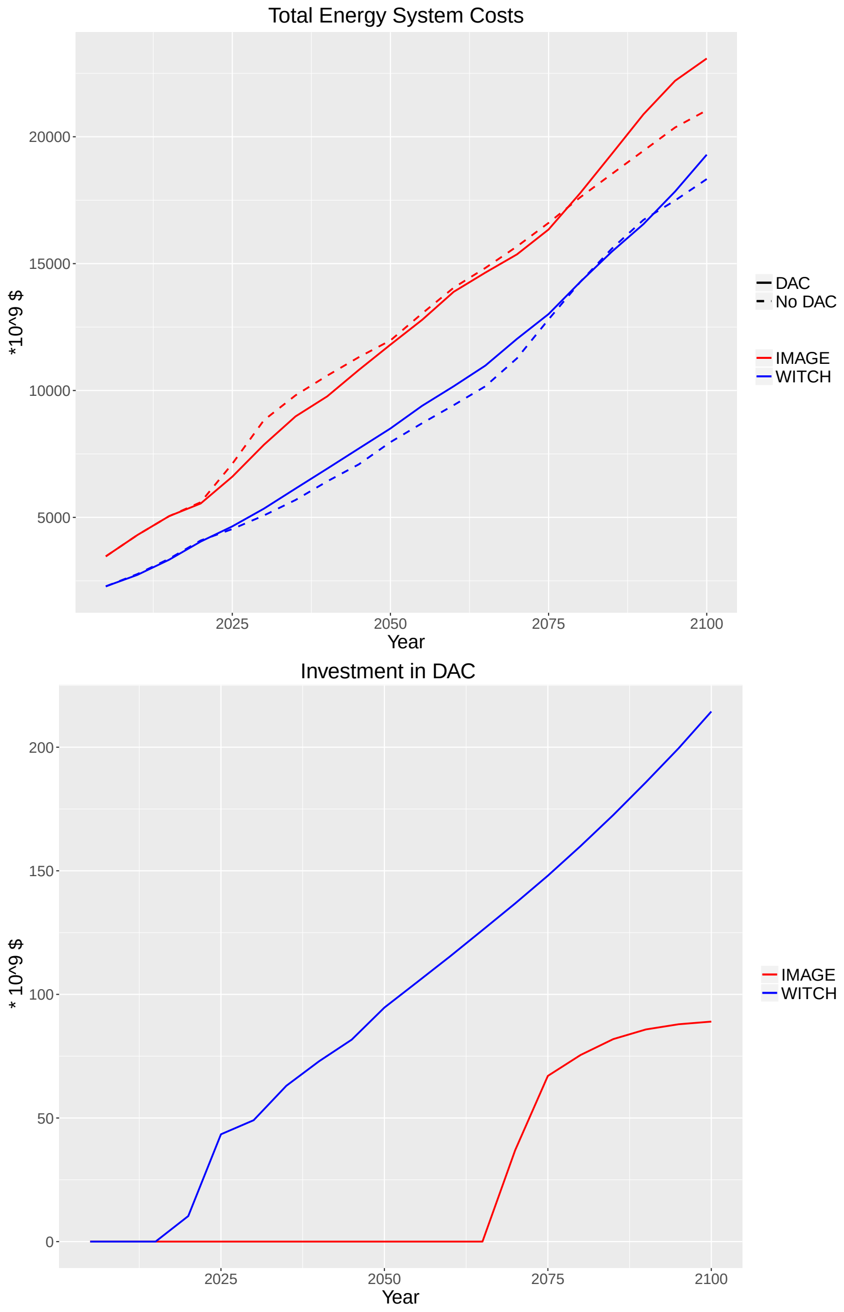

Figure 4.11: Total Investment in the energy sector and a focus on investement in DAC in the 2°C scenario

"Investment in Energy System" stands for the total annual amount of money spent in investment, fuel and operation and maintenace in the energy sector. The two models follow an identical path and the influence of DAC is similar in both the cases, staying close to the original line for most of the time. The biggest difference is evident at the end of the century in IMAGE where more money is needed, the overall amount of money invested is very similar though since during the middle of the time period investement needed in the DAC case were lower.

4.7.1 Investment in DAC

Here there are shown the capital investments in DAC, so considering only the capital costs. And the shapes are of course very similar to the trends of the total DAC installed. The maximum value is reached in the WITCH model in 2100 reaching a value of more than 200 bn$. This is a very big amount of money but comparing it to the amount of money spent in oil and gas sector that reaches the value of 650 bn$ in 2016 and in 2015 it was even higher reaching 870 bn$ [18]. If also the other component of the costs like fuel and storage are considered the total investment increases. Those costs account for about half of total costs at the beginning of the simulations, but at the end of the simulation their influence is bigger accounting for two thirds of the total costs in IMAGE while they stay around half in WITCH. Even multiplying by three times the total investment, the amount of money spent in oil and gas is still not reached.

4.8 Regional Focus on Energy Exporting Countries

Very often Energy Exporting Countries (EEX), such as the Middle East and North Africa (MENA), Russia (TE) and Sub-Saharian Africa (SSA), are said to be the biggest losers in case of this type of climate scenarios. Their economy are mainly based on the exporting of fossil fuels, gas and oil particularly, so if the world is going to low carbon sources their economies can be considered endangered. For these reasons these countries, in particular Saudi Arabia, Iran and Russia, have always been reluctant in taking actions to tackle climate change. DAC may change their point of view, it has already been shown that DAC will postpone the phasing out of fossil fuels, it is reasonable to think that this will help EEX countries to continue using their oil and gas reserves and so reducing the "damages" to their economies due to climate policy actions. For these reasons an analysis on how DAC influences their energy production and GDP is definetely intresting and has to be done.

In both the models these three regions are among the top installers and the quantitiy of DAC installed is similar. As shown before, the installation in WITCH starts earlier with respect to IMAGE. In WITCH it is intersting to notice that the installation in SSA is delayed of 20,25 years with respect to the others regions due to the different type of storage available. Even if SSA total capacity storage is very large, it is mainly composed by aquifers offshore which are more expensive with respect to depleted oil fields onshore, which is the main component of TE capacity for example.

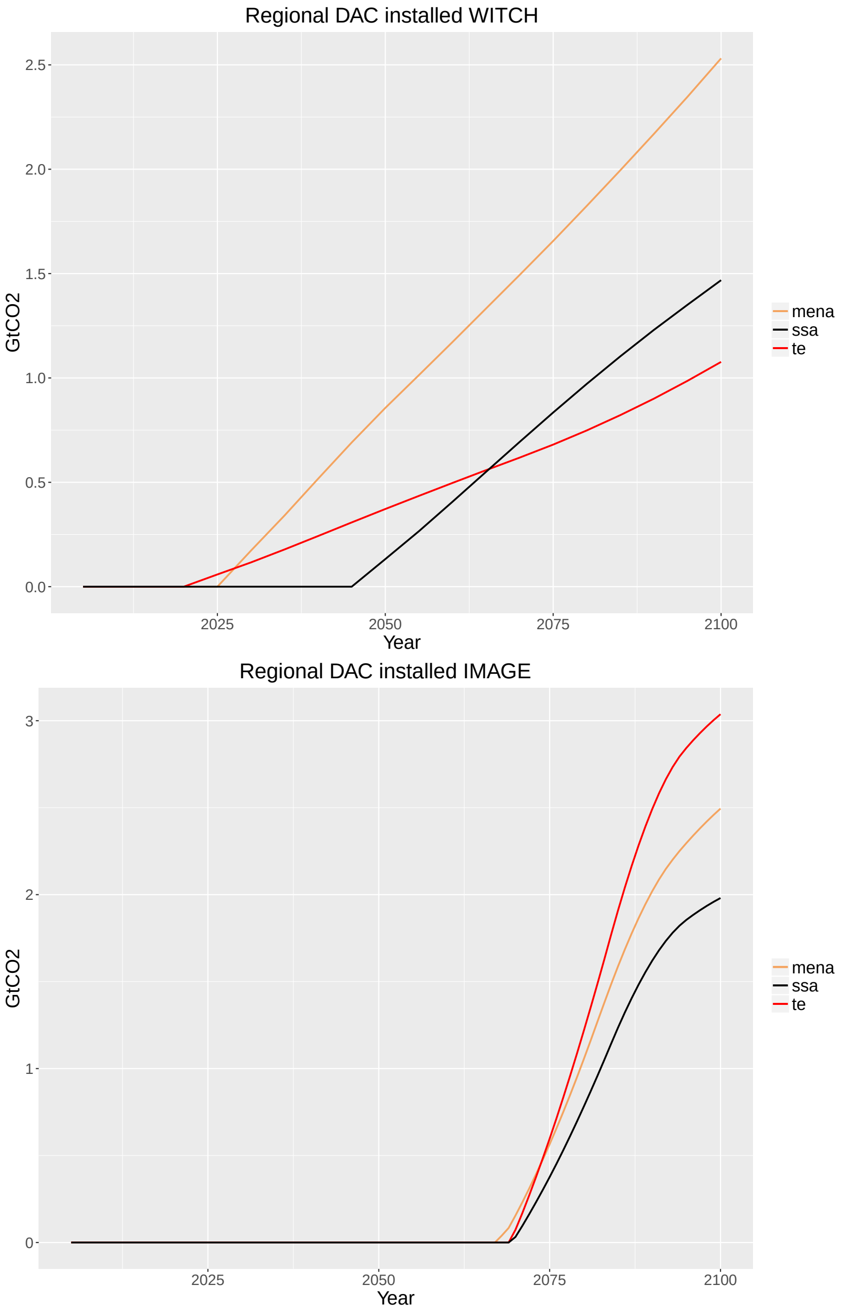

Figure 4.12: DAC installed in EEX countries in the 2°C scenario

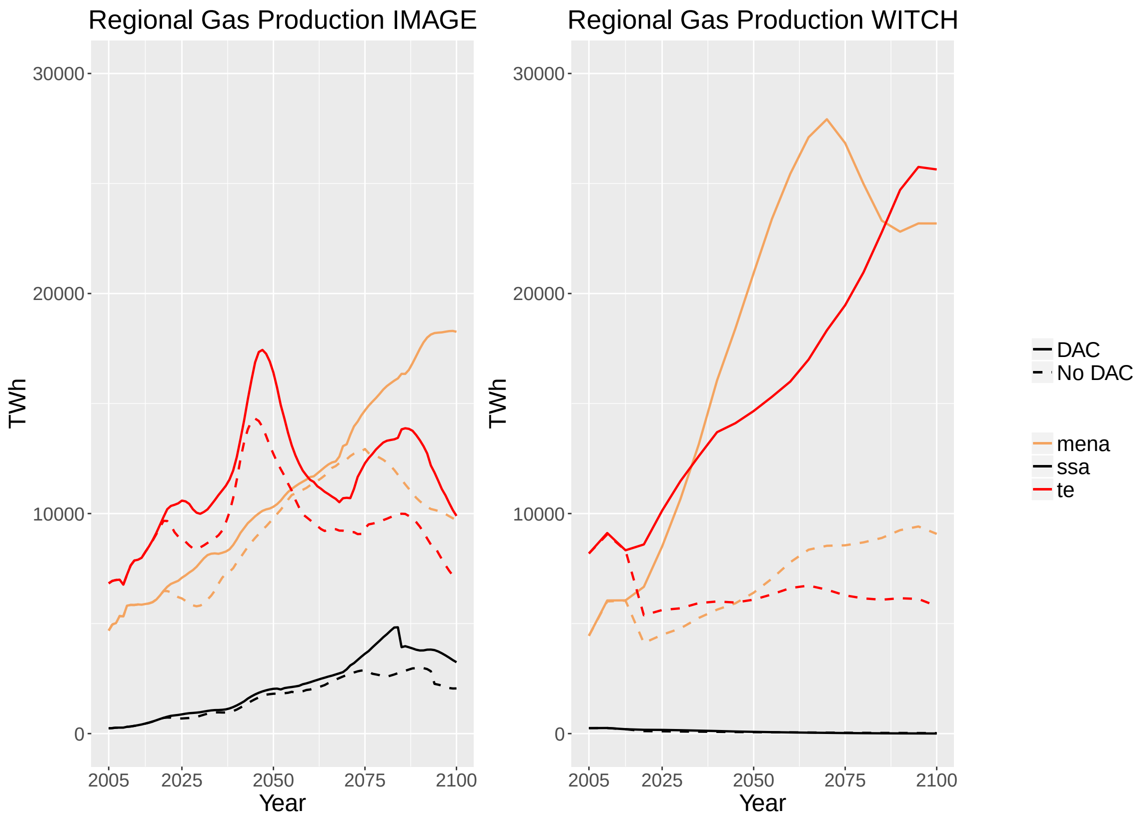

Figure 4.13: Gas production in EEX countries in the 2°C scenario

In Figure 4.13 and 4.14 it is possible to see the evolution of gas and oil production in these countries.

In IMAGE gas production curves in the DAC case are similar to the no-DAC case but lifted so these gas exporting countries are expected to produce more gas, especially MENA countries that in 2100 are expected to produce more than 1.5 times the amount of gas produced in the no-DAC case going from 10000 TWh to 18000 TWh. The increase in the other two regions is smaller but still significant. WITCH shows that gas production in MENA and TE will see a huge increase, MENA will see its production grow by a factor of 4 and TE by a factor of 3. Surprisingly SSA production will not show an increase staying very close to zero for the whole century.

IMAGE oil production reflects what it was seen in the global view. The final value of oil produced is still very low but the amount of oil produced in the whole century is definetely bigger with respect to the normal case. WITCH projections say that, thanks to DAC, MENA countries are expected to peak their production somewhere around 2060, while TE and SSA only in 2080. This delayed peak can be important from an ethic point of view that is often discussed when there are discussion about climate change. SSA countries says that their historical contribution to the global emissions is very limited with respect to the western countries, for this reason they want to have the possibility to exploit their natural resources, as the developed countries have done in the past, in order to have the

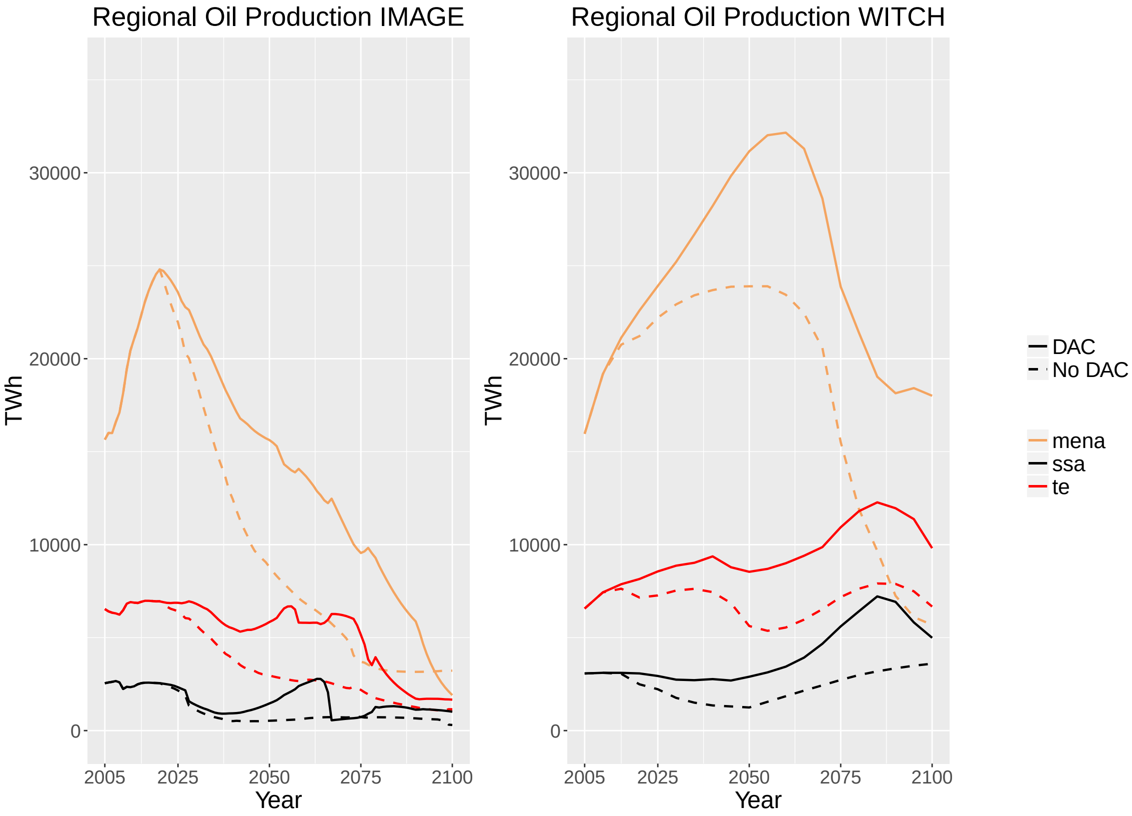

Figure 4.14: Oil production in EEX countries in the 2°C scenario

possibility to have an economical development. DAC, after having seen the results, show that this is possible if the technology is developed.

