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Energy and climate scenarios in the global policy perspective

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Energy and climate scenarios in the global policy perspective

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1. The Project

1.1   Preface

The MERCURY project – "Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy" is a H2020-MSCA Marie Skłodowska-Curie 2015 Global Fellowship carried out by the Fellow Samuel Carrara.

The Beneficiary is Fondazione Eni Enrico Mattei (FEEM), Milan, Italy. The outgoing host is the Renewable & Appropriate Energy Laboratory (RAEL) of the University of California, Berkeley (UC Berkeley). The project Supervisor at FEEM was Prof. Massimo Tavoni until July 2018 and Prof. Manfred Hafner afterwards, while the Supervisor at UC Berkeley is Prof. Daniel M. Kammen.

The project lasted two years. It started on January 16, 2017 and it finished on January 15, 2019. The first year was dedicated to the outgoing phase at UC Berkeley, while the second year was dedicated to the return phase at FEEM.

1.2   Proposal Abstract

The reduction of greenhouse gas emissions is a vital target for the coming decades. From a technology perspective, power generation is the largest responsible for CO_2 emissions, therefore great mitigation efforts will be required in this area. From a policy perspective, it is common opinion that the European Union is and will remain leader in implementing clean policies.

Basing on these considerations, the power sector and the European Union will be the two key actors of this project. The main tool adopted in this work will be WITCH, the Integrated Assessment Model (IAM) developed at Fondazione Eni Enrico Mattei (FEEM).

The description of the power generation sector in WITCH is quite detailed, but needs to be integrated, especially as far as the electric infrastructure downstream the power generation system is concerned. In the first half of the project, developed at the outgoing host, the modeling of the electric sector will thus be completed and refined. In particular, four main aspects need to be assessed: i) system integration (i.e. the issues related to the non-negligible penetration of intermittent renewables in the grid), ii) electricity storage, iii) electrical grid, and iv) electricity trade.

In the second half of the project, developed at the return host, the improved WITCH model will be employed in scenario assessment calculations.

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Firstly, the prospects in Europe of renewables, Carbon Capture and Storage (CCS) and nuclear will be analyzed. In particular, attention will be focused not so much on the pure technology aspects, but rather on policy issues such as the role of incentives in renewable diffusion, the slow CCS deployment, or the effects of the nuclear reactors ageing, or of their phase-out.

Secondly, the focus will move on assessing the role of these technologies (and the consequent evolution of the electric infrastructure) according to different mitigation scenarios, and in particular considering different levels of global participation in EU-led climate mitigation.

2. Introduction – Scope of Deliverable 3.1

Deliverable 3.1 refers to the last paragraph of the proposal abstract reported in Section 1.2, i.e. to Work Package 3, aimed at exploring different energy and climate scenarios in the context of the global climate policies.

The original title of the deliverable as conceived in the proposal was "Technology prospects: global climate policies". Indeed the technological aspect has been analyzed (even if neglecting grid), but the focus has eventually been more on policy, therefore the title has been modified accordingly.

The activity is divided into two parts.

The first and main part explicitly develops what has been mentioned in the proposal abstract, i.e. policy scenarios have been explored considering different levels of participation by world regions in mitigation policies, assuming Europe as the fully-committed trailblazer in climate change mitigation in all scenarios. This activity moves from the consideration that if it is true that the Paris Agreement was signed by essentially all world countries, USA has announced its intention to withdraw, and the practical implementation of clean policies in other regions may not be full or sufficient. Hence, a globally coordinated action cannot be taken for granted.

The second part refers to a research activity that had started before the beginning of MERCURY with the collaboration of two colleagues of the Fellow and that has been included as a complementary task in the project. The activity investigates the role of technology innovation in the electricity sector in the context of the Sustainable Development Goals (SDGs), especially with reference to SDG7, which is the goal dedicated to energy. SDGs are global targets for sustainability, developed by the United Nations, to be achieved within 2030. As said, SDG7 refers to energy; another

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goal (SDG13) refers to climate change. The SDG framework is thus relevant in the global policy perspective, that is why this activity has been included in Work Package 3.

A paper has been produced for each of the two topics. The present deliverable is essentially the collection of these two papers, attached in the next pages. The relevant titles are:

- Sharing the burden: the change in mitigation costs with different levels of participation in global climate actions
- Energy futures and climate change mitigation: a qualitative and quantitative assessment in the Sustainable Development Goals perspective

Sharing the burden: the change in mitigation costs with different levels of participation in global climate actions

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Abstract

Climate change mitigation is a priority for the decades to come and requires coordination at global level. The Paris Agreement set a milestone shared by almost all world countries. However, USA has announced its intention to withdraw from the agreement. Additionally, diverse reasons may lead to the implementation of insufficient measures in some regions.

The main aim of this work is to explore mitigation scenarios, compatible with the long-term Paris targets, considering different levels of climate participation by world regions, i.e. assuming full or only partial efforts in the implementation of low-carbon policies. The objective is to investigate the relevant changes in the energy mix and, more importantly, in the mitigation costs associated to the level of participation. The main focus is on Europe, as this is considered the region that will lead the global mitigation action independently of the actual participation of the other regions of the world.

The analysis, conducted via the Integrated Assessment Model WITCH, shows that, in case of partial participation, the fully participating regions averagely suffer relative additional cumulative GDP losses between 15% and 60% (depending on the levels of participation of the other regions) with respect to the reference mitigation scenario where the climate action is uniformly shared at global level. These relative changes rise to 18%-74% in Europe, which however overall shows the lowest cumulative GDP losses (comprised between 3% and 5% depending on scenario).

Globally, the more and more partial climate participation leads to progressively higher costs, unless mitigation action is restricted to the high-income countries, as this would require innovation and efficiency benefits which would be able to more than compensate the costs.

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1. Introduction

Climate change mitigation is one of the main challenges for the decades to come. The key point, in particular, is to cope with the expected energy demand growth – both due to the population increase and to higher per-capita consumption – via sustainable solutions which have low impacts on climate and environmental systems (IPCC, 2014).

With this main goal in mind, at the 21st edition of the Conference of Parties (COP21) held in Paris in 2015, almost all world countries signed a global agreement (Paris Agreement) whose objective was to "*keep the increase in global average temperature to well below 2°C above pre-industrial levels; and pursue efforts to limit the increase to 1.5°C, since this would substantially reduce the risks and effects of climate change*". The objectives were and are deemed to be feasible, even if they imply a profound change in the energy and economic paradigm (Schellnhuber et al., 2016).

Syria and Nicaragua were the two only countries which did not sign the agreement, even if both with specific reasons not related to an opposition to climate action. On the contrary, Nicaragua complained an insufficient level of ambition in the targets. This is not surprising, considering that nowadays Nicaragua generates more than half of its electricity via renewable sources (mainly wind, geothermal, hydro, and biomass) and plans to rise to 90% by 2020 (Ponce de Leon Barido et al, 2015). However, Nicaragua eventually joined the agreement in 2017. Syria, instead, has been involved in a tragic civil war for several years and could not participate in the negotiations.

On the other hand, the President of the United States on June 1, 2017 announced the US intention to withdraw from the Paris Agreement. In accordance with Article 28 of the agreement, the withdrawal notification can be given no earlier than three years after the agreement enters into force for the country and the actual withdrawal is effective after one year from that moment. This means that no formal acts can be made at the moment. More precisely, since in the US the Paris Agreement entered into force on November 4, 2016, this means that the first possible withdrawal date will be November 4, 2020.

This paper aims at exploring different scenarios related to different levels of participation in climate mitigation action. In particular, given that the European Union is leader in the implementation of such policies, the main objective of this paper is to assess scenarios where one or more regions do not participate in the mitigation policies led by the EU. Specifically, the goal is to investigate by how much policy costs would rise for the participating regions (and in particular for the EU) and how the optimal energy and electricity mix would change. The adopted tool is the Integrated Assessment Model WITCH.

The MERCURY project was drafted in 2015, before the Paris Agreement was signed. The objective of the task, as initially conceived, was to investigate a possible boycott by the oil-exporting Middle-Eastern countries which would hypothetically jeopardize the Paris Agreement selling cheap oil in order to maintain their market shares, which would naturally decrease in the case of constraints on carbon dioxide emissions. Eventually, as said, all those countries signed the Agreement, even if the long-term application is yet to be verified. Indeed, this obviously applies to any other country. On the other hand, the announcement by the US administration adds an interesting scenario. Hence, different relevant scenarios can be developed in order to carry out this exercise, as will be discussed in the next pages.

The paper is structured as follows. Section 2 describes the WITCH model. Section 3 describes the scenario design, developed based on the considerations reported in this Introduction. Section 4 presents the main outcome of the scenarios. Section 5 concludes.

2.   Methodology – The WITCH model[1]

The tool adopted in this research is the World Induced Technical Change Hybrid (WITCH) model. WITCH is a dynamic optimization Integrated Assessment Model designed to investigate the socio-economic impacts of climate change over the 21st century (Bosetti et al., 2006 and Emmerling et al., 2016). It combines a top-down, simplified representation of the global economy with a bottom-up, detailed description of the energy sector, nested in a Constant Elasticity of Substitution (CES) structure (Figure 1). The model is defined on a global scale: countries are grouped into thirteen aggregated regions, which strategically interact according to a non-cooperative Nash game. The thirteen economic regions are USA (United States), OLDEURO (Western EU and EFTA countries[2]), NEWEURO (Eastern EU countries), KOSAU (South Korea, South Africa, and Australia), CAJAZ (Canada, Japan, and New Zealand), TE (Transition Economies, namely Russia and Former Soviet Union states, and the non-EU Eastern European countries), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa except South Africa), SASIA (South Asian countries except India), EASIA (South-East Asian countries), CHINA (People's Democratic Republic of China and Taiwan), LACA (Latin America and Central America) and INDIA (India).[3] As the model acronym suggests, technological change is endogenously modeled in WITCH, and it regards energy efficiency and the capital cost of specific clean technologies. Global prices of fossil fuels are endogenously calculated, while the model is coupled with the Global Biosphere Management Model, GLOBIOM (Havlík et al., 2014) to describe land use. GLOBIOM provides biomass supply cost curves to WITCH for different economic and mitigation trajectories. This allows assessing woody biomass availability and cost.

The CES structure reported in Figure 1 shows how the top-down aggregated economic model is linked with the disaggregated energy sector. In particular, energy services (ES) and the aggregated capital and labor node (KL) are combined to produce the final economic output of the model. Energy services are provided by the combination of the capital of energy R&D (RDEN), which is a proxy of energy efficiency, and the actual energy generation (EN). This node models the fact that the same energy services can be obtained through a lower level of energy input if there is higher energy efficiency. The EN node is divided between the electric (EL) and non-electric sector (NEL), with a progressive disaggregation down to the single technologies. The electric sector has a higher detail, while the non-electric sector mostly reports nodes which collect consumption from all the non-electric usages of one specific energy source, except for the road passenger and road freight transport sectors, which are the only demand sectors being explicitly modeled[4] (see Bosetti and Longden, 2013, and Carrara and Longden, 2017).

Focusing on the electric sector, the hydroelectric technology is found first (ELHYDRO), which is essentially exogenous in the model. The other technologies converge to the EL2 node, which is divided between two further nodes: EFLFFREN, i.e. the combination of fossils and renewables, and ELNUKE&BACK, i.e. the combination of nuclear and backstop. The fossil node (ELFF) has three group of technologies: i) coal&biomass (ELCOALBIO), further divided into pulverized coal without CCS (ELPC), pulverized biomass without CCS (ELPB), integrated gasification coal with CCS (ELCIGCC), and integrated gasification biomass with CCS (ELBIGCC); ii) oil, only without CCS (ELOIL); iii) gas (ELGAS), with and without CCS (ELGASTR and ELGASCCS, respectively). Variable renewable energies (ELW&S) have i) wind (ELWIND), further divided

between onshore (WINDON) and offshore (WINDOFF); ii) solar PV (ELPV); iii) solar CSP (ELCSP). Nuclear and backstop feature traditional fission nuclear (ELNUKE) and a backstop technology (ELBACK). The latter models a hypothetical future technology which generates electricity with no fuel costs and no carbon emissions, although characterized by high capital costs. It can be interpreted as an advanced nuclear technology, for instance nuclear fusion or advanced fast breeder fission reactors. However, this technology is not considered in the scenarios explored in this work. Concerning the non-electric sector, the first distinction is between traditional biomass (TradBiom), coal (COALnel) and the aggregated node formed by oil, gas, and modern biomass (OGB), which precisely features gas (GASnel), traditional biofuels (Trad Bio), and the combination (OIL&BACK) between oil (OILnel) and a non-electric backstop technology, i.e. advanced biofuels (BACKnel).
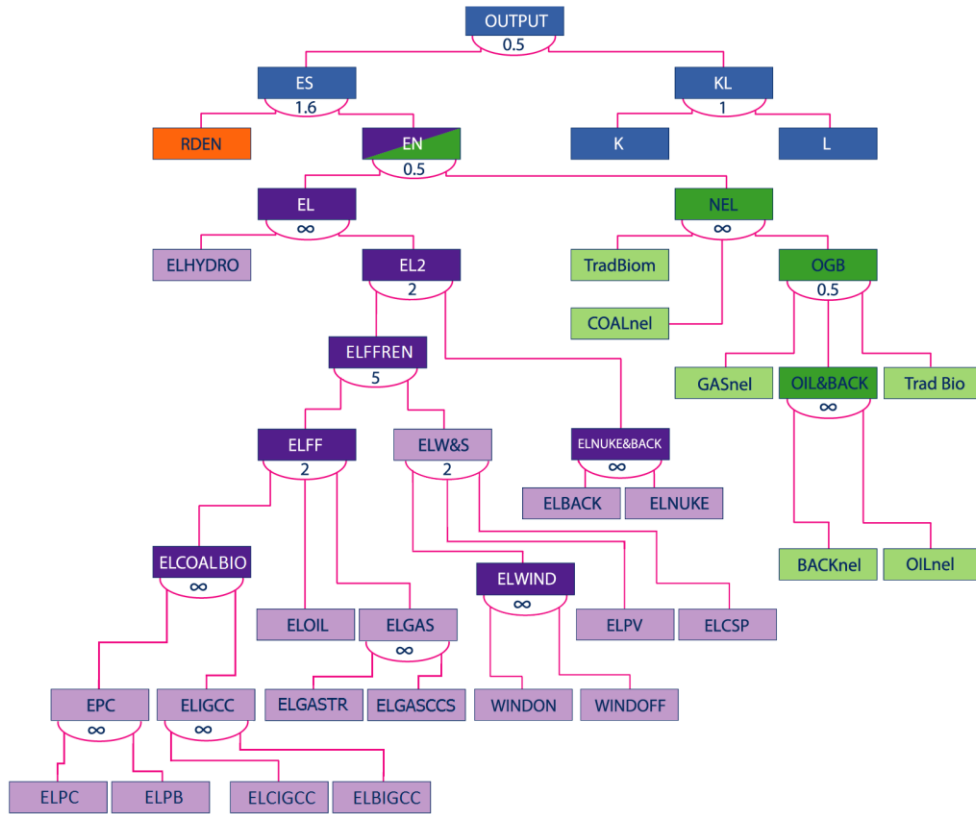

Figure 1 – The CES structure in WITCH.

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

3.   Scenario design

The Introduction partially anticipated the scenarios that are explored in this exercise. Although the number of combinations in terms of participation of the different regions to climate policies may be enormous, the meaningful scenarios taken into consideration are six in total.

Firstly, a baseline or Business-as-Usual (BAU) scenario has been run for benchmarking reasons. No constraints are imposed in this scenario.

The other five scenarios have been developed considering a mitigation policy compatible with the Paris targets. From a modeling point of view this is done via the application of a carbon tax to greenhouse gas (GHG) emissions. The carbon tax, which grows exponentially, is applied from 2020 and its value is calibrated depending on the participating regions so as to reach a global cumulative amount of CO_2 emissions equal to 1000 Gt in the period 2011-2100. This would limit the temperature increase in 2100 with respect to the pre-industrial levels below 2°C with a likely chance (IPCC, 2014). In particular, this cumulative amount of carbon dioxide emissions leads to a temperature increase of 1.8°C in WITCH, whereas the baseline scenario leads to a temperature increase of about 4°C.

The value of the carbon tax depends on the different levels of participation in the mitigation effort: comprehensibly, the value must increase as the number of participating regions decreases. The exact value has been calibrated accordingly, based on optimal paths found in past research works. Indeed, a smaller carbon tax is imposed in the regions formally not participating in the mitigation policies as well: both the initial value and the yearly growth rate are halved with respect to the full tax applied in the participating regions. Given that in the different scenarios the starting value is around 50-150 $/t$CO_2$eq and the annual growth rate is around 7% , this means that in 2100 the tax applied in the non-participating regions is 25-30 times lower than that applied in the fully participating regions (from the order of 10000 $/t$CO_2$eq to the order of few hundreds of dollars per ton of CO_2 equivalent). This is done for two main reasons: i) without fixing a minimal carbon tax in even just one important region (e.g. USA) the climate target would not be feasible, as will be discussed shortly, and ii) this tax somehow mimics the decarbonization signal that in any case the non-participating regions would receive from the surrounding participating regions, which could not be otherwise modeled in WITCH.

The reference mitigation scenario (CTAX) consists in a uniform application of the carbon tax in all world regions, i.e. a global participation is envisioned. One scenario (CTAX_no_fos-exp) considers the withdrawal from the global coordinate action by the main fossils exporting regions, i.e. MENA and TE. In the CTAX_no_fos-exp_low-inc scenario, which could be somehow called "Kyoto scenario", MENA and TE are joined by the low-income regions (SSA, EASIA, SASIA, and INDIA) which are (partially) exempted from the mitigation obligations. In the CTAX_no_fos-exp_USA scenario, instead, it is USA that joins MENA and TE, while all the other regions do participate in the global effort. The final scenario (CTAX_no_USA) mimics the present situation where only the United States are expected not to implement Paris-compatible mitigation policies. OLDEURO, NEWEURO, KOSAU, CAJAZ, CHINA, and LACA are the regions that, in all scenarios, take part in the full implementation of the mitigation policies.

Figures 2 and 3 show the global CO_2 and GHG emissions, respectively. GHG emissions comprise carbon dioxide as well as the other Kyoto gases, i.e. methane, nitrous oxide, and fluorinated gases. Results do not vary much across the mitigation scenarios precisely because all of them must meet the cumulative CO_2 emissions target: a stronger emission drop in 2020 due to a higher tax is compensated by a slower decrease in the following decades.
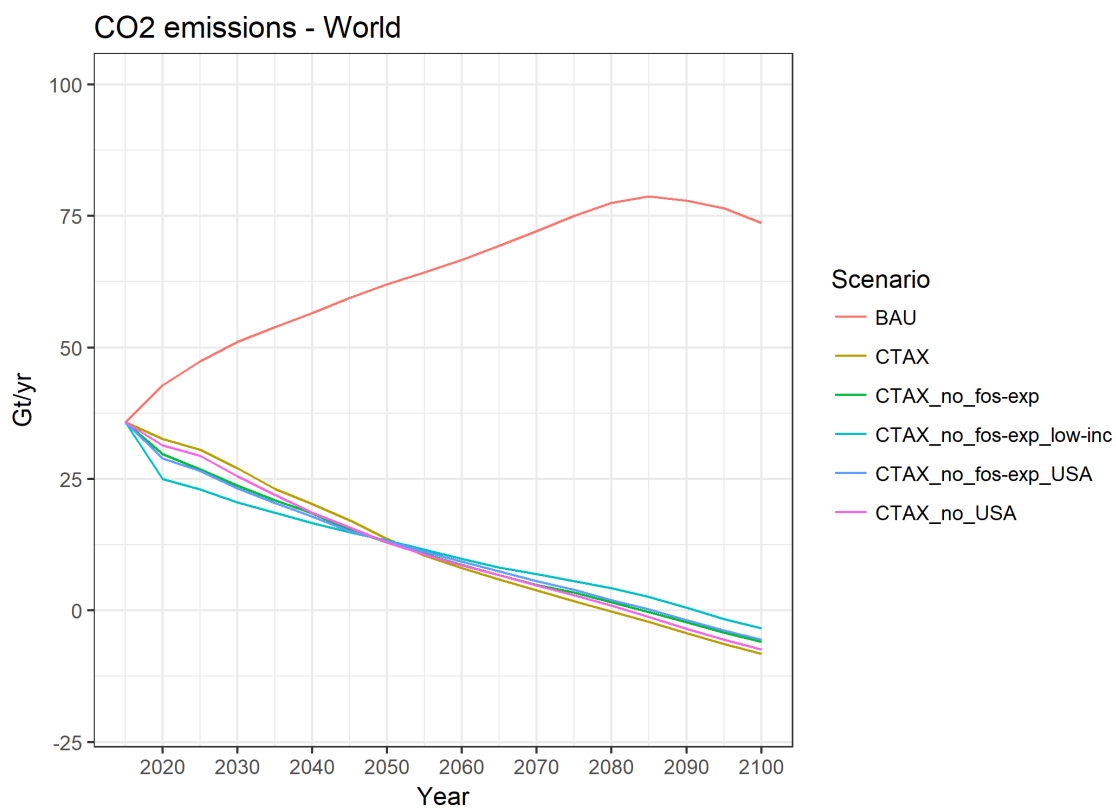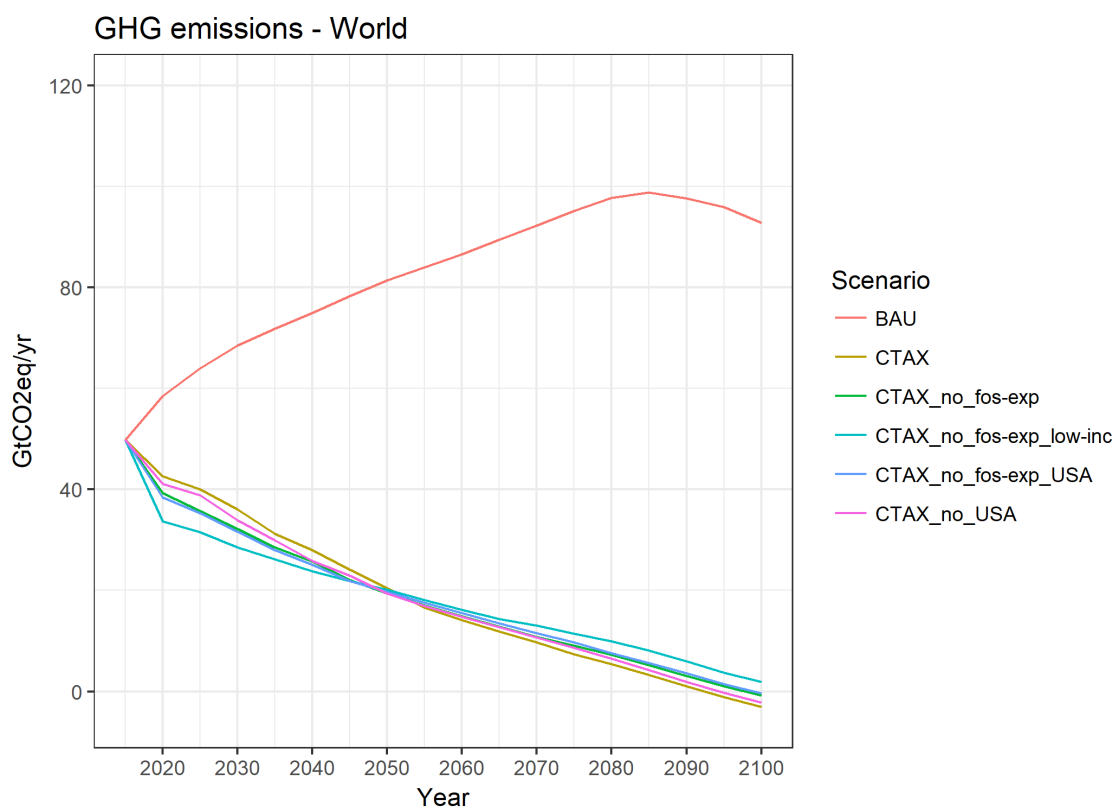
Figure 2 – Global CO₂ emissions.
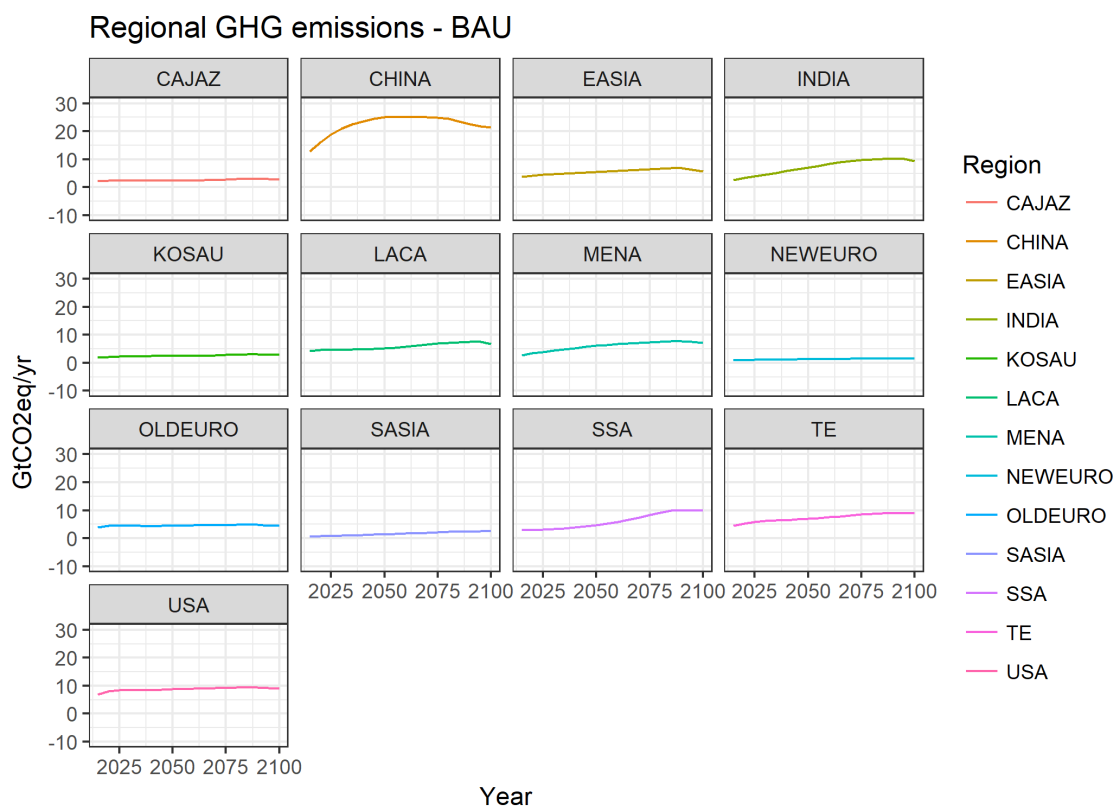

Figure 3 – Global GHG emissions.

