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Reactor Ageing and Phase-out Policies: Global and European Prospects for Nuclear Power Generation

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Summary

Nuclear is considered as a valuable option for the decarbonization of the power generation, as it is a no-carbon, yet commercially consolidated technology. However, its real prospects are uncertain: if some countries, especially in the non-OECD area, have been extensively investing in nuclear, many OECD countries, which host the vast majority of operational reactors worldwide, feature old fleets which will not be replaced, as phase-out policies are being implemented. Research scenarios often consider polarized conditions based on either a global unconstrained nuclear development or a generalized phase-out. The main aim of this work is instead to explore the techno-economic implications of policy-relevant scenarios, designed on the actual nuclear prospects in the world regions, i.e. mainly differentiating policy constraints between the OECD and the non-OECD regions. The analysis, conducted via the Integrated Assessment Model WITCH, shows that nuclear generation constantly grows over the century, even if in general the nuclear share in the electricity mix does not significantly change over time, both at a global and at a European level. Over time, and especially if constraints are applied to nuclear deployment, the nuclear contribution is compensated by renewables (mainly wind and solar PV) and, to a lower extent, by CCS (only marginally in the EU). The policy costs related to the nuclear phase-out are not particularly high (0.4% additional global GDP loss with respect to the unconstrained policy scenario), as they are almost completely compensated by innovation and technology benefits in renewables and energy efficiency. Phase-out policies applied only to the OECD regions do not entail any additional policy costs, while non-OECD regions marginally benefit from lower uranium prices. A sudden shutdown of nuclear reactors in the OECD regions results in a doubling of these losses and gains.

Keywords: Nuclear, Power Generation, Climate Change Mitigation, Integrated Assessment Models

JEL Classification: C69, Q43, Q54

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Reactor ageing and phase-out policies: global and European prospects for nuclear power generation

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Abstract

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Research scenarios often consider polarized conditions based on either a global unconstrained nuclear development or a generalized phase-out. The main aim of this work is instead to explore the techno-economic implications of policy-relevant scenarios, designed on the actual nuclear prospects in the world regions, i.e. mainly differentiating policy constraints between the OECD and the non-OECD regions.

The analysis, conducted via the Integrated Assessment Model WITCH, shows that nuclear generation constantly grows over the century, even if in general the nuclear share in the electricity mix does not significantly change over time, both at a global and at a European level. Over time, and especially if constraints are applied to nuclear deployment, the nuclear contribution is compensated by renewables (mainly wind and solar PV) and, to a lower extent, by CCS (only marginally in the EU).

The policy costs related to the nuclear phase-out are not particularly high (0.4% additional global GDP loss with respect to the unconstrained policy scenario), as they are almost completely compensated by innovation and technology benefits in renewables and energy efficiency. Phase-out policies applied only to the OECD regions do not entail any additional policy costs, while non-OECD regions marginally benefit from lower uranium prices. A sudden shutdown of nuclear reactors in the OECD regions results in a doubling of these losses and gains.

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1. Introduction

Meeting with increasing energy demand via low-carbon solutions is a major goal for the 21st century in order to avoid detrimental effects on climate (IPCC, 2014). In 2015, almost all world countries signed the Paris Agreement committing to limiting to 2°C the global temperature increase in 2100 with respect to the pre-industrial levels and to pursuing efforts to reach 1.5°C, in order to further contain potential negative impacts (Schellnhuber et al., 2016). Clearly, these targets are very ambitious, since they entail profound technological and economical efforts as well as political coordination among countries.

Nuclear is widely recognized as one of the main technologies which will play an important role in decarbonizing the power sector (Krey et al., 2014 and Koelbl et al., 2014). Its main advantage is the possibility to couple technological maturity (nuclear has commercially been exploited since the 50s of the 20th century) with virtually no carbon dioxide emissions and without the dispatchability issues that affect variables renewable energies such as wind and solar.[1]

Nuclear power was characterized by a huge development especially in 70s and 80s. The accidents in Three Miles Island, USA (1979) and, above all, in Chernobyl, Former Soviet Union (1986) determined a substantial fall in the investments, mostly due to the safety concerns that were raised by those events. A general renaissance took place during the first decade of the 21st century, but the accident at the Fukushima-Daiichi, Japan (2011) revived public concerns about safety, which ultimately resulted in a reconsideration of the nuclear expansion policies in many countries of the world (Wittneben, 2012). Concerns about nuclear proliferation, waste management that is still an open issue, the shortage of qualified workforce in the reactor construction and high or uncertain costs (at least in some areas of the world) are the other main points representing an obstacle to nuclear diffusion (Ahearne, 2011). The long construction time (8-10 years) and operational life of plants (40+ years) make the uncertainty concerning electricity demand and public acceptance particularly relevant in discouraging investments (Cardin et al., 2017).