In Figure 4.15 it is possible to see how much these countries have produced more with respect to the base case and the total value of the market. For the whole century both the size and the value of the market are significantly higher in the DAC case. The value of this market in 2100 is roughly the double with respect to the base case, reaching almost 2.5 T$ in opposition to a value smaller than 1.25 T$ that is reached in the no-DAC case. Considering the cumulative value of this market, DAC allows these three regions to have earnt along the whole century around 60 T$ more with respect to the base case.

WITCH gives the possibility to see the effects of DAC on the economy. A good way to see its economic impact is to see the impact on the GDP. Climate policies influences negatively the GDP with respect to a business as usual solution because in order to reach the target imposed sometimes less ecomonically competitive solutions have to be chosen with respect to more competitive but polluting solutions. In the no-DAC case the world sees a percentage loss of GDP of more than 7.5% with respect to BAU, but the losses are not equally divided between the regions. TE and MENA are definetely the biggest loser from these climate policies losing almost 25 and 20% of their GDP in 2100. DAC decrease the global loss up to less than 5% and the biggest winners are these EEX countries. TE could limit the losses to 10% and MENA to 7%. The losses in SSA's GDP are lower because of the lower

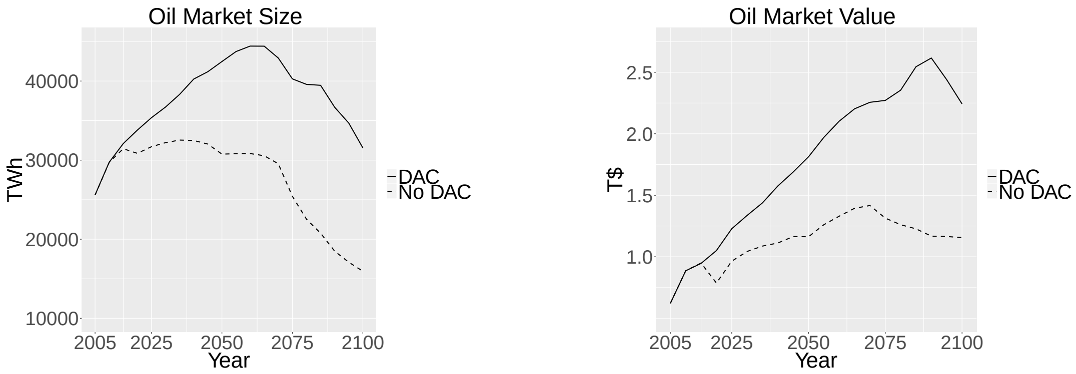

Figure 4.15: Oil market size and oil market value in the EEX in the 2°C scenario (WITCH)

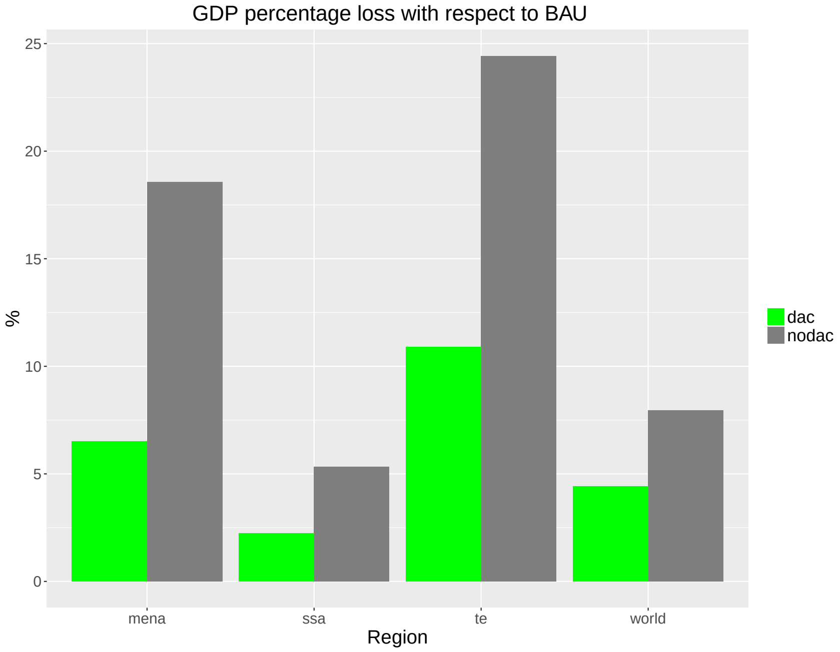

Figure 4.16: Comparison of percentage loss in GDP with respect to Business as Usual with and without DAC in the 2°C scenario

GDP in the BAU case with respect to the other regions. Being the starting value of GDP very low with respect to the other regions also the GDP baselines projections are low, for this reason even if there were losses due to the policy costs this would be in absolute, and relative, value less important than losses other countries with higher GDP projections could have.

4.8.1 The Australian Case

Top installer regions in WITCH are usually the same with respect to IMAGE, with a big exception. Australian region in IMAGE is one of the biggest installer of DAC while in WITCH the amount of DAC installed is very small, as it possible to see in the figure 4.17, and the reason behind this difference has to be found. The most likely cause is the difference in the storage capacity this region has between the models. The logistic function used in the implementation part tends to foster the installation in the countries with the most relative storage capacity with respect to the global one and so a difference in the proportions could be the reason behind this difference. In IMAGE, which uses the datas given by Hendriks [15][16], Oceania is considered to have one of the biggest aquifer storage capability accounting for 12% of total global storage and being the aquifer storage one of the cheapest storage options the model is prone to built there. WITCH instead relies on the same database but updated for some regions as Europe and North America . The new values increases a lot the value of the storage capacity especially for Canada and USA while there is a decrease in relative storage capacity in some other regions as Oceania [2] [19]. These differences are the main cause of discrepancy between the models, and for this reason more detailed studies on the availability of CO_2 storage are needed.

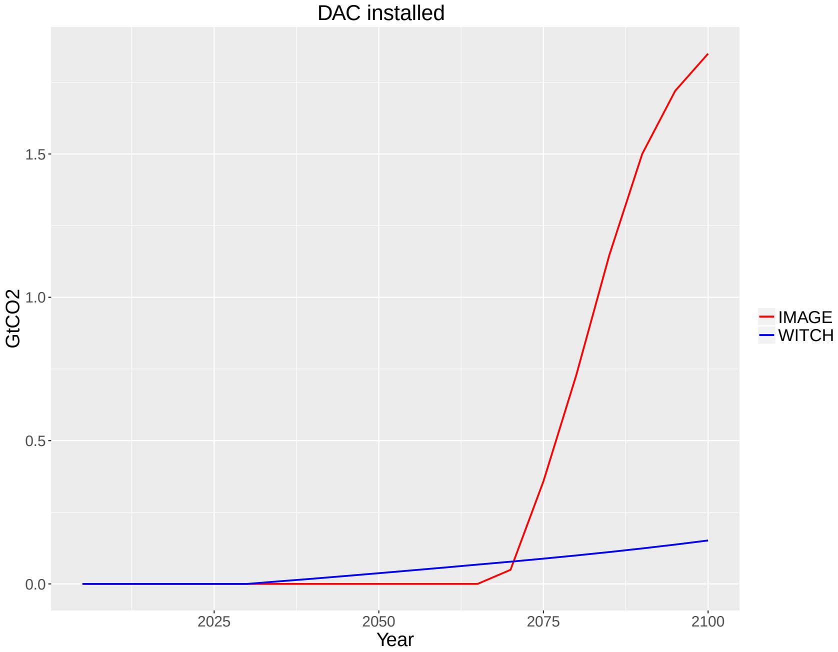

Figure 4.17: DAC installed in the Australian region in the 2°C scenario

4.9 Parameter Uncertainty Analysis

When new technologies are implemented into IAMs it is important to assess the robustness of the model, so to see the variation in the results varying some of the input parameters. This analysis has been done varying the iniitial datas of:

- Initial Capital and O&M costs
- Learning Rate
- Storage Capacity

Parameter	Low	Middle	High
Capital and O&M Costs [\$/tonCO$_2$]	35 - 10	185 - 90	350 - 120
Learning Rate [-]	0.017	0.06	0.184
Storage Capacity	According to model's database		
Maximum Growth Rate [GtCO$_2$/year]	0.5	1	1.5

Table 4.1: Parameters of the sensitivity analysis

- Maximum Growth Rate

Before analyzing these results it is important to underline that there are some differences in the procedures done between the models. In WITCH it has been possible to do this analysis within the whole model so making also the carbon tax vary in function of the new datas, it was not possible to do so in IMAGE. The sensitivity has been done only on the energy module TIMER this means that the carbon tax in every scenario was exactly the same. So if before talking about TIMER or IMAGE was essentialy the same, now it is not the case and every results is just a TIMER results and not an IMAGE one. So this also means that in WITCH the target is still reached in every scenario, while in TIMER it is not something that can be said with absolute certainty.

In the following paragraphs it will be shown only the variation in the emission profile and in the amount of DAC installed, after having seen the previous results understanding how the unshown variables changes is pretty straight-forward.

4.9.1 Investment and O&M Costs

Initial investment costs are one of the most uncertain data about this technology because there are a lot of optimist projections which claim very low costs and there are some pessimist projections which claim the exact opposite. So the range is very wide going from 35 to 350 \$/tonCO$_2$, with the middle estimate, used as base case, of 185 \$/tonCO$_2$. It is important to underline that these costs do not comprehend everything linked to electric energy demand, gas demand and storage costs. These three additional costs are not input of the model because they are calculated year after year, for this reason only the capital and O&M costs are inputs.

The differences in both the WITCH curves are very small, there is a slightly more pronounced emission overshoot in the case of *low costs* due to the increased amount of DAC installed. In the *low costs* case it is economically convenient to invest in DAC in regions like LACA (Latin and Central America) and MENA earlier in time increasing the final value of GtCO$_2$ installed. TIMER in the *low costs* case show a more important decline in emissions that may lead to even lower final temperatures. This decline is due to the early installation of DAC that happens 30 years before the base case. It is also interesting to notice that even with high capital costs the implementation of DAC still happens even if delayed in time.

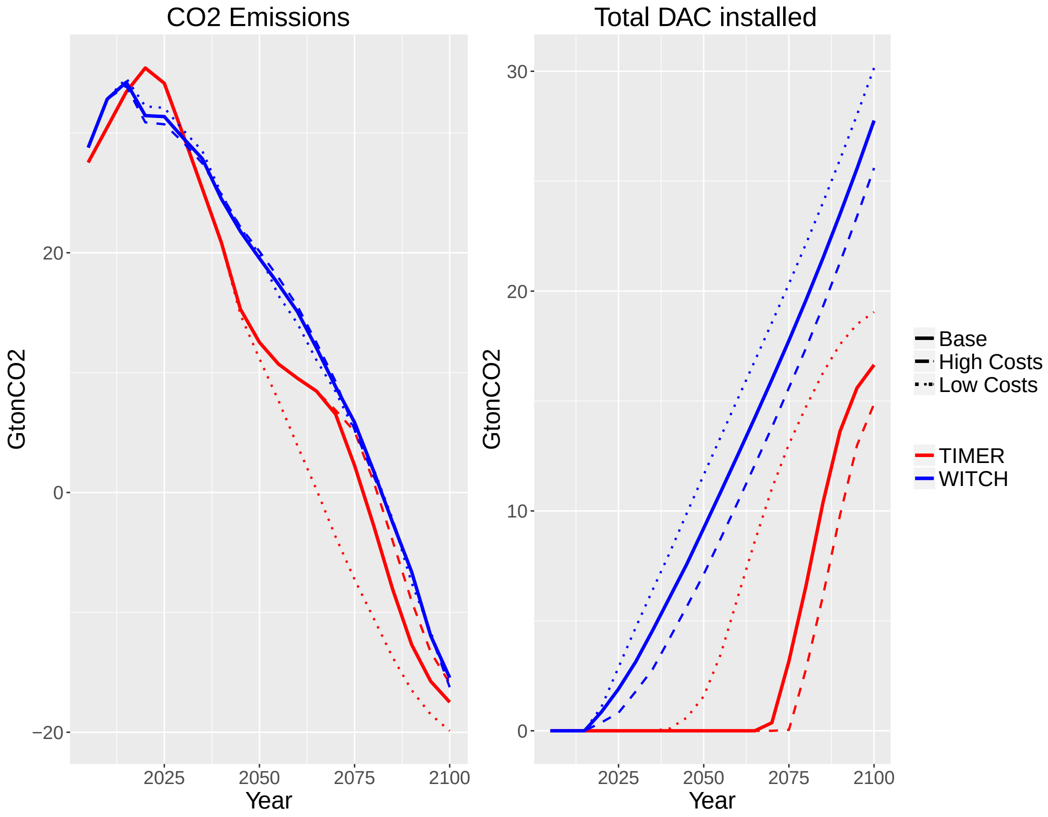

Figure 4.18: Cost sensitivity results in the 2°C scenario

4.9.2 Learning Rate

The learning rate is the parameter *b* of the equations 3.1 and 3.2 and represents the speed those equations go to the floor costs. The value in which the parameter has been varied in are taken from the bibliography [40]. The results obtained show that there is basically no change in the final output no matter the value of this value is and for this reason no graphs are proposed here.

4.9.3 Storage

As shown before storage capacity is an important parameter for DAC diffusion. High capacity estimates do not influence the results, low estimates are more critical though. In WITCH the possible overshoot is reduced making this solution closer to a no-DAC solution even if the amount of DAC installed is still significant. Total emissions in TIMER are increased and the total amount of DAC installed is significantly reduced. The difference in the emissions in TIMER are given by a combination of less traditional CCS installed that leads to an higher emission profile around 2050. This happens, even if the carbon tax is the same, because lower storage capacities lead to higher storage costs and so some CCS plants that were convenient with more storage capacity they are no more convenient in this case. Later in the century this increase in emissions is even increased by the less amount of DAC installed.

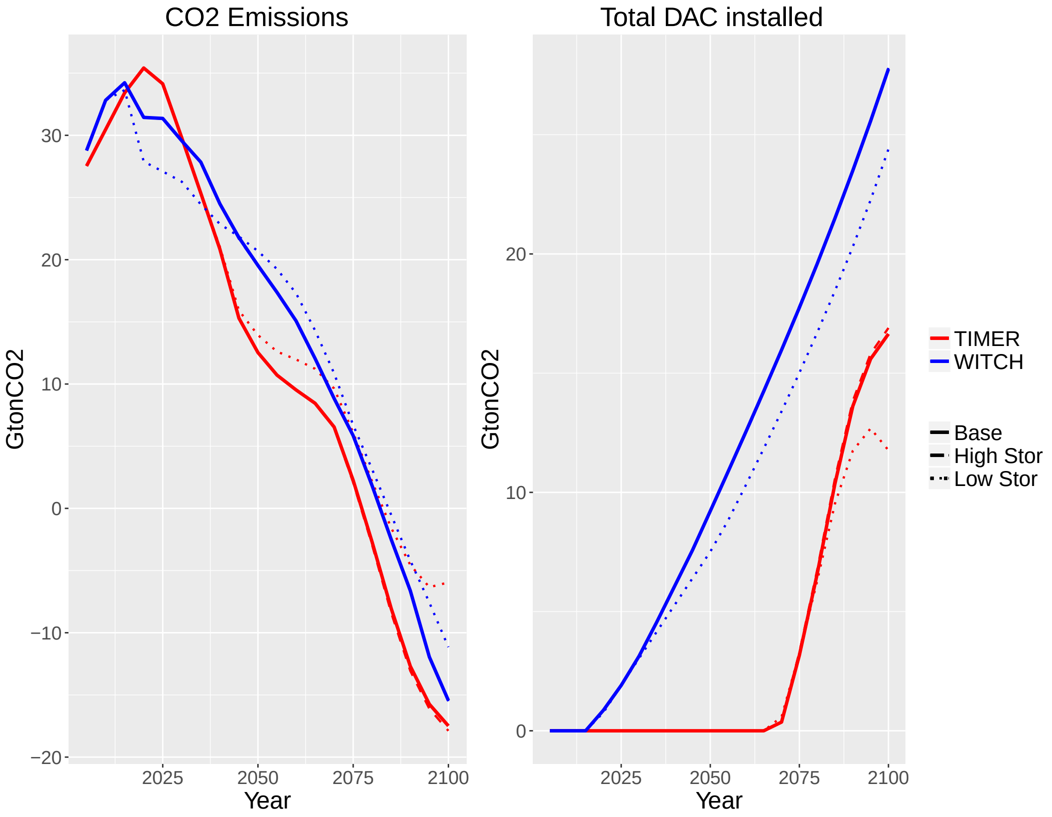

Figure 4.19: Storage sensitivity results in the 2°C scenario

4.9.4 Maximum Growth Rate

The maximum growth rate is a critical parameter since it is an arbitrary parameter so it was one of the most important parameter to do the sensitivity on. The base max value is chosen to be 1 $GtCO_2$/year of installable DAC every year, this number has been decided considering the Socolow plant as reference plant in the case of a large scale plant [43]. This plant has a capacity of 1 $MtCO_2$/year so it has been decided to set as maximum growth the number that is equal to 1000 of this reference plants. This number can be considered a reasonable number also considering that the plant already installed in Zurich has a capacity of 900 $tonCO_2$/year so to reach the $GtCO_2$ chosen as growth limit it will take a around 1.1 millions units, so it has to be understood if there is the industrial capability of producing these amount of small plants per year. Dimensions and technical building challenges of this already installed plant are very similar to big vehicles, so if we take as comparison automotive industry the amount of vehicles built per year is more than 70 million and for this reason building 1.1 millions of this small plants seems a reasonable target to reach [28]. Nevertheless the sensitivity on this parameter has been made varying this number from 0.5 to 1.5 $GtCO_2$ covering a wide range of possibilities trying to reduce the arbitrariety.