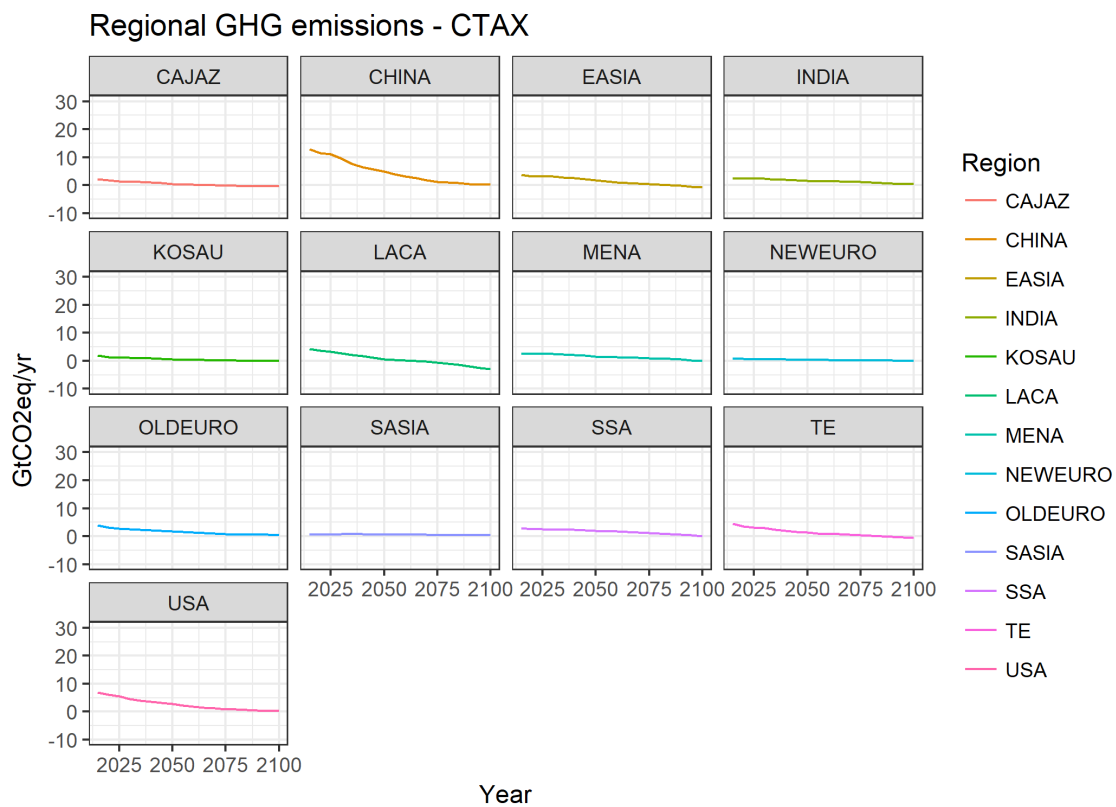Figure 4 – Regional GHG emissions, BAU scenario.

Figure 5 – Regional GHG emissions, CTAX scenario.

In the BAU scenario, annual global CO_2 emissions grow from 36 Gt/yr in 2015 to about 80 Gt/yr until around 2085, with a slight decrease in the last part of the century, while they constantly decrease immediately after 2015 to a level ranging from -8 Gt/yr to -3 Gt/yr in 2100 in the policy scenarios. GHG emissions have a similar path: in the BAU scenario they start at 50 GtCO₂eq/yr in 2015 and increase to 99 GtCO2eq/yr in 2085, with a slight reduction to 93 GtCO₂eq/yr in 2100 in the baseline scenario, while they constantly decrease to a level ranging from -3 GtCO₂eq /yr to 2 GtCO₂eq /yr in the policy scenarios.

Figures 4 and 5 show the regional evolution of GHG emissions in the BAU and CTAX scenarios, respectively. First of all, it can be seen that emissions approximately converge to zero in the CTAX scenario in all world regions, i.e. the substantially net zero emission required by the policy at global level (Figure 3) is translated in an analogous behavior in all regions (i.e. there are no major positive emitters compensated by major negative emitters). Additionally, it can be noted that USA – just to mention one relevant region – in the BAU scenario has substantially constant GHG emissions around 10 GtCO₂eq/yr all over the century, a level that alone would globally be excessive in the policy scenario already in 2070 (see Figure 3) and which could not be compensated simply via the application of a very high carbon tax in the other regions leading to an equivalent level of negative emissions in 2100. This aspect is specified to justify the assumption of imposing a small carbon tax also in the non-participating regions.

4.   Results

It is interesting to start the Results section showing the GHG emissions obtained in the most relevant regions in all the six explored scenarios. Figures 6, 7, 8, and 9 report these results for OLDUERO, MENA, TE, and USA, i.e. one of the most important regions which are not characterized by differentiated policies (OLDEURO) and the three main regions on which the differentiated policies are focused (MENA, TE, and USA). It should be noted that, in WITCH, Europe is given by the combination of OLDEURO and NEWEURO, where the former substantially accounts for 90% of the total in terms of economic and social weight: hence, OLDEURO can be considered as an almost fully exhaustive proxy for Europe as a whole.

The emission path in OLDEURO is not surprising: in the BAU scenario, GHG emissions slightly grow over the century, while in the policy scenarios they decrease to almost zero in 2100, with minor differences across the policy scenarios. Indeed a non-negligible difference is found in 2020, which is due to the different carbon tax values needed to reach the mitigation target: the CTAX_no_fos-exp_low-inc is the scenario with the lowest number of participating regions (only seven out of thirteen, in particular USA, OLDEURO, NEWEURO, KOSAU, CAJAZ, CHINA, and LACA), therefore the tax applied here is the highest across scenarios (especially in the very first years for optimization reasons), which leads to lower emissions. Over time the difference in taxes become smaller, and the emission paths tend to converge accordingly, leading to the same final temperature increase.

It is more interesting, instead, to analyze the emissions obtained in the other three regions. In all of them, as indeed already noted in Figure 5, the GHG emissions converge to zero in the reference policy scenario (CTAX) and in the other scenarios where the full tax is applied, but quite a similar path is also found in the scenarios where the reduced carbon tax is applied: this highlights the non-linear behavior of carbon taxes and also highlights the innovation benefits (especially for the cost of renewables) obtained from the participating regions, which must deeply change their energy and economic systems and thus innovate towards a low-carbon framework (for more details on this point, please refer to Carrara, 2019).
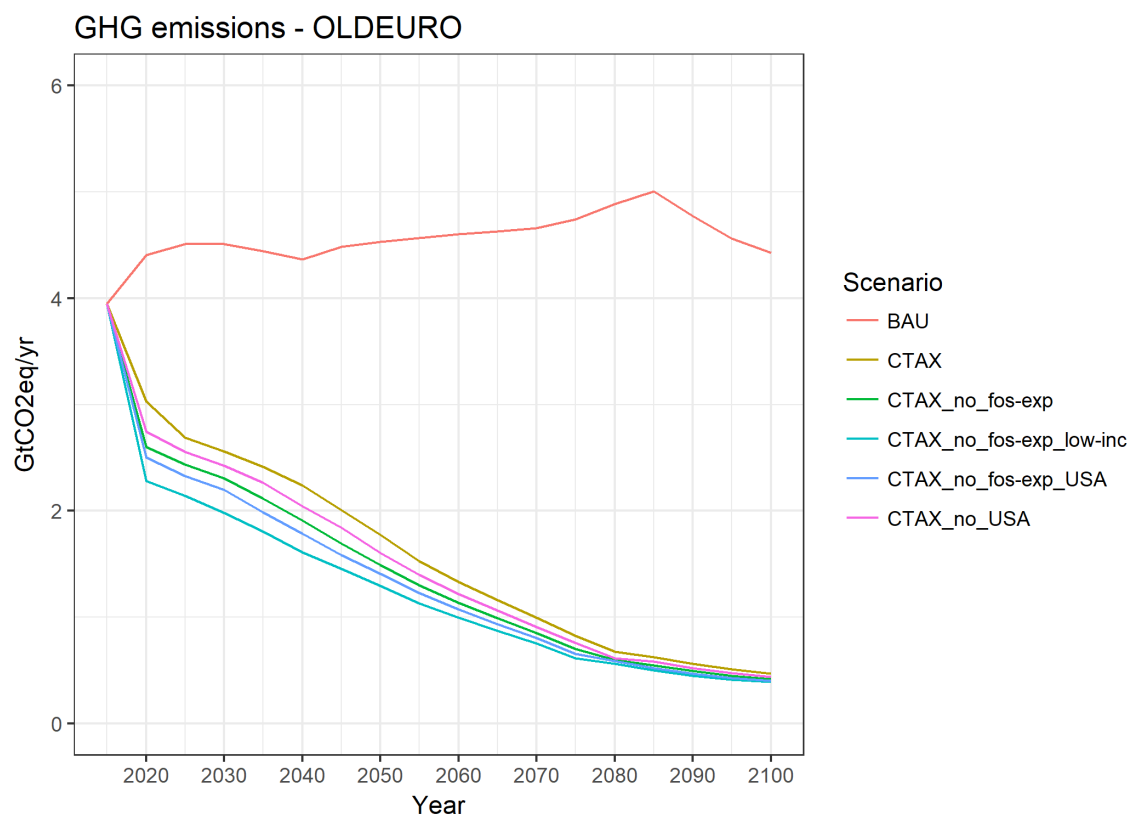
GHG emissions - OLDEURO

Figure 6 – GHG emissions in OLDEURO.
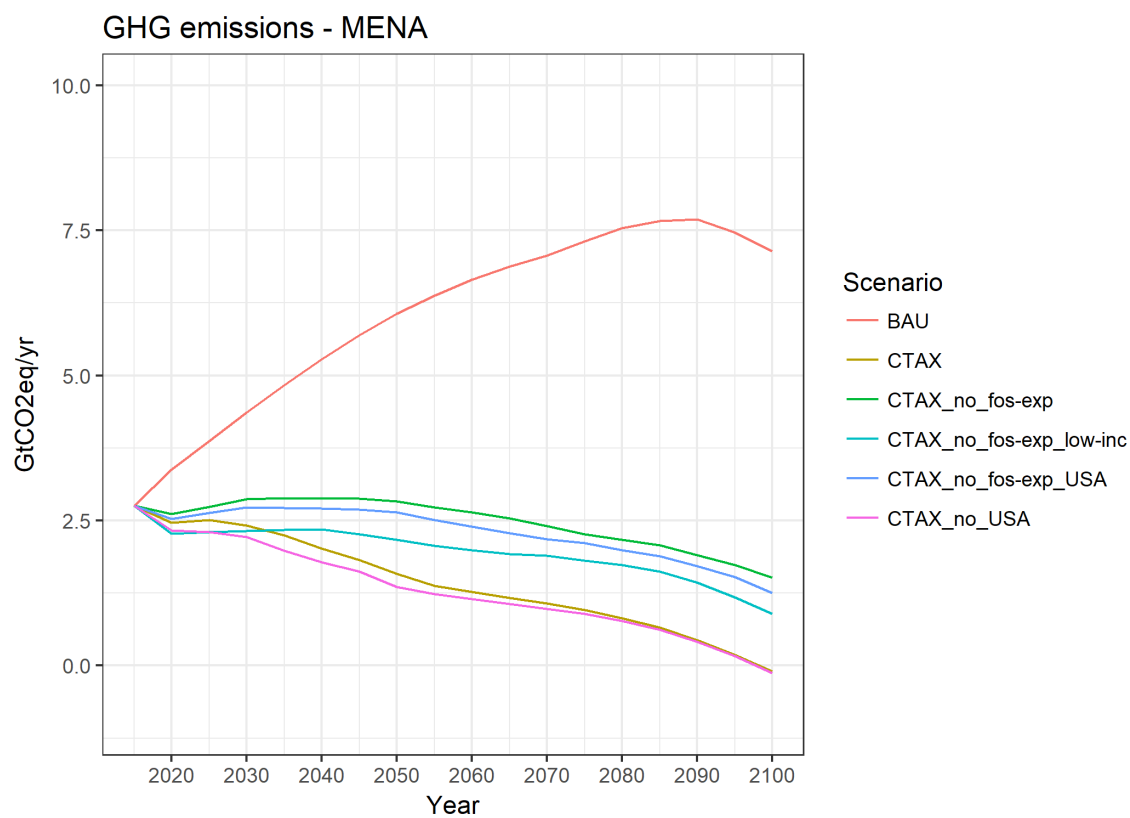
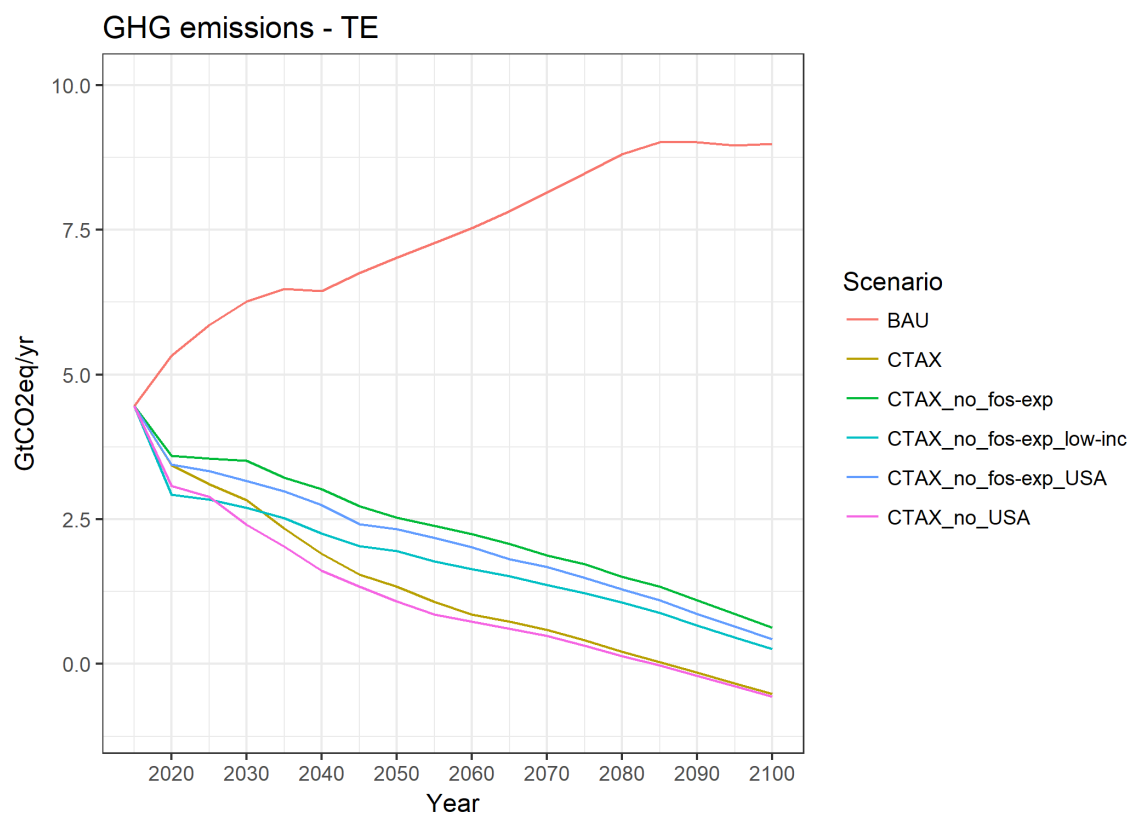## GHG emissions - MENA

Figure 7 – GHG emissions in MENA.

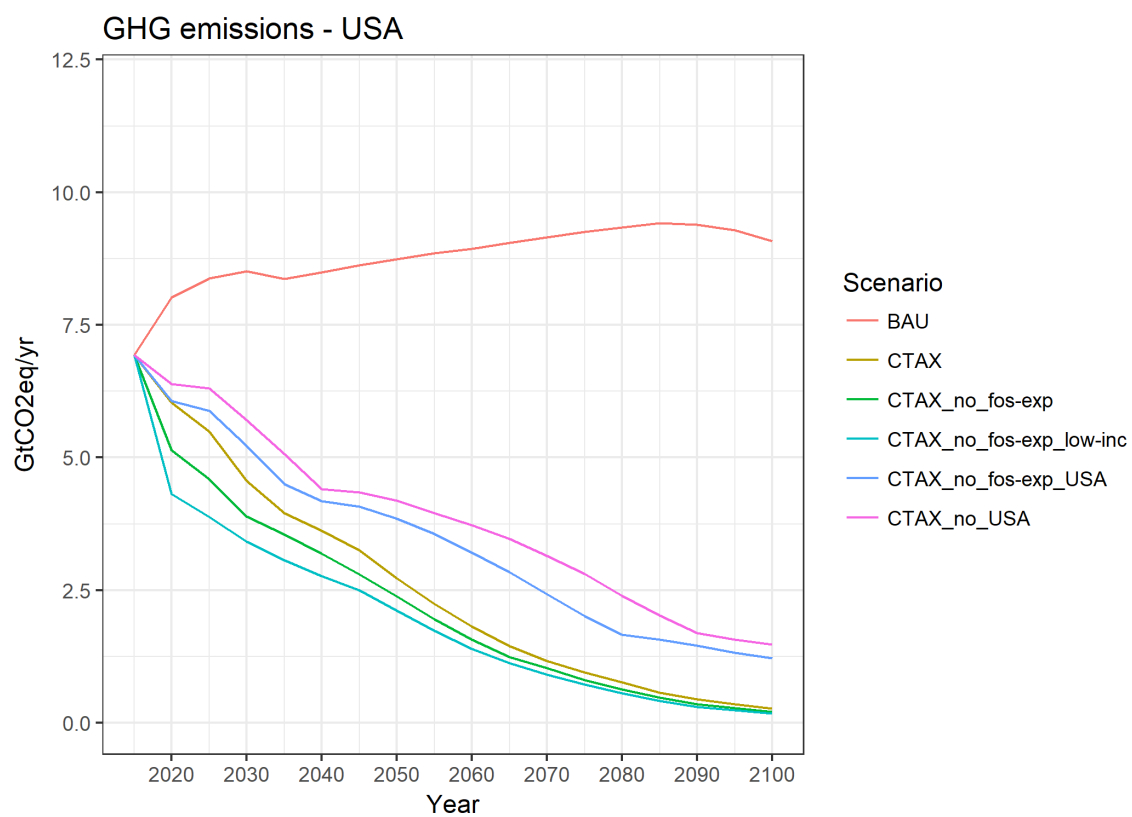*Figure 8 – GHG emissions in TE.*

Figure 9 – GHG emissions in USA.

The overall primary energy demand does not vary across the policy scenarios, even if the growth over time is well lower than in the BAU scenario, see Figure 10. This is quite a consolidated result, as the decarbonization targets result in higher energy efficiency and thus lower demand.
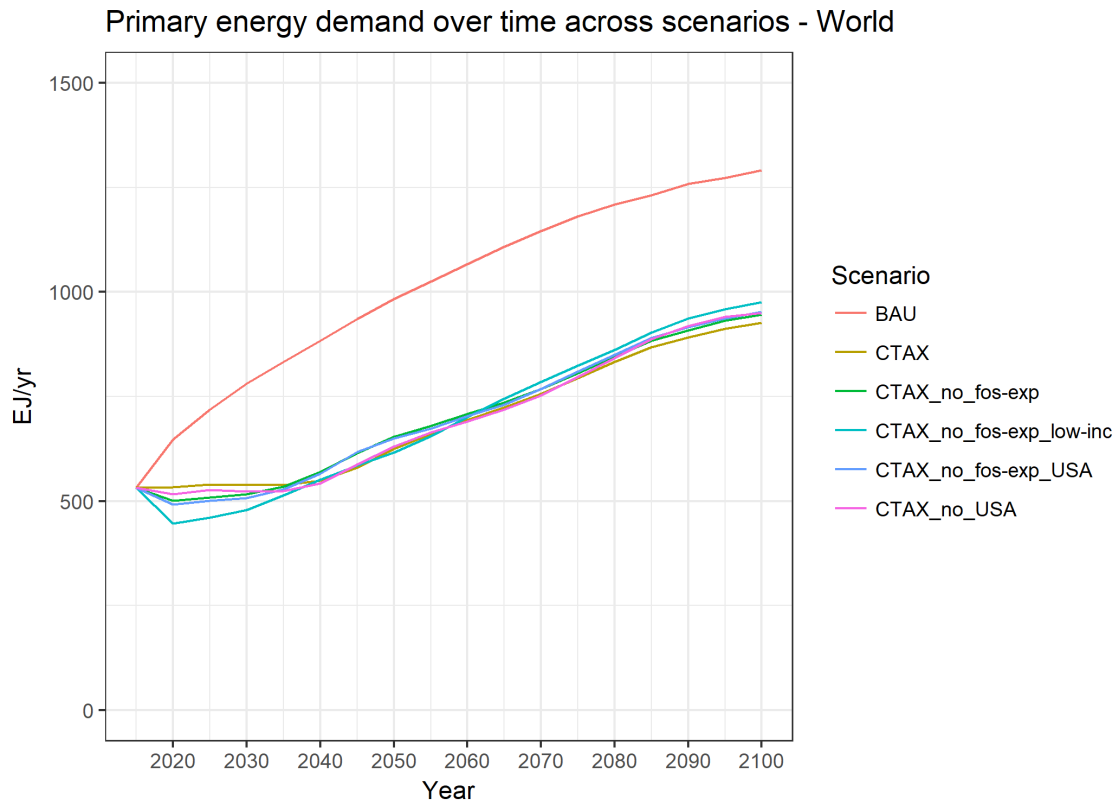
Primary energy demand over time across scenarios - World

Figure 10 – Global primary energy demand across scenarios.

