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A water impact analysis with TIAM-FR

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Abstract

A sustainable energy future requires a wide range of different mitigation options that can reduce the CO2 emissions. Particularly, renewables and carbon capture and storage appear as preferred or more largely evocated options. The aim of this study is to analyze alternative development paths of the energy system investigating different constraints on the use of CCS and BECCS, under climate policy context, and using the global multiregional optimization model, TIAM-FR. The analyze also focuses on the increasing pressure involved by the development of carbon capture technologies (fossil and biomass) on the water resources. Water and energy are indeed inextricably linked and interdependent sectors. Water requirements of existing and emerging technologies (such as carbon capture technologies) are so necessary to completely assess the water impacts of a developing decarbonizing economy.

Keywords: Energy system, long-term modelling, TIAM-FR, Climate change, CO2 mitigation, Carbon Capture and Storage (CCS), Water impact

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I - Introduction

According to the 5th assessment report from IPCC, all key GHG emissions mitigation options (energy efficiency, renewables, carbon capture and storage - CCS) need to deliver to 2050 on a vast scale. More particularly, the technology 'readiness' of advanced technologies, as the industrial scale of carbon capture and storage (CCS) and the combination of Bioenergy, Carbon Capture and geologic Storage (BECCS) appear more and more as incontrovertible to attain stringent CO2 mitigation targets and reduce future CO2 emissions in line with the consensual limit of 2°C temperature increase. This all the more if we consider that coal fossil fuels will remain the dominant sources of energy over the next decades and that, as a result, CO2 emissions will drastically increase to reach unsustainable levels. Furthermore, between 250 and 300 EJ (a quarter to a third of the world's energy supply in the second half of this century) may need to come from biomass to make the decarbonation of energy system possible. In the transport sector, according to IEA, as key challenges and opportunities, the integration of advanced (2nd generation / 2G) biofuel plants with conventional (1st generation / 1G) biofuel plants can lead to significant synergies and cost savings, especially for bioethanol plants. For biodiesel, conversion of fossil refineries to advanced biofuel production is another promising option as well. In the electricity sector, where electricity generation alone accounts for approximately a third of the global emissions, those climate targets accentuate the need for negative emissions on a large scale. Indeed, BECCS offers a unique opportunity for a net carbon removal from the atmosphere while fulfilling energy needs (Herzog et al., 2005; Azar et al., 2006; van Vuuren et al., 2007; Katofsky et al., 2010) (figure 1)

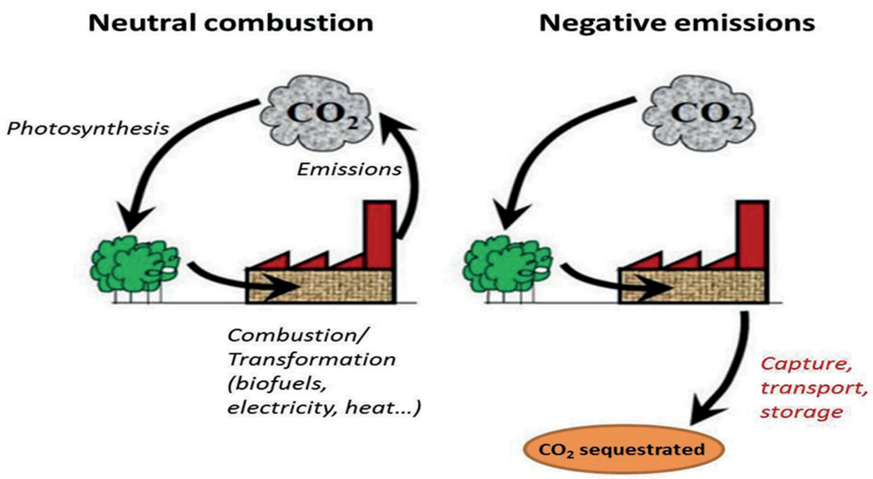


Figure 1: Negatives emissions in the bioenergy lifecyle
Source: Adapted from Assessment Report from the Global Climate and Energy Project (GCEP) workshop (Milne and Field, 2012)

In the case of a fossil fuel facility, adding CCS technology allows to drastically reducing the level of CO2 emissions, it is expected even ideally to lead to a zero net emission as could a dedicated biomass facility. The combination of biomass and CCS could lead to a net reduction in atmospheric CO2 levels from the lifecycle of the process (Milne and Field, 2012, from Henrik Karlsson) as the level of CO2 sequestrated are higher than the one that is released to the atmosphere over a given time. The aim of this study is to analyze alternative development paths of the energy system investigating different constraints on the use of CCS and BECCS, under climate policy context. This analysis is conducted using the global multiregional TIAM-FR optimization model.