Since the only parameter changed is the penetration rate TIMER does not show an earlier or later adoption of DAC because the only parameters that affects the first year of implementation are the one linked to the costs. The variation is only

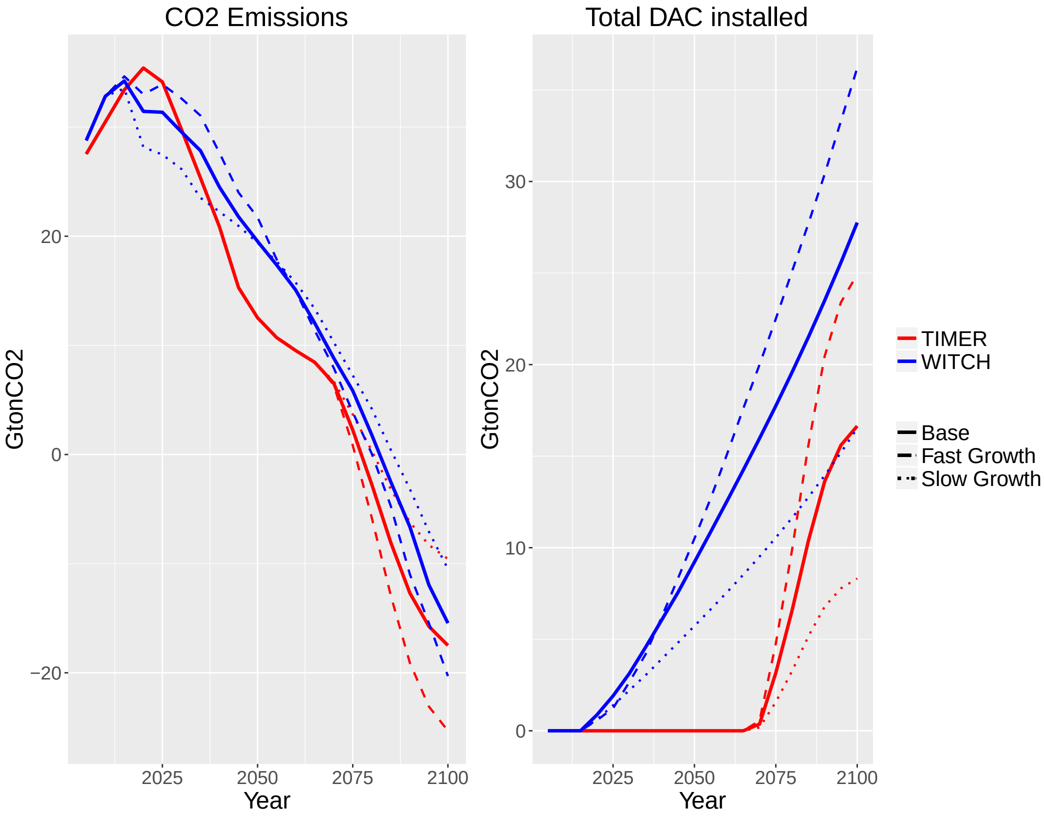

Figure 4.20: Growth rate sensitivity results in the 2°C scenario

in the amount of DAC installed in 2100, and this is reflected on the final value of emissions as well. Thanks to the foresight capability WITCH results are more interesting. The total amount of DAC installed covers a range that goes from 15 to more than 35 GtCO$_2$/year allowing even more overshooting in the case of *fast growth*. Another interesting implication of the growth rate is that installation of DAC is delayed in the case of *fast growth* and anticipated in some regions in case of *slow growth*. The reason for this anticipation is that the model wants to install as much as possible DAC in the last part of the century and to do so an installation in the previous years has to be done but if it is too slow the amount of DAC in 2100 would not be optimal so an earlier adoption is done. *Fast growth*, on the opposite, allows the model to have the desidered amount of DAC easier with respect to slow case so there is no need of installing a big amount of DAC when is not economically available and for this reason everything is delayed of about 5/10 years.

Chapter 5

1.5°C Scenario

The second scenario analyzed is the 1.5°C scenario. Like in the previous case the parameter chosen as target is the radiative forcing. This time, as it can be seen in Figure 5.1, the target is 1.9 W/m^2 in 2100. In this case it is intresting to notice that there is a temperature overshoot. This means that during the century the temperature is expected to be above 1.5°C and so to the target is expected to be respected only at the end of period.

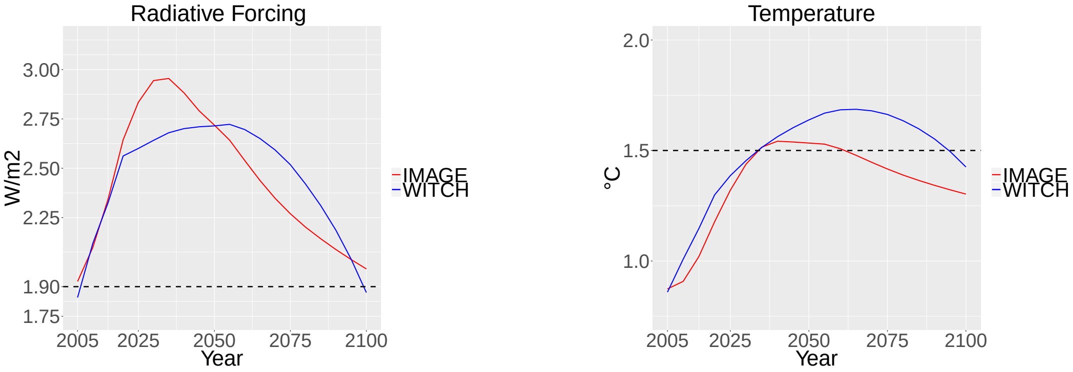

Figure 5.1: Radiative Forcing and Temperature Profile for the 1.5°C Scenario

In this chapter the results will be shown and discussed with a focus on the differences between the DAC case and the non DAC case and on the differences with the previous scenario. Also at the end of the chapter a parameter uncertainty analysis will be shown to check the robustness of the models.

What it expected here is to have results very similar to the previous scenario. All the effects of DAC should be the same, the differences should be only on the values, less fossil fuel consumption and more DAC installed, and not on the trends. The results obtained reflect exactly the predictions. This more extreme installation of DAC made the parameter sensitivity analysis more crucial highlighting some potential issues that will be explained later.

5.1 CO$_2$ emissions path

The shape of the curves are very similar to the less stringent scenario shown before, with the difference that the values, in term of emissions, are definetely lower.

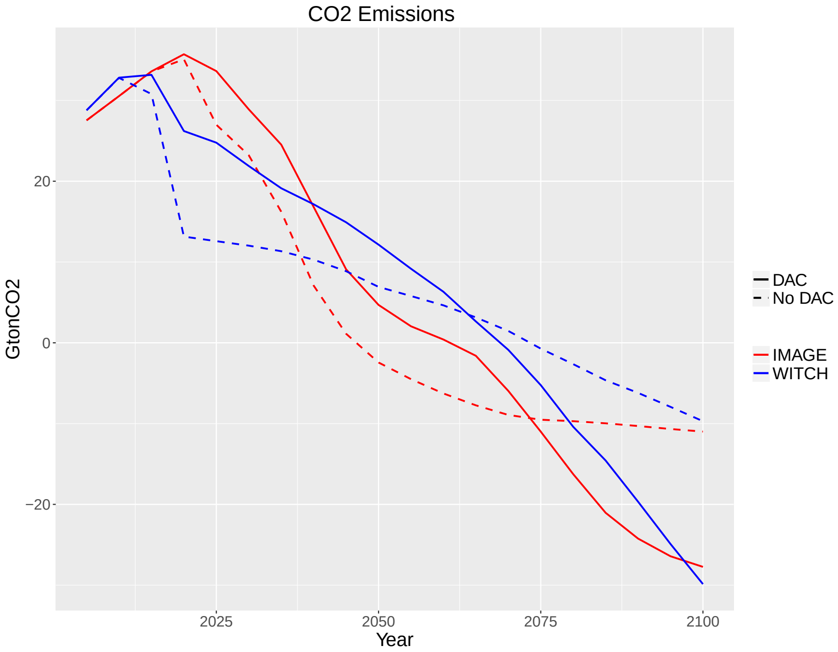

Figure 5.2: World Industrial CO_2 emission paths in the 1.5°C scenario

All the reductions are more important and happens early in time. For example the year when the emissions have to be negative is 2060 for IMAGE and 2075 for WITCH so 10 and 15 years before with respect to the previous scenario. DAC would allow, in the first years, way more emissions with respect to the base case.

According to WITCH, in 2020 the emissions allowed by DAC are, roughly, 25 $GtCO_2$/year while without DAC the rapid decrease needed would lead to only 12.5 $GtCO_2$/year (Figure 5.2). The emissions allowed in the DAC case are more until 2065 when we have the intersection between the two curves at a value of 5 $GtCO_2$. After this point, thanks to DAC, the emissions decrease faster with respect to the no-DAC case allowing to reach 25 $GtCO_2$/year while the no-DAC case reaches only 5 $GtcO_2$/year of negative emissions. In IMAGE the differences between the two cases are less extreme but the pattern of the curves is exactly the same. Comparing the values with the previous scenario it is evident that the decrease in emissions needed has to be much faster, especially in the no-DAC case. In the other scenario, in both the models, in 2050 the emissions are 17.5 $GtCO_2$/year in WITCH and 5 $GtCO_2$/year in IMAGE; In this scenario, in the same year, the emissions are 5 $GtCO_2$/year in WITCH and has to be negative in IMAGE.

5.2 Carbon Tax profile

Figure 5.3 shows extremely well the importance of DAC in terms of reducing the cost of carbon if targets like this want to be reached. In IMAGE the top limit is reached very early in time in the no-DAC case, a tax of 1100 $/ton$CO_2$ is needed already in 2040 while in the DAC case this value is reached only few years before 2100. The impact in WITCH is even more evident. Without this technology the

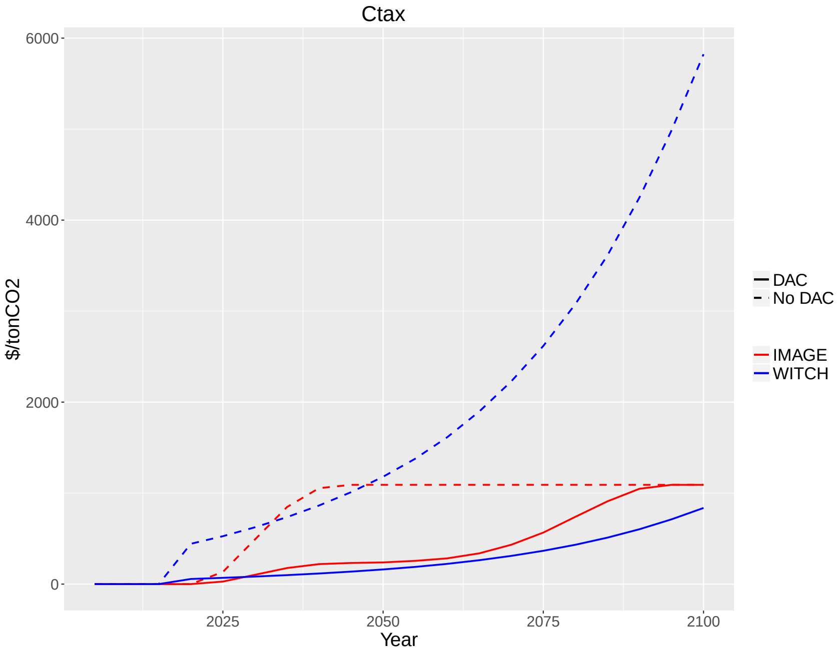

Figure 5.3: Carbon Tax profiles in the 1.5°C scenario

carbon tax will reach 6000 $/tonCO$_2$ in 2100 with a starting value of 450 $/tonCO$_2$ in 2020. In DAC scenario instead the carbon tax is reaching a value close to 1000 $/tonCO$_2$ and the starting value would be only 55 $/tonCO$_2$. To understand the challenge of such a scenario it is interesting to compare the WITCH results for the carbon taxes in this scenario and the taxes in the 2°C scenario, in fact to decrease of 0.5°C it is necessary to implement a tax that is 4 times bigger in the no-DAC case and 2 times in the DAC case.

5.3 DAC installed

Higher values of carbon tax lead to more DAC installed of course. WITCH in 2100 has 35 GtCO$_2$ of DAC installed and IMAGE 17.5 GtCO$_2$ (Figure 5.4). IMAGE shows also an anticipation in the installation, the first plants are installed before 2060 while in the previous scenario there were no plants before 2065. The increase in DAC installed is bigger in WITCH because of the non limited carbon tax it is possible to have in this model. A limit in the top value in the carbon tax as happens in IMAGE is limiting the *r(t,n)* term in the equation 3.4. Limiting this value is an additional limit in the growing rate and so in the maximum value reached. And this is the reason why the IMAGE values in the 1.5°C scenario and 2°C scenario are way closer with respect to the WITCH ones.

5.3.1 CO$_2$ Stored

In order to reach more stringent targets the usage of storage is even more important than in less stringent targets. The amount of carbon dioxide stored per

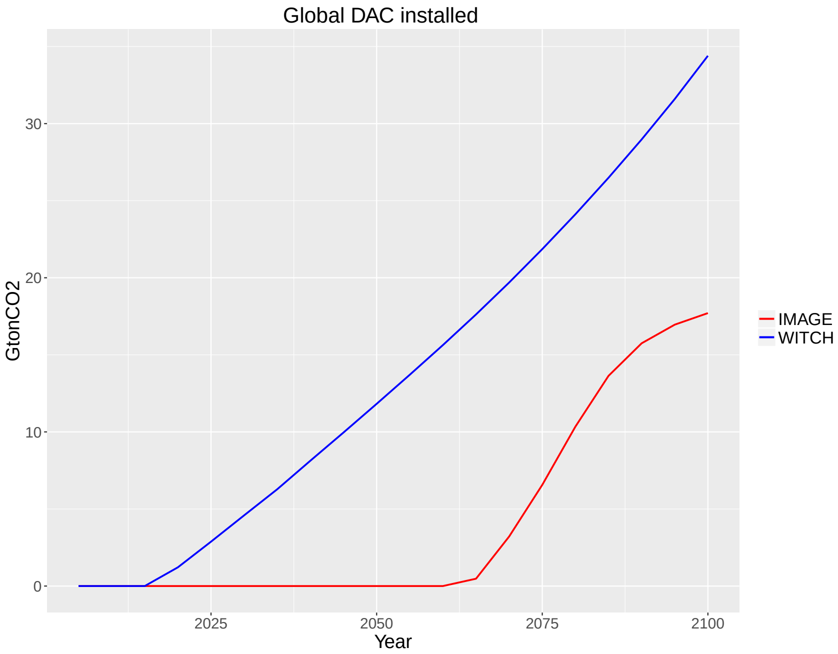

Figure 5.4: Amount of DAC installed globally in the 1.5°C scenario

year is more than 50 $GtCO_2$ in IMAGE and more than 70 $GtCO_2$ in WITCH (Figure 5.5). In both models the presence of DAC is not affecting in a sensible way the amount of storing due to point-source CCS, according to what was happening in the previous target. Considering the no-DAC case the final value of CO_2 storedshows some differences between the models with respect to the previous scenario . In WITCH the final values of the two scenarios are very similar, with traditional CCS storing an amount of carbon dioxide in the range of 25 $GtCO_2$/year, IMAGE instead shows a big increase going from 20 to 30 $GtCO_2$/year. This is due to the fact that IMAGE tends to use more fossil fuels in the electricity production with respect to WITCH and for this reason there are more CCS plants and so more CO_2 stored by this technology. This can also be seen looking at the cumulative CO_2 stored by the models. IMAGE stores through traditional CCS 1225 $GtCO_2$ and through DAC 514 $GtCO_2$. In WITCH CCS cumulatevely stores around 1000 $GtCO_2$ while DAC 1700 $GtCO_2$.