The global electricity demand too evolves very similarly in the policy scenarios, again with a considerable difference with the BAU scenario, see Figure 11. However, if the primary energy path for the policy scenarios is lower than in the BAU scenario all over the century, a more peculiar behavior is found here: the electricity demand in the policy scenario is lower than the BAU levels in the first decades, but then it grows at a much faster pace, exceeding the no policy level towards the end of the century. In order to understand this behavior, it must be reminded that decarbonization, in general, can be attained via two main strategies. The first one is to reduce emissions by reducing energy demand, which is essentially what has been noted for primary energy and is what happens in the policy scenarios in the first decades: here the electricity demand shows a mild growth, much lower than the growth in the BAU scenario. However, the increase in the BAU scenario is fairly regular over the century, while in the policy scenarios a much faster growth takes place starting from around 2040, which leads to an overcome of the electricity demand with respect to the BAU levels around 2080. This highlights the second decarbonization strategy which is now applied and which consists in the electrification of the energy sector with a parallel decarbonization of the electricity sector, as this is in general easier to decarbonize (Nelson et al., 2012 and Wei et al., 2013).
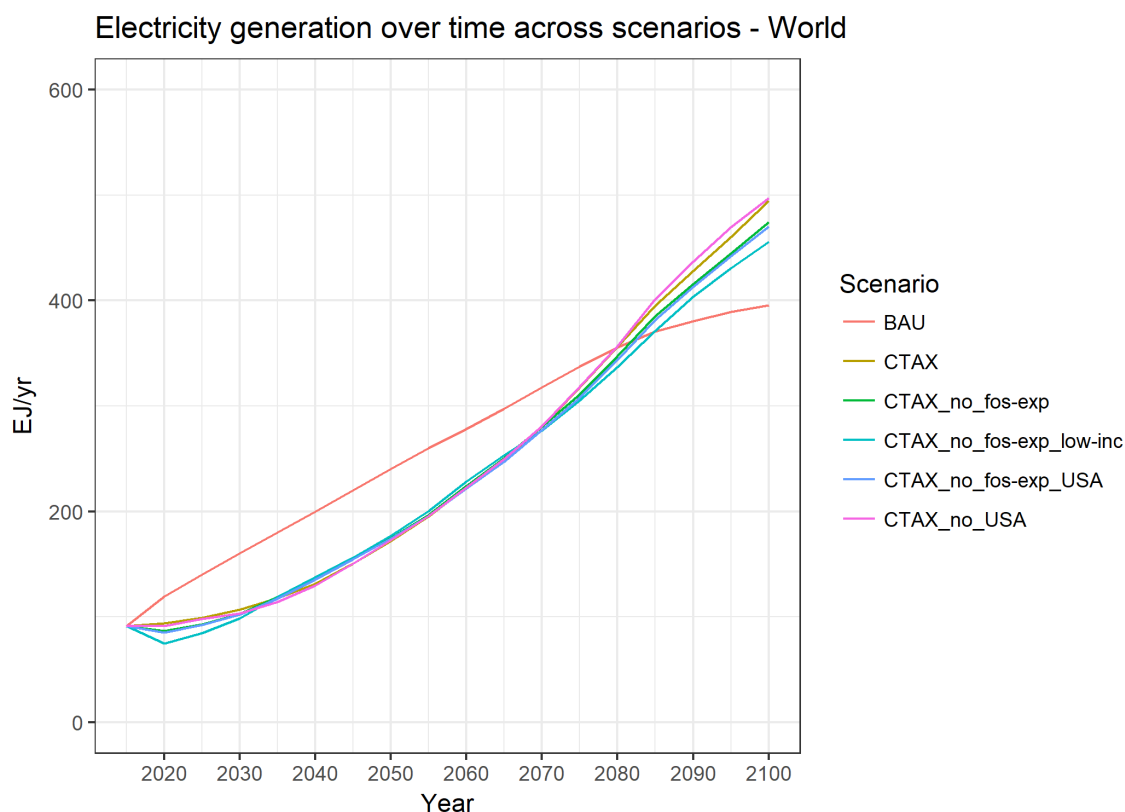
Figure 11 – Global electricity demand across scenarios.

The decarbonization of the energy sector is clear if one observes the evolution of the electricity mix (Figure 12) and of the primary energy mix (Figure 13). The mitigation target in the policy scenarios leads to an electricity sector which is already fully decarbonized by 2050, apart from a marginal contribution from gas without CCS, while decarbonization of the primary mix requires more time and it is fully achieved only towards the end of the century. The energy landscape in the BAU scenario, instead, follows the historical patterns and in 2100 the primary mix is still dominated by fossils without CCS, even if renewables (signally wind and solar) achieve about one fifth of the mix even in the absence of a carbon signal (one third in the electricity mix). At first glance, no major differences are found across the five policy scenarios, as in 2100 a more or less balanced mix of wind (especially onshore), solar (especially PV), nuclear, hydro, as well as coal, gas, and biomass – the former two only with CCS, the latter both with and without CCS – is found. It is therefore more interesting to focus punctually on the specific regions.

Before proceeding, only a few lines are dedicated to reminding that such a huge penetration of solar and wind imply non-negligible issues in terms of stability of the grid, as the variability characterizing by nature these energy sources is in contrast with the need of guaranteeing a constant balance between demand and supply. This aspect is not easy to model in Integrated Assessment Models, as the technical phenomena occur on scales that are incompatible with these tools, which thus require complementary ways to deal with these aspects. No further details are reported here, however: the reader is referred to Carrara and Marangoni, 2017 for further details on the WITCH model; Carrara, 2019 for a similar discussion within the MERCURY project; Pietzcker et al., 2017 for an overview of IAMs. Here it is sufficient to note that such a renewable expansion implies the deployment of a huge storage capacity as well as the expansion of the electrical grid.
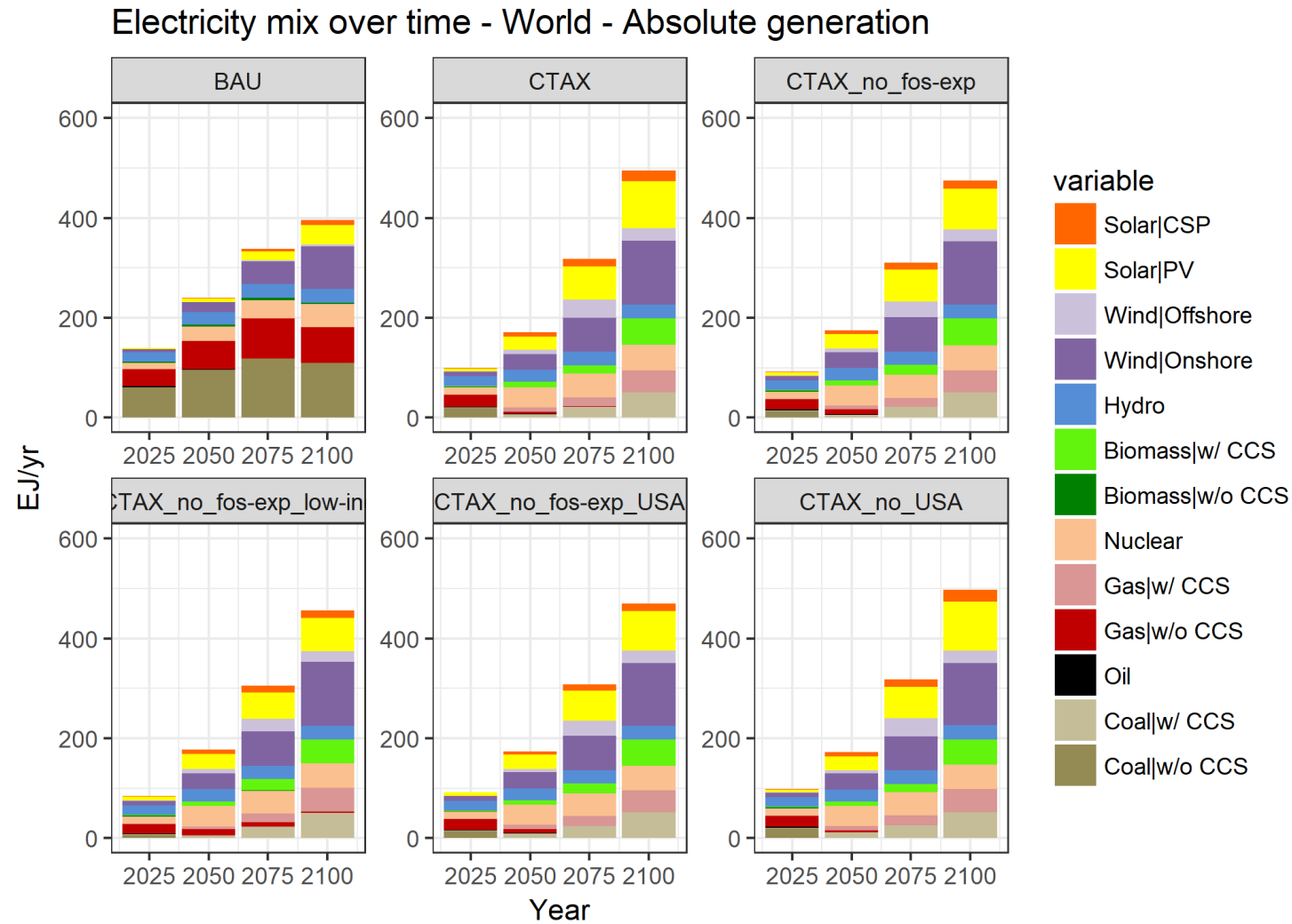
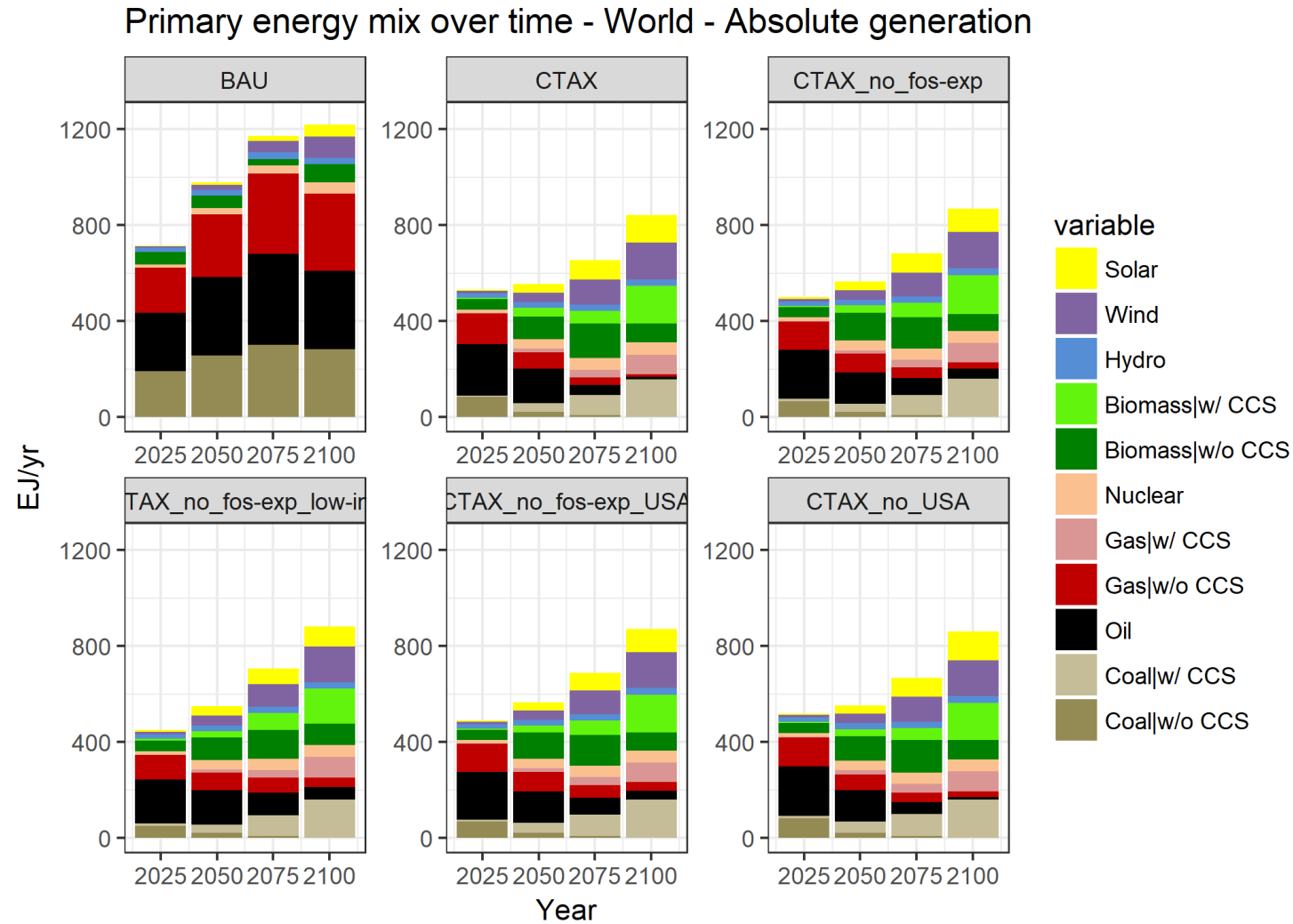*Figure 12 – Global electricity mix over time (absolute generation).*

Figure 13 – Global primary energy mix over time (absolute generation).

The regional analysis focuses on the regions that have been considered for the GHG emissions, i.e. OLDEURO, MENA, TE, and USA. The results in 2100 are highlighted, in order to allow an easier comparison across scenarios.

Again, OLDEURO (Figure 14) shows negligible changes in the electricity mix across the policy scenarios. Indeed, Europe is the region that would rely most on renewables also in the BAU scenario: thanks to high technology maturity and renewable potential, renewables (with nuclear) would dominate the mix even in the absence of a carbon policy. Biomass and gas (without CCS) and coal (with CCS) complete the primary energy mix (Figure 15), which is very different from what would be achieved in the BAU scenario.

In MENA, the electricity mix is dominated by coal and gas with CCS in the policy scenarios (Figure 16). Interestingly, this contribution does not change with the application of the full or reduced carbon tax: a stringent policy (applied in the CTAX and CTAX_no_USA scenarios) only entails a much higher solar deployment (both PV and CSP). The solar contribution would indeed be higher in the BAU scenario than in the policy scenarios with the reduced tax, but this would be related to the absence of CCS in the BAU scenario. The primary energy demand (Figure 17) is basically constant between the BAU and the policy scenarios, and indeed oil – which is obviously fundamental in the MENA economy – has a relevant share even in the full tax scenarios. Summarizing, with the full tax, the renewable generation grows in the electricity mix, while with the moderate tax the fossil consumption grows in the primary energy mix.

TE shows a very similar behavior. In the electricity mix (Figure 18) the shares of nuclear, coal with CCS and gas with CCS are essentially constant across the mitigation scenarios. What differentiates the full tax scenarios (CTAX and CTAX_no_USA) is a higher wind generation, notably wind offshore. Concerning the primary energy mix (Figure 19), the scenarios with the reduced tax allow the consumption of oil and gas without CCS, which are not present in the mixes if the full tax is applied.

Finally, USA shows an electricity mix which is very similar to the OLDEURO one (Figure 20), being dominated by renewables (especially wind onshore) and nuclear. If the full tax is applied, wind generation slightly increases, while a small contribution from coal and gas with CCS is allowed in the cases with the reduced tax (CTAX_no_fos-exp_USA and CTAX_no_USA). Gas would dominate the primary energy mix (Figure 21) in the BAU scenario, and it is present in the policy scenarios with a limited carbon tax (together with biomass without CCS), while the full carbon tax leads to the complete absence of these two sources (as well as all the other fossils without CCS).
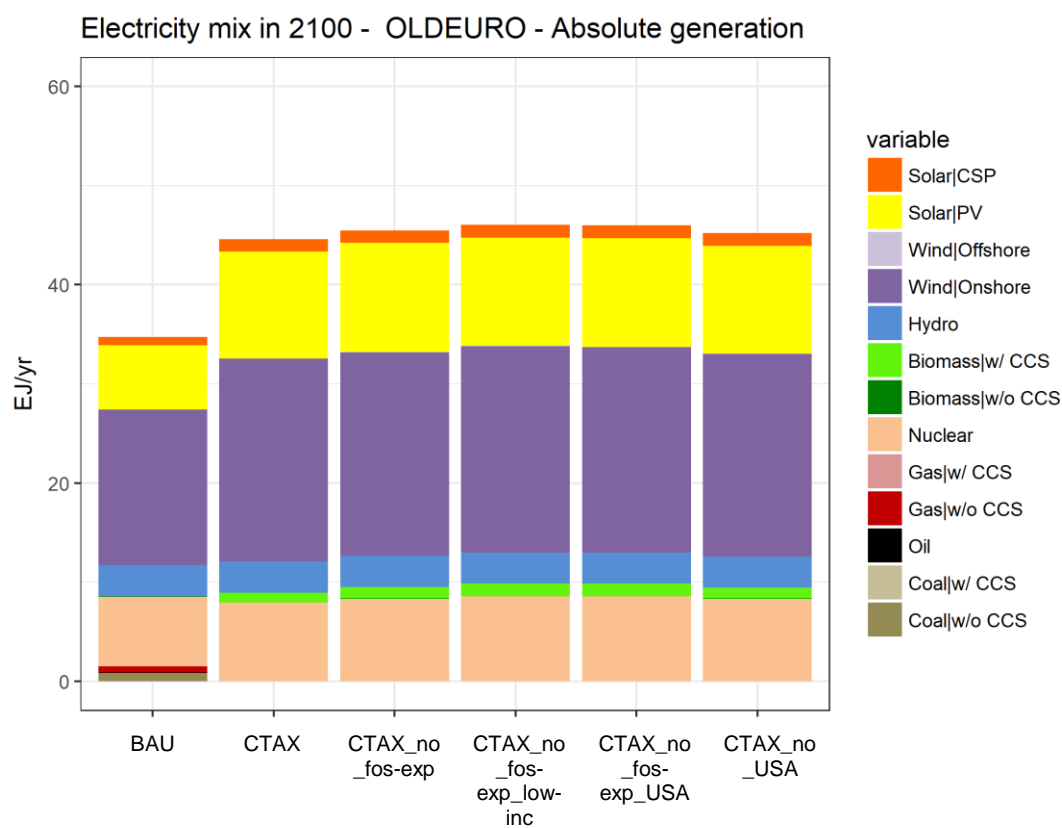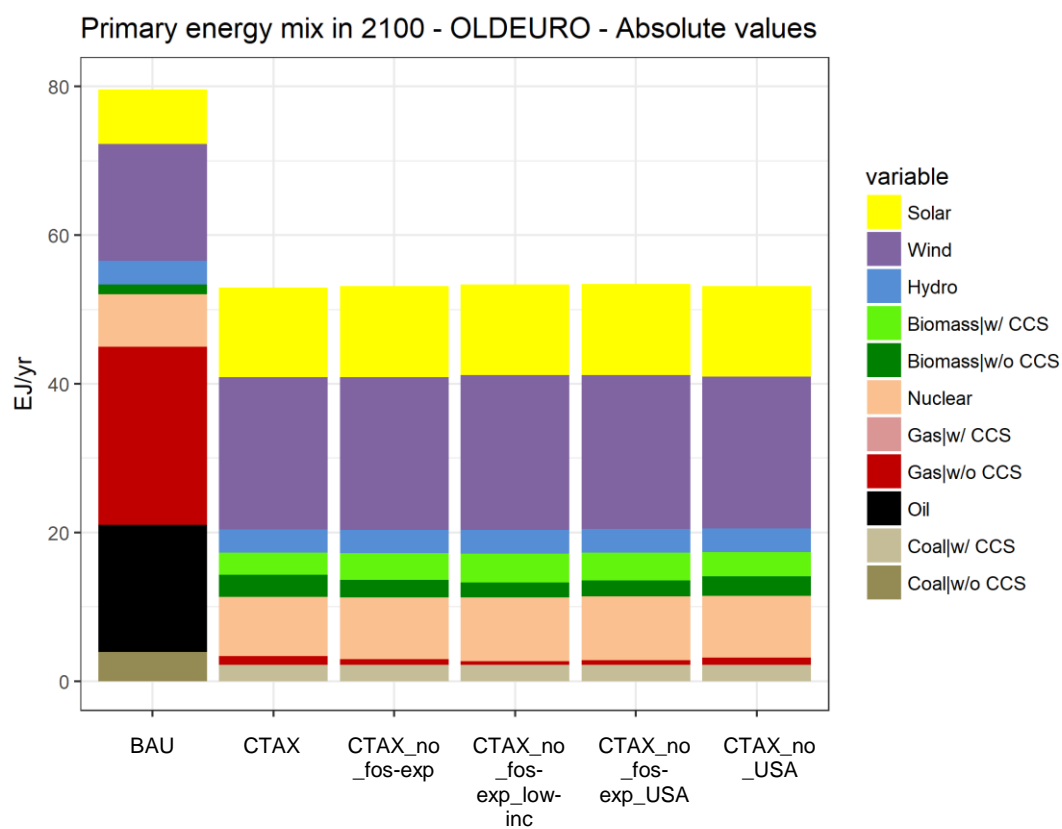
Figure 14 – Electricity mix in 2100 in OLDEURO.

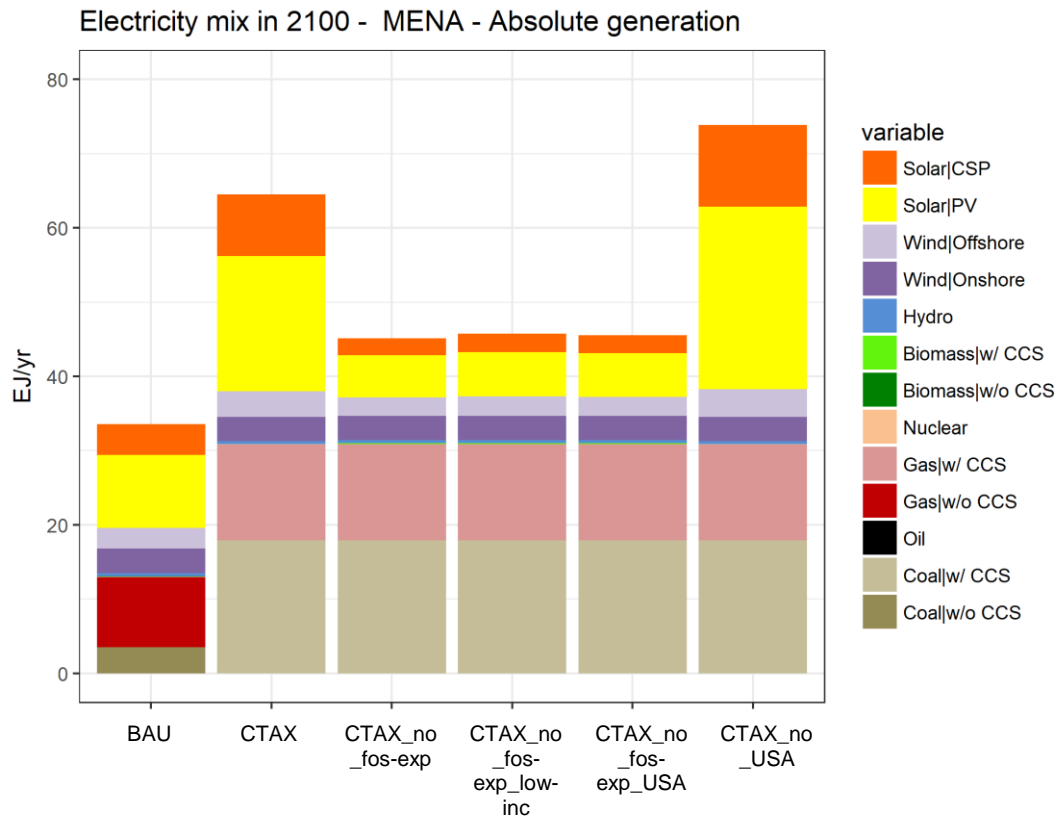

Figure 15 – Primary energy mix in 2100 in OLDEURO.