These factors jeopardize the future prospects of nuclear energy. As will be discussed in Section 3, in general two opposite tendencies are found worldwide, which roughly distinguish OECD and non-OECD countries. In OECD countries (with the main exception of the Republic of Korea), on the one hand many nuclear reactors are approaching the end of their operational life and on the other hand political, social, and economic constraints hinder the construction of new plants. Therefore, even in presence of massive investments to extend the operational lifetime of reactors (from about 40 to about 60 years), the prospects in these countries are controversial. Instead, in non-OECD countries, and especially China, India, and Russia, nuclear is characterized by high momentum and ambitious expansion plans are in place for the next decades.

In this context, the main objective of this work is to investigate the actual prospects of nuclear and their consequent impacts on the electricity mix and the policy costs, taking into consideration real-world aspects such as the policies implemented by countries and the ageing of reactors. This allows exploring more credible and meaningful scenarios, whereas assessment exercises often consider “digital” options only, i.e. either a global unconstrained nuclear expansion or global phase-out (Rogner and Riahi, 2013 and Hof et al., 2019). The exercise is carried out with the Integrated Assessment Model (IAM) WITCH.

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[1] It is true, however, that the functioning and huge dimensions of reactors (averagely around 1000 MW, up to 1600 MW in the latest models) result in a general inflexibility, so that a plant normally operates at full rate 7-8000 hours per year with limited load variations. These aspects could be addressed by developing smaller plants, the so-called Small Modular Reactors (SMRs), whose commercial maturity, however, is yet to come (Budnitz et al., 2018).

The paper is structured as follows. Section 2 describes the WITCH model, and especially how nuclear is modeled therein. Section 3 discusses more in detail the nuclear global scenario and the policy context, and in particular the policies implemented or planned by world countries. Section 4 illustrates the scenario design which has been defined according to the policy landscape described in the previous section. Section 5 presents the main results of the analysis. Section 6 finally concludes.

2. Methodology

2.1 The WITCH model

The tool adopted in this work is the World Induced Technical Change Hybrid (WITCH) model. WITCH is a dynamic optimization IAM aimed at studying the socio-economic impacts of climate change over the 21st century (Bosetti et al., 2006 and Emmerling et al., 2016) with a time step of five years. It is defined as hybrid because 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 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] WITCH endogenously models technological change, which regards energy efficiency and the capital cost of specific clean technologies. Global prices of fossil fuels are also 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 gives an overview of the aggregated economic model and of the disaggregated energy sector. Energy services (ES) and the aggregated capital and labor node (KL) are combined to generate the final economic output. ES derives from the combination of the capital of energy R&D (RDEN), which is a proxy of energy efficiency, and the actual energy generation (EN). The concept is that in presence of higher energy efficiency, lower levels of energy input provide the same final energy services. The EN node is divided between the electric (EL) and non-electric sectors (NEL), with a progressive disaggregation to the single technologies. The electric sector has a higher detail, while in the non-electric sector each node comprises all the non-electric usages of one specific energy source. No demand sectors are explicitly modeled, except for the road passenger and road freight transport sectors[4] (see Bosetti and Longden, 2013, and Carrara and Longden, 2017).

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[2] EFTA (European Free Trade Association) features Iceland, Liechtenstein, Norway, and Switzerland.

[3] The aggregated results for Europe derive from the combination of OLDEURO and NEWEURO.

[4] These sectors are not shown in the CES scheme.