5.4 Total Primary Energy Supply

DAC, in this scenario as well, tends to increase the energy demand and the supply. The final values in the DAC case are slightly higher with respect to the one in the 2°C scenario with more than 350000 TWh and around 225000 TWh in WITCH and IMAGE (Figure 5.6). In the no-DAC case the increase is more evident. The reason of this increase is given by the big exploitation of the renewable sources and their fluctuability. The more fluctuant renewables are present in the supply, and the stricter the scenario the more renewables are present, the more TW have to be installed, and so more TWh would be produced along the year, to satisfy the

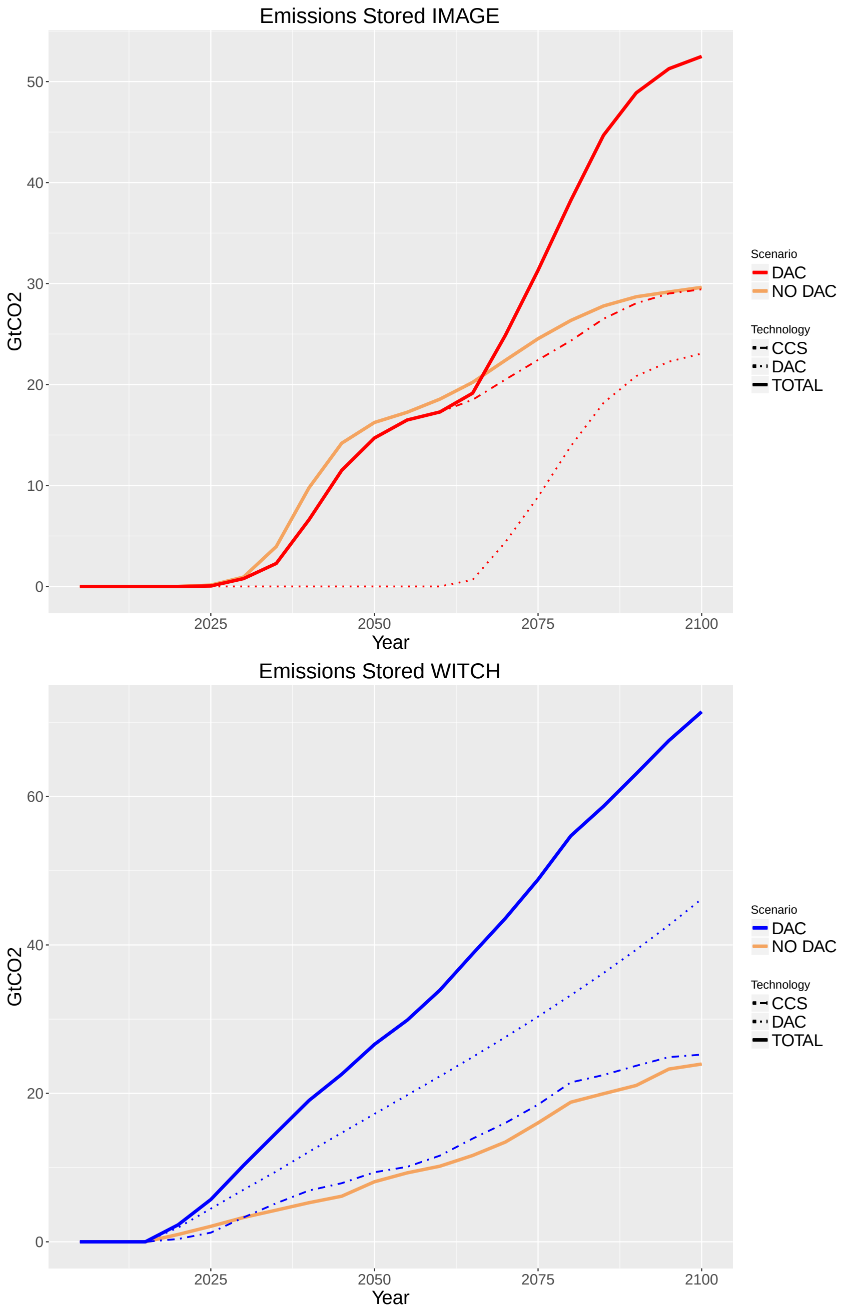

Figure 5.5: Total amount of CO_2 stored per year in the 1.5°C scenario divided into traditional CCS (dot-dashed line) and DAC (dotted line). In the No-DAC case all the emissions stored come from CCS

Figure 5.6: Total Primary Energy Supply in the 1.5°C scenario

same demand of energy with respect to fossil fuel plants.

5.5 Electricity Mix

The trends are the same shown in the 2°C. In WITCH there is a small decrease in total production but looking to the numbers it is possible to say that the decrease is so small that the demand can be considered constant. The electricity demand in IMAGE is increased and in this case the additional electricity request is significant. This increase in energy demand is supplied mainly by solar energy and, in a smaller part, by wind energy.

In the case without DAC the usage of fossil fuels as source of energy is very limited before 2050 and after, besides some GAS CCS, they are not used anymore. The DAC scenario presents reductions in term of fossil fuel usage with respect to the 2°C but still uses them as source of energy. Gas CCS and Coal CCS, only in IMAGE, are still part of the energy mix even if their contribution is very small.

Wind and Solar are the two sources of energy that dominates the electricity sector in the second half of the century. Biomass CCS also has a relevant position and it is important to underline that both the models limits the usage of this technology according to the different potential capacity of growing biomass every region has. For this reason it is safe to assume that, even if the amount of electricity produced is significant, the risk of land competition with food industry is avoided. In this scenario, even more with respect to the previous one, the shifting to a renewable energy sources powered grid is essential. If there is the willingness to respect the targets this shifting is something that has to be done as soon as possible.

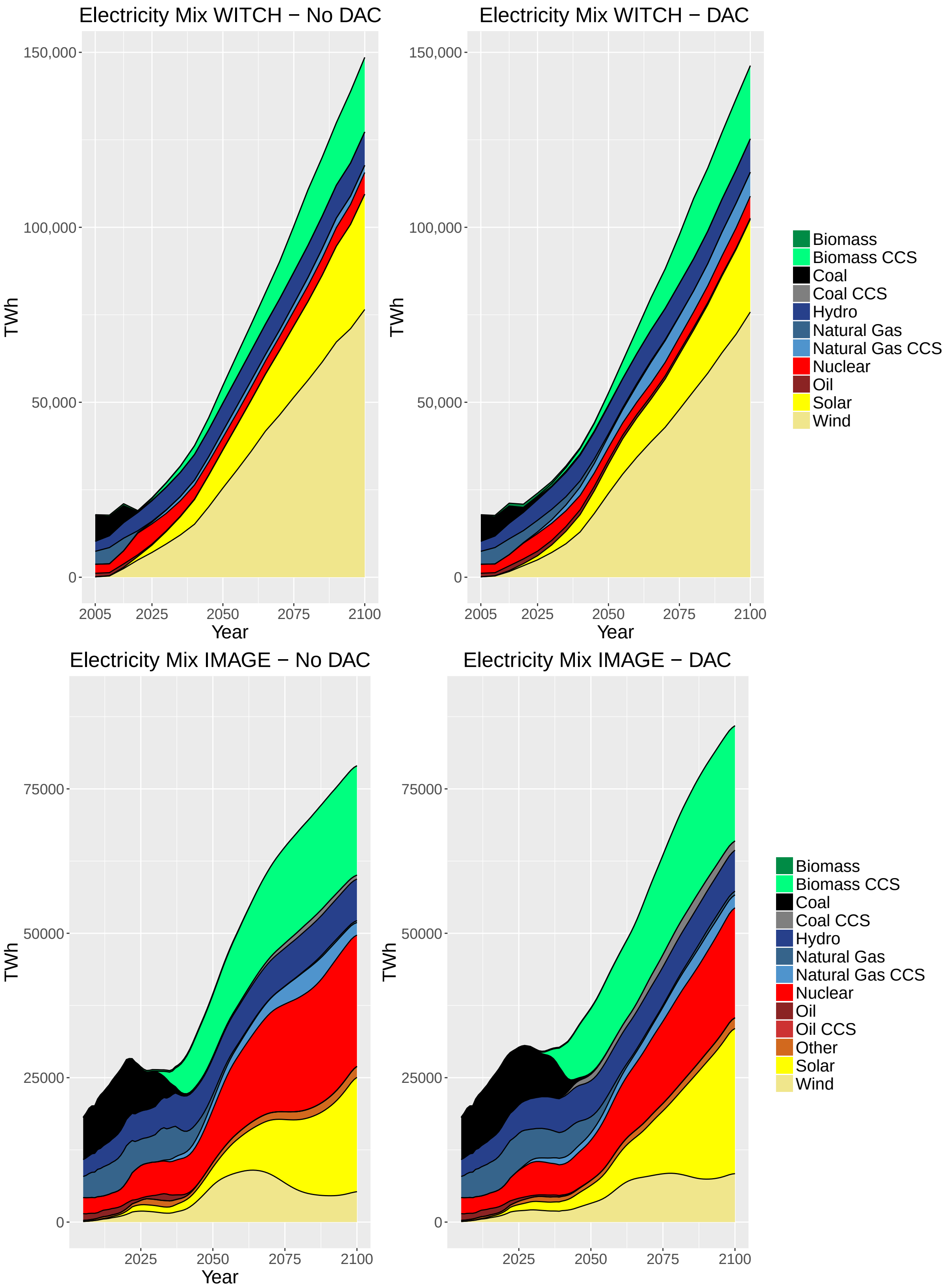

Figure 5.7: Electricity Mix in WITCH and IMAGE for 1.5°C scenario

5.5.1 Electricity Dedicated to DAC

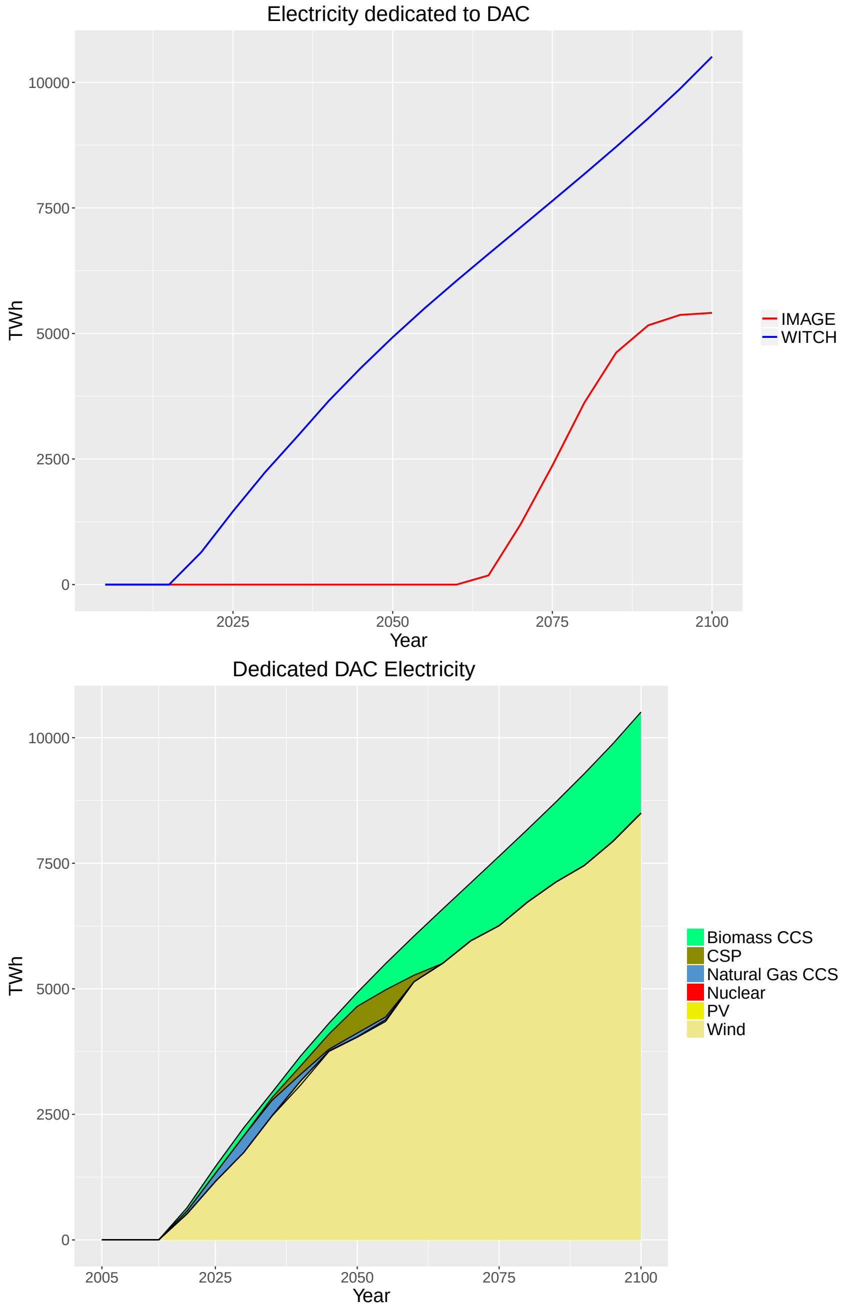

Figure 5.8: World total electricity consumption of DAC in the 1.5°C scenario and the electricity sources powering DAC (WITCH)

The total amount of electricity DAC needs is 11000 TWh in WITCH and 5500 TWh in IMAGE, those numbers correspond to the 7.5 % and 6 % of the total. With respect to the previous scenario, these numbers have increased in the WITCH scenario and stayed more or less constant in the IMAGE one, both in absolute and relative terms. Looking at which source of energy are used the results are the same with respect to the 2°C scenario with wind as the bigger source followed by BECCS. In IMAGE-TIMER, even if fossil fuels are present in the electricity mix, is it safe to assume that the electricity still comes from low CO_2 sources since all the fossil fuels plant in the mix are coupled with CCS.

5.6 Fossil Fuels Consumption

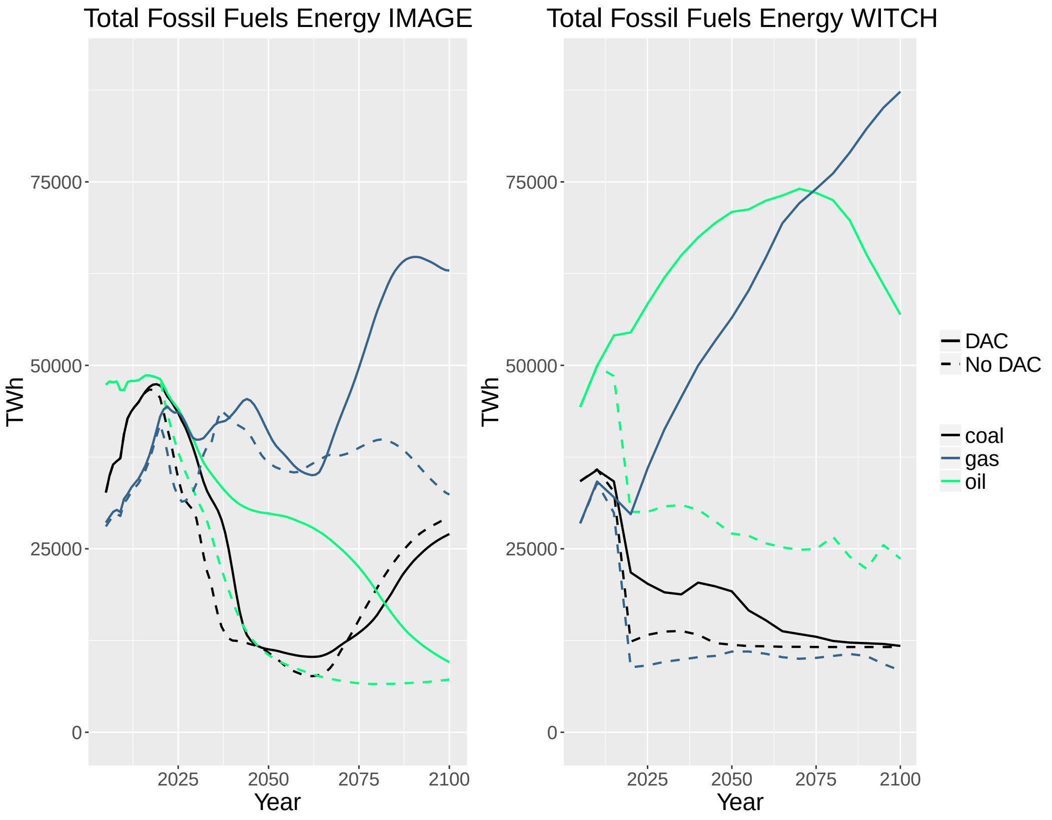

Figure 5.9: Fossil fuels production/consumption in the 1.5°C scenario

In both the cases WITCH shows a decrease in total fossil fuel consumptions with respect to the other scenario, in particular this is evident in the no-DAC case where the reduction in oil and gas consumption is evident. DAC allows to limit this decrease, in particular in the gas production. IMAGE results are a little more complex. In the no-DAC case in the 1.5°C scenario the production of gas is bigger with respect to the 2°C one, this is needed in order to compensate the bigger decrease in the coal production that is a direct consequence of the reducing emissions allowed of this target. Also in the DAC case 1.5°C scenario shows a bigger usage of gas with respect to the 2°C scenario, the increase is the combination of the new gas DAC demand and the necessity of the shifting to a less pollutant source with respect to coal.