Furthermore, the perspective of investments in CCS implies awareness on the water impacts of this climate strategy. Indeed, the global increase of coal power, along with the coal industry's adoption of new technologies, will drive the largest share of water consumption for energy use through 2035, and the amount of fresh water consumed for world energy production should double within the next 25 years, according to the IEA. A transition to a less carbon-intensive electricity sector results in an increase in water consumption per unit of electricity generated, depending on the choice of technologies and cooling systems employed. Particularly, low-carbon emitting technologies that utilize cooling towers as pulverized coal with carbon capture technologies appear as a very high (among the highest) water consumption factors (Macknick et al., 2011). Water needs of the processes have been implemented in this model (Bouckaert et al., 2012, 2014). Water and energy are two areas closely related and highly interdependent. Measures taken in one area impact directly and indirectly on the other domain, whether positive or negative. The amount of water required to produce energy depends on the chosen type of energy production. Demand for energy and fresh water will increase considerably in the coming decades. This growth will pose major challenges and will exert strong pressure on the resources of almost all regions, particularly in developing economies and emerging. So, in this study, we also analyze the increasing pressure by the development of carbon capture technologies (fossil and biomass) on the water resources and introduce the question of the plausibility of technological choices in terms of water availability. The paper is organized as follows: section 2 describes the methodology used for the analysis and the constraints scenarios. Section 3 presents the results of the long-term modeling, and the final section concludes with a discussion on CCS options and water impact.

II - Modeling approach and scenario analysis

a/ Modeling approach: The TIMES Integrated Assessment Model (TIAM-FR)

TIAM-FR is the French version of the TIMES Integrated Assessment Model, the widely used global multiregional model from the TIMES family models developed by the Energy Technology Systems Analysis Program (ETSAP), under the aegis of the International Energy Agency (IEA) (Loulou and Labriet, 2008). This linear programming model estimates an inter-temporal partial economic equilibrium on energy markets and, in other words, minimizes the total discounted cost of the world energy system over a long time period under environmental, technological and demand constraints. The net present value (NPV) of the total energy system costs for all regions is the sum of all annual costs per region r and year t, ACr,t, discounted at a dr,y general rate:

$$NPV = \sum_{r=1}^{R} \sum_{t \in T} \left(1 + d_{r,t}\right)^{t_0 - t} AC_{r,t} \qquad (1)$$

Where: t0 is the reference year for discounting; T is the set of years for which costs are incurred, which includes all years in the model horizon, plus past years (before the reference year t0) if costs have been defined for past investments, plus a number of years after the end of the planning period where some investment and dismantling costs are still being incurred, as well as the salvage value of fixed capital; R is the set of TIAM-FR regions.

An important feature is that global investment decisions are made in each period with full knowledge of the future cost and demand trajectories. In other words, the decision makers are assumed by the model to operate globally with the benefit of full information and perfect foresight (clairvoyance of energy planner) for the calculation period, the described economic sectors, and commodities. TIAM-FR formulates and computes its projection of optimal energy systems based on the Linear Programming approach. It can be summed up as follows:

$$Min\ c \cdot X \qquad (2)$$

subject to

$$\forall t \in [1,T]\ \forall i \in [1,I]\ \sum_{k}^{K} Q_{k,i}(t) \geq D_i(t) \qquad (3)$$

and

$$B \cdot X \geq b \qquad (4)$$

where X is the vector of all variables with associated discounted cost vector c, I the number of demands categories for energy services; Qk,i(t) the capacities of end-use technologies k susceptible of addressing service demand i at time t; Di(t) the exogenous demand for energy service i to be satisfied at time t; B and b vectors or matrixes of exogenous parameters (echoing emission contents and potential caps, energy contents and energy efficiency mandates, technology mandates, etc.). Expression (2) defines the total discounted cost to be minimized. Expression (3) formulates the set of demand satisfaction constraints. Expression (4) synthesizes the set of constraints weighing on the cost minimization, a large number of which express the physical and logical relations that must be satisfied in order to properly depict the energy system (Loulou, 2008).

Cost of the energy system includes investment costs, operation and maintenance costs, costs of imported fuels, incomes of exported fuels, and the residual value of technologies at the end of the horizon. TIAM-FR aims to supply energy services at minimum global cost by simultaneously making decisions on equipment investment, equipment operation, primary energy supply, and energy trade. End-use demands (i.e. energy services) are based on socio-economic assumptions and on external projections of the growth of regional GDP as well as population and volume of various economic sectors (transport, residential, industry, etc.) over the planning horizon. These drivers and IEA statistics for a given base year, in this case 2005, are the basis for future projections of the consumption of different energy such as road passenger transportation, steel demand or residential heating. In order to satisfy the energy services demands, the system includes the extraction, transformation, distribution, end-uses, and trade of various energy forms and materials.