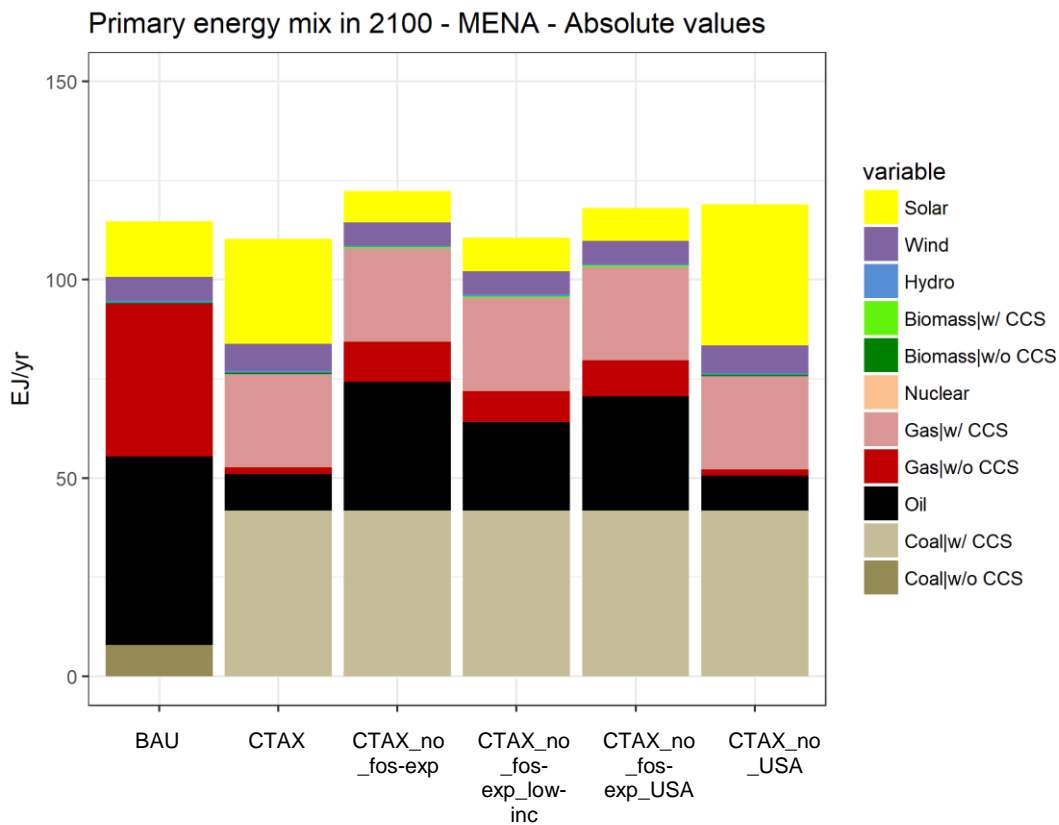*Figure 16 – Electricity mix in 2100 in MENA.*

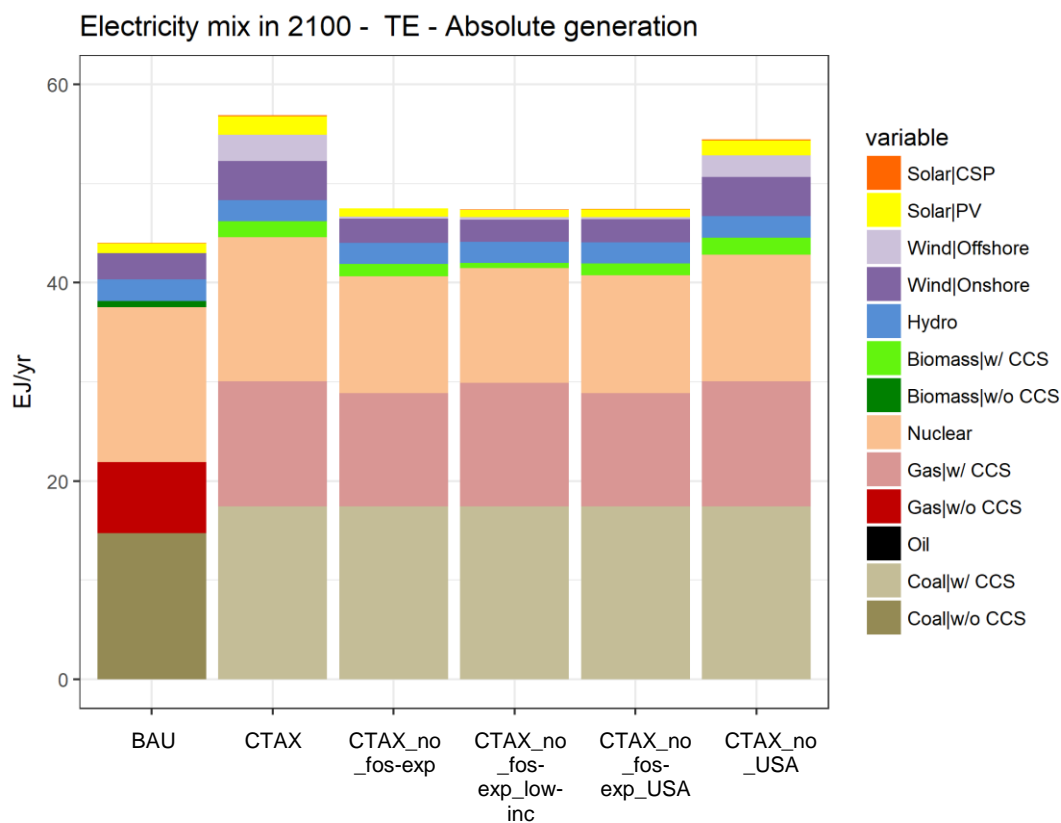

Figure 17 – Primary energy mix in 2100 in MENA.

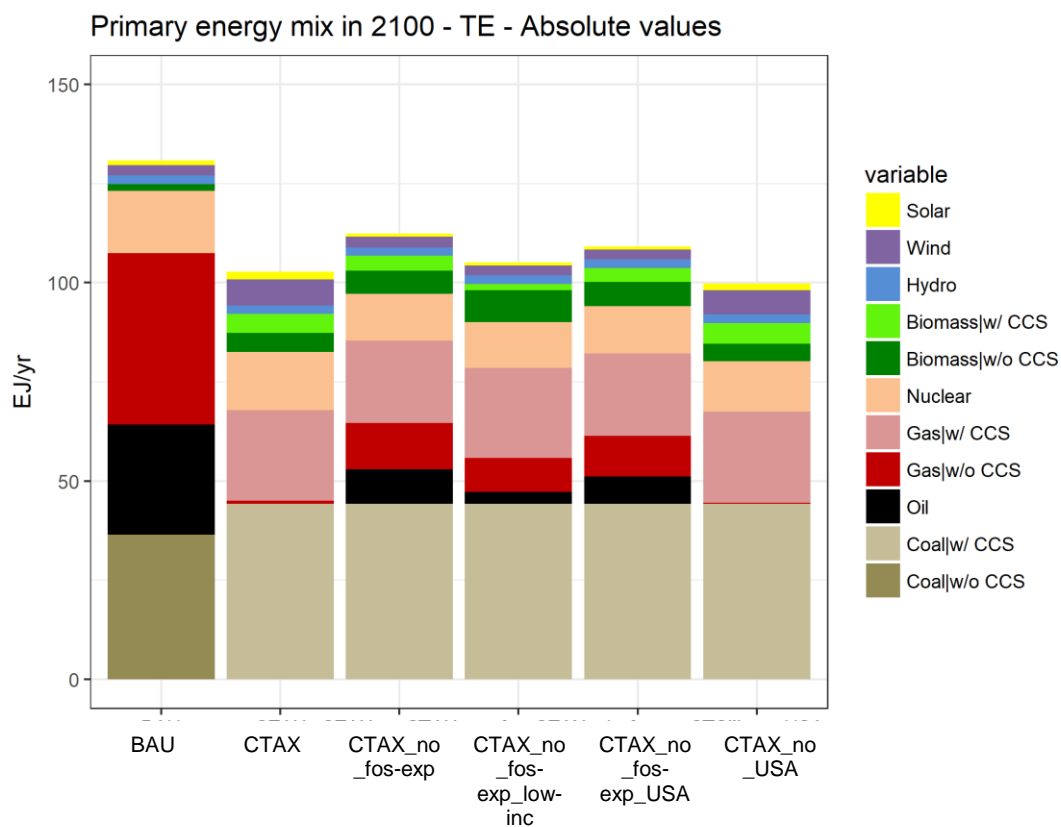*Figure 18 – Electricity mix in 2100 in TE.*

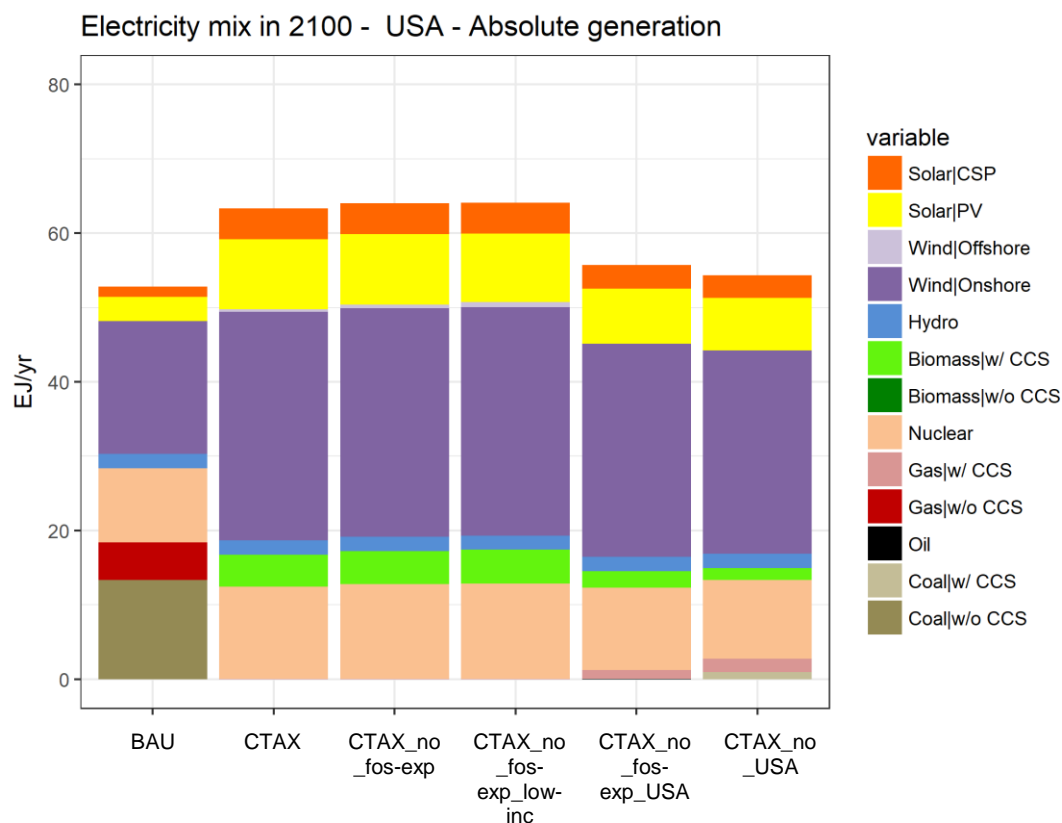*Figure 19 – Primary energy mix in 2100 in TE.*

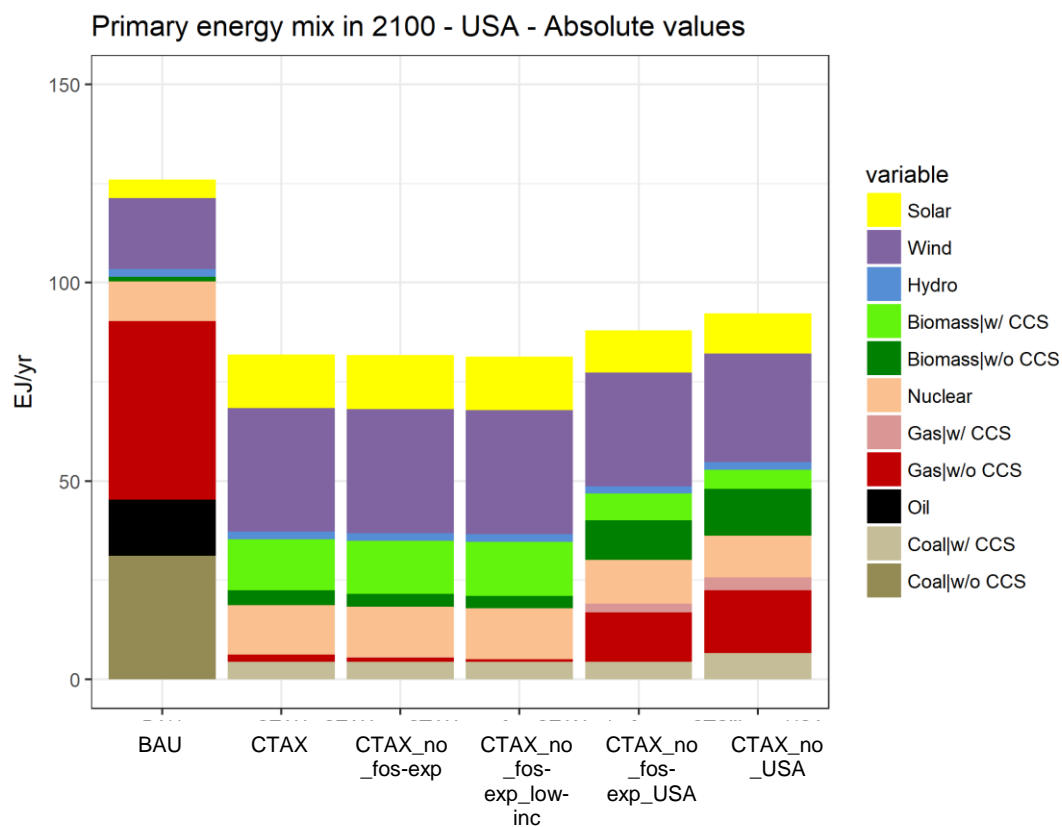*Figure 20 – Electricity mix in 2100 in USA.*

Figure 21 – Primary energy mix in 2100 in USA.

In the last part of the paper, it is interesting to focus on the economic impacts of the different scenarios, and in particular on the policy costs, which are evaluated as the cumulative GDP loss over the century with respect to the cumulative GDP of the baseline scenario, assuming a yearly discount factor equal to 2.5%.

First of all, Figure 22 shows the global GDP loss in the thirteen regions and at a global level in the CTAX scenario, in order to assess the economic loss in the standard mitigation scenario.
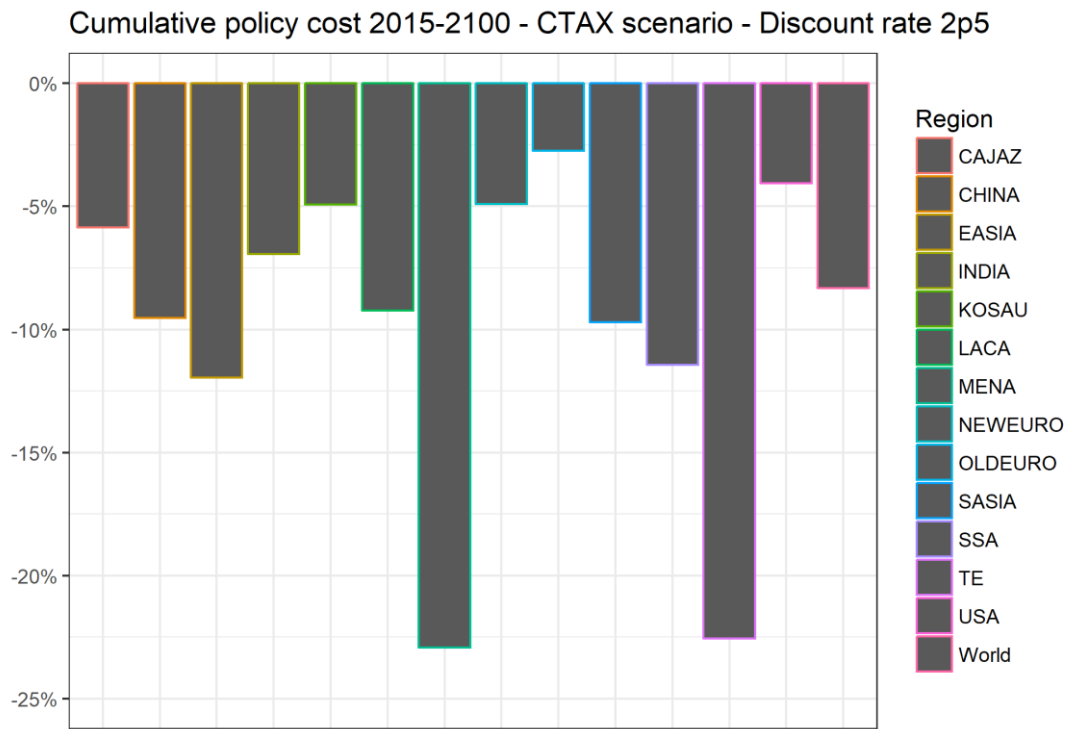

Figure 22 – Regional and global policy costs in the CTAX scenario.

The average cumulative global GDP loss is 8.3%, however marked differences can be found across regions. With a cumulative GDP loss of about 23%, MENA and TE are the regions being most hit by the mitigation policies. The reason of this result is obviously related to the structure of the exercise, as these are the main exporters of fossil fuels. The application of a carbon tax necessary to reach the 2°C-target in 2100 requires a global fall in fossils consumption, which means less revenues from exports and less possibility of domestic consumption (as indeed clearly shown in Figures 16-19). OLDEURO is instead the region which is affected least by the mitigation policy: the GDP loss does not reach 3% here. After all, Figures 14 and 15 have highlighted that a strong decarbonization takes place in this region already in the BAU scenario, i.e. without requiring the implementation of a carbon tax to trigger the low-carbon transition, therefore the additional effort needed to reach a 2°C-compatible mix is quite limited. The same substantially applies to USA, even if to a slightly lower extent (the cumulative GDP loss is 4% here).

Having depicted the overview of the reference mitigation scenario, the next figures show the policy costs in the remaining four mitigation scenarios, highlighting the differences related to the different levels of participation to mitigation policies. Figure 23 shows the GDP losses while Figure 24 shows the additional or lower losses with respect to the unconstrained CTAX scenario in percentage points. Figures 25, 26, 27, 28, and 29 report detailed results for OLDEURO, MENA, TE, USA, and the world, respectively.
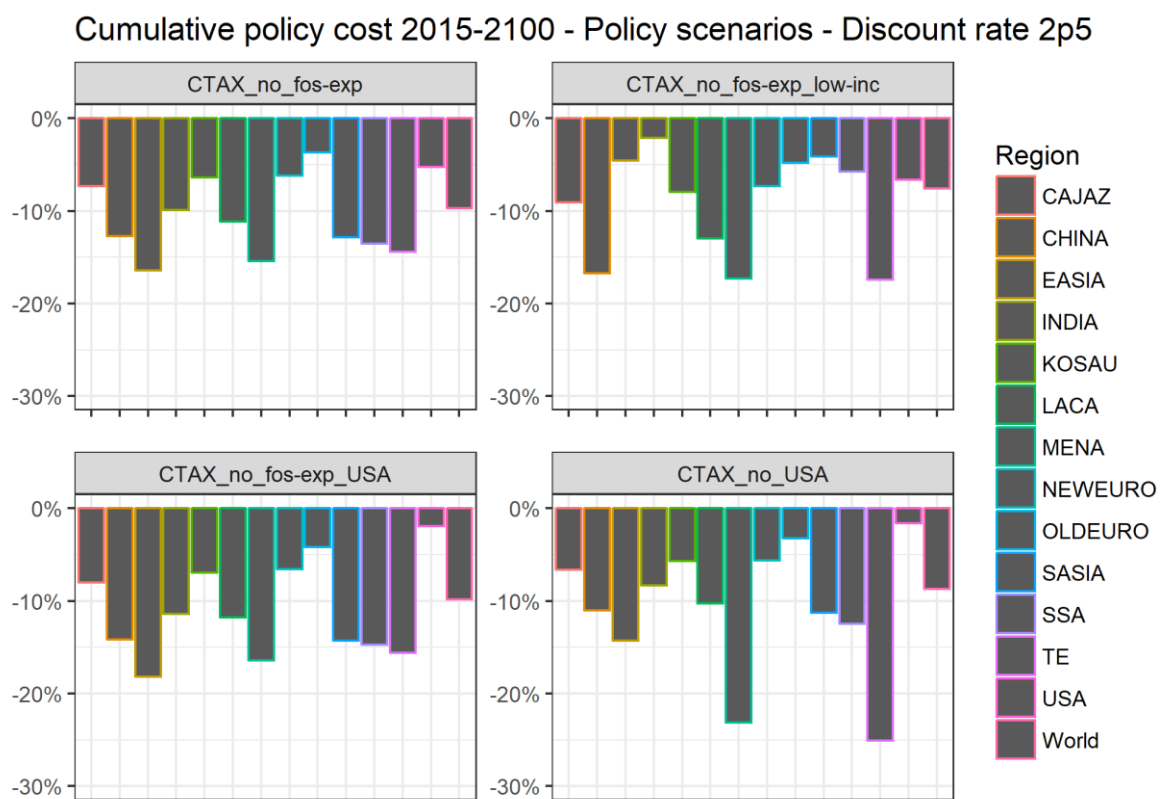
Figure 23 – Regional and global GDP loss in the mitigation scenarios (except CTAX).
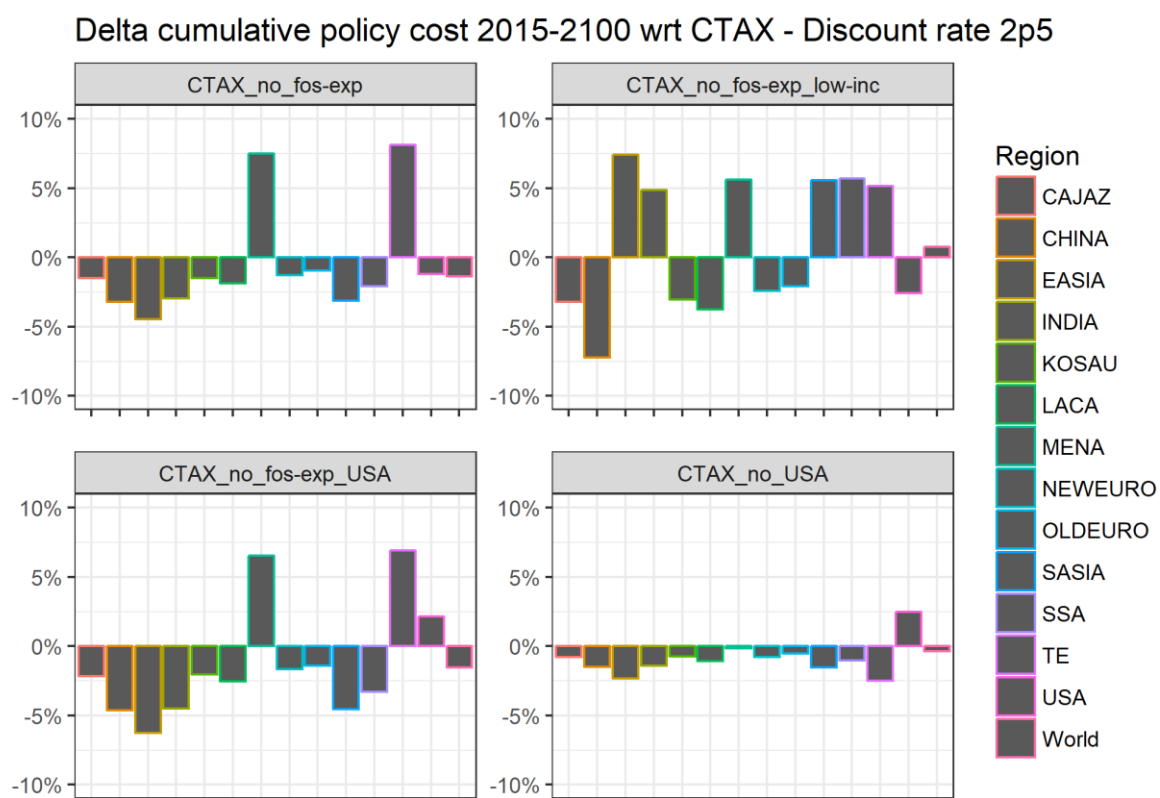