5.6.1 Gas Dedicated to DAC

The amount of gas needed to power DAC is by far the major component of the total gas demand, even more with respect to the other scenario. Accounting for

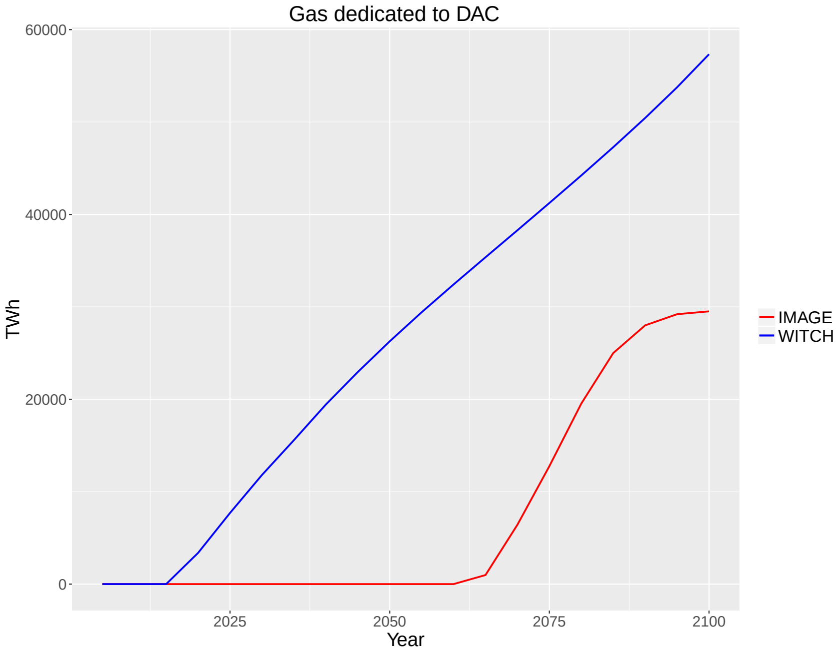

Figure 5.10: Gas consumption of DAC in the 1.5°C scenario

roughly 60000 TWh in WITCH and 30000 in IMAGE, DAC gas demand is 67% of the total demand in WITCH and 50% of the total demand in IMAGE. These percentages and the results of the electricity mix shown before make safe to say that the differences with respect to the base case are mainly caused by DAC itself and not to the increased consume of gas due to gas power plants. In case of climate polices, gas industries should definetely look at DAC as an opportunity because it would help to maintain, and increase, the size of the gas market.

5.7 Investment in Energy System

There is an overshoot in the investment in the energy sector as well, DAC allows to postpone the investments later in time. The total amount of investment needed is very similar to the 2°C scenario. In this scenario is even more evident the principle of the time value of money according to which money in the present is more valuable than money in the future. According to this if it is possible it is better to spend money later in time because that same amount of money would value less and this is exactly what happens in both models.

5.7.1 Investment in DAC

The investment in DAC reaches 250bn$ in WITCH and is very close to 100bn$ in IMAGE. The proportions in the costs are the same as in the previous case bringing the total investments in DAC, in the WITCH model, somewhere very close to the oil and gas investments in 2015 that represented the historical peak in the investments. The total amount of money needed could be an obstacle to the

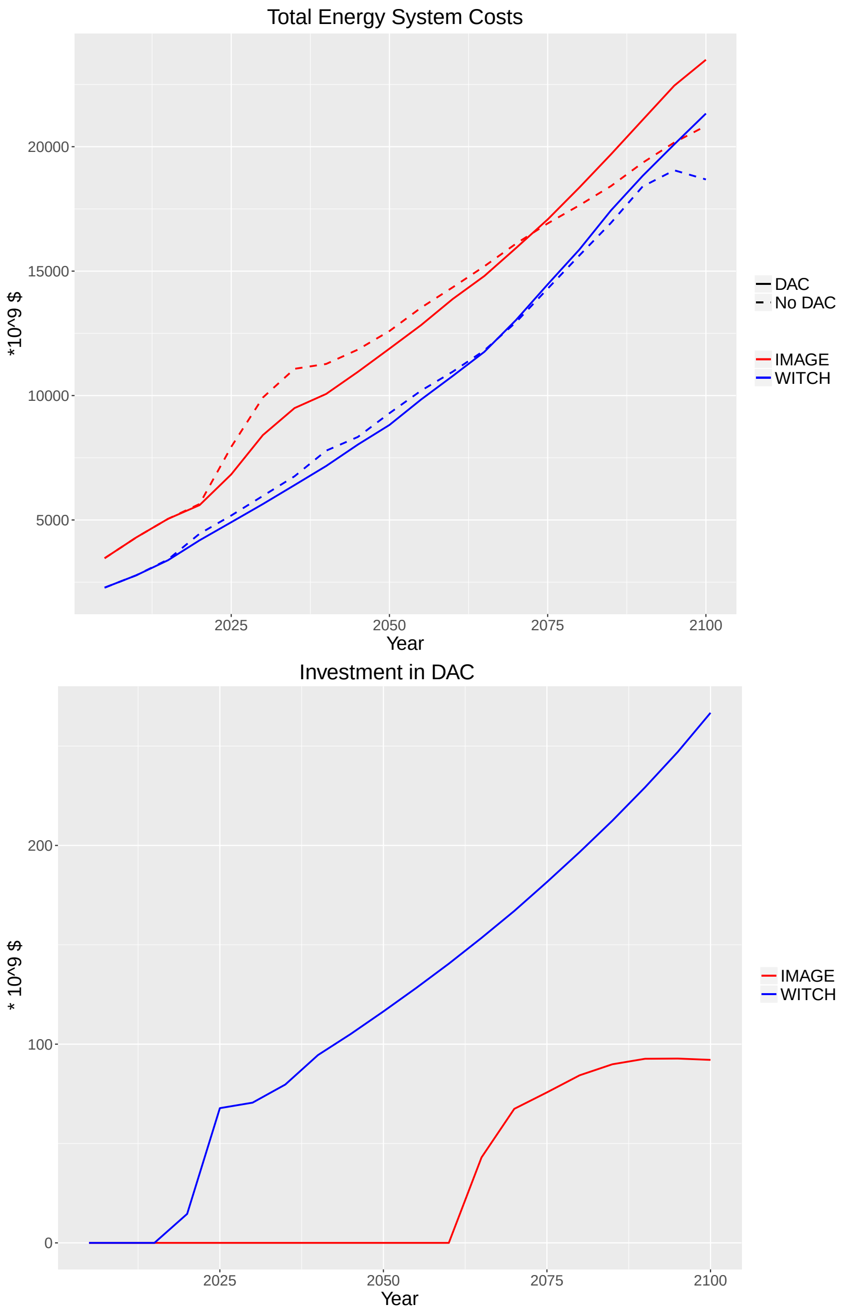

Figure 5.11: Total Investment in the energy sector and a focus on investement in DAC in the 1.5°C scenario

diffusion of the technology but as it will be explained in the following section this investment is essential to limit the economical losses in the scenario (Figure 5.16).

5.8 Regional Focus on Energy Exporting Countries

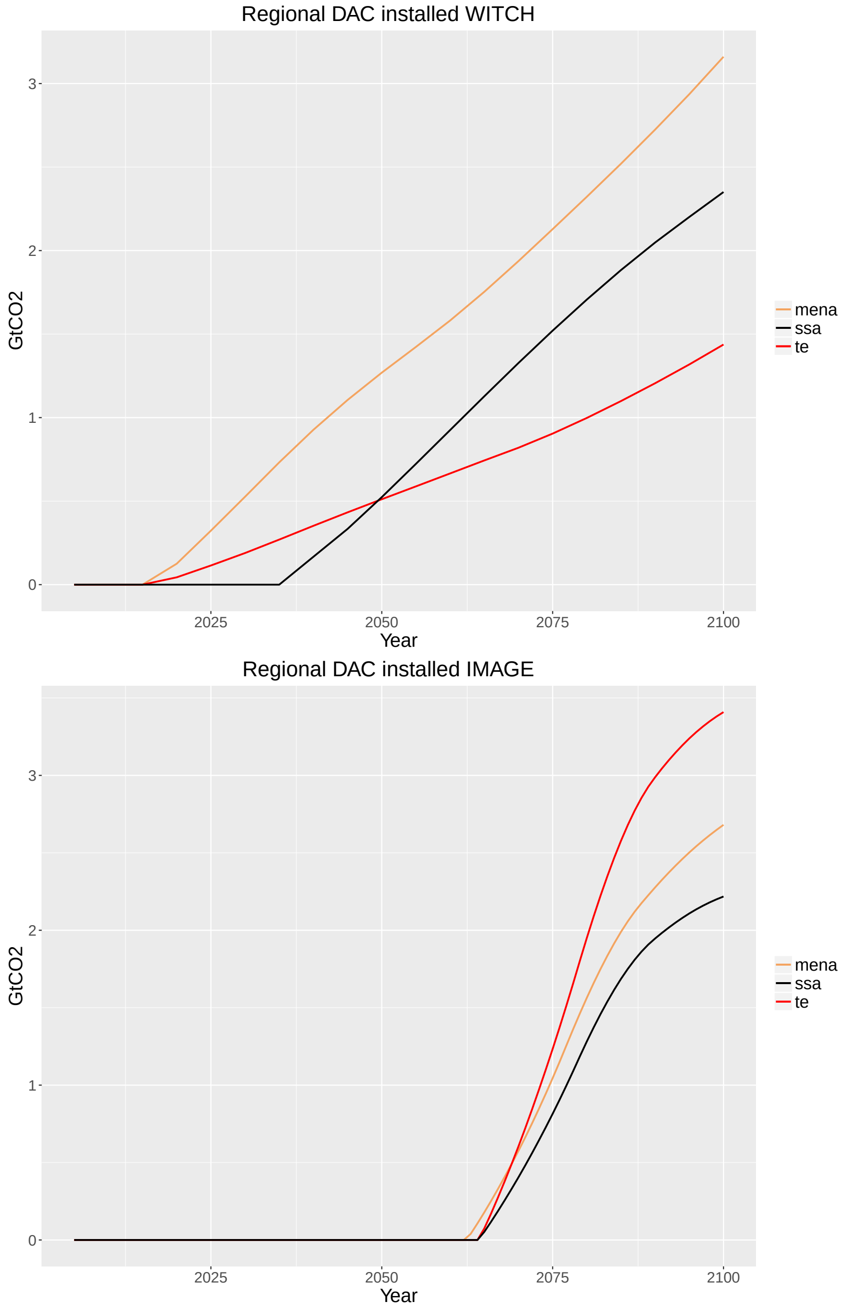

Figure 5.12: DAC installed in EEX countries in the 1.5°C scenario

EEX countries still result among the top DAC installer. In WITCH TE and MENA starts installing the first plants already in 2020 while, for storage reasons already explained, SSA delays the installation waiting until 2040. In IMAGE all the installations starts around 2060, with only MENA starting before that year. As expectable the values are higher with respect to the 2°C scenario.

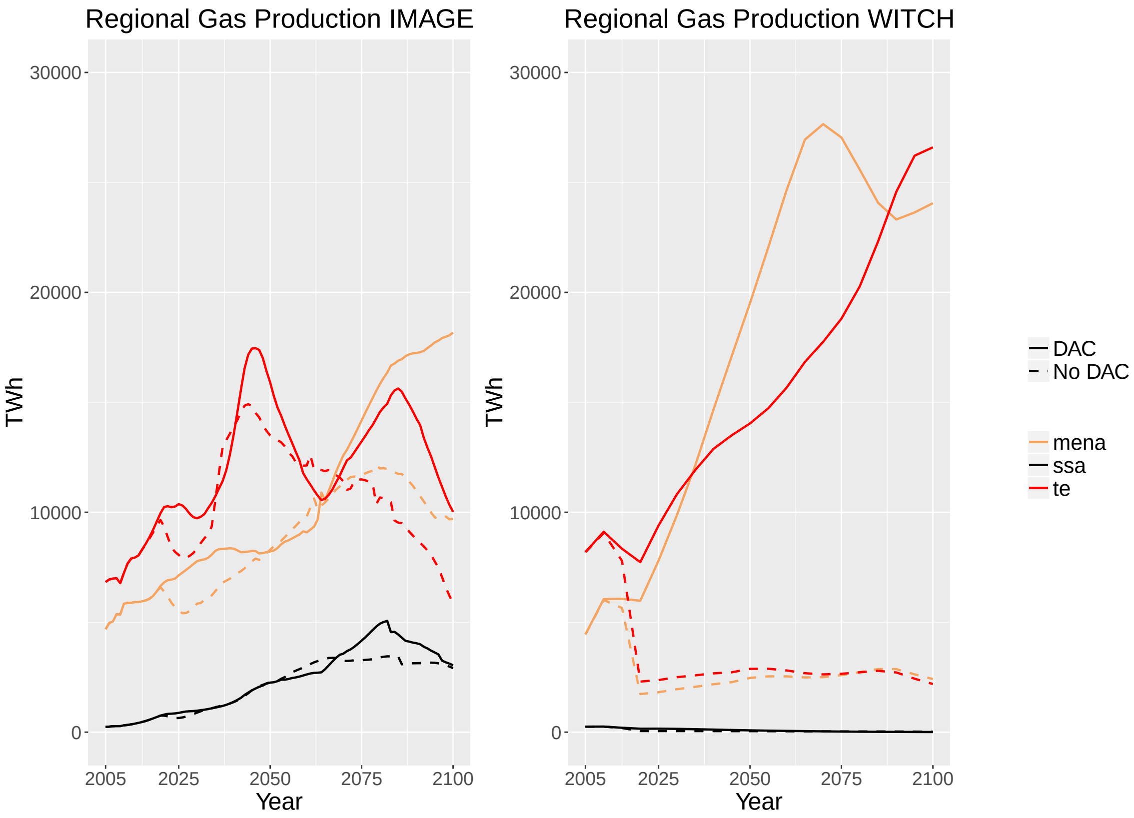

Figure 5.13: Gas production in EEX countries in the 1.5°C scenario

Gas and Oil curves show important results. Even if the target is very strict, thanks to DAC, the reduction in the production with respect to less stringent scenarios is very small. Looking at gas production in IMAGE it is clear how DAC is supposed to help that industry. The case of TE is a very good example, without DAC the production after having peaked around 2035 is constantly decreasing. In the DAC scenario it is evident that in a moment around 2060 the demand increased, and consequently the production, and that moment coincides exactly when DAC is installed. In the other regions it is less clear but the change in the slope of the curves indicates the same results. The sudden decrease that happens after that is a combination of the phasing out of the first DAC plants installed, technological improvements and phasing out of natural gas plants in the electricity sector. The same behaviours, even if less evident, can be seen in WITCH where instead of having a drop in production there is a small plateau and then the increase of the production.

Oil production shows the same patterns as in the other scenario. In IMAGE the curves have the same shape and their values are just reduced of a very small amount, in WITCH the decrease is more sensible. Looking at the 2°C scenario without DAC it is possible to see that the production in SSA was increasing, while this is not happening in this scenario. DAC would still allow oil production in SSA

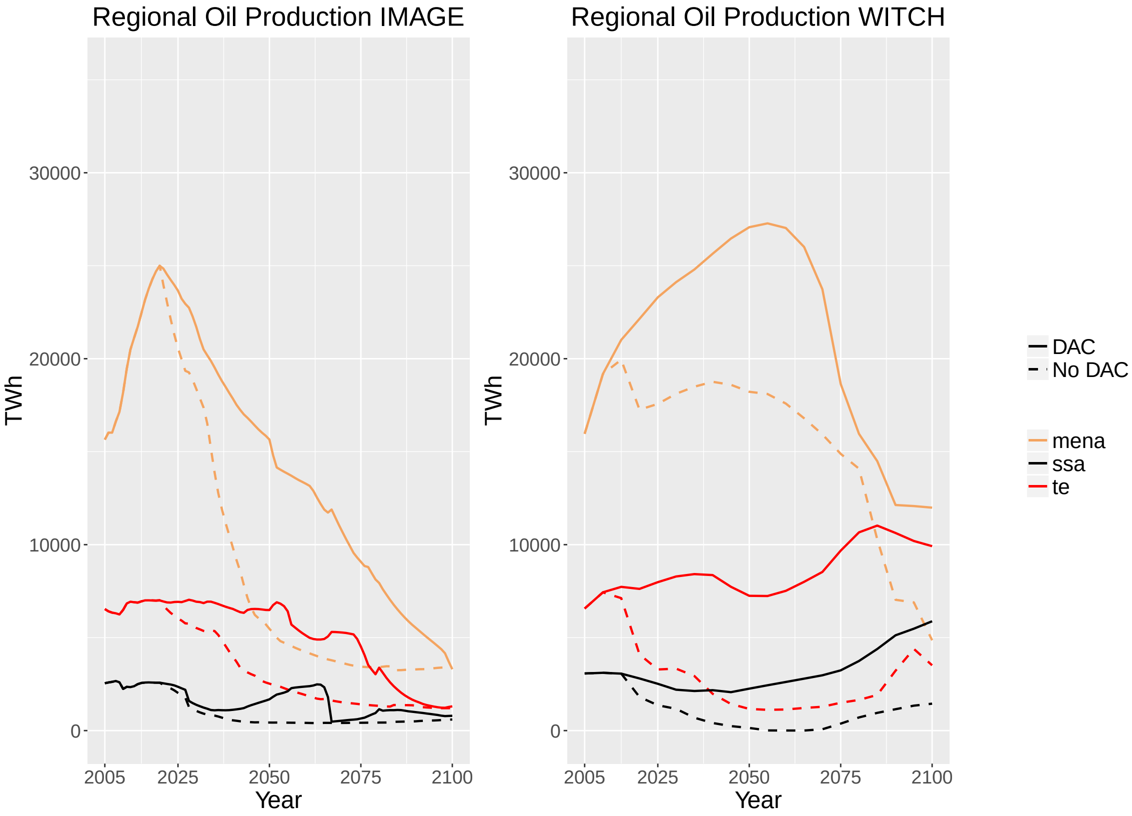

Figure 5.14: Oil production in EEX countries in the 1.5°C scenario

even in very stringent scenarios helping its economy as it is possible to see in the Figure 5.16.