Indeed, TIAM-FR is a technology-rich, bottom-up model which depicts the energy system with a detailed description of different energy forms, resources, processing technologies and end-uses, on a Reference Energy System (RES). Each economic sector is described by means of technologies, each characterized by its economic and technological parameters in all sectors of the energy system (agriculture, industry, commercial, residential and transport; taking into account conversion and the electricity sector (Loulou and Labriet, 2008). Figure 1 gives a concise description of the RES covering the whole energy chain. The RES network links commodities to these several thousand existing and future technologies characterized by their economic and technological parameters. The system includes the extraction, transformation, distribution, and trade of various energy forms and materials, and their end-uses

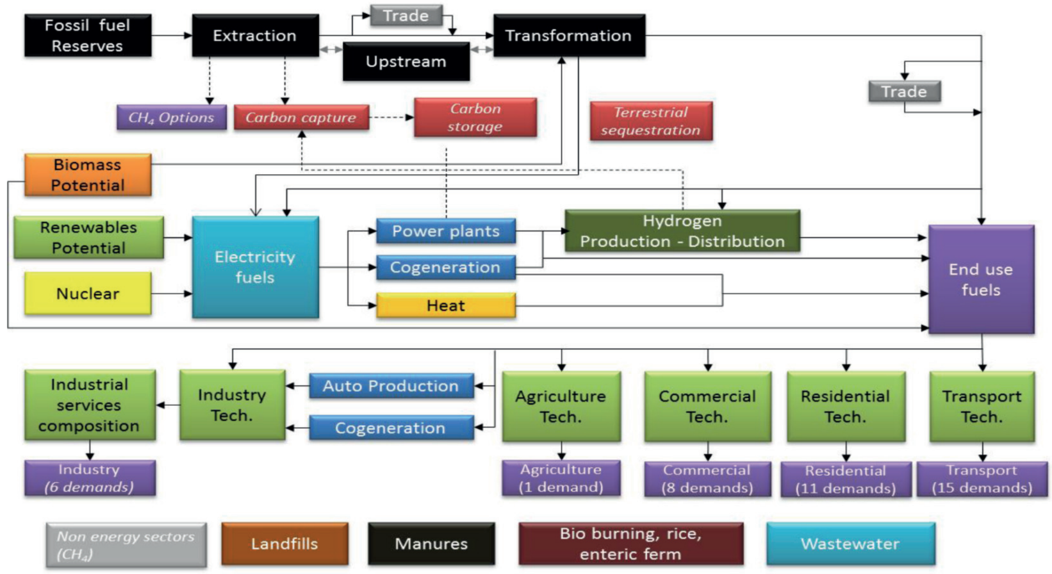
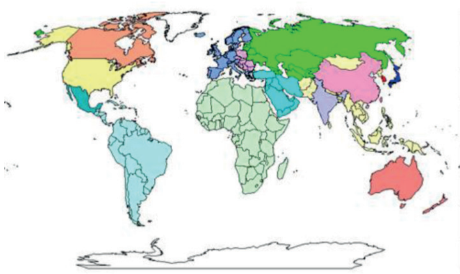


Figure 1: Overview of the reference energy system of the TIAM-FR model
Source: Adapted from Loulou and Labriet, 2008

TIAM-FR covers the time horizon from 2005 to 2100 and is geographically integrated and offers a representation of the world energy system under a disaggregation in 15 regions (figure 2): Africa (AFR), Australia-New Zealand (AUS), Canada (CAN), China (includes Hong Kong, excludes Chinese Taipei; CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (includes the Baltic states, FSU), India (IND), Japan (JPN), Mexico (MEX), Middle-East (includes Turkey; MEA), Other Developing Asia (includes Chinese Taipei and Pacific Islands; ODA), South Korea (SKO), United States of America (USA) and Western Europe (EU-15, Iceland, Malta, Norway and Switzerland; WEU). In each region, TIAM-FR describes the entire energy system with the same level of technological disaggregation. The regions are linked by energy and material trades.



AFR	Africa
AUS	Australia and New Zealand
CAN	Canada
CHI	China
CSA	Central and South America
EEU	Eastern Europe
FSU	Former Soviet Union
IND	India
JPN	Japan
MEX	Mexico
MEA	Middle-East
ODA	Other Developing Asia
SKO	South Korea
USA	United States of America
WEU	Western Europe

Figure 2. The regional distribution of the TIAM-FR model

The main outputs of the model are future investments and activities of technologies for each time period. Furthermore, the structure of the energy system is given as an output, i.e. type and capacity of the energy technologies, energy consumption by fuel, emissions, energy trade flows between regions, transport capacities, a detailed energy system costs, and marginal costs of environmental measures as GHG reduction targets. The model calculates CO2, CH4, and N2O emissions from fuel combustion and processes and integrates a climate module which allows calculating or constraining atmospheric GHG concentration, radiative forcing and temperature changes. Emission reduction is brought about by technology and fuel substitutions (leading to efficiency improvements and process changes in all sectors), carbon sequestration (including CO2 capture at the power plant and hydrogen plant level, sequestration by forests, and storage in oil/gas fields, oceans, aquifers, etc.). An additional output of the model is the implicit price, or opportunity cost (shadow price), of each energy form, material and emission.