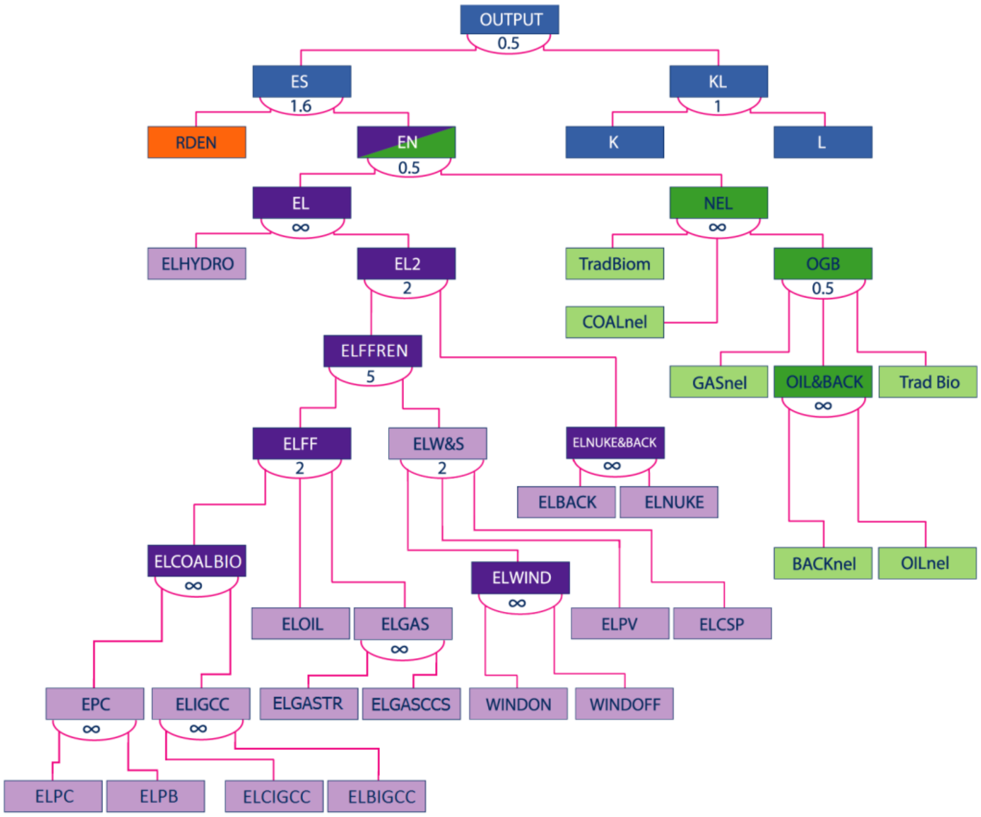

Figure 1 – The CES structure in WITCH.

Considering the electric sector, the hydroelectric technology is found first (ELHYDRO), which is essentially exogenous in the model. All the other technologies converge to EL2, 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) features: i) coal&biomass (ELCOALBIO), further divided into pulverized coal without CCS, i.e. Carbon Capture and Storage (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) consider 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 characterized by high capital costs, but generating power with no fuel costs and no carbon emissions. 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 developed in this work. Concerning the non-electric sector, the first distinction is between traditional biomass (TradBiom), coal (COALnel) and the aggregated node formed by oil, gas, and modern biomass (OGB), which features gas (GASnel), traditional biofuels (Trad Bio), and the combination (OIL&BACK) between oil (OILnel) and a non-electric backstop technology, i.e. advanced biofuels (BACKnel).

The CES structure tries to model the preference for heterogeneity that is experienced in the real world, where the choice of investing in energy technologies does not solely depend on economic considerations. In the CES scheme, the figures reported under the nodes indicate the relevant elasticity of substitution. This value quantifies the level of substitutability between the sub-nodes converging to the 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 they are linearly combined, i.e. the competition takes place on an economic basis only. Intermediate elasticities entail an intermediate behavior. See Carrara and Marangoni, 2017 for more details concerning the CES structure.

2.2 Nuclear modeling

The investment cost for new nuclear plants is 4709 \$/kW[5]. The same cost is applied to all world regions, even if in reality some differences may be found. Future model improvement will differentiate costs across regions. O&M costs do vary across regions, instead. Only fixed O&M costs are explicitly considered, which are comprised between 160 \$/kW and 220 \$/kW, while no variable O&M are accounted for. However, waste management and storage costs are explicitly considered: they start at 0.1 c\$/kWh in 2015 and increase slightly more than linearly with the relative increase in nuclear generation (MIT, 2003), which is a direct proxy of waste production. Uranium ore is considered sufficiently abundant to meet the increasing nuclear demand over the century. In particular, reserves are considered sufficiently large at prices below 350 \$/kg, i.e. the level at which reprocessing spent fuel and fast breeder reactors become competitive, which would prevent any further rise in the uranium price (Bunn, 2005). The process of conversion, enrichment, and fuel fabrication of the uranium ore is also taken into account, and the relevant cost is fixed to 300 \$/kg (MIT, 2003). The efficiency of nuclear power plants is 35%, the capacity factor is 85%, while the standard lifetime is 40 years (Tavoni and van der Zwaan, 2011).

3. Nuclear global landscape

As of June 30, 2019, there are 449 operational reactors in 31 countries worldwide, with an equivalent net capacity of 398 GW, while 54 reactors are under construction in 18 countries (4 of which not included in the previous 31), with an equivalent net capacity of 55 GW (IAEA, 2019).[6,7] Additional 26 countries have decided or have been considering to invest in nuclear, even if no reactors are under construction yet (Budnitz et al., 2018).

Overall, 66% of the capacity installed worldwide is more than 30 years old[8], as shown in Figure 2. In particular, this figure clearly highlights a strong change of the slope few years after the Chernobyl incident, proving the impact that the event had on the nuclear power industry.[9] It can also be seen that a considerable amount of capacity has already exceeded the normal reference lifetime of 40 years.

Figure 3 shows the global situation in terms of operational and under construction rectors, grouping countries according to the WITCH regions. The age of the operational reactors is also reported. In the following, a brief description of the current status and the implemented policies is provided for each region.

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[5] Costs are expressed in USD2015.

[6] These figures indicate that the average capacity for each reactor is about 1 GW.

[7] Henceforth, the reference IAEA, 2019 will implicitly be assumed for all statistical data if not differently specified.

[8] Although, for the sake of simplicity, the expression “average reactor age” will be used, in this work the age is calculated weighing on the reactors capacity.

[9] The delay is due to the completion of the projects that were in advanced state at the moment of the incident and that were not essentially affected: effects on deployed capacity were visible starting from the early 90s.