Figure 24 – Regional and global GDP loss in the mitigation scenarios: difference with respect to CTAX.
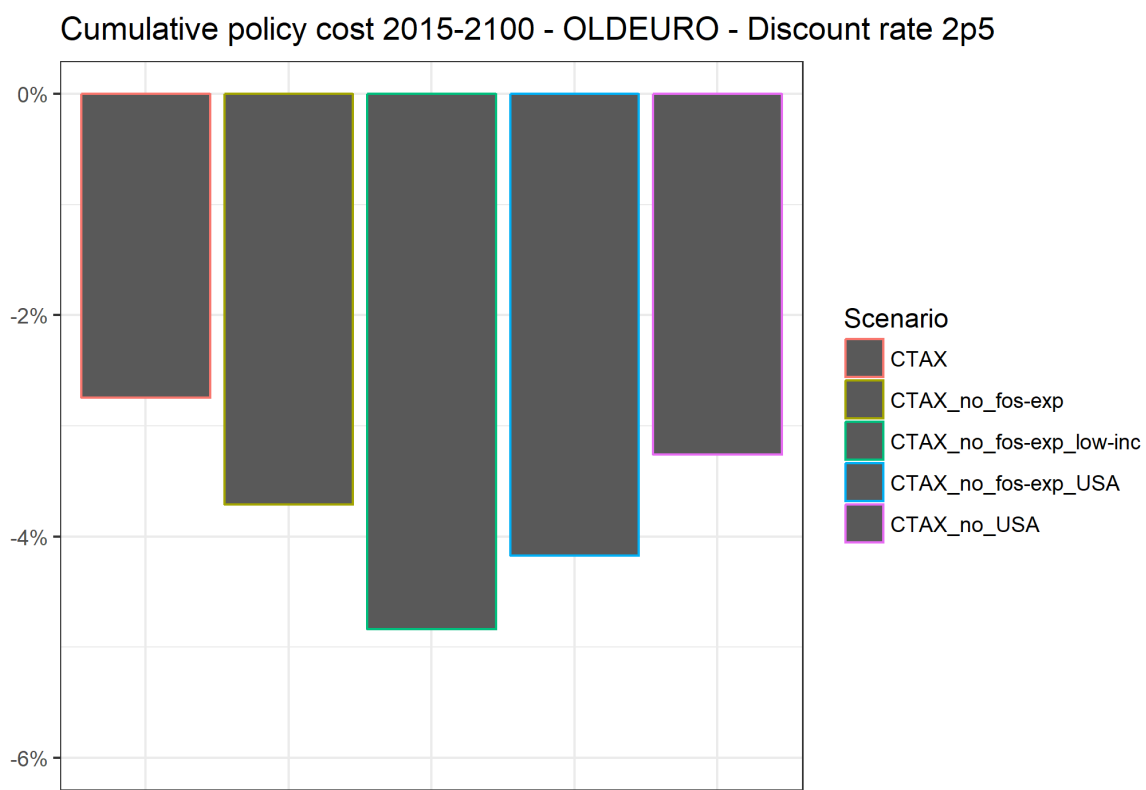
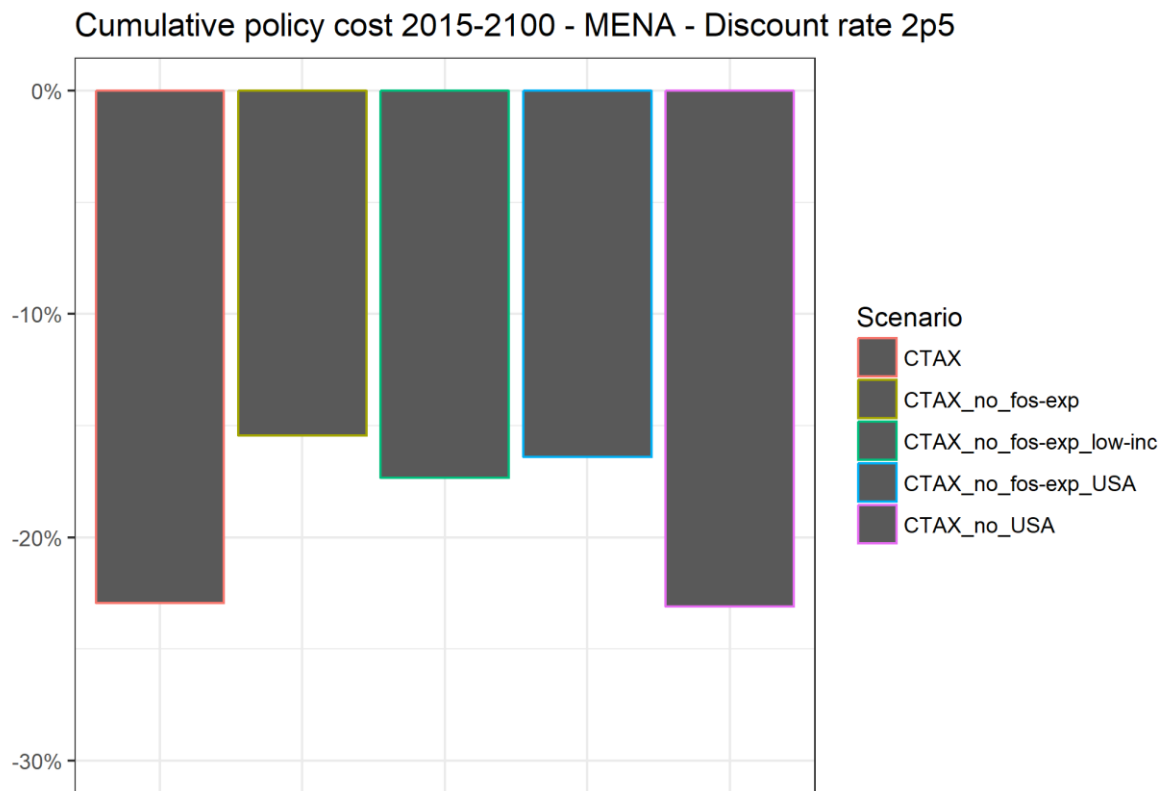*Figure 25 – GDP loss in the mitigation scenarios in OLDEURO.*

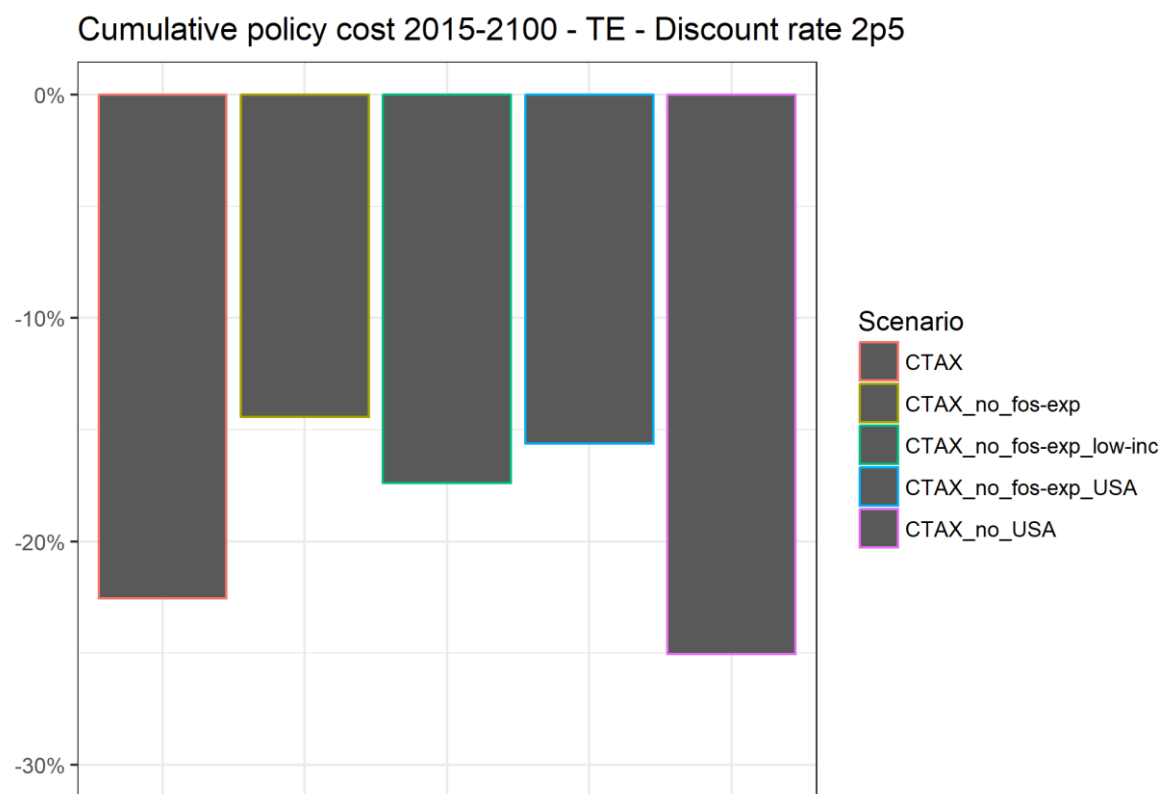*Figure 26 – GDP loss in the mitigation scenarios in MENA.*

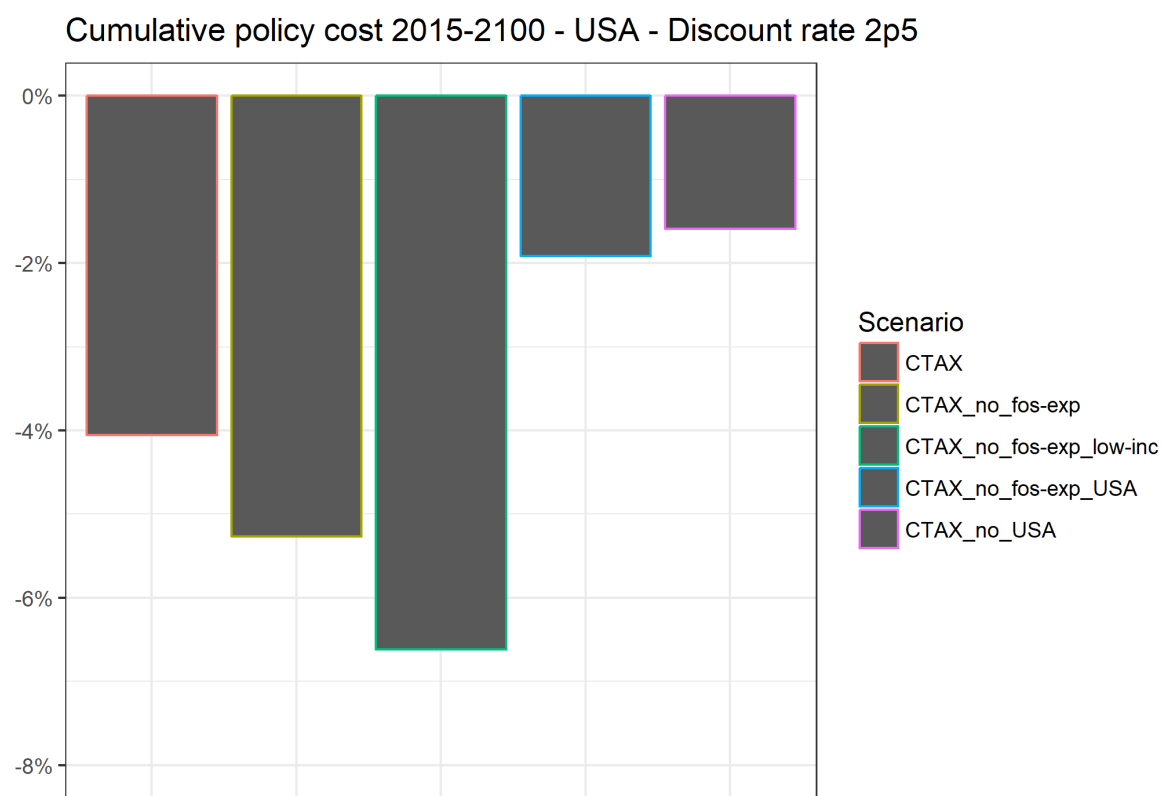*Figure 27 – GDP loss in the mitigation scenarios in TE.*

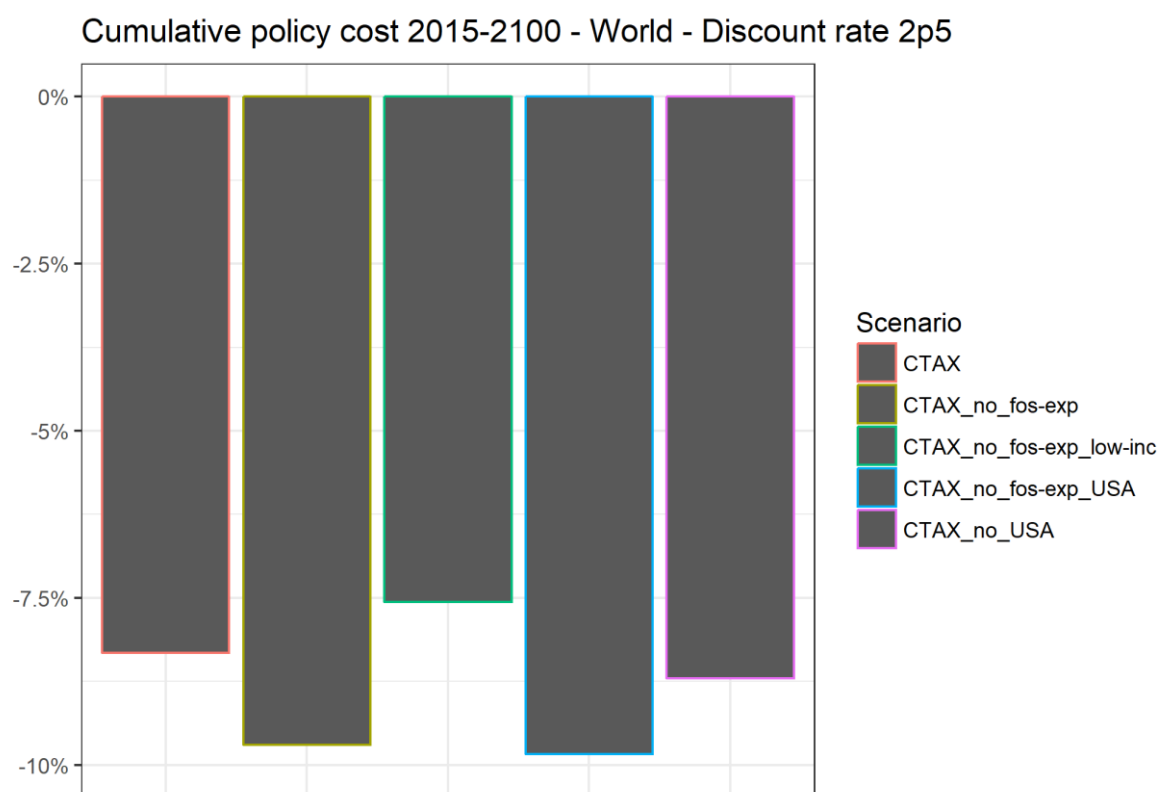*Figure 28 – GDP loss in the mitigation scenarios in USA.*

Figure 29 – Global GDP loss in the mitigation scenarios.

The application of a reduced carbon tax in MENA and TE allows these region to partly recover from the severe GDP losses that the mitigation policy entails. In the CTAX_no_fos-exp scenario, they averagely recover eight percentage points, but the GDP loss – mostly related to the lower fossil consumption in the rest of the world – still remains among the highest across world regions. The lower losses of MENA and TE are distributed among the other regions, which suffer additional 1-5% losses (especially the regions which already show difficulties in decarbonizing, like EASIA and SASIA). If the facilitated policy regime in MENA and TE is shared with USA (CTAX_no_fos-exp_USA scenario) or with the low-income regions (CTAX_no_fos-exp_low-inc), the loss reduction in the two fossils exporting regions is lower by one or two percentage points as it is shared with a higher number of regions, which strongly benefit from this, averagely by five percentage points (the low-income regions) or by about two points (USA), reaching negligible mitigation costs. Overall, MENA and TE only recover losses to an extent comprised between 23% and 36% in relative terms in the different scenarios.

The USA manages to recover relatively more than the fossils exporting regions in the scenarios with the reduced tax: in the CTAX_no_USA scenario the GDP loss is about 1.5%, i.e. 60% less than in the reference CTAX scenario, while the GDP loss is only halved if the facilitated regime is shared with MENA and TE.

Naturally, the regions which always bear the full mitigation effort are severely affected if the climate action is less and less participated. In particular, in OLDEURO the GDP loss is 2.7% in the CTAX scenario, rising to 3.3% in the CTAX_no_USA scenario (+19% in relative terms), 3.7% in the CTAX_no_fos-exp scenario (+35%), 4.2% in the CTAX_no_fos-exp_USA scenario (+52%), and 4.8% in the CTAX_no_fos-exp_low-inc scenario (+76%). Interestingly, this proportion approximately holds for all the fully participating regions, even if indeed OLDEURO is the region mostly affected by the relative increase, arguably due to the low starting

point. In the other regions, in fact, the relative increase is averagely 15% in the in CTAX_no_USA scenario and 60% in the CTAX_no_fos-exp_low-inc scenario. In particular, the combination of OLDEURO with NEWEURO leads these two values to 18% and 74% for Europe. Similar results are found for the USA in the scenarios where it fully participates in climate action: with respect to the CTAX scenario, the GDP loss is 30% higher in the CTAX_no_fos-exp scenario and 63% in the CTAX_no_fos-exp_low-inc scenario.

It is finally interesting to note that the lower and lower participation has a progressively negative impact in global terms, as the cumulative GDP loss grows from 8.3% in the CTAX scenario to 8.7% in the CTAX_no_USA scenario, 9.7% in the CTAX_no_fos-exp scenario, and 9.8% in the CTAX_no_fos-exp_USA scenario. However, there is a very interesting and main exception to this, as the CTAX_no_fos-exp_low-inc scenario indeed shows a lower global GDP loss, which is equal to 7.6%. This is probably due to the combination of, on the one hand, the lower losses in the low-income regions which would have the highest difficulties in decarbonizing and that would benefit most from the reduced carbon tax, and, on the other hand, the innovation benefits which would be urgently required in the few fully participating regions, which would boost advancements in the renewable and general energy efficiency sectors (according to a mechanism already described in Carrara, 2019), eventually leading to more than compensate the losses.

5.   Conclusions

Achieving ambitious targets of climate change mitigation requires globally coordinated action. The Paris Agreement has been signed by virtually all world countries, yet negative scenarios may be envisioned. On the one hand, the United States, the second world emitter of carbon dioxide, have announced their intention to withdraw from the Agreement. On the other hand, the practical implementation of sufficiently ambitious mitigation policies may not be taken for granted in some regions of the world.

The main aim of this work has been to explore different mitigation pathways associated to different levels of participation in climate mitigation action by world regions, in order to assess the additional costs that the participating regions must bear if there is no global coordination and the savings that may be achieved in the regions which do not fully participate in mitigation, as well as to investigate the changes in the energy mix. Scenarios are explored considering the application of a carbon tax on greenhouse gas emissions, compatible with the 2°C long-term Paris target. As reduced tax has been applied in the non-participating regions, in order to model the decarbonization feedback that these would receive even in the absence of a direct and full implementation of the tax. The explored scenarios have considered USA, the main fossils exporting regions (MENA and TE), and the low-income regions (SSA, EASIA, SASIA, and INDIA) as potential regions which may not fully participate in global mitigation. Europe is considered the trailblazer in climate change mitigation, therefore it has been considered as always fully participating, together with the other OECD regions – i.e. CAJAZ and KOSAU – as well as CHINA and LACA.

Withdrawing from the climate action results in economic benefits in the relevant regions (especially in the USA, which almost fully compensates its mitigation losses), but the fossils exporting regions still have the relatively highest losses among regions, because, although they are allowed to consume more fossil fuels domestically, climate change mitigation entails the reduction of fossil fuels demand in the participating regions.

The fully participating regions can have GDP losses that grow averagely between 15% and 60% in relative terms with respect to the reference fully-participated scenario if the mitigation action is shared among

fewer and fewer regions. Europe shows higher relative changes (from 18% to 74%), even if in absolute terms losses are quite low in this region (between 3% in the CTAX scenario and 5% in the CTAX_no_fos-exp_low-inc scenario), as the resource potential and the technological maturity are such that renewables gain significant shares in the energy mix already in the baseline scenario, so that the mitigation targets do not imply major changes in the mix that would already be achieved as a consequence of the mere economic optimization.

Globally, the progressively lower and lower participation to climate action entails slightly higher costs, but only if this is limited to the USA and/or the fossils exporting regions. If the low-income regions do not implement the full tax, and therefore if the mitigation burden is mostly born by the advanced countries, the overall cumulative GDP loss is lower than in the reference mitigation scenario, thus highlighting that the considerable innovation benefits required in the participating regions needed to achieve the targets, especially for renewables and energy efficiency, more than compensate the additional costs.

References

Bosetti, V., Carraro C., Galeotti M., Massetti E., and Tavoni M. (2006), *WITCH: A World Induced Technical Change Hybrid Model*, Energy Journal, Special issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38

Bosetti, V. and Longden, T. (2013). *Light duty vehicle transportation and global climate policy: The importance of electric drive vehicles*, Energy Policy, Vol. 58, pp. 209-219

Carrara S. (2019). *Reactor ageing and phase-out policies: global and European prospects for nuclear power generation*, Deliverable 2.1 of the MERCURY project

Carrara S. and Longden T. (2017). *Freight futures: The potential impact of road freight on climate policy*, Technological Forecasting and Social Change, Vol. 55, pp. 359-372

Carrara S. and Marangoni G. (2017), *Including system integration of Variable Renewable Energies in a Constant Elasticity of Substitution framework: the case of the WITCH model*, Energy Economics, Vol. 64, pp. 612-626

Emmerling, J., Drouet L., Reis L.A., Bevione M., Berger L., Bosetti V., Carrara S., De Cian E., D'Aertrycke G.D.M., Longden T., Malpede M., Marangoni G., Sferra F., Tavoni M., Witajewski-Baltvilks J., and Havlik P. (2016), *The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways*, FEEM Working Paper 2016.042

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S. Fritz, S. Fuss, S., Kraxner, F., and Notenbaert A. (2014). *Climate change mitigation through livestock system transitions*, Proceedings of the National Academy of Sciences (PNAS), Vol. 111, pp. 3709-3714

IPCC, Intergovernmental Panel on Climate Change (2014). *Climate Change 2014: Synthesis Report*, Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the IPCC

Nelson, J., Johnston, J., Mileva, A., Fripp, M., Hoffman, I., Petros-Good, A., Blanco, C., Kammen, D.M. (2012). *High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures*, Energy Policy, Vol. 43, pp. 436-447

Pietzcker, R.C., Ueckerdt, F., Carrara, S., de Boer, H.S., Després, J., Fujimori, S., Johnson, N., Kitous, A., Scholz, Y., Sullivan, P., and Luderer, G. (2017). *System integration of wind and solar power in integrated assessment models: a cross-model evaluation of new approaches*, Energy Economics, Vol. 64, pp. 583-599

Ponce de Leon Barido, D., Johnston, J., Moncada, M.V., Callaway, D., and Kammen, D.M. (2015). *Evidence and future scenarios of a low-carbon energy transition in Central America: a case study in Nicaragua*, Environmental Research Letters, Vol. 10, 104002

Schellnhuber, H. J., Rahmstof, R., and Winkelmann, R. (2016) *Why the right climate target was agreed in Paris*. Nature Climate Change, Vol. 6, pp. 649-653

Wei, M., Nelson, J.H., Greenblatt, J.B., Mileva, A., Jonhston, J., Ting, M., Yang, C., Jones, C., McMahon, J.E., and Kammen D.M. (2013). *Deep carbon reductions in California require electrification and integration across economic sectors*, Environmental Research Letters, Vol. 8, 014038

Energy futures and climate change mitigation: a qualitative and quantitative assessment in the Sustainable Development Goals perspective

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Abstract

The 2030 Agenda – with its seventeen Sustainable Development Goals (SDGs) – and the Paris Agreement represent a turning point for Sustainable Development. For the first time, world leaders have developed an integrated sustainable agenda and ratified a global agreement to reduce greenhouse gas emissions, recognizing that the current development model is not sustainable from an economic, social, and environmental standpoint. Sustainable energy, being the driver of social and economic growth, will play a crucial role in the achievement of the 2030 Agenda objectives and for closing the gap to the mitigation targets of 2°C and 1.5°C defined by the Paris Agreement.

This paper aims at showing that SDG 7 – the SDG dedicated to energy – can be considered as an enabling factor for the implementation of the other SDGs, and in particular of SDG 13, the goal on climate action. This relation is bidirectional, meaning that mitigation of climate change is positively driven by the deployment of sustainable energy services, and that the integration of climate change mitigation strategies into national policies positively contributes to the deployment of sustainable energy solutions. The paper also shows that future energy scenarios, compatible with the abovementioned ambitious mitigation targets, are in line with the SDG 7 targets that can benefit from the strong technology innovation that those scenarios will require.

Keywords: sustainability, Sustainable Development Goals, technology innovation, electricity

1. Introduction

2015 can be considered the "Year of Sustainable Development" (Sachs, 2014).

In September, during the 70th General Assembly held in New York, the Secretary-General of the United Nations Ban Ki-moon launched the 2030 Agenda and the related seventeen Sustainable Development Goals (SDGs) (UN, 2015) with the aim of tackling the global economic, social, and environmental challenges and eradicating the extreme poverty around the world over the next fifteen years. These Goals, covering a much broader range of issues than their predecessors, the Millennium Development Goals (MDGs) (UN, 2000), aspire to be universal and therefore to be addressed to all countries and not only to the developing ones.

In December, in the 21st Conference of the Parties (COP21) held in Paris, 195 States reached the Climate Agreement by committing themselves to holding the increase in the global average temperature in 2100 well below 2°C above the pre-industrial levels and to pursuing efforts to limit the temperature increase to 1.5°C above the pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change (UNFCCC, 2015).