The increased oil market (Figure 5.15), DAC allows to have, is one of the main reasons why there is such a decrease in the losses, as already stated by Chen [7] and seen as well in the previous scenario. Increased prices and bigger production during the century allow to have a final global oil market having a size that is roughly 3 times the one that is possible to have in the non-DAC case. The total final value of this market is only 1.5 more with respect with the base case because in the final years a very fast increase in oil price in the final two periods in the base case has been noticed while the price in the DAC case has grown at a lower pace. The increased size of the market would lead to an increase combined production that is, considering the whole time period, worthy more than 50 T$.

This scenario implies big losses in terms of economy with a GDP global loss of 17% that can be reduced to 6% with DAC. EEX are the big winners from DAC installation also in this scenario. TE would face a loss of 42% with respect to their BAU gdp and MENA of 35 %. DAC would limit the losses to 15% and 12% that are still important numbers but significantly lower with respect to the no-DAC case losses.

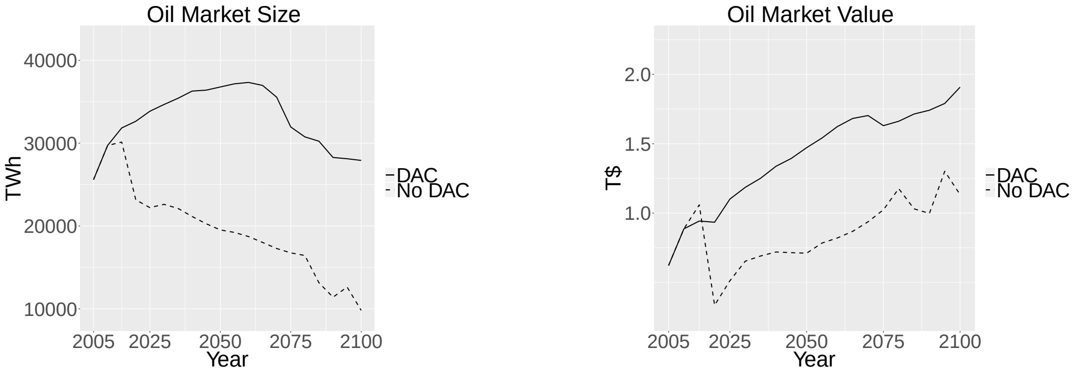

Figure 5.15: Oil market size and oil market value in the EEX in the 1.5°C scenario (WITCH)

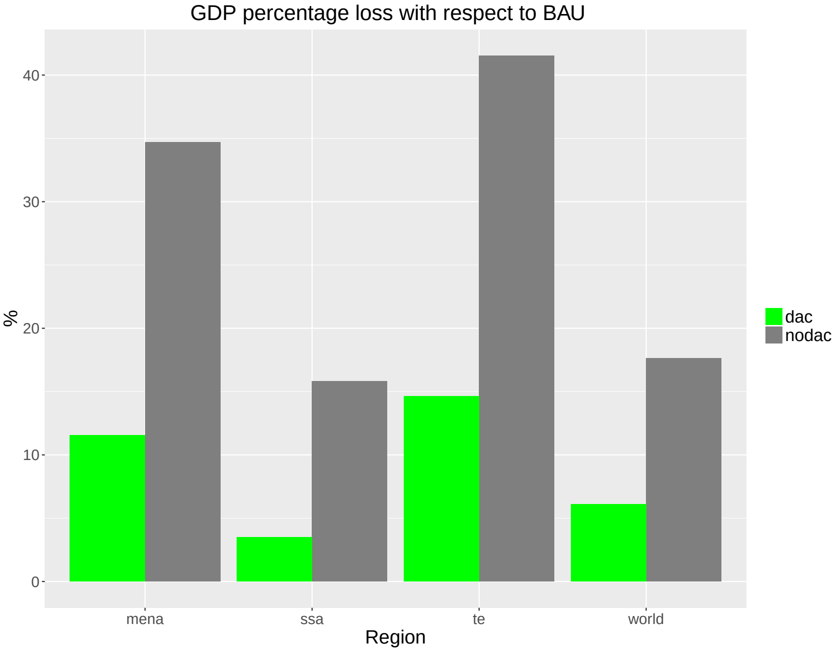

Figure 5.16: Comparison of percentage loss in GDP with respect to Business as Usual with and without DAC in the 1.5°C scenario

5.9 Parameter Uncertainty Analysis

The parameters that vary are the same of the Table 4.1. This analysis here is even more important because the differences between the cases with and without DAC are expected to be more significant due to the increase amount of DAC installed, making this a more significant test for the robustness of the models.

5.9.1 Investment and O&M Costs

The differences in DAC installed and emissions profile generally are not very different, stating again that investment costs are not the most important parameter in the diffusion of this technology. *High costs* scenarios do not present big differences

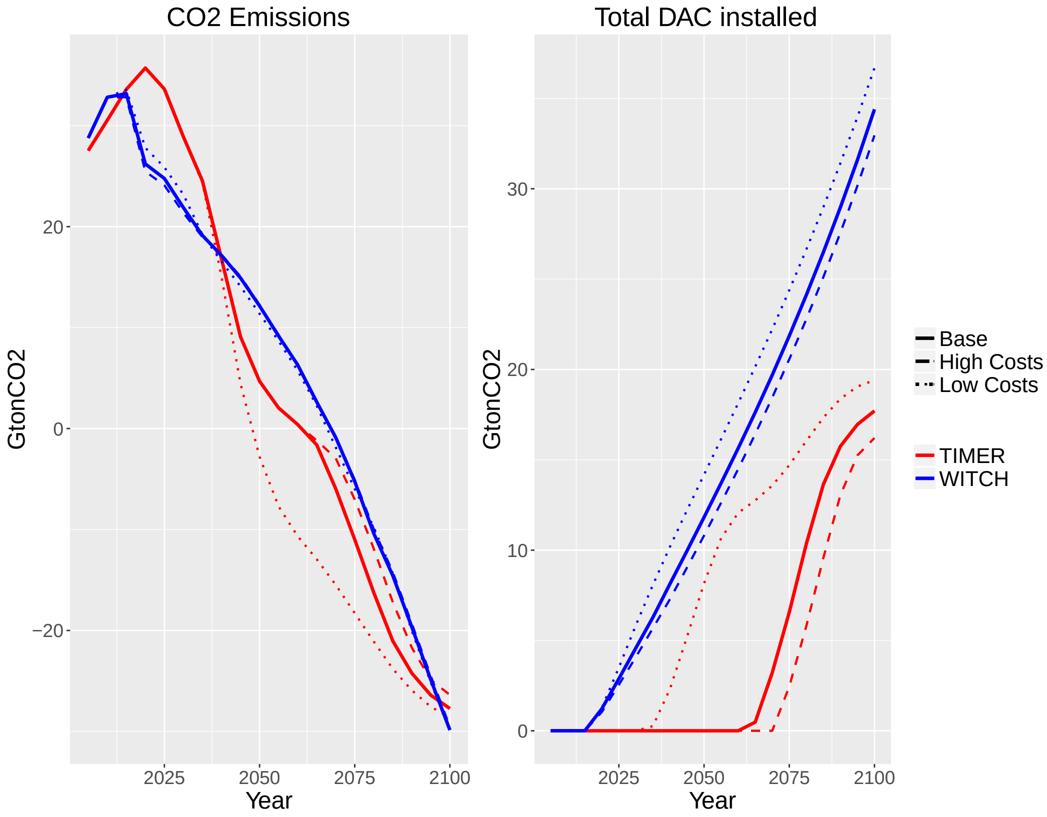

Figure 5.17: Cost sensitivity results in the 1.5°C scenario

with respect to the base case, the reason is that, even if this technology is made more expansive, DAC, having the capability of creating negative emissions, is always seen by the models as the quickest and easier way to decrease emissions. In stringent scenarios, as this one, negative emissions are needed as so, no matter what the costs are, DAC is always needed. The only significant difference is shown in TIMER's *low costs* case. In this case the first plants are installed in 2030, 30 years before respect to the standard case. This early installation brings an increase in total amount of DAC installed that reaches 20 $GtCO_2$. The effect is visible in the emission curve that shows a rapid decrease between 2040 and 2050. In this case the target reached in TIMER would lead to temperature even lower than 1.5°C.

5.9.2 Learning Rate

Also in this case the learning rate is not influencing the total amount of DAC installed and the emission curve.

5.9.3 Storage

An increase in storage capacity is not influencing the results. Low capacity estimates, instead, are more critical. In both the models there is a difference of 10 $GtCO_2$ in the *low storage* case with respect to the base one. The evident decrease of global DAC in TIMER is due to the quick approaching to the capacity limit

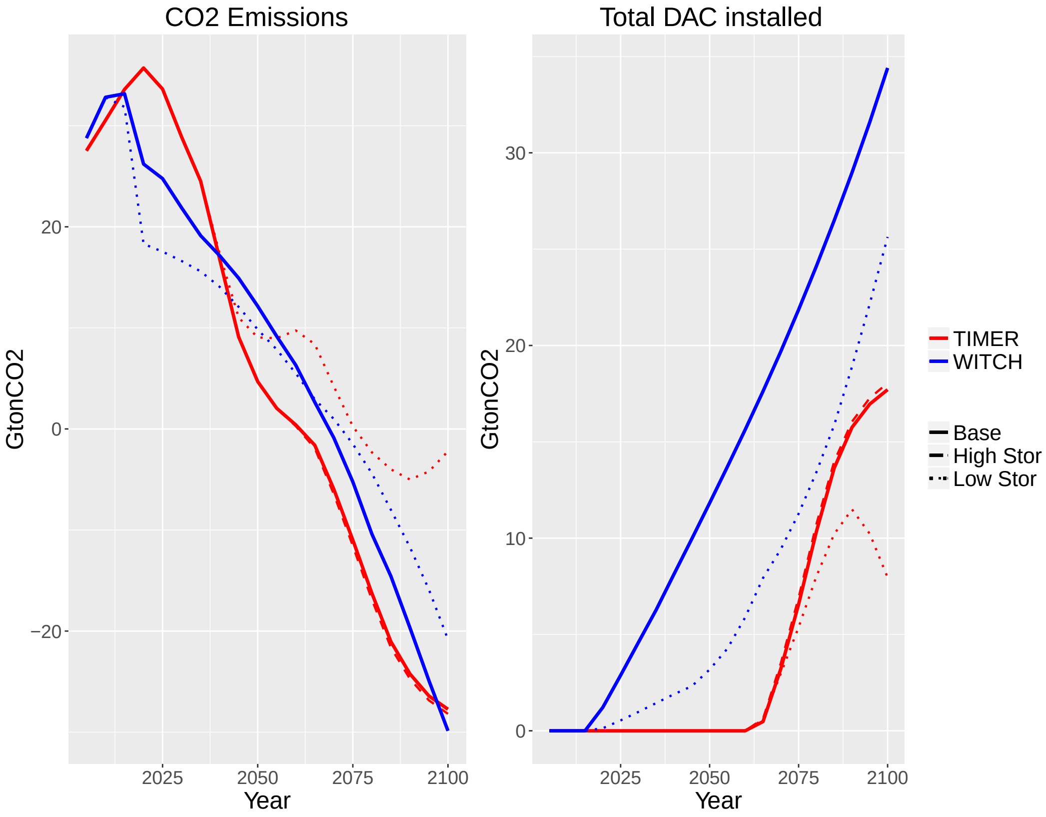

Figure 5.18: Storage sensitivity results in the 1.5°C scenario

explained in the equation 3.8. Already in the base case the total amount of CO_2 stored was very close to the limit and with low capacity estimates that limit is very binding. When this limit is reached the amount of DAC that is naturally phasing out because of the capital depreciation is bigger with respect to the possible new DAC installable and for this reason a decrease in global DAC installed is present. The decrease in DAC is evident also in the emissions curve thanks to the final tail of the curve. The effects of storage in WITCH is less extreme due to the bigger storage available also in *low storage* case. In order to compensate the less amount of DAC installed, and so the reduced capability to have negative emissions, the model has reduced the amount of emissions in the first half of the century reducing the possible overshoot. The emissions in this *low storage* case have to drop below 20 $GtCO_2$ from 2020 while in the normal case emissions reach that value only around 20 years after.

5.9.4 Maximum Growth Rate

The effect of the penetration rate is very important also in this scenario. The differences in final DAC installed between *fast growth* and *slow growth* is 18 $GtCO_2$ and 23 $GtCO_2$ in TIMER and WITCH respectevely. The anticipation in installation that is present in the 2°C scenario is even more evident here, all the regions here starts to install DAC as soon as possible in the *slow growth* while in the *fast growth* in some regions (SSA and SASIA) the first plants are built in 2040. The differences

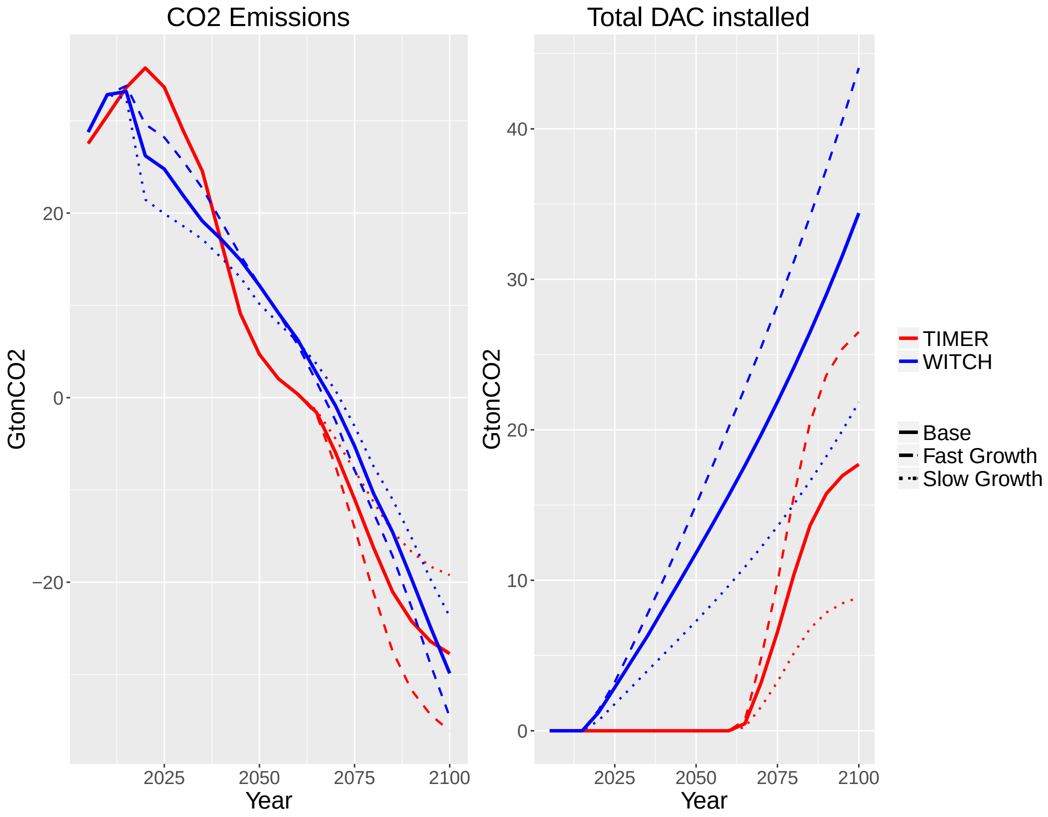

Figure 5.19: Growth rate sensitivity results in the 1.5°C scenario

in the emissions are very evident in the WITCH case in the first half of the century where the difference in emissions between *fast growth* and *slow growth* reaches almost 10 $GtCO_2$ leading the model to two very different emission curve shapes in terms of value and shape. The final values also differs of around 10 $GtCO_2$ but even in the *slow growth* case the amount of negative emissions reached is 15 $GtCO_2$ more with respect to the no-DAC case.

Chapter 6

Conclusions

At the beginning of this thesis some questions were put forward. For sake of clarity they are reported here:

1. What are the DAC plant designs that exist? What is their energy consumption? What are their costs?

2. What impact could DAC have on climate change policies if there is the possibilty to use it?

3. What impact could DAC have on the electricity production and on the fossil fuel usage?

4. How the uncertainties on costs, storage, learning rate, installation rate could influence the impact of DAC?

Our experimental approach of using two different, yet widely known integrated assessment models, allows us to provide some first answers to those questions:

1. DAC is a technology that is still in its early stage so there are different designs and it is too early to assess which one is the best one. Some designs are more studied and are more likely to be used in the future but it would not be correct to say that these are the designs that will be implemented in the future. The most common designs are based on Sodium Hydroxide and Calcium Hydroxide. Due to the relative semplicity of the plant scheme and availability of the chemicals, this is the design that appears to be the most suitable for a large scale deployment. There are also some drawbacks, the major one is the dependance from fossil fuels, natural gas in particular, in order to make the plant run. Some alternative designs propose to use solar energy as source of heat, removing this drawback but adding a limitation on the suitable areas where to install it. In order to reduce thermal consumption other designs are based on potassium carbonate but a real plant has not been proposed yet. Other designs proposes to reduce the thermal needs to zero, this is the case of the so called "Artificial Trees". The system here is based on a wind-driven filter able to capture CO_2, however it is still in a very early stage even with respect to the other DAC plants.