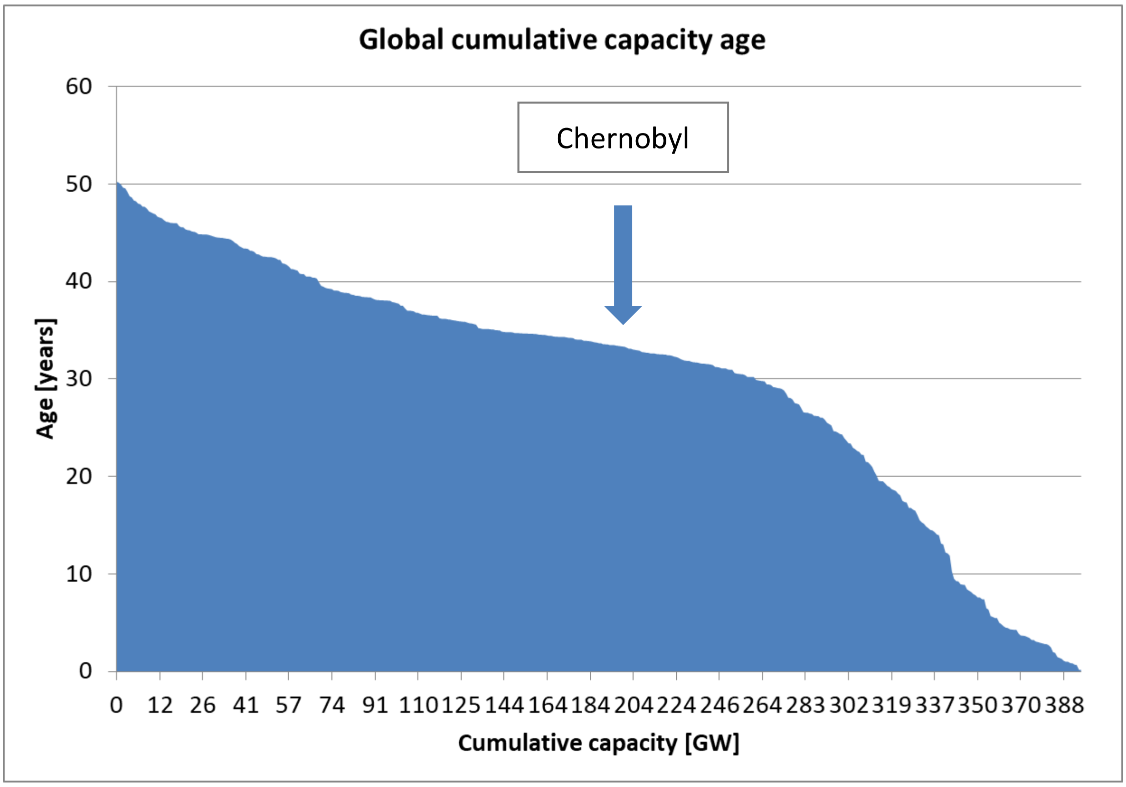

Figure 2 – Global cumulative capacity age.