Climate change mitigation is one of the challenges taken into account in the SDGs, and in particular in SDG 13 ("*Take urgent action to combat climate change and its impacts*"). The Paris Agreement and SDG 13 represent the international strategic guidelines to struggle against climate change and its impacts. SDG 7 ("*Ensure access to affordable, reliable, sustainable and modern energy for all*") is a Sustainable Development Goal closely related to SDG 13. In fact, as will be discussed throughout the paper, the fulfilment of the SDG 7 targets, especially as far as renewable energies and energy efficiency measures are concerned, contributes to the achievement of SDG 13 and to the promotion of a sustainable growth.

In this perspective, this paper focuses on SDG 7 with a twofold objective. First, we aim at showing that SDG 7 can be considered as an enabling factor for the achievement of the other SDGs. Second, we discuss how technology innovation, especially in the electricity sector, which is fundamental in the SDG 7 perspective, can promote the achievement of a low-carbon energy system.

The paper is structured as follows. Section 2 describes the SDG 7 targets and analyzes the existing interactions between SDG 7 and the other SDGs by using a framework developed by the International Council for Science (Nilsson et al., 2016). Following the key findings of the analysis, as well as the relationships existing between SDG 7 and SDG 13 and vice versa, Section 3 focuses on the role of technology innovation in relation to the SDG 7 targets as a key means of implementation to decarbonize the electricity sector. Section 4 reports the final discussion and conclusions.

2. Mapping the interactions between SDG 7 and the other SDGs

2.1 SDG 7 and its targets

The analysis aims at understanding how each target of SDG 7 impacts on the targets of the other SDGs, with a special focus on the relationships existing between SDG 7 and SDG 13.

SDG 7 is structured in the following three main targets, all with the year 2030 as a time horizon:

- 7.1: Ensure universal access to affordable, reliable and modern energy services
- 7.2: Increase substantially the share of renewable energy in the global energy mix

- 7.3: Double the global rate of improvement in energy efficiency

SDG 7 calls for the access to "affordable, reliable, sustainable, and modern energy". The adjectives affordable, reliable, and modern are explicitly included in Target 7.1, while the remaining adjective (sustainable) is indirectly comprised in Target 7.2 and Target 7.3.

2.1.1   Target 7.1

Access to energy is key for the development of a society. Energy is an input to support the delivery of fundamental services such as education, health, and other social services (see Bonan et al., 2016 for a thorough literature review on this topic). The Industrial Revolution was made possible, among other factors, by the availability of relatively high quantities of energy at relatively low prices (Stern and Kander, 2012). The clear and unequivocal link between energy availability and development is summarized in Figure 1, which reports the relationship between the Human Development Index (HDI) and the energy use (Karekezi et al., 2012). The relationship is not linear: at low levels of HDI, a small increase in energy availability results in a significant growth in development, which is why energy availability is fundamental especially in developing countries.
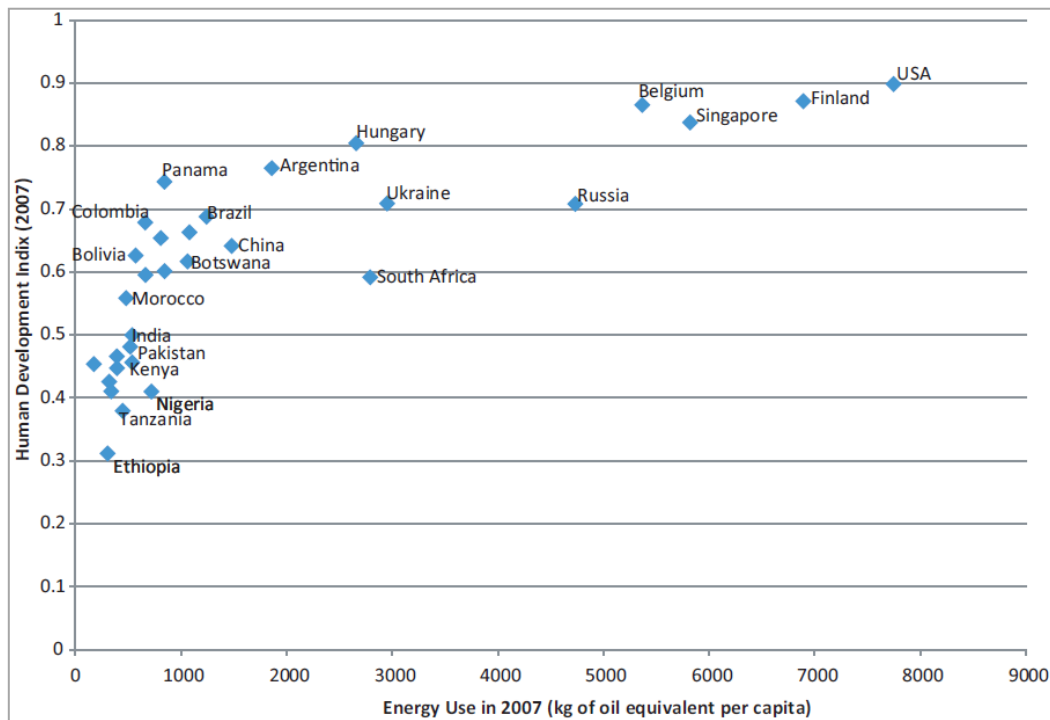
Figure 1 – Relationship between the Human Development Index and energy (Source: Karekezi et al., 2012).

Two indicators can be considered relevant to evaluate access to energy (Karekezi et al., 2012): the first is access to electricity, the second is referred to the use of solid fuels for household applications (essentially heating and cooking).

Electricity is indeed the most valuable form of energy: it is clean, it can be converted into other forms of energy with virtually 100%-efficiency, and it can be delivered over long distances, among other advantages.

Hence electricity is key in showing the level of development of a country. Figure 2 reports the relation between the HDI and electricity use (IAC, 2007). As one can see, the graph is very similar to Figure 1.
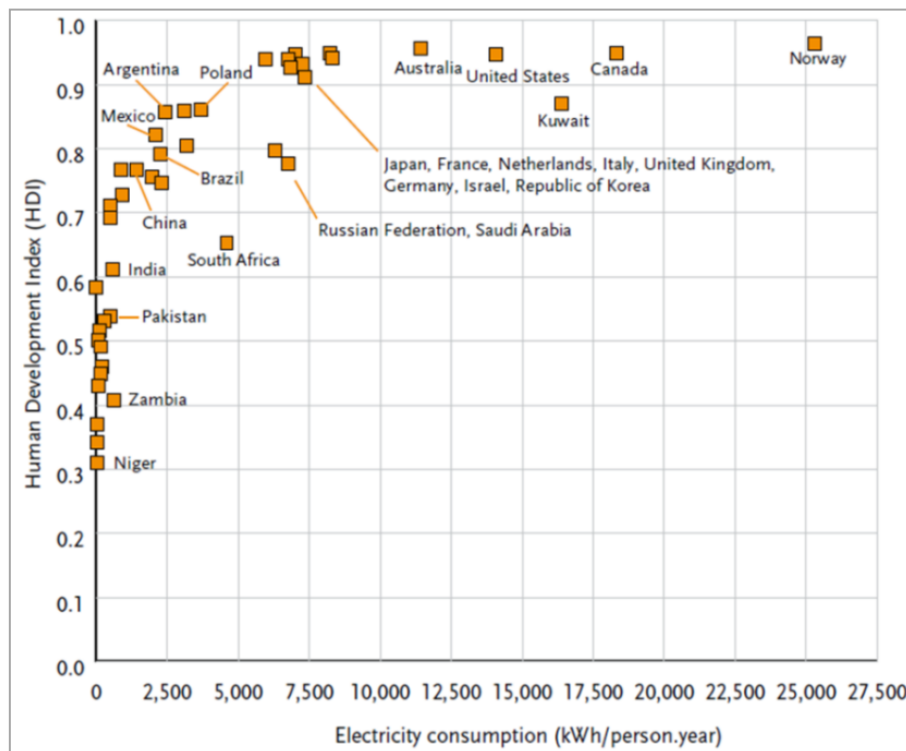

Figure 2 – Relationship between the Human Development Index and electricity (Source: IAC, 2007).

The second indicator is relevant because populations which have no or low access to modern forms of energies normally use solid fuels (biomass or charcoal) for heating and cooking purposes. These fuels are burnt in open devices inside houses, which is very inefficient from an energy point of view and, above all, is highly impacting from a health point of view, as the untreated emissions cause serious diseases at the breathing apparatus of the occupants (Smith et al., 2004, Dherani et al., 2008, Martin et al., 2011). Naturally, this does not happen in developed countries where gas (or electricity) is normally used for cooking purposes, while the use of solid fuels for heating purposes is limited to few complementary biomass-based appliances.

Figure 3 highlights the areas of the world with low electricity access and high rate use of solid fuels for cooking devices (Karekezi et al., 2012). It can be noted that the regions characterized by the latter point are mostly located in the warm areas of the world, making the use of energy for heating purposes relatively less relevant. The most critical areas of the world are Sub-Saharan Africa and South Asia, and East Asia as far as the use of solid fuels for cooking purposes is concerned. Not surprisingly, these are also the regions with the highest shares of poverty (Figure 4) (Karekezi et al., 2012).
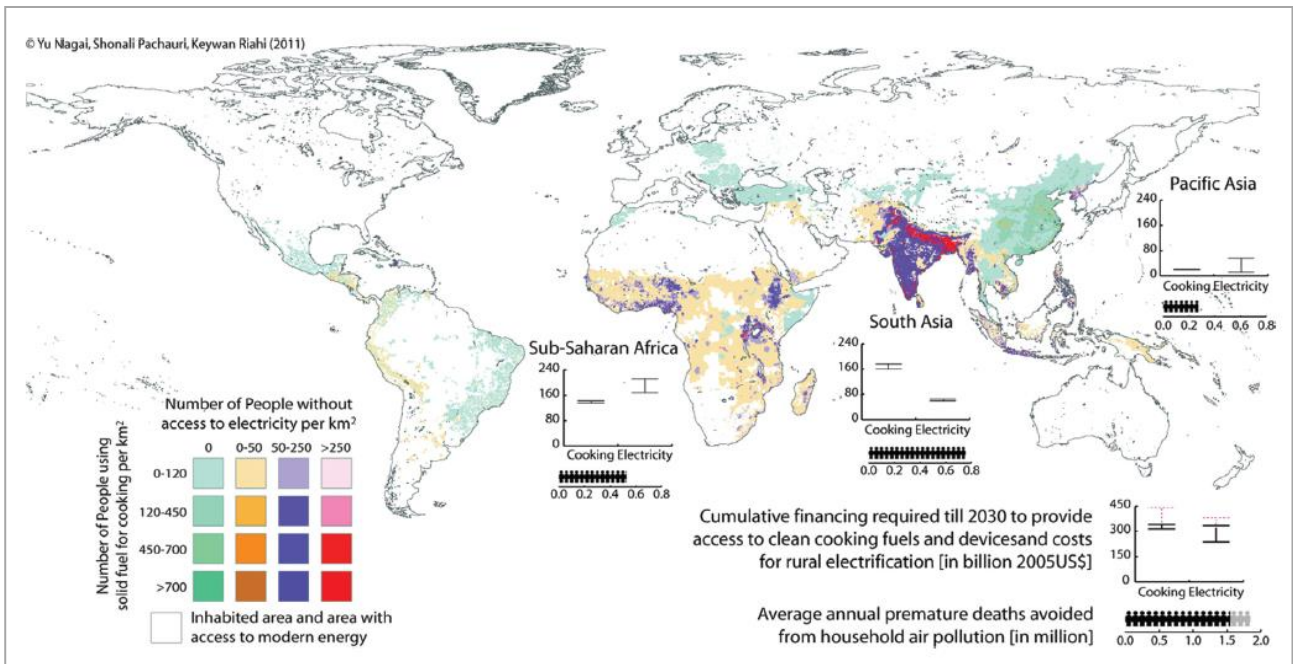
Figure 3 – Areas of the world with low electricity access and high rate use of solid fuels for cooking devices (Source: Karekezi et al., 2012).
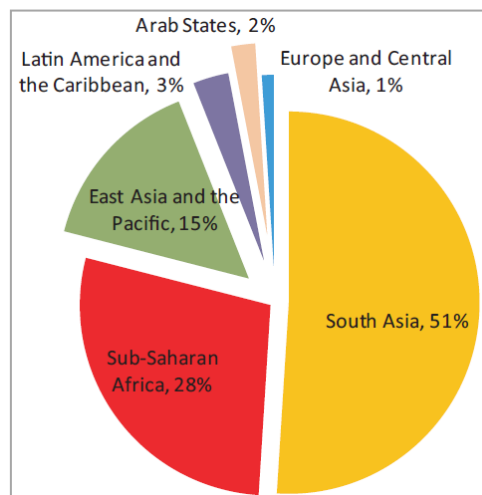
Figure 4 – World regions with the highest shares of poverty (Source: Karekezi et al., 2012).

2.1.2 Target 7.2

There is common agreement in considering renewable energies as a key factor in attaining sustainable, low-carbon energy mixes, especially in the electricity sector (Luderer et al., 2014). Obviously the concept of sustainability is very broad, but carbon mitigation may be considered the most relevant dimension when analyzing sustainability in energy technologies. For instance, the European Union has set the target of achieving a 27%-share of renewable energies over the total final energy consumption by the year 2030 (EC, 2014). The diffusion of renewable energies in future energy scenarios will be better discussed and described in Section 3.

2.1.3 Target 7.3

Similarly to Target 7.2, Target 7.3 can be associated to the adjective "sustainable" (and partly "affordable") of SDG 7. The objective is not only to provide energy services, but to achieve the same (and high) level of energy services with lower energy inputs, which is the concept of energy efficiency. Note that energy efficiency is not only advantageous for the supply side which provides energy services at lower costs, but also for energy consumers who will have access to more efficient energy and at lower prices.

Energy efficiency is not an easy concept to be dealt with in general terms, however. It is typically evaluated by referring to energy intensity, which is expressed as the ratio between energy and GDP, i.e. it expresses the quantity of energy necessary to produce one unit of income. An increase in energy efficiency is thus assessed as a reduction in energy intensity (Förster et al., 2013).

2.2 SDG 13 and its targets

As anticipated in the Introduction, this paper especially focuses on the relationship between SDG 7 and SDG 13. Hence, it is important to analyze the three main targets of SDG 13 as well:

- 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries
- 13.2: Integrate climate change measures into national policies, strategies and planning
- 13.3: Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning

2.2.1 Target 13.1

Target 13.1 refers to climate change adaptation. Adaptation means anticipating the adverse effects of climate change by taking appropriate actions to prevent or minimize the damage they can cause, or even taking advantage of opportunities that may arise. Examples of adaptation measures include building flood defenses and raising the levels of dykes; improving efficiency by, for instance, using scarce water resources more efficiently or adapting building codes to future climate conditions and extreme weather events; working on a more resilient agriculture production by developing drought-tolerant crops; choosing tree species and forestry practices less vulnerable to storms and fires (Bosello et al., 2013).

The IPCC's Fifth Assessment Report (IPCC, 2013) and the contribution by Working Group II (WGII AR5) constitutes the scientific base for the assessment of impacts, adaptation, and vulnerability, and evaluates how patterns of risks and potential benefits are shifting due to climate change.

2.2.2 Target 13.2

Target 13.2 calls for integrating climate change mitigation strategies both on adaptation and mitigation into national policies. This target makes implicit reference to the Intended Nationally Determined Contributions (INDCs) submitted by the UNFCCC Country Parties in the framework of the Paris Agreement (UNFCCC, 2015) that entered into force on November 4, 2016. The INDCs are national climate change mitigation plans

made by Parties intending to commit themselves, on a voluntary basis, to reducing their greenhouse gas (GHG) emissions. Being the energy sector responsible for about two thirds of global greenhouse gas emissions (IEA, 2015a), the INDCs are to be turned into concrete national energy plans, each according to countries' national resource endowments and financial capabilities. Most of the INDCs set adaptation strategies as well. Any national mitigation policy needs to encounter both mitigation and adaptation strategies as well as the water-food-energy nexus approach in an integrated manner (Cervigni et al., 2015).

2.2.3 Target 13.3

Target 13.3 is the most qualitative of the three although not the least relevant. Indeed, it calls for improving education and raising awareness and institutional capacity towards climate change mitigation and adaptation actions. Because it refers explicitly to education, Target 13.3 is correlated with SDG 4 Quality Education. For this reason it will not be further analyzed.

2.3   Scope and Methodology

The 2030 Agenda is the first international agenda for sustainable development whose Goals and Targets are closely integrated. The integration can be assessed at two levels: the integration of sustainability within the SDGs (OECD, 2015) and the multiple interactions existing among Goals and Targets. Regarding the first level, the SDGs adopt an integrated vision of sustainability in its dimensions allowing us to understand the complexity of current issues and the links among different topics: for instance, SDG 2 ("*End hunger, achieve food security and improved nutrition, and promote sustainable agriculture*") contains targets related to social (e.g. malnutrition and vulnerability), economic (e.g. agricultural productivity and financial services), and environmental dimensions (e.g. genetic diversity and climate resilience). In relation to the second level, the interactions existing among Goals and Targets help to view the SDGs within a network, with links among Goals through the respective Targets. In this perspective, an analysis of the interactions among Goals is essential for supporting policy-makers in adopting an integrated approach in their policy definition and investment decisions.

In this analysis we have neglected SDG 17 since it refers to the means of implementation which are addressed to the whole set of the SDGs. Accordingly, we also have discarded the Targets of each Goal (i.e. 7.a, 8.a) that are referred to the means of implementation. This is not to underestimate the importance of the means of implementation, but the analysis is focused on thematic areas underlined by the SDGs. This restriction leaves us with 107 Targets under 15 Goals (excluding SDG 7). The nature of interactions between SDG 7 and the other SDGs has been identified by using the framework developed by Nilsson et al. (2016) (Figure 5) which allows qualitatively scoring the interactions and identifying their nature. The seven-point ordinal scale in Figure 5 highlights the explanation for each value indicating how a specific type of interaction occurs. For instance, an indivisible interaction exists when one Goal or Target is inextricably linked to the achievement of another Goal or Target: achieving Target 5.1 ("*End all forms of discrimination against all women and girls everywhere*") would in itself lead to the achievement of Target 5.5 "*Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life*". Instead, a reinforcing interaction occurs when one Goal or Target directly create conditions that lead to the achievement of another Goal or Target. For example

strengthening resilience and adaptive capacity to climate-related hazards (Target 13.1) will directly reduce losses caused by disasters (Target 11.5).

Figure 5 – Goals scoring (Source: Nilsson et al., 2016).

The score for each SDG in relationship with SDG 7 is evaluated by summing all the scores of the relevant Targets, divided by the number of Targets. This is done in order to obtain an average value independent of the number of Targets, which allows a comparison across SDGs. Thus we obtain a scale between -3 and 3, coherent with the scale described in Figure 5. The procedure is repeated for the three SDG 7 main Targets, then an average value is calculated in order to obtain an aggregated value for the whole SDG 7 in relationship with the other SDGs. The same methodology has been repeated for SDG 13 in order to understand how this Goal relates to SDG 7, both at aggregate and disaggregate level.

In order to cover the whole spectrum of continuous values, we assume that the interaction name associated to one specific score is actually valid for a band whose mean value is the specific score. Thus values between -0.5 and 0.5 are considered consistent (mean value: 0), between 0.5 and 1.5 they are enabling (mean value: 1), between 1.5 and 2.5 they are reinforcing (mean value: 2), and above 2.5 they are indivisible (mean value: 3). The same applies to the negative values.

In order to understand the existing trade-off between SDG 7 and the other SDGs, the research also studies the directionality of each interaction in terms of unidirectionality or bidirectionality (Figure 6).
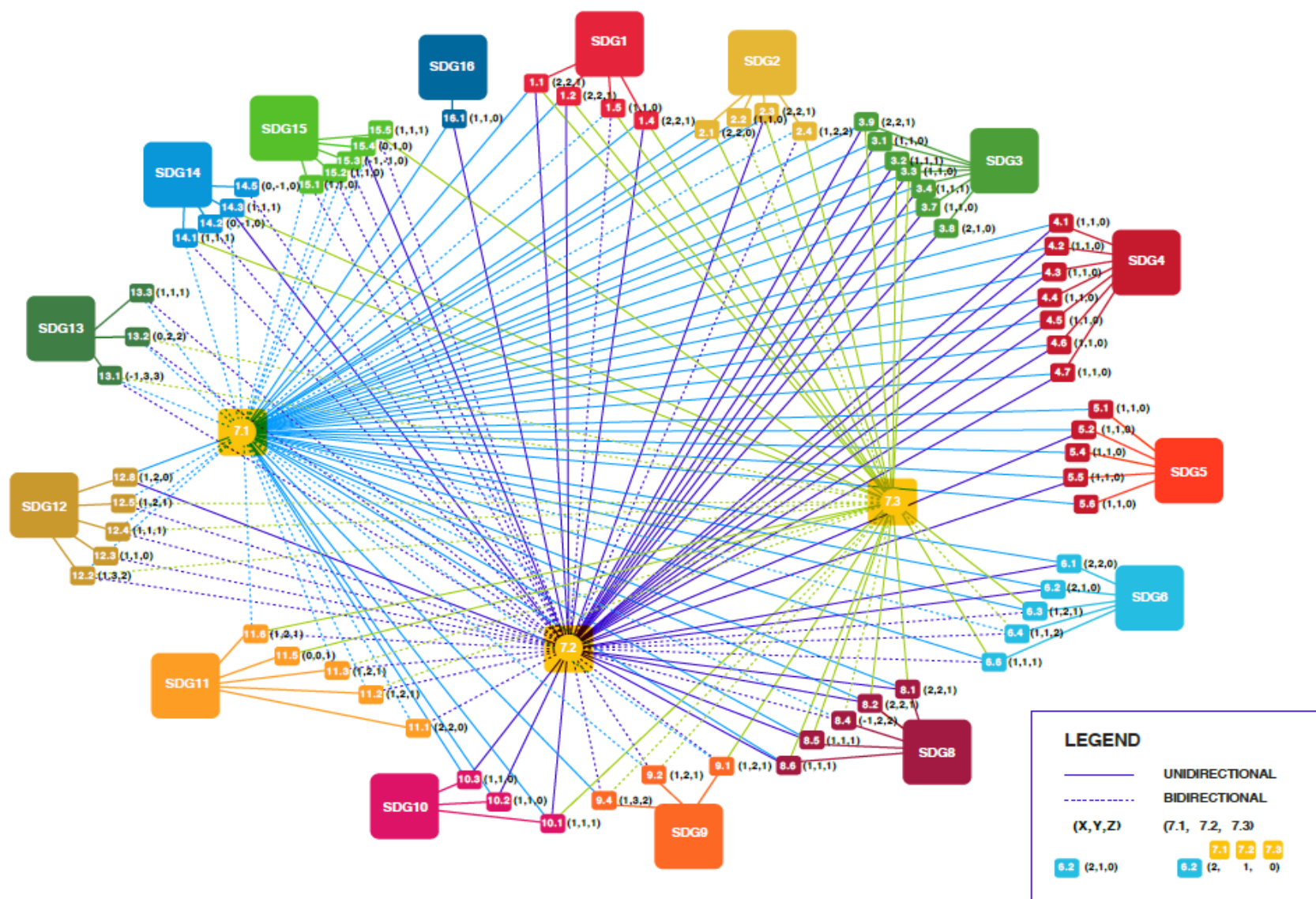
Figure 6 – Interactions between SDG 7 and the other SDGs.

The interaction is unidirectional when A (in our case SDG 7) impacts B and not vice versa: for instance, energy is crucial for providing electricity for hospitals and clinics but these infrastructures are not necessary for providing energy. With bidirectionality we mean that both A impacts B and B impacts A: for instance, ensuring universal access to energy may limit the achievement of Target 13.1, which in turn can limit the option for access to energy. As bidirectionality can help to analyze the existing trade-off between SDG 7 and the other SDGs, it would be useful to identify through a further analysis the interactions among the Goals in terms of means of implementation: for instance, although no Target of SDG 7 impacts on Target 13.a ("*Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible*"), this Target is fundamental for raising investments in modern energy services, renewable energies and energy efficiency.

Finally, it is important to specify that an analysis of interactions should take into account the dimension of reversibility in order to understand which Goals cannot be achieved if the world fails in pursuing SDG 7: for instance, failing on SDG 7 can generate irreversible consequences on the mitigation and adaptation of climate change. The awareness of these interactions could thus support policy-makers in understanding how important SDG 7 is in relation to the other Goals and prioritizing investment decisions for those for which an irreversible correlation may exist.