Indeed, TIAM-FR integrates several carbon capture and sequestration technologies derived from fossil or bioenergy resources. In the power sector, the model considers two capture technologies for bioplants: pre-combustion for the biomass gasification process, and post-combustion for the direct combustion process. Biomass co-firing in coal power plants has also been implemented in TIAM-FR, with and without carbon capture technologies (Ricci and Selosse, 2013).

In the model, biomass is characterized by manifold sources - industrial waste, municipal waste, landfill gas, bioenergy crops, and solid biomass resources – and the fact that it is not traded between regions. The maximum amount of available biomass for each region is determined exogenously according to IEA data. The global potential is estimated at 234 EJ per year in 2050. In literature, biomass potential varies greatly given the different assumptions on land use, yield development, food consumption and other criteria of sustainability such as water scarcity and loss in biodiversity (van Vuuren et al, 2009). This potential varies between 100 EJ and 400 EJ per year over the period 2050-2100. To highlight the importance of water impact in the evolution of energy system and discuss the plausibility of future technological options, particularly in climate policy context, water footprints of the different processes have been implemented in the model. So water consumption and withdrawal have been indicated for all processes (Bouckaert et al, 2012, 2014).

b/ Scenario analysis: Alternative paths of the future energy system

To analyze possible alternative development paths of a lower carbonated future energy system we investigated alternative scenarios according to different assumptions concerning:

- Climate policies
  Radiative forcing: 2.6 W/m^2 (RF_2p6)
  Radiative forcing: 3.7 W/m^2 (RF_3p7)

- Technology availability
  Scenario without BECCS with co-firing (coal/biomass)
  Scenario without BECCS without co-firing
  Scenario without CCS

- Resources availability
  Biomass potential: 234 EJ/yr in 2050
  Carbon sink potential: 9,392 Gt CO2
  Water consumption

The RF_2p6 scenario consists in limiting radiative forcing to 2.6 W/m2 by 2100. This objective is compatible with the UNFCCC consensual 2-2.4°C objective (as specified by IPCC). In TIAM-FR, global CO2 emissions decrease by 50% in 2050 and by 84% in 2100 compared to the model's reference year of 2005. The RF_3p7 scenario limits radiative forcing to 3.7 W/m2 by 2100. In this context, CO2 emissions increase by 66.5% from 2005 to 2050 and reach their highest level in 2050 (43.9 Gt of CO2). Then emissions decrease in the second part of the century and reach 15.7 Gt of CO2 in 2100, a reduction of 40% compared to 2005. Whatever the investigated climate scenario, resources availability assumptions state that 1) the world potential of biomass is limited to 234 EJ/year in 2050 (figure 2) and 2) the world carbon storage is bounded to 9,392 GtCO2.

2050- EJ/y	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	WORLD
Industrial wastes	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	7.5
Municipal wastes	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	75.0
Crops	13.7	1.3	2.1	11.2	9.2	1.4	2.0	8.2	0.8	1.1	1.8	8.6	0.6	6.0	3.5	71.5
Biogas	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	7.5
Liquid biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.8
Solid biomass (1)	6.6	0.6	0.6	6.8	3.0	0.5	0.5	6.3	0.2	0.4	0.6	5.4	0.1	2.0	1.0	34.4
Solid biomass (2)	5.3	0.2	0.5	3.0	1.2	0.4	0.5	1.0	0.1	0.2	0.2	2.2	0.0	2.0	1.5	18.4
Solid biomass (3)	1.8	0.5	1.0	1.4	5.0	0.5	1.0	1.0	0.5	0.5	1.0	1.0	0.5	2.0	1.0	18.7
TOTAL BIOMA	**33.5**	**8.7**	**10.2**	**28.5**	**24.5**	**8.9**	**10.1**	**22.5**	**7.6**	**8.2**	**9.6**	**23.3**	**7.2**	**18.1**	**13.1**	**233.8**

Figure 3: Biomass potentials (EJ/year)

Scenarios forbidding the development of CCS and BECCS technologies allow the analysis of the sensitivity of the electric system to the carbon capture technology availability according to fossil, biomass or mix sources.

III - Results

a/ What development of CCS in the climate pathways?

The analysis of the results focuses on the effects of the assumed various constraints (environmental, resources and technological) on the power mix and on the future technological investments. The water impact of the latter, in terms of water needs, is also analyzed, insofar as the fresh water consumptions for energy production are assessed by the model. This study constitutes a first analysis of the water impact resulting from technological options under climate pathways.

Indeed, the investigated climate policy scenarios highlight the importance of technological improvements and lead to a noticeable expansion of renewable energy and CCS technologies in the power sector, fossil and/or BECCS according to technological constraints (figure 3). In 2050, in the RF_2p6 scenario, renewables (hydro excluded) represent 32.8% of the electricity production. This contribution reaches 37.6% in 2100 in the same scenario. The large development of renewables appears later in the RF_3p7 scenario, these electricity sources representing 33.7% of the power generation in 2100 but 7.8% in 2050.