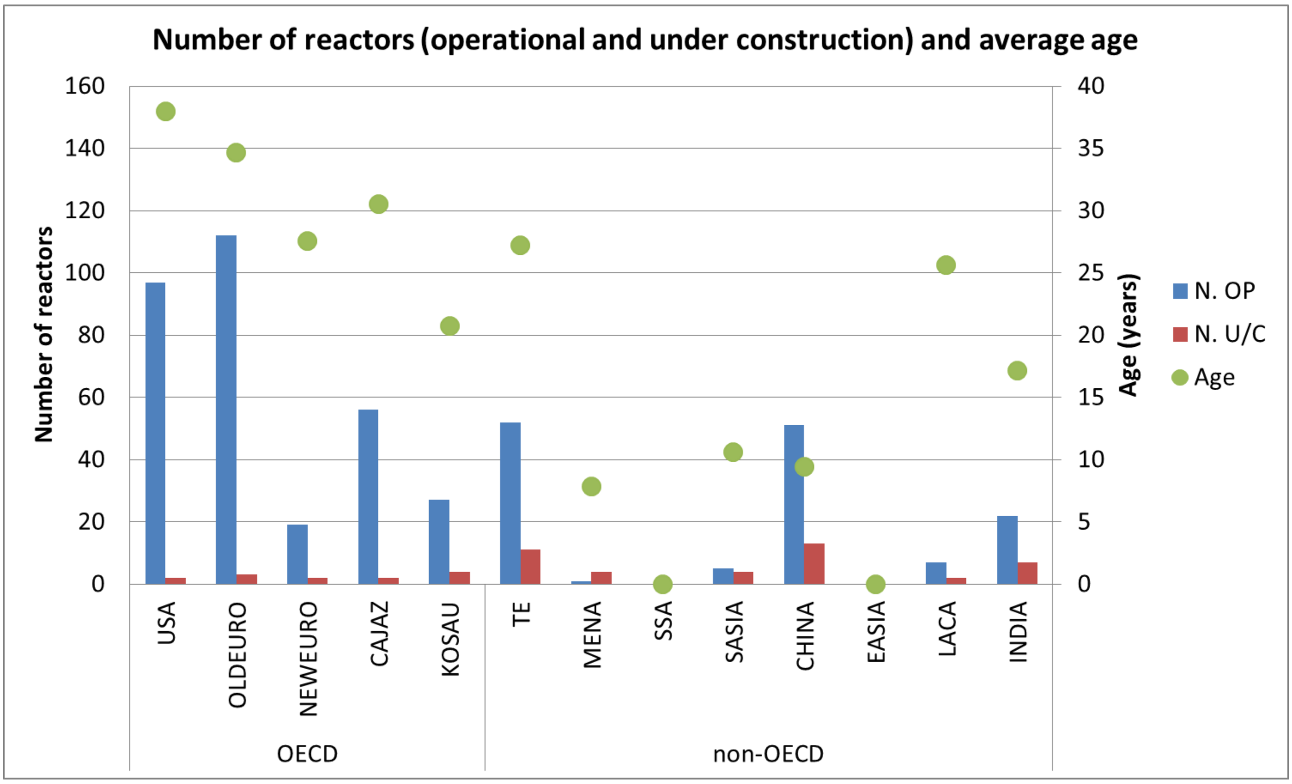

Figure 3 – Regional distribution of nuclear reactors and their age.

The **USA** have 97 operational reactors, i.e. the highest number worldwide. The American fleet is also the oldest, as the average reactor age is around 38 years, i.e. close to the reference operational life of 40 years. On the other hand, only two reactors are under construction, expected to come online in 2021 and 2022 respectively (Gattie et al., 2018). This means that the US are going to face severe ageing issues in the coming decades. Indeed, as mentioned in the Introduction, the operational lifetime of a nuclear reactor can normally be extended from 40 to 60 years, if dedicated upgrade and revamping works are carried out (Perrier, 2018). This strategy is extensively applied in the US (Volk et al., 2019), and most reactors have already obtained the relevant authorization (Davis, 2012). Still, in the absence of investment in new reactors, the retirement of the existing ones will begin around 2030 and will result in a complete phase out after some 20 years (Gattie et al., 2018).

Similar conditions occur in the **OLDEURO** region, i.e. in Western Europe. Here the operational reactors are 112 with an average age of 35 years, whereas only three reactors are under construction, specifically in France (Flamanville), Finland (Olkiluoto) and the United Kingdom (Hinkley Point). Construction works for an additional reactor at Hinkley Point will shortly be started. All these four plants are EPR (European Pressurized Reactors) of 1.6 GW of net capacity each. With its 58 reactors, France is the country which relies most on nuclear: this technology accounted for about 71% of the total national electricity generation in 2017. The plan would be to decrease this share to 50% in 2025, but this target is unlikely to be met (Volk et al., 2019). Most likely, life extension programs will be implemented. In 2010, Germany had 17 operational reactors and approved a policy allowing the extension of the reactors operational lifetime by averagely 12 years. The Fukushima accident in 2011 determined a radical change: the oldest 8 reactors were immediately shut down, while the remaining 9 will be closed within 2022, well before their planned operational end (Rogner, 2013). Most of the other countries also have been implementing phase-out policies, even if early retirement is not normally considered and life extensions are often planned or applied. These countries are Sweden (8 reactors), Belgium (7), Spain (7), Switzerland (5), and the Netherlands (1), which will all phase out nuclear plants within the next some twenty years. The same applies to Finland apart from the plant under construction in Olkiluoto (its other four operational plants are already about 40 years old). The United Kingdom plans to phase out its 15 plants (accounting for 9 GW) within 2030, but it is the only country in the region considering nuclear as its main carbon mitigation technology (apart essentially from France), so that 16 GW of new installations are planned in the next years (Volk et a., 2019). All in all, a strong capacity reduction is easily forecastable in the OLDEURO region in the near future.

A similar situation is found in **NEWEURO**, i.e. Eastern Europe, which features 19 operational reactors, with an average age of about 28 years, and two reactors under construction, in Slovakia. Lithuania, Bulgaria and Slovakia had partly to shut down their old plants as one of the conditions to be admitted to the EU (Volk et al., 2019). The remaining plants will progressively be phased out in the next decades.

The **CAJAZ** region includes the country that obviously has most been affected by the Fukushima accident, i.e. Japan. Nowadays, 37 of the 54 existing plants in 2011 are still considered operational (while additional two are under construction), even if only 5 generated electricity in 2017, whereas the remainder are still waiting for decisions on their future (Volk et al., 2019). However, the Japanese government still aims at achieving a nuclear share in the electricity mix of 20-22% in 2030 (WNA, 2019a), i.e. slightly below the pre-Fukushima levels: the share was equal to 26% in 2010 (IEA, 2012). Canada essentially replicates the conditions of the other Western countries: old reactors, no new constructions ongoing, and investment in extending the operational life.[10]

The **KOSAU** region is quite peculiar within the OECD regions. The core country here is the Republic of Korea. This country has 25 relatively recent reactors (the average age is 20 years) and it has strongly been investing in nuclear: 4 reactors are under construction and plans are to continue along this path in the next decades, which makes the Republic of Korea the only Western country strongly investing in nuclear without major issues. South Africa has two operational reactors which are 34 and 35 years old, respectively. Plans to build new capacity within 2030 have been suspended, therefore only life extension interventions may reasonably be considered in this country for the near future (WNA, 2019b).