2.4   Energy as a driver for development

The main result of this analysis is that energy is a cross-cutting agent for tackling the economic, social and environmental dimensions underlined by the SDGs. Energy is a key driver for social inclusion, economic development (as we have already discussed in Section 2.1.1) and environmental protection. From a social point of view, the lack of access to energy is one of the biggest constraints to the main scope of Agenda 2030 that lies in the eradication of extreme poverty (SDG 1). Energy access contributes to improve the quality of life since it provides better health-care services and a greater life expectancy (SDG 3), and the possibility to have access to quality education (SDG 4). Moreover, the use of electricity allows replacing or facilitating time-consuming rural activities, especially for women and children (SDG 5), allowing them to develop their human and social potential empowering their role within their households and society. In addition, energy provides access to electricity, the use of less polluting systems for cooking and heating (SDG 2), it promotes industrialization (SDG 9), telecommunication services (SDG 9), and it is critical for the supply of safe and drinking water (SDG 6) as well as for the development of inclusive human settlements (SDG 11). In relation to the economic dimension, it is difficult to imagine an economic development without access to modern energy that is a key factor for the majority of products and services enabling the development of companies which, in turn, allows the creation of jobs (SDG 8). Lastly, from the environmental perspective, if produced in a sustainable way and/or from sustainable sources, energy is crucial to mitigate the risk of climate change (SDG 13) and limit the use of unsustainable firewood reducing deforestation and soil degradation (SDG 15).

At an aggregate level (Figure 7), SDG 7 can be considered as an enabling factor for sustainable development since the value of correlation is between 0.5 and 1.5 for eleven SDGs out of fifteen. In terms of intensity value of interactions, SDG 7 shows the strongest correlation with respect to SDG 13, followed by SDG 1, SDG 9, SDG 6, and SDG 2. The lowest interactions are found with SDG 14, SDG 15 and SDG 16. Results also

highlight the strong correlation existing between energy, water, and food that is analyzed by the water-food-energy nexus approach.
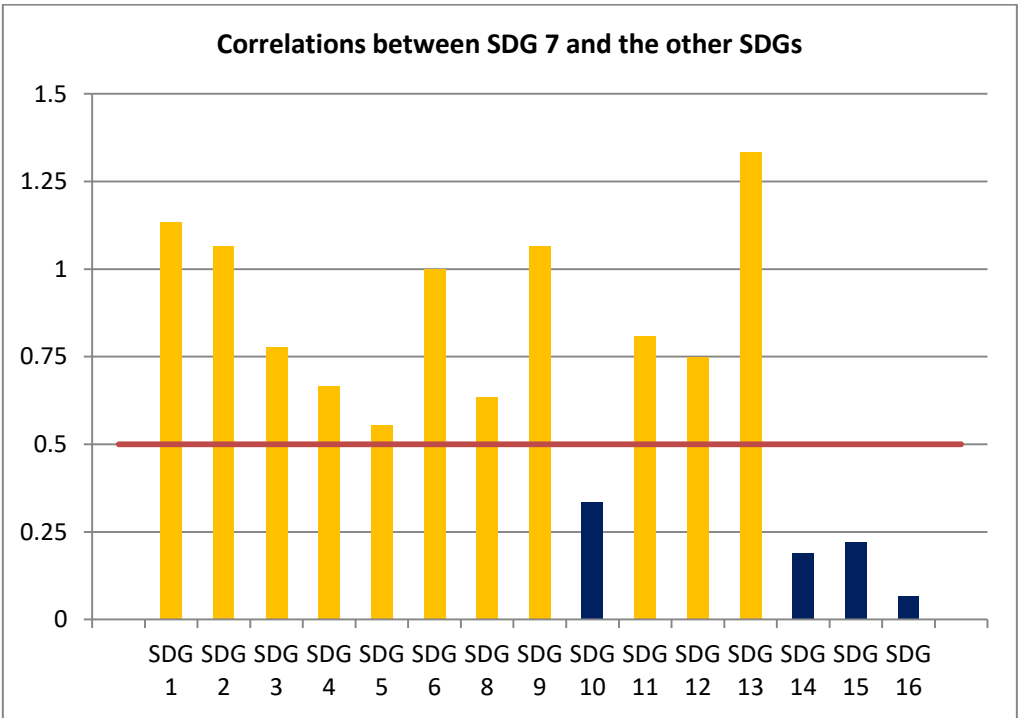

Figure 7 – Values of correlations at aggregate level (values below 0.5 indicate a consistent relationship, highlighted in blue; values from 0.5 to 1.5 indicate an enabling relationship, highlighted in yellow).

2.4.1 The interactions from SDG 7 to SDG 13

Figure 8 shows that SDG 7, at aggregate level, acts as enabling factor for the achievement of SDG 13 with an average intensity value of about 1.3.

However, to really understand the relationship between SDG 7 and SDG 13 we have to analyze the interactions at disaggregate level, i.e. considering how the three single Targets of SDG 7 relate to the three single Targets of SDG 13.

The analysis shows that Target 7.1 is consistent in relationship to SDG 13 with an average intensity value of 0, which results from the scores that Target 7.1 records in relation to the three targets of SDG 13 under analysis. Table 1 reports that Target 7.1 is constraining in relationship with Target 13.1 since the first Target of SDG 7 does not require that universal access to energy go through sustainable energy services, but only through affordable, reliable, and modern services. Thus, if we take into consideration that not all forms of modern energy are sustainable, the achievement of Target 7.1 could limit the options for the achievement of climate mitigation and adaptation strategies failing on strengthening resilience to climate change-related events. A further point that suggests this kind of relationship is that the world cannot immediately abandon fossil fuels, which means that these energy sources will be a part of the energy landscape for several decades into the future (WEF, 2015). Moreover, if universal access to modern energy is achieved by 2030, global energy-related CO_2 emissions will rise by 0.7% (IEA, 2011a), a value that suggests the absence of a positive relation between Target 7.1 and Target 13.1.
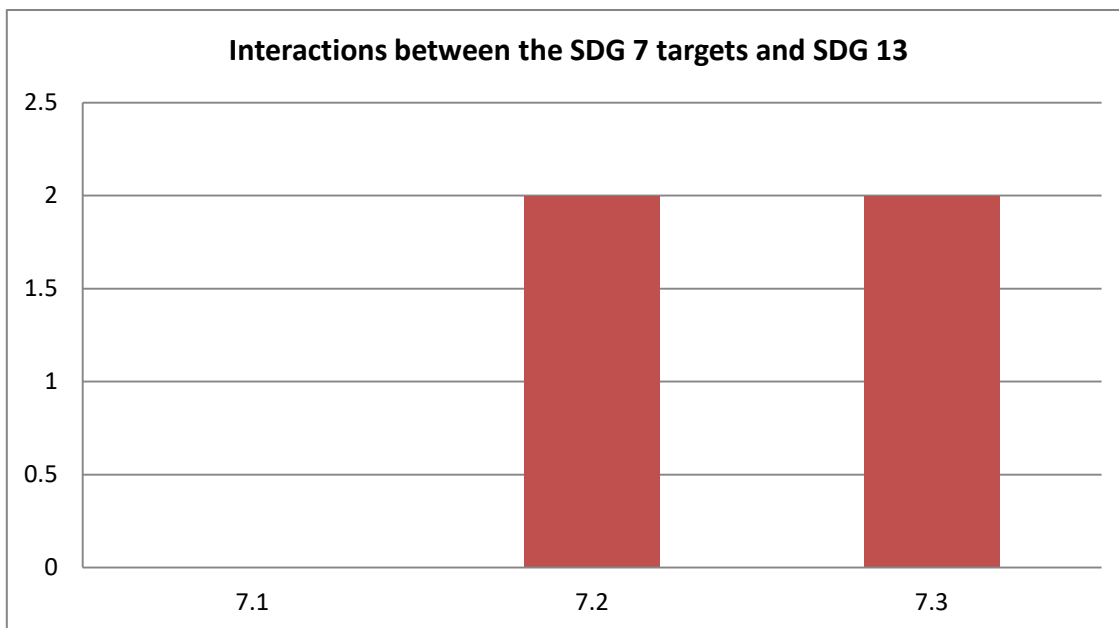
Figure 8 – Values of correlations between SDG 7 and SDG 13 at disaggregate level (between 1.5 and 2.5 indicate a reinforcing relationship, highlighted in red; for Target 7.1, the value is perfectly 0).

		SDG 7		
		7.1	**7.2**	**7.3**
Goal 13: Take urgent action to combat climate change and its impacts	**13.1** Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	-1	3	3
	13.2 Integrate climate change measures into national policies, strategies and planning	0	2	2
	13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	1	1	1
	Total	0	6	6

Table 1 – Values of interactions from SDG 7 to SDG 13.

On the other hand, Target 7.2 and Target 7.3 have a reinforcing relationship with climate change: the average values of intensity is equal to 2. Table 1 highlights the relationship existing between Target 7.2 and Target 7.3 with Target 13.1 that underlines the critical role of renewable energies as well as energy efficiency measures in reducing GHG emissions. Indeed, in terms of Target 7.2, investments in renewable energy technologies will allow saving about 37 Gt of CO_2 from 2015 to 2040 in the 2°C-compatible scenario[1] (IEA 2015b), which suggests an interaction of indivisible nature (+3) with Target 13.1. Moreover, in 2012 an estimated amount of 3.1 Gt of CO_2 emissions was avoided through renewable energy use, compared to the emissions that would otherwise have occurred from fossil fuel-based power. Without renewable-based power generation, total emissions from the power sector would have been 20% higher (REN21, 2015).

An indivisible relation also exists between Target 7.3 and Target 13.1. In the 2°C scenario, energy efficiency improvements in end uses make the largest contribution (38%) to global emissions reductions through

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[1] This scenario is defined as "450" as it defines an energy pathway consistent with the goal of limiting the global temperature increase to 2°C by limiting concentration of GHGs in the atmosphere to 450 ppm of CO_2 (see IEA, 2011b).

2050 (IEA, 2016). Moreover energy efficiency investments since 1990 have helped to reduce IEA countries emissions to below 1996 levels. In 2014 alone, 870 Mt CO_2 were avoided (Figure 9). Energy efficiency is indeed an important tool for carbon mitigation (by reducing greenhouse gas emissions from energy production and consumption in order to avoid climate change) and for climate adaptation: energy efficiency can help to address increased energy demand and constrained supply due to regional weather shifts and greater temperature volatility, such as increased building cooling needs and lowered efficiency of thermal generating plants.
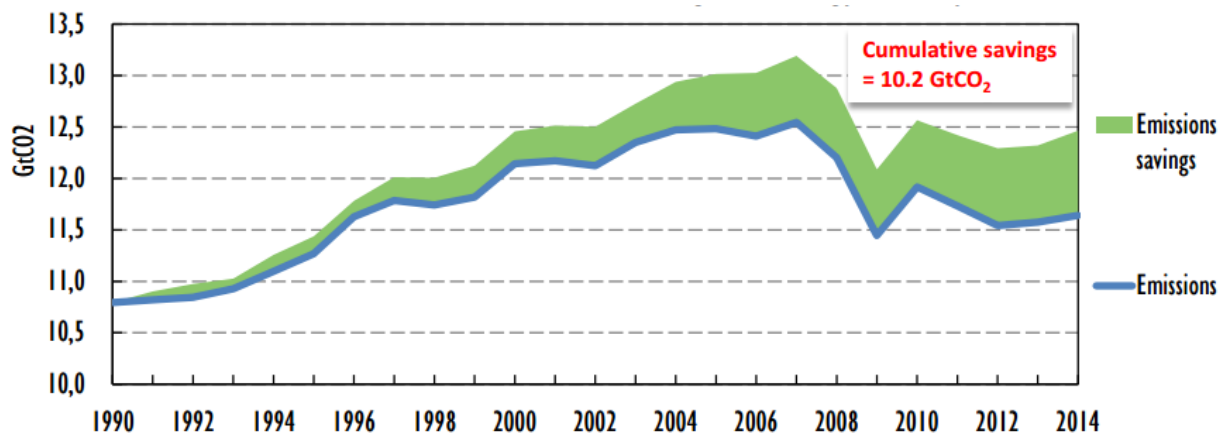

Figure 9 – IEA emissions from fossil fuel combustion and emissions savings from energy efficiency investments since 1990 (Source: IEA, 2015b).

Target 7.1 does not show any significant positive or negative relationships with Target 13.2 since the latter aims at developing policies that allow the reduction of GHG emissions and because, as already explained, climate impacts of achieving universal access to modern energy technologies might be negative, should access be provided from unsustainable energy sources.

Targets 7.2 and 7.3 reinforce the integration of climate change measures into national policies, instead. The climate benefits resulting from renewable energy and energy efficiency technologies act as a driver for the development of enhanced climate-related policies (IEA, 2015c). Also the market potential in terms of renewable capacity to 2020, which is estimated around USD 230 billion annually, and investments worldwide in energy efficiency which are envisioned to keep growing despite lower oil and gas prices (IEA, 2015b), represent relevant factors that can induce policy makers to favor the deployment of sustainable energies systems within the market through dedicated policies. In this perspective policies can be seen as a result of a clear awareness by local governments and institutions about the environmental, social and economic benefits resulting from the adoption of more sustainable energy systems. There is also another important reason for the justification of climate-related policies to be considered: a full and effective deployment of renewable energies and energy efficiency is constrained by a variety of barriers (costs and prices, legal and regulatory, institutional, etc.) that put renewable energy at an economic, regulatory, or institutional disadvantage relative to other forms of energy supply. This means that a full achievement of Targets 7.2 and 7.3 is not possible without policies that can help to overcome market failures of new technologies, thus suggesting that the achievement of these Targets positively trigger the adoption of climate policies.

Finally, in relation to Target 13.3, the three main Targets of SDG 7 can create the conditions that lead to greater awareness on climate change mitigation, adaptation, impact reduction, and early warning by showcasing the climate benefits resulting from the deployment of sustainable modern energy services as well as renewable and energy efficiency technologies, which indeed are means for adaptation and mitigation strategies.

2.4.2 The interactions from SDG 13 to SDG 7

By applying the same methodology used for the analysis of interactions existing between SDG 7 and the other SDGs, it is possible to quantify the relationships between SDG 13 and SDG 7. The analysis shows that SDG 13 enables the achievement of SDG 7 with an average intensity value of 1.3.

However, also for these relationships the analysis shows different and interesting results at disaggregate level (Figure 10).

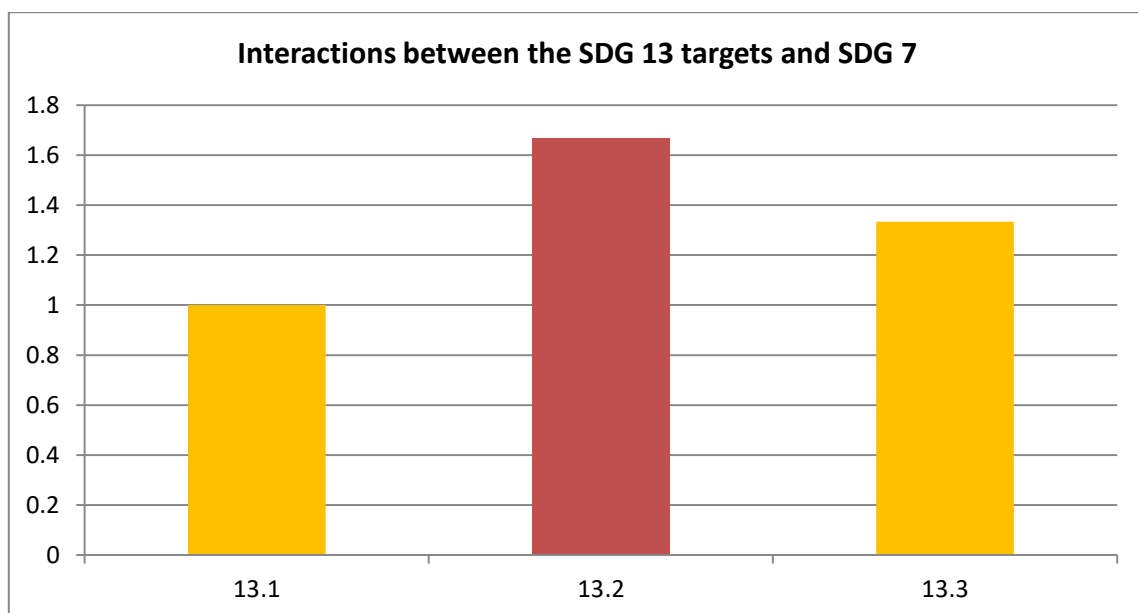**Interactions between the SDG 13 targets and SDG 7**

Figure 10 – Values of correlations from SDG 13 to SDG 7 at disaggregate level (values between 0.5 and 1.5 indicate an enabling relationship, highlighted in yellow; values between 1.5 and 2.5 indicate a reinforcing relationship, highlighted in red).

First of all, Target 13.1. is enabling in relation to SDG 7. Table 2 highlights that Target 13.1 is constraining with Target 7.1 since the objective of resilience and adaptive capacity to climate change can limit the options as how to pursue energy access, especially because Target 7.1 does not mention sustainable energy services to reach its goal. Instead, Target 13.1 can create conditions that lead to the achievement of Target 7.2 and Target 7.3, since renewable energies and energy efficiency measures represent crucial means for mitigating climate change. According to the World Meteorological Organization (WMO, 2016) the first decade of the 21st century saw 3,496 natural disasters from floods, storms, droughts, and heat waves which may have been influenced by climate change. Thus, since climate change can be one of the

causes of natural disasters, the deployment of renewable energies and energy efficiency measures can be boosted with the aim of strengthening resilience and adaptive capacity to climate-related events.

		SDG 13		
		13.1	13.2	13.3
Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all	**7.1.** By 2030, ensure universal access to affordable, reliable and modern energy services	-1	1	1
	7.2 By 2030, increase substantially the share of renewable energy in the global energy	2	2	2
	7.3. By 2030, double the global rate of improvement in energy efficiency	2	2	1
	Total	3	5	4

Table 2 – Values of interactions from SDG 13 to SDG 7.

Secondly, Target 13.2 reinforces the achievement of SDG 7, especially Targets 7.2 and 7.3. According to a research conducted by the World Future Council (Stephan et al., 2016) on the role of renewable energy in the Intended Nationally Determined Contributions, 142 INDCs out of the 158 analyzed mention renewable energy within their mitigation strategy, 108 name the increase of renewable energy as one of their mitigation actions, and 75 include quantified goals. Thus, if INDCs are fully implemented, in the next years we will see a substantial growth of renewable energies deployment creating the conditions for the achievement of Target 7.2. This is true for Target 7.3 as well, since several INDCs highlight actions to achieve energy efficiency in terms of: energy efficiency standards; modernization of energy generation and transmission infrastructure; promotion of smart grids; efficiency improvements in industrial processes and the building sector; energy conservation standards. In detail, out of the 163 INDCs submitted, 143 mention energy efficiency as a means to implement adaptation strategies (WMO, 2016). Target 13.2 is consistent with Target 7.1, since it does not present any kind of relation with universal access to energy.

Finally, in relation to Target 13.3, activities and investments toward educational programs on climate change issues can enable the achievement of the three main Targets of SDG 7. Education and awareness raising through dedicated communication and dialogue initiatives (IPCC, 2012) can indeed create a favorable (or, according to the terminology used above, enabling) environment for the deployment of renewable energies presenting them as one means for mitigation and adaptation strategies. Also in relation to energy efficiency, educational initiatives can enable its deployment since energy efficiency is an important tool for climate mitigation and adaptation, i.e. preservation of natural resources. The same consideration applies to Target 7.1, since educational initiatives have the power to raise awareness toward the adoption of modern and more sustainable services, especially in developing countries.

The analysis shows that according to the adopted methodology, SDG 7 enables the achievement of SDG 13 with an average intensity value of 1.3 and, at the same time, it underlines how the struggle against climate change is positively driven by the deployment of sustainable energy services given the average intensity value of 1.4. SDG 7, through Targets 7.2 and 7.3, plays a crucial role for the achievement of SDG 13 and carbon mitigation targets given an indivisible relation existing among them. Moreover Target 13.2 reinforces the achievement of Targets 7.2 and 7.3 since the integration of climate change measures into national policies, i.e. the INDCs, positively contributes to the deployment of renewable energies and energy efficiency measures.

3. Technology innovation in the next decades: The power sector and renewable technologies

3.1 Mitigation pathways and compliance with SDG 7

As discussed in the Introduction, carbon mitigation has been identified as a vital target for the coming decades. The transition towards a low-carbon economy will entail deep changes in the economic, social, climatic, and environmental dimensions. Integrated Assessment Models (IAM) are widely adopted tools in the scientific community to explore the interaction between these dimensions (Clarke and Kejun, 2014). In this work, we have used the WITCH model to develop scenarios consistent with the ambitious 2°C mitigation target, in order to frame the macro-economic and energy prospects which will serve as a background for the following analysis on the importance of technology innovation.

WITCH (World Induced Technical Change Hybrid) is an integrated assessment model aimed at developing socio-economic trends in the 21st century with respect to climate change and its relevant impacts and constraints. It is defined as a hybrid model because it combines an aggregated macro-economic model with a more disaggregated description of the energy sector. WITCH scenarios should not be considered as predictions, but rather projections: the aggregated economic model is an optimal growth mitigation model which maximizes each region's welfare in order to yield the economically optimal solution under a set of constraints, the most important of which is the carbon mitigation policy, if any. The model is defined on a global scale: world countries are grouped into thirteen regions, defined on the basis of geographical or economic coherence. One distinguishing feature is the endogenous modeling of technological change in energy efficiency and specific clean technologies. A more detailed description of the model can be found in Emmerling et al. (2016) or in the web, see www.witchmodel.org.

Figure 11 shows the evolution of greenhouse gas emissions from 2005 to 2100 in the baseline and in the 2°C policy scenarios. The baseline case (also identified as BaU, Business-as-Usual) is a benchmark scenario where no mitigation policies are implemented. The 2°C scenario is obtained by applying a carbon tax on GHG emissions starting from 2020. It can be easily seen that the achievement of ambitious mitigation targets implies a complete phase-out of GHG emissions over time.[2]

How can the zero emission scenario be achieved? The mitigation target requires major changes in the energy landscape. Overall, carbon mitigation is likely to take place through an electrification of the energy sector and a simultaneous decarbonization of the electricity sector (Wei et al., 2013 and Capros et al., 2012). This is likely to happen because the power generation sector features many effective and efficient decarbonization options (both from a technical and an economic point of view), while the same hardly applies to other sectors (industrial, residential, transport). Figure 12 reports the evolution over time of the global share of the electricity sector over the total secondary energy (left), and the global share of low-carbon technologies (renewables, nuclear, and CCS) over the total electricity generation (right) as obtained in the WITCH scenarios.