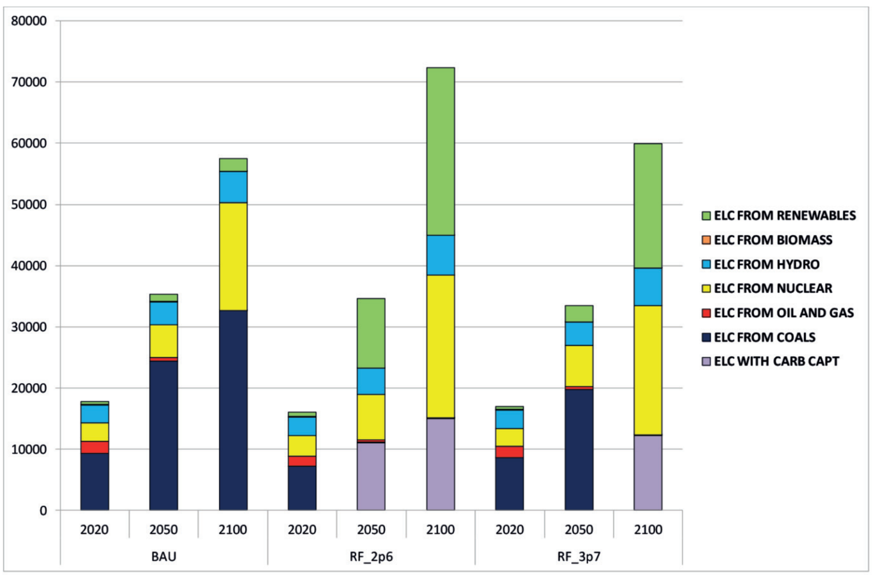


Figure 4: World power generation (TWh)

It is interesting to note an increase of the nuclear production of electricity at the end of the period, but whatever the scenario. In the climate scenario, nuclear represents around 21% (15% in BAU) of the electricity sources in 2050 and between 32 and 35% in 2100 (30% in BAU). Nuclear then appears not specifically as a decarbonation option by comparison with renewables and CCS that emerge. As regards the latter, plants with CCS represent 20% of the power generation in 2100 in RF_2p6 and RF_3p7. In 2050 CCS only appears in the strong climate constrain scenario, RF_2p6, representing 32% of the electricity mix. More precisely, CCS is developed in the RF_2p6 scenario from 2030 and in RF_3p7 scenario from 2070. Plants equipped with CCS are mainly coal plants but BECCS grows increasingly until 2060 in RF_2p6 scenario and 2090 in RF_3p7 scenario. BECCS represents 50% and 62%, respectively in 2050 and 2060, of the CCS plants in the RF_2p6 scenario and until 52% in RF_3p7 scenario. By cons, gas plants with CCS develop less in both scenarios. BECCS knows then a growing attention because of the opportunity to account for negative emissions facilitating the achievement of strong climate policy.

In a general manner, CCS from fossil fuel is mainly deployed in fast developing countries that are well endowed with coal. The remaining fossil fuel use is indeed in combination with carbon capture and storage. Gas and CCS is mainly deployed in developing countries in 2050 as BECCS in the RF_2p6 scenario. In 2100, in both scenarios, coal is the most important source of CCS power plants, even if BECCS is highly distributed in developing countries. However, biomass resources are widely available in all regions and it is interesting to note that BECCS tends to replace CCS at the end of the period in both scenarios.

The assumptions according to carbon storage capacities and BECCS investments involve different sets of mitigation options across regions, with varying shares of renewable energy, CCS, gas, and biomass (figure 4). We focus here on the stronger climate scenario, the RF_2p6 scenario and investigate an analysis of the power mix according to different options of development of the CCS technologies. In the RF_2p6_NoBECCS scenario, we assume that no investment is made in bioplants with CCS. Note that the co-firing associating coal and biomass is allowed, that is not the case in the RF_2p6_NoBECCSCF scenario where investments are only possible in fossil power plants with CCS. In the RF_2p6_NoCCS scenario, no investment is made in the CCS option. In this case, the electricity mix is dominated by renewables up to 55% in 2050 and 59% in 2100. Nuclear represents then 27 and 31% respectively in 2050 and 2100 and hydroelectricity 15% and 9% at the same periods. The situation is quite the same in 2100 in the RF_3p7_NoCCS scenario with a mix composed by 45%, 41% and 11% of renewables, nuclear and hydro respectively. Biomass is however developed up to 3%. In 2050, the climate constraint is not strong enough and the mix remains dominated by coal (55%). Nuclear represents then 22% of the electricity generation and hydro 11%. Renewables account for only 9% of the production.