Transition Economies (**TE**) face similar problems as Western countries in terms of ageing of nuclear reactors, as most reactors were built during the Cold War in the 70s and 80s and are currently undergoing works for life extension (Volk et al., 2019). However, considerable investments in new capacity are in place, especially in Russia (6 reactors are under construction), but also in Ukraine (2), Belarus (2), and Turkey (1), which allows forecasting optimistic futures for nuclear in this region.

Middle East and North Africa (**MENA**) is a “young” nuclear region. The first plant was inaugurated in the Islamic Republic of Iran in 2011, while 4 reactors are under construction in the United Arab Emirates, with works expected to progressively end in the very next years. No other countries have implemented or planned investments, however.

Sub-Saharan Africa except South Africa (**SSA**) and South-East Asian countries (**EASIA**) do not have any operational nor under construction reactors.[11]

South Asian countries (**SASIA**) have considerably been investing in nuclear. Pakistan has a very recent fleet, as 3 of its 5 reactors were inaugurated in the last decade, and two additional reactors are under construction. Two reactors are also under construction in Bangladesh.

The same applies to the main other South Asian country, that is an independent region in WITCH, i.e. **INDIA**. 22 operational reactors with an average age of 17 years and 7 reactors under construction highlight bright prospects for nuclear in this country.

A similar and even more positive scenario is found in **CHINA.** In the People’s Republic there are 46 reactors with an average age of 7 years, while 11 plants are under construction. Similarly to India, huge development can be predicted for the next decades, as nuclear is considered an excellent technology to cope with the enormous growth in energy demand while also meeting with the climate mitigation requirements. For this region, it should be noted that Taiwan is also a nuclear country: its prospects are less bright, however, as its five operational reactors are approaching the age of 40 and the construction of two reactors has recently been suspended.[12] It is clear, however, that the dimensions of this country are not such as to affect the overall evaluation of the CHINA region.

Finally, Latin and Central America (**LACA**) features three countries with nuclear power plants, i.e. Argentina, Brazil, and Mexico. There are 7 operational reactors in the region, with quite a high average age (26 years). Two reactors are under construction, and plans (especially in Argentina, see WNA, 2019c) are to continue

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[10] Nuclear power plants are not present in New Zealand, and no different plans are in place. The same will apply to Australia in the KOSAU region.

[11] For an overview on the nuclear debate in the EASIA countries, see Putra, 2017.

[12] These two reactors formally still appear as under construction in IAEA, 2019, however.

investing in this technology. Hence, the nuclear share in this region is not very high, but it is expected to at least maintain its levels in the coming future.

To conclude, this overview has described in detail the general distinction between the OECD and non-OECD regions that has been anticipated in the Introduction. The OECD features 311 of the 449 operational reactors worldwide (69%), but only 13 of the 54 reactors under construction (24%). The average age of reactors in the OECD countries is 34 years against 18 in the non-OECD countries (the global average is 30 years). Hence, optimistic nuclear prospects can be expected for most non-OECD countries that have nuclear power, and especially Russia, India, and China, while more complicated futures can be estimated for OECD countries, with the exception of the Republic of Korea. This exception will implicitly be assumed henceforth with no further specification: OECD regions in the following will thus be USA, OLDEURO, NEWEURO, and CAJAZ.[13]

4. Scenario design

The nuclear landscape described in the previous section is the main reference for the definition of the scenarios explored in this exercise. Indeed, the coherent picture which characterizes the OECD and the non-OECD countries allows considering a limited set of scenarios, which are five in total.

First of all, a baseline or Business-as-Usual (BAU) scenario has been run as a benchmark. No mitigation policies nor other technological constraints are considered in this scenario.

The other four scenarios are explored in a mitigation policy compatible with the Paris targets. In particular, a uniform carbon tax is applied in all regions starting from 2020 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 corresponds to a temperature increase of 1.8°C in WITCH, whereas the baseline scenario leads to a temperature increase of about 4°C. In terms of annual global CO_2 emissions, the policy scenarios entail a constant decrease from 36 Gt/yr in 2015 down to -8 Gt/yr in 2100[14], while CO_2 emissions constantly grow to about 75 Gt/yr until around 2080 in the no policy scenario, then remaining substantially constant until the end of the century.[15]

One scenario (CTAX) is run without any other constraints, and in particular nuclear energy is freely optimized by the model in all regions. On the opposite, one scenario (CTAX_global_phase-out) considers a nuclear phase-out in all regions of the world, considering a life extension to 60 years for all reactors.[16] A more realistic scenario (CTAX_OECD_phase-out) applies the phase-out policy to the OECD countries only, i.e. to the USA, OLDEURO, NEWEURO, and CAJAZ regions, while no constraints are applied to non-OECD regions. The last scenario (CTAX_OECD_switch-off) considers a more extreme situation where nuclear is immediately and completely abandoned in the OECD regions starting from 2020.