The graph of the left shows that the share of electricity over the total secondary energy grows over time in both the explored scenarios. However, in the baseline case this growth substantially follows the historical patterns, while in the mitigation scenario the growth accelerates after the initial decades, leading to a

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[2] Note that zero net emissions do not necessarily correspond to no emissions in absolute terms, but they might correspond to an equilibrium between residual positive emissions and negative emissions, the latter being possible thanks to several techniques such as afforestation and reforestation, implementation of biomass-fed CCS (Carbon Capture & Storage) plants, direct air capture, and others.

scenario where electricity dominates the energy sector by the end of the century. In terms of technologies, the graph on the right clearly shows that low-carbon technologies (which in 2015 accounted for about one third of the total, especially thanks to nuclear and hydro) mildly grow over the century in the baseline case, while fossil-fueled plants (without CCS) are completely phased out within mid-century in the mitigation scenario.
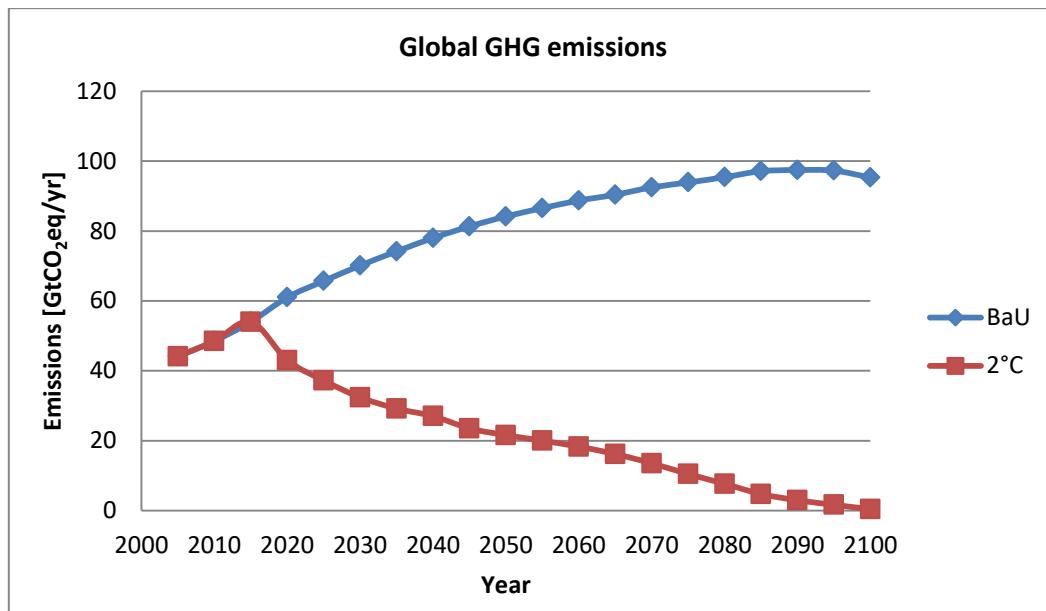

Figure 11 – Global GHG emissions in the WITCH scenarios.
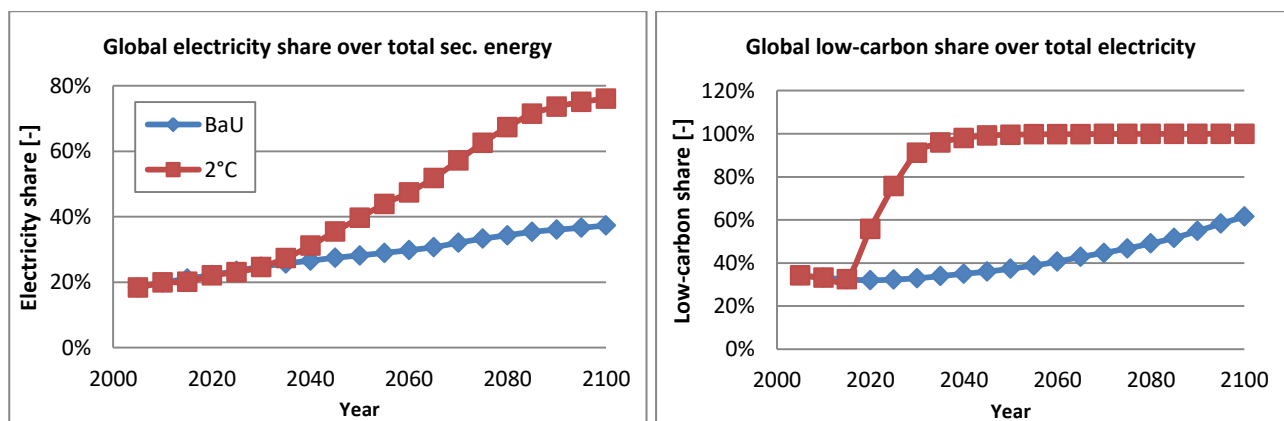

Figure 12 – Global electricity share over total secondary energy (left) and low-carbon generation share over total electricity (right) in the WITCH scenarios.

Having outlined the overall scenario context, we will now show that the mitigation scenario is compatible with the SDG 7 Targets, thus confirming also from a modeling point of view the positive correlation between SDG 7 and SDG 13 qualitatively highlighted in Section 2.

The increase in the electricity share over the total energy demand is clearly in line with Target 7.1, since electricity is the most valuable form of energy, which allows the delivery of a great number of modern services, as already discussed in Section 2. In order to stress the concept, Figure 13 reports the absolute

electricity demand in the WITCH scenarios, highlighting the different behavior in OECD and non-OECD countries. Results are quite similar in the two policy scenarios (but note that the total secondary energy is much lower in the 2°C scenario than in the BaU scenario), but above all the growth in non-OECD countries is much higher than in the OECD ones (in the 2°C scenario, the average yearly growth in the 21st century is 2.7% in the non-OECD regions against 1.5% in the OECD regions).
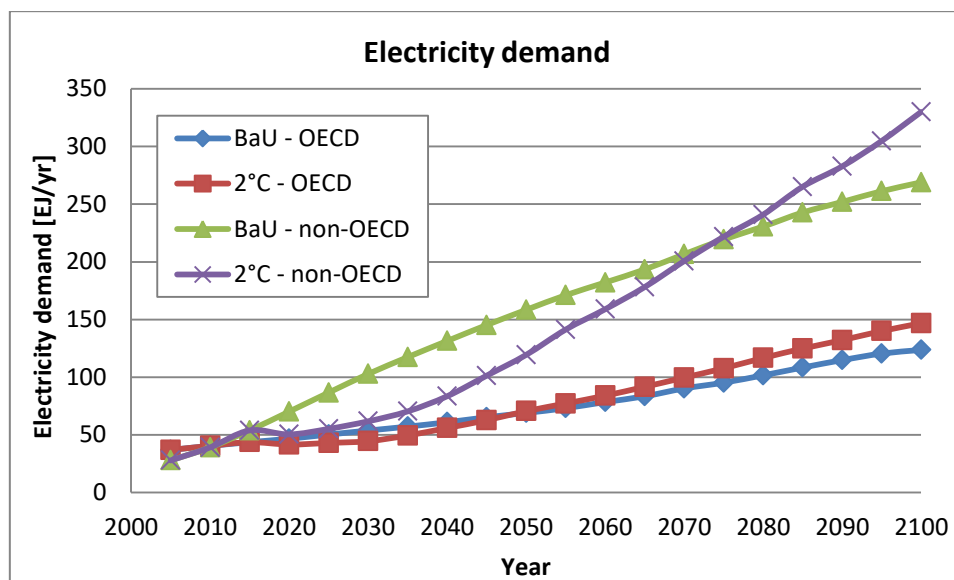

Figure 13 – Electricity demand in OECD and non-OECD countries in the WITCH scenarios.

The compliance with Target 7.2 is already evident from Figure 12 (right). However, that graph does include all low-carbon technologies, i.e. CCS and nuclear in addition to renewables. Figure 14 thus specifically highlights the global share of renewables in the electricity mix. Indeed, renewables have by far the lion's share among the low-carbon technologies, thus the graph substantially replicates Figure 12.
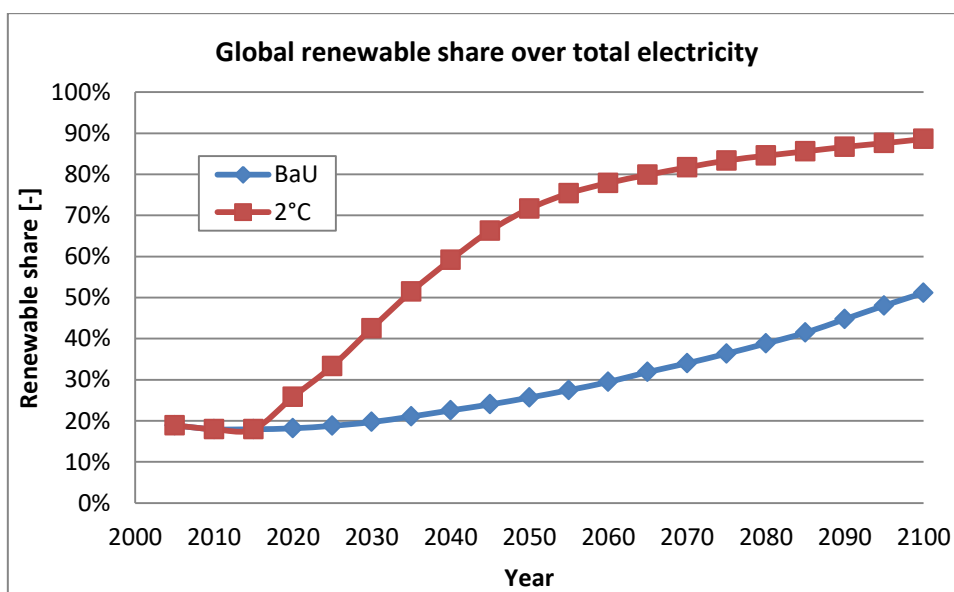

Figure 14 – Global renewable generation share over total electricity in the WITCH scenarios.

Finally, the mitigation scenario as depicted by WITCH is in line with Target 7.3 as well. In this work we assess the increase in energy efficiency as a decrease in energy intensity, following the modeling rationale described in Section 2.1.3. Figure 15 reports the global yearly decrease rate of energy intensity (calculated as the ratio between primary energy and GDP PPP[3]). The average yearly rate from 2005 to 2015 was about 0.6%. From 2020 to 2030 it would be 2% in the mitigation scenario, and 1.3% in the BaU. Thus, both results would be in line with the Target, even if the figures in the mitigation scenario are partly biased by the drastic fall which is found in correspondence of the beginning of the policy implementation in 2020. On average, from 2005 to 2030 the energy intensity decreases by 1.3% in the baseline case and 2.7% in the policy case, i.e. about twice as much as the former, perfectly in line with the Target.
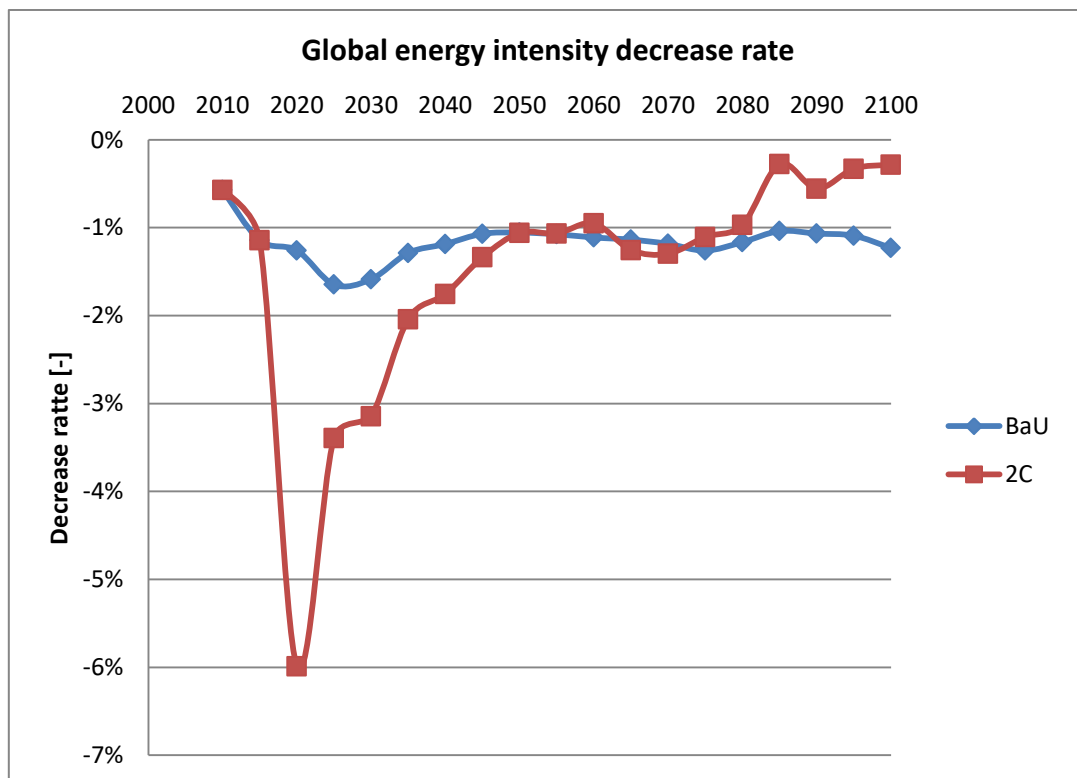

Figure 15 – Global energy intensity decrease rate in the WITCH scenarios.

3.2 The role of technology innovation

All the main changes in the energy sector described in Section 3.1 are possible only via deep transformations from different points of view: technical, social, economic, and regulatory. In this Section we focus on the role of technology innovation in making those changes possible, especially in the perspective of the three SDG 7 Targets. Again, the analysis is carried out adopting WITCH as a tool to explore future scenarios. WITCH is an integrated assessment model, so the level of technological detail is quite limited, nonetheless some interesting considerations can be derived.

Target 7.1 is indeed the Target where the role of technology innovation is more difficult to assess, especially in the WITCH perspective. Actually, the access to modern forms of energy does not seem primarily a matter of technology innovation, but it seems to be more related to financial, regulatory, social,

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[3] Purchasing Power Parity.

and political issues. Theoretically, energy access could be guaranteed by old, inefficient and highly impacting technologies. The real issue is to promote the actual realization of the needed infrastructure.

In Target 7.2 the role of technology innovation is instead clear. Renewable technologies have been characterized by huge technical improvements in the last decades and further improvements are required for the future. Innovation is twofold: it might be purely technical (e.g. better materials which allow higher conversion efficiencies) or economic (e.g. obtaining the same performance with lower costs). Technology innovation in WITCH is modeled more in the light of the second dimension, and in particular it is described through learning-by-researching and/or learning-by-doing. According to these schemes, the investment costs decrease over time thanks to dedicated investments in R&D and to the experience gained through the progressive plant deployment over time, respectively (see De Cian et al., 2016, and Emmerling et al., 2016 for details). In our model, renewable energies (in particular wind and solar) feature learning-by-doing only. Figure 16 shows the investment cost evolution of PV plants in the two explored scenarios. The cost fall is remarkable in both scenarios, even if it is more marked in the policy scenario, as the mitigation requirement leads to a greater PV deployment. Technology innovation is not explicitly modeled, but it is the condition that makes the shown behavior possible.
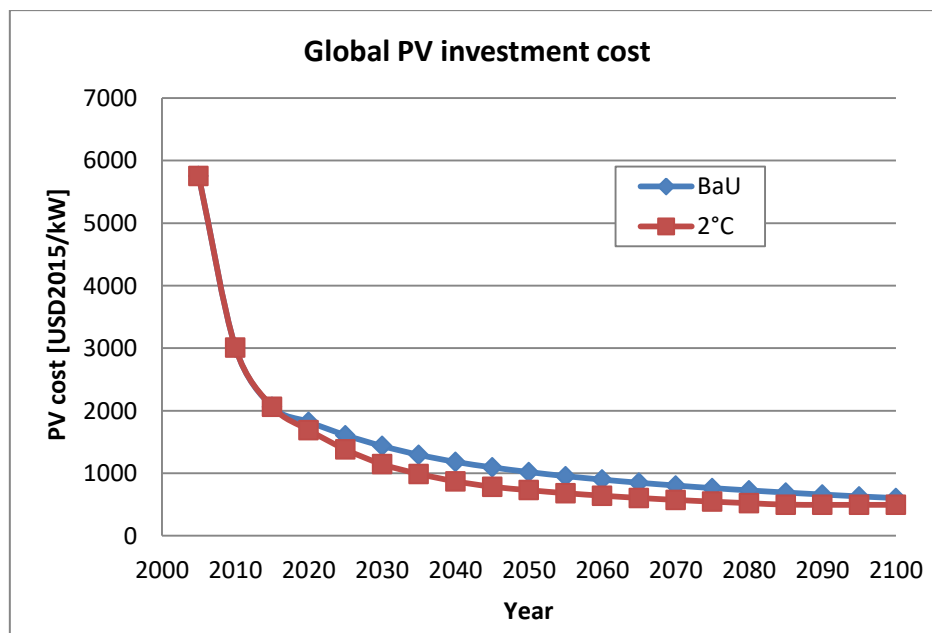

Figure 16 – Global PV investment cost in the WITCH scenarios.

Technology innovation is also relevant for Target 7.3. In fact, technology innovation promotes the energy efficiency improvements, or the decrease in energy intensity. In WITCH we endogenously model the investments in the broad R&D sector aimed at fostering energy efficiency, i.e. at decreasing energy intensity, i.e. at obtaining the same final economic output with a lower energy input. Figure 17 reports the global yearly R&D investments in energy efficiency. Unsurprisingly, these investments increase over time, and in particular the growth is much higher in the 2°C scenario than in the BaU scenario, which stresses the importance of energy efficiency improvements under a sustainable carbon mitigation scenario.
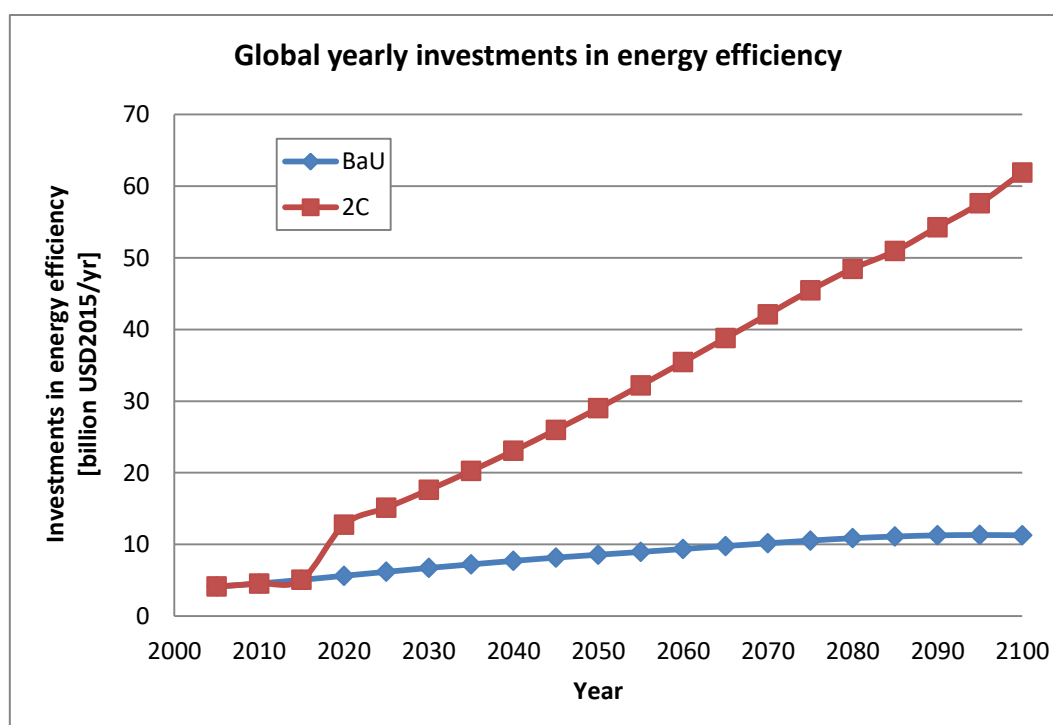
Figure 17 – Global yearly R&D investments in energy efficiency in the WITCH scenarios.

4. Discussion and conclusions

The seventeen Sustainable Development Goals defined in the 2030 Agenda represent major global objectives towards a sustainable world. These objectives should drive the political, economic, and social efforts in the next decade. In this paper, we have shown that reaching the energy Targets described by SDG 7 enables the achievement of most of the other SDGs. In terms of qualitative interaction, the analysis has highlighted a bidirectional relation between SDG 7 and SDG 13, the latter being the goal addressing the pivotal issue of climate change. This means that sustainable energy is critical for reducing greenhouse gas emissions and, at the same time, the measures against climate change can favor the deployment of sustainable energy solutions. In detail, Targets 7.2 and 7.3 show the strongest interactions in relation to SDG 13, meaning that energy generation and use need to be efficient, sustainable, and renewable, if the aim is to achieve a low-carbon energy system.

However, without leveraging and investing in means of implementation (especially technology innovation), it is difficult to favor the transition to a low-carbon energy system and overcoming all those challenges that can prevent the decoupling of economic growth from environmental degradation. Investments in technology innovation in the electricity sector are indeed consistent with the energy prospects as resulting in the mitigation scenario developed by the WITCH model.

References

Bonan J, Pareglio S, Tavoni M. (2016) Access to modern energy: a review of barriers, drivers and impacts. FEEM Working Paper 2016.068, Milan, Italy: Fondazione Eni Enrico Mattei.

Bosello F, Carraro C, De Cian E (2013) Adaptation can help mitigation: an integrated approach to post-2012 climate policy. Environment and Development Economics, 18(3): 270–290.

Capros P, Tasios N, De Vita A, Mantzos, L, Paroussos L. (2012) Transformations of the energy system in the context of the decarbonisation of the EU economy in the time horizon to 2050. Energy Strategy Reviews 1: 85-96. DOI: 10.1016/j.esr.2012.06.001.

Cervigni R, Liden R, Neumann JE, Strzepek KM (Eds.). (2015). Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors. World Bank Publications.

Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, Hourcade J-C, Krey V, Kriegler E, Löschel A, McCollum D, Paltsev S, Rose S, Shukla PR, Tavoni M, Van der Zwaan B, Van Vuuren DP (2014) Chapter 6 - Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

De Cian E, Buhl J, Carrara S, Bevione M, Monetti S, Berg H. Learning in Integrated Assessment Models and Initiative Based Learning Case Study Research - An Interdisciplinary Approach, forthcoming on Technological Forecasting and Social Change.

Dherani M, Pope D, Mascarenhas M, Smith KR, Weber M, Bruce, N (2008) Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under 5 years: A systematic review and meta-analysis. Bulletin of the World Health Organization 86(5): 390-398.

Emmerling J, Drouet L, Reis LA, Bevione M, Berger L, Bosetti V, Carrara S, De Cian E, De Maere D'Aertrycke G, Longden T, Malpede M, Marangoni G, Sferra F, Tavoni M, Witajewski-Baltvilks J, Havlik P (2016) The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways, FEEM Working Paper 2016:42, Milan: Fondazione Eni Enrico Mattei.

European Council Conclusions (2014) 2030 climate & energy framework. EUCO 169/14 CO EUR 13 CONCL 5. Brussels: European Union.

Förster H, Schumacher K, De Cian E, Hübler M, Keppo I, Mima S, Sands RD (2013) European energy efficiency and decarbonization strategies beyond 2030 – A sectoral multi-model decomposition. Climate Change Economics, Vol4 supp01: 1340004.

InterAcademy Council (2007) Lighting the way: toward a sustainable energy future, Amsterdam: IAC.

Intergovernmental Panel on Climate Change (2012) Renewable energy sources and climate change mitigation. Bonn: IPCC.

International Energy Agency (2011a) CO_2 emissions from fuel combustion, Paris: IEA.

International Energy Agency (2011b) 450 Scenario: Methodology and Policy Framework. Paris: IEA.

International Energy Agency (2015a) Energy and Climate Change. World Energy Outlook. Paris: IEA.

International Energy Agency (2015b) Energy efficiency. Market Report. Paris: IEA.

International Energy Agency (2015c) Renewable Energy. Medium-Term Market Report. Paris: IEA.

International Energy Agency (2016) Energy, Climate Change & Environment. Paris: IEA.

International Renewable Energy Agency (2015) REthinking Energy: Renewable Energy and Climate Change. Abu Dhabi: IRENA.

Karekezi S, McDade S, Boardman B, Kimani J (2012) Energy, Poverty and Development. In: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 151-190.

Luderer G, Krey V, Calvin K, Merrick J, Mima S, Pietzcker R, Van Vliet J, Wada K (2014) The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Climatic Change 123.3-4: 427-441.

Martin WJ, Glass RI, Balbus JM, Collins FS (2011) A Major Environmental Cause of Death. Science, 334: 180–181.

Nilsson M, Griggs D, Visbeck M. (2016) Map the interactions between Sustainable Development Goals. Nature 534 - 2016: 320-322.

OECD (2015) Policy Coherence for Development and the Sustainable Development Goals. Concept Note. Paris: OECD.

Sachs J.D. (2015), The Age of Sustainable Development, Columbia University Press.

Smith KR, Mehta S, Desai MA (2004) Indoor Smoke from Solid Fuels: assessing the environmental burden of disease at national and local levels. WHO Environmental Burden of Disease Series, No.4.

Stephan B, Schurig S, Leidreiter A. (2016) What Place for Renewables in the INDCs?. Hamburg: World Future Council.

Stern, DI, Kander A (2012) The Role of Energy in the Industrial Revolution and Modern Economic Growth. The Energy Journal, Volume 33, N.3: 125-152.

UNFCCC (2015) Adoption of the Paris Agreement, Decision 1/CP.21 FCCC/CP/2015/10/Add.1. Bonn: UNFCCC.

United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly 70/1.

United Nations (2000) United Nations Millennium Declaration. Resolution adopted by the General Assembly 55/2.

Wei M, Nelson JH, Greenblatt JB, Mileva A, Johnston J, Ting M, Yang C, Jones C, McMahon JE, Kammen DM (2013) Deep carbon reductions in California require electrification and integration across economic sectors. Environmental Research Letters 8 014038. DOI: 10.1088/1748-9326/8/1/014038.

World Economic Forum (2015) What role will fossil fuels play in our low-carbon future?. Cologny/Geneva: WEF.

World Meteorological Organization (2016) The Role of National Meteorological and Hydrological Services (NMHSs) in Implementation of Intended Nationally Determined Contributions (INDCs) Policy brief. Geneva: WMO.