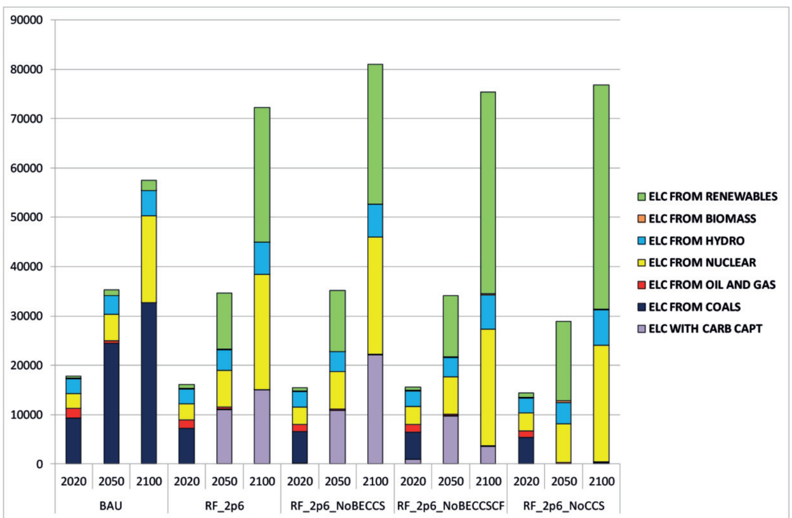


Figure 5: World power generation (TWh) according to carbon capture technologies availability

What is interesting to note, if we compare RF_2p6_NoBECCS and RF_2p6_NoBECCSCF, is the level of investment on CCS in 2100. Indeed, while the share of coal, hydro and nuclear in the electricity production is similar in both scenarios during the time period, while the share of renewables and CCS is similar in 2050, with around 35% and 30% respectively, the level of development of CCS in 2100 decreases a little in the RF_2p6_NoBECCS but decrease sharply in the RF_2p6_NoBECCSCF. Plants with CCS then represent 27% of the power generation in the RF_2p6_NoBECCS scenario but it falls to 5% in the RF_2p6_NoBECCSCF scenario. Conversely renewables increase drastically and represent 54% of the power generation in the RF_2p6_NoBECCSCF scenario by comparison with 35% in RF_2p6_NoBECCS, the same level than as in 2050. The unavailability of negative emissions permitted by the combustion of biomass makes it more competitive, given the strong climate constraint, to develop renewables, compared to CCS on power plants using fossil fuels.

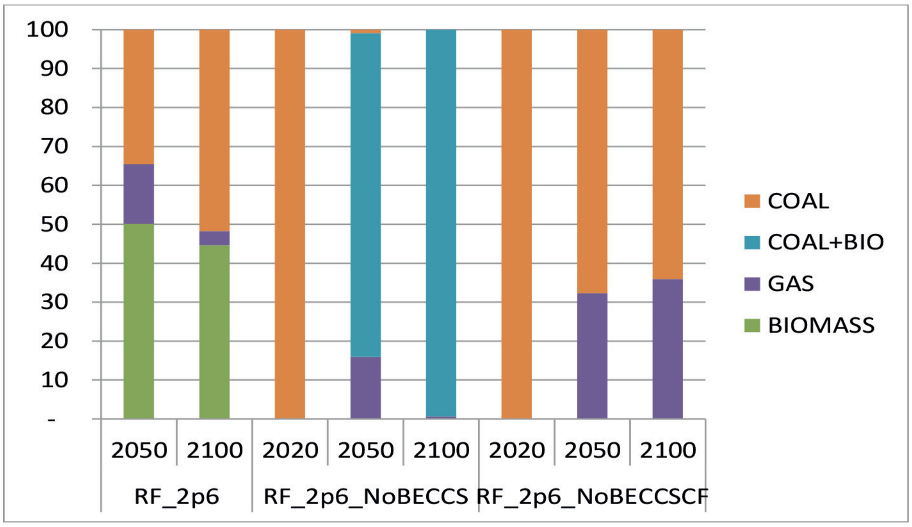


Figure 6: Power plants with CCS by resources (%)

Figure 5 highlights the important, not to say the exclusive, development in co-firing plants with CCS in the RF_2p6_NoBECCS scenario – while it is not developed in the RF_2p6 scenario because of the investment in bioplants with CCS – and the switching to fossil power plants with CCS in the RF_2p6_NoBECCSCF scenario.

b/ The water impact analysis of the CCS development

The water analysis allows us to introduce the dependence between water and the energy production system and, by the way, to put in perspective the technological solutions to climate and environmental constraints. In the context of our study with a climate constraint of strict control of emissions (RCP2.6; equivalent to a limitation of GHG atmospheric concentration to 450ppme) and of relatively moderate control of emissions (RCP3.7; equivalent to a limitation of GHG atmospheric concentration to 550ppme), fresh water consumption increases drastically, particularly at the end of the period where the constraint is the highest. In 2100, fresh water consumption is 2.4 times higher than the level of BAU in the RF_2p6 scenario, and 1.8 times higher in the RF_3p7 scenario. In 2050, the level is 2.1 and 1.5 times higher than the level of BAU, respectively in the RF_2p6 and the RF_3p7 scenario (figure 7). In 2050 and 2100, the fresh water consumption is around 1.3 times higher in the RF_2p6 scenario than in the RF_3p7 scenario.