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[13] Indeed, these WITCH regions do not perfectly cover the OECD member countries, but this will not affect the general validity of the distinction between OECD and non-OECD in this work.

[14] Negative emissions can be reached via biomass CCS and afforestation in WITCH.

[15] The overall greenhouse gas emissions (GHG) start at 50 $GtCO_2eq/yr$ and increase to 93 $GtCO_2eq/yr$ in 2100 in the baseline scenario, while they decrease to -3 $GtCO_2eq/yr$ in the policy scenarios.

[16] Section 3 discussed that this will be the case in most countries of the world. In Germany, all nuclear reactors will be shut down in 2022, but this roughly compensates with the intentions by the United Kingdom to keep investing in nuclear. Therefore the 60-year extension hypothesis can be considered acceptable in the OLDEURO region as well.

5. Results

Figure 4 shows the global evolution of the electricity generation from nuclear in the different scenarios. It can immediately be noted that nuclear generation grows in all scenarios in the long run (it starts at 10 EJ/yr in 2015), with the obvious exception of the CTAX_global_phase-out scenario, where by definition nuclear generation tends to zero over time. The unconstrained CTAX scenario implies a higher generation than the baseline scenario, as the policy stringency would further trigger higher investments in low-carbon technologies. However, the model considers nuclear as a worthwhile technology even in the absence of carbon signal, therefore the BAU scenario is also characterized by a robust nuclear growth.

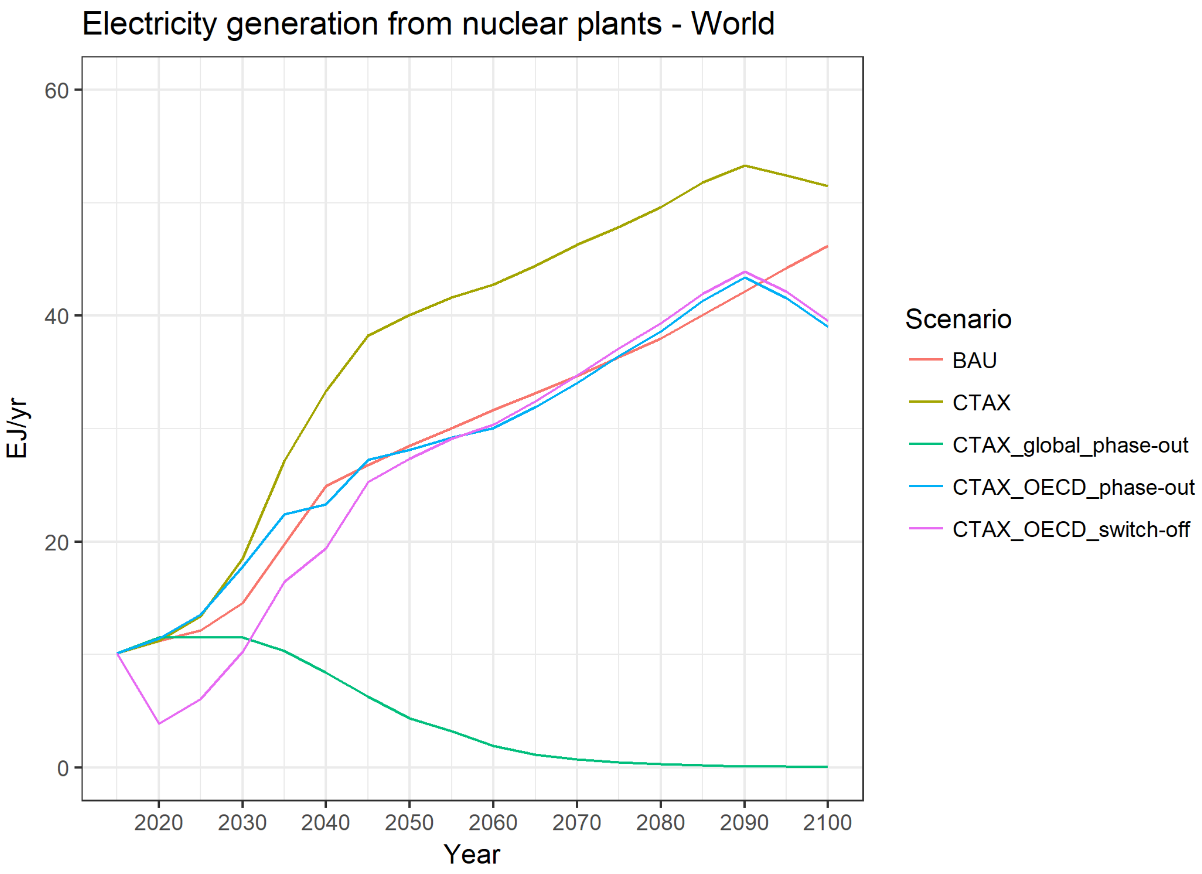

Figure 4 – Global nuclear generation.