Since there are uncertainties about what will be the actual design of such a plant, there will be uncertainties on costs and consumption as well. Cost estimates, for a plant able to capture 1 $MtCO_2$/year, go from 300 to 3000 million \$ which translates, after having done some economic considerations based on capital depreciation and return on investment, into 35 and 350 \$/$tonCO_2$ captured. Electricity consumption has a range that goes from 1.1 to 1.9 GJ/$tonCO_2$, while thermal consumption goes from 6 to 10 GJ/$tonCO_2$.

2. Despite the uncertainties, the models simulation show that DAC -if developed at scale- could have a significant bearing on climate policies. The clearest variable to show this is the carbon tax. With respect to a case without DAC, the value of the CO_2 prices are always lower, as in the WITCH case, or, if the value reached is the same as in IMAGE, the shape of this carbon tax curve is less steep. Climate policies have a cost, so with respect to a BAU case, there are always some economic losses that increase the stricter the scenario. DAC will reduce this losses making this tax more acceptable to all the countries, and especially to those whose economy is based on fossil fuels. These are also the countries which are the most fierce opponents of emission reduction legislation.

3. As already noted DAC requires electricity and gas to work so their demand has to be added to the total one. Electricity demand is very low with respect to the total electricity required so the effect of DAC on the global electricity mix is not particularly significant. Thermal demand instead is expected to be very relevant. The model similations affirm that at least half of the global gas demand in 2100 is expected to come from DAC, this result comes from a combined decline in gas demand in the electricity mix and this DAC demand that keeps gas market healthy. Oil and coal markets see their size, especially in the first half of the century, increased as well even if not at such a level as gas.

4. The sensitivity analysis on those four parameters shows that the most critical are storage capacity and the installation rate. Costs estimates show that, no matter the costs, the taxes needed to reach these targets are so big that DAC is always expected to be installed sooner or later even in the high cost case. For this reason the results allow to say the model has a good robustness with respect to this parameter. Learning rate for a similar reason is not influencing the DAC installation and all the other parameters linked to that, with respect to this parameter the robustness is even more high.

   The storing of CO_2 is something very important if climate targets want to be reached, this becomes even more important with DAC since storage sites are expected to be exploited even more. High estimates do not influence the results, results that are instead very influenced by low estimates. Low estimates reduce drastically the amount of installed DAC increasing policy costs and economic losses.

   Installation rate, which is basically representing the industrial capability to build the plants and a network able to capture CO_2, is the most uncertain parameter and so it is the one with respect to the model is less robust. The results in the three case (low, middle, high) show significant differences especially in the amount of DAC installed and underline the fact that the bigger the limit , for the intrinsic nature of IAMS, the more DAC will be installed.

DAC is definetely a technology that could change the way the climate change is faced and more technical studies should be done to understand which is the most efficient and economic design. This will allow also to have more precise costs and have an idea on what the penetration rate of this technology could be, making the results of IAMs more robust and so more reliable. More studies on storage capacities have to be done because, even in the case in which DAC would not be installed, storing CO_2 is globally considered a tool to decrease emissions so more precise estimations of the storage capacity are essential in a climate change policy point of view. This was one of the first study of this type about DAC, and we expect further studies to follow. In particular it would be interesting to differentiate all the different technologies proposed in order to see which could be the most effective on a climate change perspective.

Appendix A

WITCH and IMAGE Code

A.1 Codes

In this Appendix the codes written and implemented in WITCH and TIMER-IMAGE are shown.

A.2 WITCH code

Listing A.1: WITCH code

```
*-----------------------------------------------
* Module Name: Direct Air Capture
* Implmentation of Direct Air Capture
* ----------------------------------------------
* Authors: Marco Vitali, Laurent Drouet
* 09/2016: Module creation
*-----------------------------------------------
* All the datas used here are the middle estimations of the costs.
* The higher and lower estimations are taken into
* consideration thanks to "dac_setup" which allows the program
* to perform a sensitivity analysis on some inputs

$ifthen %phase%==’conf’

*-----------------------------------------------
$elseif %phase%==’sets’

set e         /dac/;
set sink(e)  /dac/;

set map_e(e,ee) ’Relationships between Sectoral Emissions’ /
```

```
    ccs.dac
/;

set jeldac(j) /eligcc, elnuclear, elwind, elpv, elcsp, elgasccs/;
set jneldac /nelgas/;
set iq /ces_nelgas/;


set map_ices_el_jeldac(ices_el,jeldac) /
        ces_elcoalwbio.eligcc
        ces_elgas.elgasccs
        ces_elnuclearback.elnuclear
        ces_elwind.elwind
        ces_elpv.elpv
        ces_elcsp.elcsp

/;

set eccs(e) ’Emissions stored’ /
    dac
/;

set cost(e) ’Emissions-related entities that cost’ /
    dac
/;


*------------------------------------------------
$elseif %phase%==’include_data’

scalar lrccs /0.06/;       # ’average learning rate of ccs’

scalar totfloorcost    #’floor cost for DAC’
*totfloorcost = 95;     ’[$/tonCO2]’
/0.095/   # ’[T$/GtonCO2]’
;

scalar dacinvfloorcost     #floor capital costs
/0.06/
;

scalar dacinv0        # ’initial investment costs of dac’
*dacinv0 = 185 ;        ’[$/tonCO2]’
/0.185/       # ’[T$/GtonCO2]’
```

```
;

scalar dacoem0        #  'initial oem costs of dac [$/
   tonCO2]'
*dacoem0 = 90;          '[$/tonCO2]'
/0.09/         # '[T$/GtonCO2]'
;

scalar lftm /20/;             # 'Lifetime of a DAC plant
    [year]'

scalar autolearnDAC #'Autonoumous learning of DAC'
/0.99/;

parameter dacunits(t,n);

parameter dac_inv_exo(t,n);

parameter dac_elec_cons(t,n) 'Specific Electric
   Consumption [GJ/tonCO2]';
dac_elec_cons(t,n) = 1/15000*year(t)**(2) - 427/1500*
   year(t)+3049/10;
dac_elec_cons(t,n)$(year(t) gt 2100) = dac_elec_cons
   ('20',n);

parameter dac_therm_cons(t,n) 'Specific Thermal
   Consumption [GJ/tonCO2]';
dac_therm_cons(t,n) = 1/3000*year(t)**(2) - 427/300*year
   (t)+1525;
dac_therm_cons(t,n)$(year(t) gt 2100) = dac_therm_cons
   ('20',n);

parameter wK_DAC(t);

parameter delta_enDAC;
delta_enDAC = 1 / (lftm - (0.01/2)*lftm**2);

parameter limitdac(t,n);

parameter kdac(t,n);

parameter cumstor(t,n);
parameter cumstorccsplant(t,n);

parameter dacratio(t,n);

scalar dacmax
```

```
/1/;            # [GtCO2/year]

parameter capstorreg(n);
parameter totcapstor;

parameter totavstorreg(t,n);
parameter totavstor(t);
parameter totstored(t);
parameter totstoredreg(t,n);

parameter daccarbonprice(t,n);

* Parameters for sensitivity
$ifthen.dcc %dac_setup% == 'high_costs' #[T$/GtonCO2]
dacinv0 = 0.350;
dacoem0 = 0.120;
dacinvfloorcost = 0.09;
$endif.dcc

$ifthen.lc %dac_setup% == 'low_costs' #[T$/GtonCO2]
dacinv0 = 0.035;
dacoem0 = 0.01;
dacinvfloorcost = 0.015;
$endif.lc

$ifthen.dcl %dac_learning% == 'high_learning'
lrccs = 0.184;
$elseif.dcl %dac_learning% == 'low_learning'
lrccs = 0.017;
$endif.dcl

$ifthen.dcm %dac_max% == 'fast_growth'
dacmax = 1.5;
$endif.dcm

$ifthen.dcm %dac_max% == 'slow_growth'
dacmax = 0.5;
$endif.dcm

*$offtext

*-------------------------------------------------
$elseif %phase%=='compute_data'

capstorreg(n) = sum (k_storage, capacity_maximum(
   k_storage,n));
totcapstor = sum (n, capstorreg(n));
```

```

*-----------------------------------------
$elseif %phase%=='vars'

positive variable K_DAC(t,n) 'Installed capacity of DAC
   [GtC]';
loadvarbnd(K_DAC,'(t,n)',1e-5,0,8.18);

positive variable I_DAC(t,n) 'Yearly investment of DAC [
   T$]';
I_DAC.lo(t,n) = 0;

loop((t,tp1)$(pre(t,tp1)),
I_DAC.fx(t,n)$(year(t) le 2015 and not t_fix(tp1)) = 1e
   -8;
);

positive variable QEL_DAC(jeldac,t,n) 'Electricy
   dedicated to DAC [TWh]';
QEL_DAC.lo(jeldac,t,n)=1e-8;

positive variable QNEL_DAC(jneldac,t,n) 'Non-electricy
   dedicated to DAC [TWh]';
QNEL_DAC.lo(jneldac,t,n)=1e-8;

Positive Variable DAC_INV(t,n) 'Capital costs of DAC [T$
   /GtonCO2]';
DAC_INV.fx(t,n)$(year(t) le 2015)=dacinv0;
DAC_INV.lo(t,n)=dacinvfloorcost;

Positive Variable DAC_OEM(t,n) 'O&M costs DAC [T$/
   GtonCO2]';
DAC_OEM.fx(t,n)$(year(t) le 2015)=dacoem0;

MCOST_EMI.up('dac',t,n) = 100;
MCOST_EMI.up('ccs_plant',t,n) = 100;

*-----------------------------------------
$elseif %phase%=='policy'

*-----------------------------------------
$elseif %phase%=='eql'


eqq_ces_nelgas_%1
eqq_eldac_%1
eqq_neldac_%1
```

```
eqq_emi_dac_%1
eqcost_emi_sinks_dac_%1
eqcum_emi_dac%1
eq_depr_k_dac%1
eq_emi_stor_dac_%1
eq_limit_dac_log%1

*------------------------------------------------
$elseif %phase%=='eqs'

* Compute nelgas part dedicated to DAC
eqq_ces_nelgas_%1(t,n)$(mapn_tfix('%1'))..
        Q('ces_nelgas',t,n) =e= Q_EN('nelgas',t,n) - QNEL_DAC('nelgas',t,n);

* Compute the depreciation of DAC
eq_depr_k_dac%1(t,tp1,n)$(mapn_tfix1('%1'))..

                K_DAC(tp1,n) =e= K_DAC(t,n)*(1-delta_enDAC)**tstep
                +tstep*I_DAC(tp1,n)/(DAC_INV(t,n)*c2co2);

* Compute the total cost of emissions
eqcost_emi_sinks_dac_%1(t,n)$(mapn_tfix('%1'))..
                COST_EMI('dac',t,n) =e= I_DAC(t,n) +
                                        K_DAC(t,n) * c2co2 * DAC_OEM(t,n) +
                                        sum(k_storage, Q_STORED('dac',k_storage,n,t)*(cost_storage(k_storage,n)*44/12));

* Compute the total electricity needed by DAC
eqq_eldac_%1(t,n)$(mapn_tfix('%1'))..
               K_DAC(t,n) * c2co2 * dac_elec_cons(t,n) * (1000/3.6) =e= sum(jeldac, QEL_DAC(jeldac,t,n));

* Compute the total thermal energy needed by DAC
eqq_neldac_%1(t,n)$(mapn_tfix('%1'))..
```

```
               K_DAC(t,n) * c2co2 * dac_therm_cons(t,n) *(1000/3.6) =e= sum(jneldac, QNEL_DAC(jneldac,t,n));

* Compute the total amount of emissions stored by DAC
eqq_emi_dac_%1(t,n)$(mapn_tfix('%1'))..
                Q_EMI('dac',t,n) =e= K_DAC(t,n) +
                                      sum(jneldac, QNEL_DAC(jneldac,t,n))* emi_st('gas') * ccs_capture_eff('elgasccs');

* Compute the cumulative amount of emission stored by DAC
eqcum_emi_dac%1(t,n)$(mapn_tfix('%1'))..
                CUM_EMI('dac',t,n) =e= sum(tt$(tperiod(tt) le tperiod(t)), tstep * Q_EMI('dac',tt,n));

* Allocation of DAC CCS emissions to storage
eq_emi_stor_dac_%1(t,n)$(mapn_tfix('%1'))..
                          Q_EMI('dac',t,n)=e=sum(k_storage, Q_STORED('dac',k_storage,n,t));

* Logistic function to limit the growth
eq_limit_dac_log%1(t,tp1,n)$(mapn_tfix1('%1'))..
                    K_DAC(tp1,n) =l= K_DAC(t,n)  +
                        tstep * (totavstorreg(t,n)/totavstor(t)) *
                        (dacmax / c2co2) / (1 + (2.7)**(-(dacratio(t,n) - 1))) ;

*------------------------------------------
$elseif %phase%=='fix_variables'

tfixvar(K_DAC,'(t,n)')
tfix1var(I_DAC,'(t,n)')
tfixvar(QEL_DAC,'(jeldac,t,n)')
tfixvar(QNEL_DAC,'(jneldac,t,n)')
tfixvar(DAC_INV,'(t,n)')
tfixvar(DAC_OEM,'(t,n)')

*------------------------------------------
$elseif %phase%=='before_nashloop'
```

```

dacunits(tfirst,n) = 1;
dac_inv_exo(tfirst,n) = dacinv0/(0.99*0.99*0.99);

*-------------------------------------------------
$elseif %phase%==’before_solve’

MCOST_EMI.fx(’dac’,t,n) = div0(COST_EMI.l(’dac’,t,n), Q_EMI.l(’dac’,t,n));

* In this sector the reduction in costs is calculated

loop(
        (tnofirst(t),tm1)$pre(tm1,t),
            dacunits(t,n) = K_DAC.l(tm1,n)*c2co2*(1000/1)+1; #+1 is needed to avoid having (0)^y
    )
;


loop(
        (tnofirst(t),tm1)$pre(tm1,t),
            dac_inv_exo(t,n)$(dacunits(t,n) lt 2) = dacinvfloorcost +
                              (dac_inv_exo(tm1,n) - dacinvfloorcost) * (autolearnDAC**tstep);
    )
;


loop(
        (tnofirst(t),tm1)$pre(tm1,t),
            dac_inv_exo(t,n)$(dacunits(t,n) ge 2) = dac_inv_exo(tm1,n);
    )
;

loop(
        t,
           cumstor(t,n) = K_DAC.l(t,n) + Q_EMI.l(’ccs_plant’,t,n);
    )
;

loop(
```

```
        (tnofirst(t),tm1)$pre(tm1,t),
            cumstorccsplant(t,n)$(dacunits(t,n) lt 2) = Q_EMI.l(’ccs_plant’,t,n);
    )
;


loop(
        (tnofirst(t),tm1)$pre(tm1,t),
            cumstorccsplant(t,n)$(dacunits(t,n) ge 2) = cumstorccsplant(tm1,n);
    )
;


DAC_INV.fx(t,n)$(not t_fix(t) and (year(t) gt 2015) and dacunits(t,n) lt 2) = dac_inv_exo(t,n);

DAC_INV.fx(t,n)$(not t_fix(t) and (year(t) gt 2015) and dacunits(t,n) ge 2) =
            max(dacinvfloorcost, dac_inv_exo(t,n) * (cumstor(t,n)/cumstorccsplant(t,n))**(-lrccs))
;


DAC_OEM.fx (t,n)= dacoem0 * DAC_INV.l(t,n)/dacinv0;

* In this part one of the limiting parameter of the logistic funciton is calculated

loop(c_mkt,
daccarbonprice(t,n)$trading_t(c_mkt,t,n) = CPRICE.l(c_mkt,t);
);
daccarbonprice(t,n)$(ctax(’co2’,t,n)) = ctax(’co2’,t,n);

loop(
        t,
           dacratio(t,n) = (daccarbonprice(t,n)/c2co2)/
                    ( div0(sum(jel$jeldac(jel), K_EN.l(jel,t,n) * MCOST_INV.l(jel,t,n) * Q_EN.l(jel, t, n)),
                                sum(jel$jeldac(jel), Q_EN.l(jel, t, n))) * dac_elec_cons(t,n)
                                   +
```

```
                        MCOST_EMI.l(’dac’,t,n)/(c2co2) + MCOST_FUEL.l(’gas’,t,n) * dac_therm_cons(t,n));
    )
;



loop(
        t,
        totstoredreg(t,n) =  sum (k_storage, CUM_Q_STORED.l(k_storage,t,n));
    )
;

loop(
        t,
        totstored(t) = sum (n, totstoredreg(t,n));
    )
;

loop(
        t,
           totavstorreg(t,n) = (capstorreg(n) - totstoredreg(t,n))/(totcapstor - totstored(t));
    )
;

loop(
        t,
            totavstor(t) = sum (n, totavstorreg(t,n));
    )
;

*------------------------------------------------
$elseif %phase%==’after_solve’

*------------------------------------------------
$elseif %phase%==’update_vars’

*------------------------------------------------
$elseif %phase%==’after_nashloop’

*------------------------------------------------
$elseif %phase%==’summary_report’