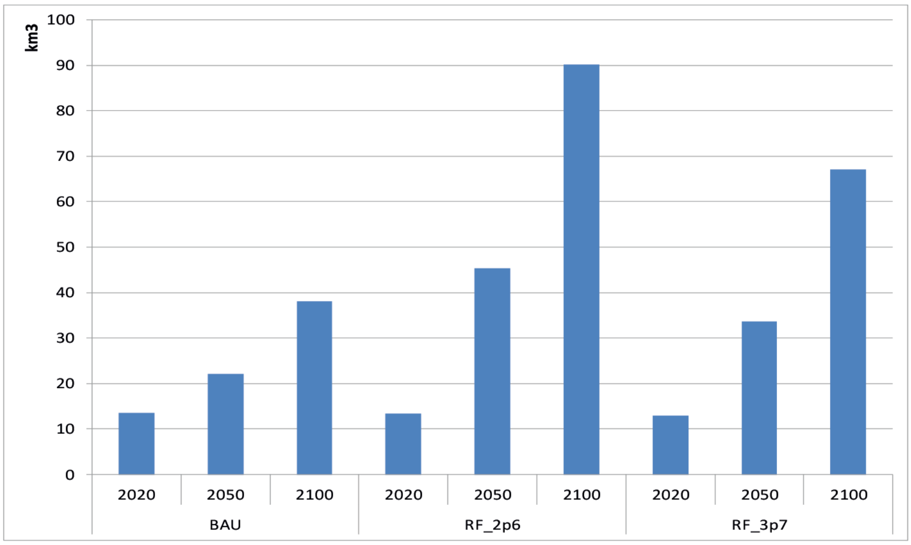


Figure 7: Fresh water consumption (km3)

If one puts into perspective the increase in water consumption and switches operated in the electricity mix, it appears clearly that the choice in technologies to decarbonize the energy system induce serious consequences on water resources. Indeed, the power sector is highly dependent on water resources. In USA for example, it is the largest user of water in the nation (Macknick et al., 2011). More precisely, the deployment of renewable energies and CCS technologies can be heavy on fresh water consumption.

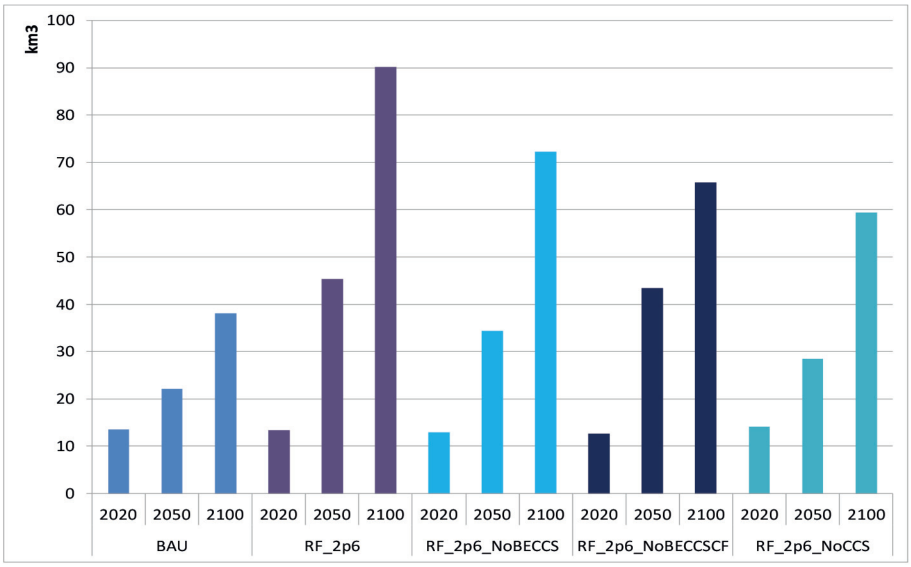


Figure 8: Fresh water consumption (km3) according to carbon capture technologies availability

Figure 8 focuses on strong climate context and highlights the decreasing consumption of fresh water gradually as the use of CCS technologies is reduced. Fresh water consumption remains nonetheless important when CCS is not developed, due to the investment on renewables energies, even if it is 1.6 times higher than the BAU level in 2100 in RF_2p6_NoCCS against 2.4 times higher than the BAU level in 2100 in RF_2p6. In 2020, when the impact of the climate constraint is lowest, it is interesting to note a limited consequence on the fresh water consumption.