```

```

parameter dac_emissions_check(t,n);
dac_emissions_check(t,n) = sum(k_storage, Q_STORED.l('dac',k_storage,n,t)) - Q_EMI.l('dac',t,n);

parameter dac_tot_cost(t,n);
dac_tot_cost(t,n) = DAC_INV.l(t,n) * 1000 + DAC_OEM.l(t,n) * 1000 +
                    sum(k_storage, Q_STORED.l('dac',k_storage,n,t)*(cost_storage(k_storage,n)*44/12))*1000/
                      sum(k_storage, Q_STORED.l('dac',k_storage,n,t)*44/12) +
                    lcost_elec_co2(t,n) * dac_elec_cons(t,n) * (1/3.6)* 1000000 +
                    FPRICE.l('gas',t) * dac_therm_cons(t,n) * (1/3.6) * (10**(6));
*-------------------------------------------------
$elseif %phase%=='gdxitems'

map_ices_el_jeldac
dac_inv_exo
dacunits
DAC_INV
K_DAC
QEL_DAC
QNEL_DAC
DAC_OEM
I_DAC
dac_emissions_check
dacratio
dac_tot_cost

$endif
```

A.3 IMAGE-TIMER code

Listing A.2: IMAGE code

```
!=====================================================
!*************** DIRECT AIR CAPTURE ****************
!=====================================================

!=====================================================
!****Authors: Marco Vitali, Harmen-Sytze de Boer*****
!=====================================================
```

```

!====================================================
! ***************** Stand alone ********************
!====================================================

#ifdef StandAloneDAC


!========== Included files ==========================

#INCLUDE ../global/gl_fnc.m   ! Global functions
#INCLUDE ../global/gl_cnst.m    ! Global constants
#INCLUDE ../global/gl_cntr.m    ! Global counters
#INCLUDE ../global/gl_flag.m    ! Global flags

MODULE main;
BEGIN

dac   dc;

end;

#endif

!====================================================
! ************** End of stand-alone ****************
!====================================================

MODULE dac;
BEGIN

! **************** Includes domain *****************

#INCLUDE importdac.m

! ***************** Declaration domain *************
EXPORT
REAL
  ElecDemDAC[NRC](t),                  ![GJ]     Total amount of electricity needed by Dac
  GFDemDAC[NRC](t),                  ![GJ]     Total amount of thermal energy needed by Dac
  TotDACcomm[NRC](t),                  ![kgC] Total CO2 storage committed by existing DAC
  TotCostDAC[NRC](t),                  ![$/tonCO2] Total cost of DAC
```

```
  DacCapCost[NRC](t),                    ![$/tCO2]      Capital cost over time
  CO2EmittDAC[NRCT](t),                  ![kgCO2]    CO2 emitted by DAC
  CO2CaptRegDAC[NRCT](t);                  ![kgCO2]      Amount of CO2 captured by DAC per region

REAL
  InstCapacity[NRC](t),                  ![GtCO2/year]    Installable new capacity of DAC
  NewDAC[NRC](t),                      ![GtCO2/year]    InstallED DAC in that year
  DACCap[NRC](t),                      ![GtCO2]      Cumulative Regional Total DAC installed considering depreciation
  GlobDAC(t),                        ![GtCO2]    Global cumulative Dac
  MaxGrowth[NRC](t),                     ![GtCO2/year]    Max amount of installable DAC each year
  CarbonTaxConv[NRC](t),                   ![$/tCO2]     Carbon tax
  InvDAC[NRC](t),                      ![$]      Amount of money invested in DAC
  fdiff[NRC](t),                       ![-]      Function used in order to find the max amount of DAC installable each year
  rprice[NRC](t),                      ![-]      Ratio between the carbon tax and the total cost of DAC
  StorageDepletionAct[NRC](t),                ![-]      Depletion of storage with respect to the ACTUAL total storage
  TotAvStor(t),                       ![kgC]      Total global storage available
  MaxRate[NRC](t),                      ![GtCO2/year] Max growth rate allowed per region
  DACDepr[NRC](t),                      ![GtCO2]      Depreciation of DAC
  CH4Dac[NRC](t),                       ![kgCH4]    Amount of natural gas needed to power Dac
  CO2CaptDAC(t),                       ![kgCO2]    Global amount of CO2 captured per year
  TotCO2CaptDAC(t),                      ![GtCO2]    Global cumulative over time of CO2 Captured
  PriceGasDac[NRC](t),                    ![$/GJ]      Price of gas that fuels DAC
  TotInvDAC[NRC](t),                     ![$]      Cumulative investments in DAC considering
```

```
      depreciation
  InvDACDepr[NRC](t),                      ![$]   Depreciation of capital
  DacOeM[NRC](t),                         ![$/tCO2]   OeM cost over time
  RunCostDac[NRC](t),                      ![$/tonCO2]   Operating costs of DAC
  DACcapCum[NRC](t),                       ![GtCO2]   Total amount of DAC installed, no depre
  DacUnits[NRC](t);                       ![-]      Number of DAC plants

CONST

! lrccs = 0.06,                          ![-]      ! lrccs is a parameter found in papers that describe the learning curve of ccs = 0.06
                                          ! MaxRate number to be set a priori based on literature, max rate of installation of DAC [GtCO2/year]
  GlobMaxRate = 1,                        ![GtCO2/year] ! The paper says that the cumulative amount of the cumulative amount of GtCO2/year would be 40 GtCO2/year. This number is reached after ~30 years of deployment
                                          ! so it is possible to say that the max rate of growing is something like 2.5 GtCO2/year. It is used 3.5 because the fdiff is very conservative
  l = 0.65,                              ![-]      ! l is the threshold before which there is no penalty in how much DAC it is possible to install. This l is set a priori (0.65)--> 0.65 means 65% is used!
  maxexpl = 0.05,                         ![-]      ! maxexpl is the max amount of available storage
```

```
     usable 0.05 means that 5% of the available reserve
     can be exploited
  DACTechLT = 20,                        ![years]    !
     Lifetime of a DAC plant
  DACEcoLT = 20,                         ![years]    !
     Economic Lifetime of a DAC plant
  avgccseff = 0.9,                       ![%]      !
     Average CCS efficiency
  autolearnDAC = 0.99,                     ![%/year]   !
     Autonomous learning of DAC
  DacMinSize = 1;                        ![MtCO2/year] !
     Minimum size of a DAC plant

! **************** Data domain *******************

INTEGER
  tcounter[NRC](t);                      ![year]

REAL
  Daclrccs[3]      =FILE("../../data/data/dac/daclrccs.
     dat"),         ![-]
  DacCapCost_i[3]    =FILE("../../data/data/dac/
     daccapital.dat"),       ![$/tonCO2] {}  {Broehm}
  DacOeM_i[3]      =FILE("../../data/data/dac/dacoem.dat
     "),         ![$/tonCO2]
  DacCapCostFloor[3]  =FILE("../../data/data/dac/
     daccapcostfloor.dat"),    ![$/tonCO2]
  DacOeMFloor[3]     =FILE("../../data/data/dac/
     dacoemcostfloor.dat"),    ![$/tonCO2]
  DacTotCostFloor[3]  =FILE("../../data/data/dac/
     DacTotCostFloor.dat"),    ![$/tonCO2]
  DacElecConsump(t) =FILE("../../data/data/dac/dacelec.
     dat"),        ![GJ/tonCO2]
  DacThermConsump(t)  =FILE("../../data/data/dac/
     dactherm.dat");         ![GJ/tonCO2]

! **************** Calculation domain *************

!-------------------------------------------
! In this block the cost of DAC is calculated
!-------------------------------------------

TotCostDac[R] = MAX(DacCapCost[R] + RunCostDac[R],
   DacTotCostFloor[FLAGDACTOTFLOOR]),
      R=1 to NRC;                    ![$/tonCO2]

! Running costs of DAC
```

```
RunCostDac[R] = DacOeM[R] + DacElecConsump * PriceSecFuel[R,1,8] + DacThermConsump * PriceGasDac[R]   ![$/tonCO2]
    + CO2STORCOST[R] * (1/(44/12)), R = 1 to NRC;

! Gas price for DAC: weighted average, based on the ccs capture rate, between price of gas with and without ctax --> 0.9 is an average ccs capture rate
PriceGasDac[R] = PriceSecFuelNT[R,1,3] * 0.9 + PriceSecFuel[R,1,3] * (1 - 0.9), R = 1 to NRC;   ![$/GJ]

tcounter[R] =
  SWITCH (
    LAST(DACcapCUM[R],0.0) < EPS ?
      0
  ELSE LAST(tcounter[R],0.0) +1
  ), R=1 to NRC;                             ![years]

DacUnits[R] = LAST(DacCapCUM[R], 0.0) * 1000 / DacMinSize, R=1 to NRC;

DacCapCost[R] =
  SWITCH ( t < 2020 ? DacCapCost_i[FLAGDACCAP]
  ELSE (
  SWITCH (
    LAST(DACcapCUM[R],0.0) < EPS ?
      DacCapCostFloor[FLAGDACCAPFLOOR] + MAX(0.0, LAST(DacCapCost[R], DacCapCost_i[FLAGDACCAP]) - DacCapCostFloor[FLAGDACCAPFLOOR]) * autolearnDAC
  ELSE (
    DacCapCostFloor[FLAGDACCAPFLOOR] + ( NLAST(DacCapCost[R],tcounter[R],DacCapCost[R])
    - DacCapCostFloor[FLAGDACCAPFLOOR]) * MAX(DacUnits[R],1.0) ** (LOG10(1.0 - Daclrccs[FLAGDACLRCCS]) / LOG10(2.0))
     )
  ))), R=1 to NRC;                  ![$/tonCO2]


DacOeM[R] =
  DacOeM_i[FLAGDACOEM] * DacCapCost[R] / DacCapCost_i[FLAGDACCAP], R=1 to NRC;                       ![$/tonCO2]

```

```
!-----------------------------------------
! In this block the maximum growth allowed by the model is calculated

MaxGrowth[R] = MaxRate[R] * fdiff[R],R = 1 to NRC;

  MaxRate[R] = (GlobMaxRate + GlobMaxRate * 0.5 * FLAGDACGROWTH)
      * ((LSUM(S = 1 to NSO,StorCap[R,S]))/(TotAvStor)), R = 1 to NRC;    ![GtCO2/year] Function that calculate the max amount of DAC installable per region, the max rate is directly proportional to the region availability with respect to the global availability
  TotAvStor = LSUM(R = 1 to NRC, LSUM(S = 1 to NSO, StorCap[R,S]));        ![kgC]    Total global amount of available storage
  fdiff[R] = 1/( 1 + EXP(-(rprice[R]-1))), R = 1 to NRC;                 ![-]    Function that limit the amount of DAC installable when the difference in cost between Ctax and Dac is not big
  rprice[R]  = CarbonTaxConv[R] /TotCostDAC[R], R = 1 to NRC ;          ![-]    Very conservative, Max Rate fully exploitable just when rprice~5


InstCapacity[R] =
  MIN(MaxGrowth[R], LSUM(S=1 to NSO, StorCap[R,S])* maxexpl* (44/12)/(10**12)), R = 1 to NRC; ![GtCO2/year]

!-----------------------------------------
! In this block we calculate if the DAC is installed or not

! Converting CarbonTax from $/GJcoal to $/tCO2 --> * (1/specific coal emissions [kgCO2/GJ]) * 1000 [kgCO2/tCO2]
CarbonTaxConv[R] = CarbonTax[R] * (1/CCCoal) * (1/(44/12)) * 1000, R = 1 to NRC;      ![$/tonCO2]

NewDAC[R]  =  SWITCH (TotCostDAC[R] > CarbonTaxConv[R] ? 0 ELSE InstCapacity[R] )
      * FlagDAC, R = 1 to NRC;                ![GtCO2/year] FlagDAC = 1 when dac.m is on, =0 when off

```

```
!DAC[R]  = LAST(DAC[R],0.0) + NewDac[R] ,R = 1 to NRC;                         ![GtCO2]  Sum over time of NewDAC[R]

DACcap[R] = LAST(DACcap[R],0.0) + NewDac[R] - DACDepr[R], R = 1 to NRC;               ![GtCO2]  Total amount of DAC per region considering the fact that a plant last 20 years so they phase out

DACcapCum[R] =  LAST(DACcapCUM[R],0.0) + NewDac[R], R = 1 to NRC;                   ![GtCO2]  Total amount of DAC installed, no depre

DACDepr[R] = LSUM(j = 0 to 10, 1/11 * NLAST(NewDAC[R], DACTechLT + (j-5),0.0)), R = 1 to NRC;    ![GtCO2]  Depreciation of DAC (as in the heatcap.m module)

GlobDAC  = LSUM(R =1 to NRC, DACCap[R]);                 ![GtCO2]  Global sum of installed DAC, over time and regions

!!!! TOTAL STORAGE COMMITTED
TotDACcomm[R] =
  LSUM(j = 1 to DACTechLT,
  (DACTechLT - j + 1) * NLAST(NewDAC[R],j,0.0))
   * 10**12 * (1/(44/12)), R = 1 to NRC;                  ![kgC]
!!!!

!-------------------------------------------
! In this block we calculate the amount of investments DAC needs

! Yearly investment in DAC
InvDAC[R]  = NewDAC[R]  * TotCostDAC[R] * 10**9 , R = 1 to NRC;                    ![$]  + LAST(DACcap[R],0.0) * RunCostDac[R]

! Total investment in DAC over the years, depreciated             ![$]
TotInvDAC[R] = LAST(TotInvDAC[R],0.0) + InvDAC[R] - InvDACDepr[R], R=1 to NRC;

! Depreciation of investments                                    ![$]
InvDACDepr[R] = LSUM(j = 0 to 10, 1/11 * NLAST(InvDAC[R],DACTechLT + (j-5),0.0)), R = 1 to NRC;
```

```

!-----------------------------------------
! In this block we calculate the electricity and thermal demand that the installed capacity of DAC needs

ElecDemDAC[R] = DACCap[R] * DacElecConsump * (10**9), R = 1 to NRC;                    ![GJ]   ! this demand should be added to the total demand
GFDemDAC[R] = DACCap[R] * DacThermConsump * (10**9), R = 1 to NRC;                    ![GJ]   ! For sake of semplicity all the plants are considered to consume as the latest plant installed
CH4Dac[R] = (1/0.9) * GFDemDAC[R] / (55.5/10**3), R = 1 to NRC;                    ![kgCH4]   ! 0.9 is the efficiency of the kiln/burner

!-----------------------------------------
! In this block we calculate the actual amount of CO2 absorbed by DAC

CO2CaptRegDAC[R]  = DACCap[R]*(10**12) + CH4Dac[R] * avgccseff * (2.8),R = 1 to NRC ;         ![kgCO2]  ! 0.9 is the efficiency of the CCS system of the burner kgco2/kgch4 = 2.8
CO2CaptRegDAC[NRCT]  = LSUM(R =1 to NRC, CO2CaptRegDAC[R]);                    ![kgCO2]  ! Global amount of CO2 captured per year
CO2CaptDAC  = LSUM(R =1 to NRC, CO2CaptRegDAC[R]);                    ![kgCO2]  ! Global amount of CO2 captured per year
CO2EmittDAC[R] = (1 - avgccseff) * CH4Dac[R] * (2.8), R = 1 to NRC;                    ![kgCO2]  ! CO2 linked to the burning of CH4 DAC can not capture
CO2EmittDAC[NRCT] = LSUM(R = 1 to NRC, CO2EmittDAC[R]);                    ![kgCO2]  ! CO2 linked to the burning of CH4 DAC can not capture
TotCO2CaptDAC = LAST(TotCO2CaptDAC, 0.0) + CO2CaptDAC / (10**12);                    ![GtCO2]  ! Total amount of CO2 captured over the time

END;
```

Acronyms

Al_2O_3	Aluminium Oxide
APS	American Physical Society
BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture Sequestration
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CCS	Carbon Capture Sequestration
CES	Constant Elasticity of Substitution
CH_4	Natural gas
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici
CO_2	Carbon Dioxide
COP	Conference of the Parties
DAC	Direct Air Capture
EEX	Energy Exporting Countries
EOR	Enhanced Oil Recovery
FEEM	Fondazione ENI Enrico Mattei
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHG	GreenHouse Gasses
H_2	Hydrogen
IAM	Integrated Assessment Model
IEA	International Energy Agency

IMAGE	Integrated Model to Assess the Global Environment
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
K_2CO_3	Potassium Carbonate
$KHCO_3$	Potassium bicarbonate
LACA	Latin America, Mexico and Caribbean
MENA	Middle East and North Africa
Na_2CO_3	Sodium Carbonate
NaOH	Sodium Hydroxide
NGCC	Natural Gas with Carbon Capture
PBL	Planbureau voor de Leefomgeving
RF	Radiative Forcing
SASIA	South-East Asia
SiC	Silicon Carbide
SSA	Sub-Saharian Africa (South Africa excluded)
TE	Transition Economies
TIMER	The IMage Energy Regional model
TPES	Total Primary Energy Supply
TSA	Temperature Swing Absorption
VRE	Variable Renewables Energies
WITCH	World Induced Technical Change Hybrid

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