IV - Discussion

A sustainable energy future requires strategies to facilitate the use of energy resources that enable the reduction of concentration of CO2 in the atmosphere whilst supplying energy needs over the years. A wide range of different mitigation options can be presented to reduce these CO2 emissions and particularly renewables and carbon capture and storage as a preferred option. Fossil energies would constitute a large share of the energy mix due to the important growth of primary energy of emerging countries probably resting heavily on the use of coal and the size of remaining reserves. That the reason why CCS/BECCS technologies appear as an increasing option to transit toward a low-carbon energy system, especially for fast developing countries and developing countries. The capture and storage of CO2 offers the potential for near-zero CO2 emissions from fossil-based power plants and negative CO2 emissions from biomass-based power plants. While biomass with CCS technology may be difficult, it is scientifically feasible. So why isn't it being deployed on a larger scale? A major issue related to the deployment of CCS and BECCS is their economic viability and the cost/advantages comparison according to alternatives. Due to the low carbon price, investors are more incited to build cheaper power plants with a high level of emission than add expensive CCS to co-fired plants. As regards BECCS, this option cannot compete in matter of price with other energy sources. Indeed, the role of CCS and BECCS in mitigating climate change partly depends on their ability to reduce costs and, by consequence, their commercialization on an industrial scale in the marketplace (technology learning), as well as sustained Research, Development & Demonstration. In addition, covering the distance to CO2 capture and storage sites will involve developing and financing infrastructure for transporting CO2. Safety problems and social acceptability must also be considered in terms of risks and concerns for long-term CO2 geological storage. A regulatory system is required to supervise the selection of appropriate sites, long-term ownership and liabilities, and a monitoring program to detect problems. For example, in the case of carbon leaking back into the atmosphere, methods should be developed to stop or control CO2 releases. Concerning biomass energy, being directly tied to forests, food and other ecosystems, its use induces environmental and social impacts, both positive and negative. That the reason why biomass has to be sustainably produced. When accompanied by incentives, BECCS appears as an option to satisfy climate constraints and, at the same time, as fulfilling energy demands (consistent with Obersteiner et al, 2001). This analysis is consistent with the necessity of large scale biomass deployment to meet the maximum temperature change of 2°C. The potential for fossil and biomass exists but regulatory barriers have to be discussed and removed as knowledge gaps are filled. The increasing need to limit CO2 emissions and the current limits of alternative technologies constitute assets in this sense. For example, renewable options should in no way be excluded from the debate, and in that sense renewables appears as an important solution to reach the climate constraint, with or without CCS, but they need to be thought out in terms of the structural costs of investments in the power network required to integrate intermittent energies. Therefore, a complete and complex chain of processes and procedures has to be thought through and determined in the design of future energy policies. In addition, even if the risks and uncertainties associated with CCS are resolved, this technology can not alone solve the climate issue. The technological development must be accompanied by strong regulatory frameworks that help to reduce CO2 emissions. That means to commit to binding targets for reducing GHG emissions. In our analysis, the RF2p6 scenario is consistent with this ambition but this is not yet the case of the national commitments pledged during the United Nation Framework Convention on Climate Change (UNFCCC)'s Conference of Parties which were organized in Paris in December 2015. According to the study made by the UNFCCC on these commitments, the Intended Nationally Determined Contributions (INDCs), despite the unprecedented international mobilization, global warming would still be between 2.7 and 3 degrees. Then, to place us on a compatible trajectory with the 2°C boundary, the Paris Agreement requires each country to review every five years from 2020 these INDCs, without being able to bring down the objectives and encouraging each states to do better. The path is so already more focused than before.

Another important issue, less developed in the energy system literature, consists in the increase pressure these energy system's technologies involve on the water resources. Energy and water security occupy a central place in the human and economic development. Both resources are now more and more interdependent than ever. Whether hydroelectricity, of course, but also the cooling of thermal power stations or the extraction and processing of fuels, almost all energy production processes, require significant amounts of water. Water and energy are then inextricably linked and interdependent sectors. While these resources are subject to an increase in global demand, water scarcity threatens the long term viability of energy projects, with serious consequences for development. The global community has also to consider that climate change will affect fresh water availability (IPCC, 2007a) leaving energy and water resources under unprecedented pressure, and subject to increasing competition on the part of the people, industries, ecosystems and economies booming. When the world population will reach 9 billion people, agricultural production will have increased by 15%. By 2030, global energy consumption will increase by 35% while the water consumption of the energy sector will increase by 85% according to projections of the International Energy Agency (IEA). It is so important to understand and estimate the dependency between water and energy systems, particularly according to the possibility of reduced water availability in the future due to climate change and the increased energy and water demands. The availability of water in certain regions may limit the penetration of low carbon technologies and can impact the choices. This could have important implications for policy makers (Siddiqi and Diaz Anadon, 2011). Decisions affecting the power sector's impact on the climate may need to include water considerations to avoid negative unintended environmental consequences on water resources. Despite this disturbing context, planning and management of energy production today rarely consider the problems that posed and will pose increasingly water supply (Macknick et al., 2011). To go further, in a second step for this study, the analysis should focus on the cooling systems configurations, as for example utilizing dry or hybrid cooling systems for power plants with CCS; the choice of cooling system playing a role in the development of a future power generation mix. Water requirements of existing and emerging technologies (such as carbon capture technologies) are so necessary to completely assess the water impacts of a developing decarbonizing economy.

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