The constraints on nuclear growth in the OECD countries are such that nuclear generation is significantly lower in the CTAX_OECD_phase-out and the CTAX_OECD_switch-off scenarios than in the unconstrained CTAX scenario, essentially replicating the BAU results. In the CTAX_OECD_switch-off, in particular, nuclear generation starts to grow immediately after the 2020 shock, implying that the growth in the non-OECD countries more than compensates the generation end in the OECD countries. Indeed, the lower uranium demand in the OECD countries related to these scenarios implies lower fuel prices for non-OECD countries. This boosts nuclear generation considerably higher than in the CTAX scenario, see Figure 5.

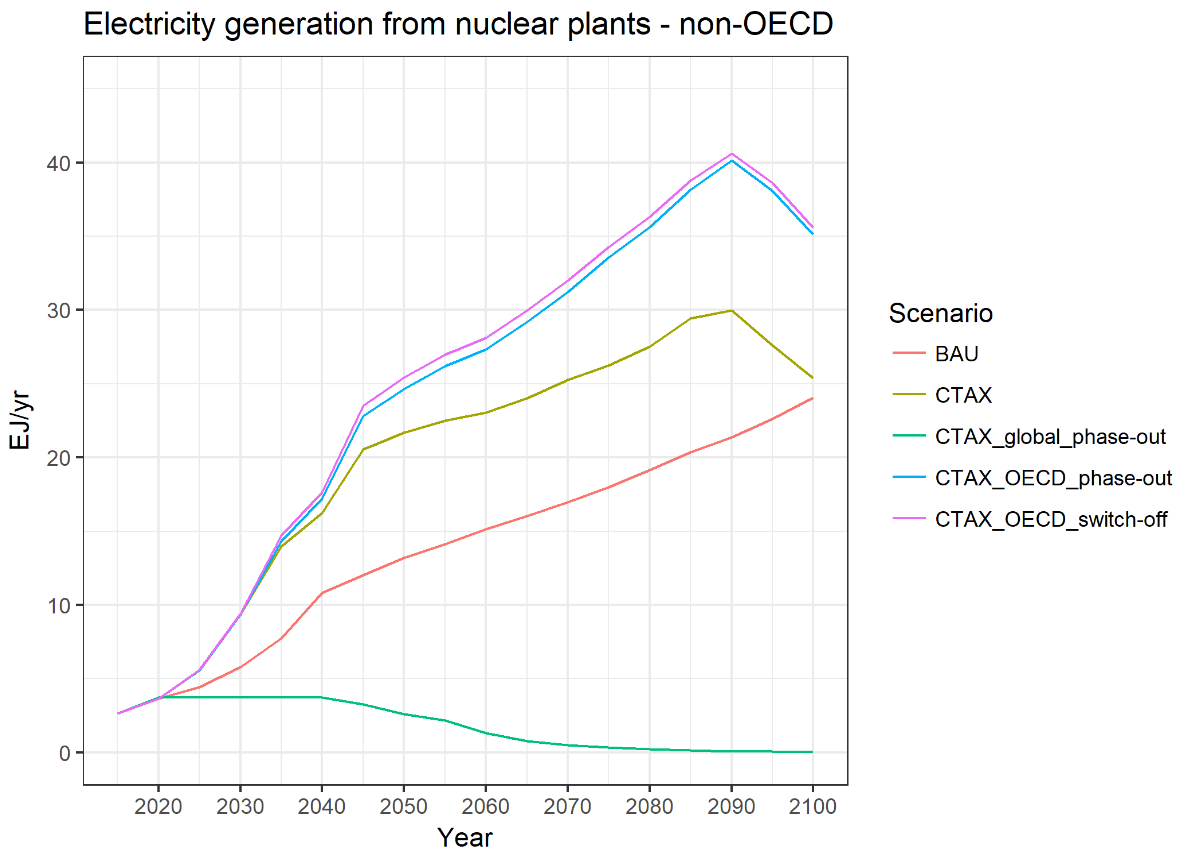

Figure 5 – Nuclear generation in non-OECD regions.

The global electricity demand does not markedly change among the four policy scenarios, even if there is a considerable difference between them and the BAU scenario, see Figure 6. This graph also indirectly highlights an important aspect of decarbonization. In general decarbonization can be achieved via two main strategies. The first one is to reduce emissions simply by reducing energy demand. This is the most straightforward strategy, as it does not entail a profound reconfiguration of the energy sector, and is what happens in the policy scenarios in the short term: here the electricity demand grows very mildly, compared to a more consistent growth in the BAU scenario. However, whereas the increase in the BAU scenario is fairly regular over the century, the electricity demand starts growing very fast after about 2040 in the policy scenarios and it overcomes the BAU levels around 2070/2080. This happens because the second decarbonization strategy is now deployed, which consists in increasing the share of electricity in the overall secondary energy demand with a parallel decarbonization of the electricity sector (which in general guarantees the easiest decarbonization routes).

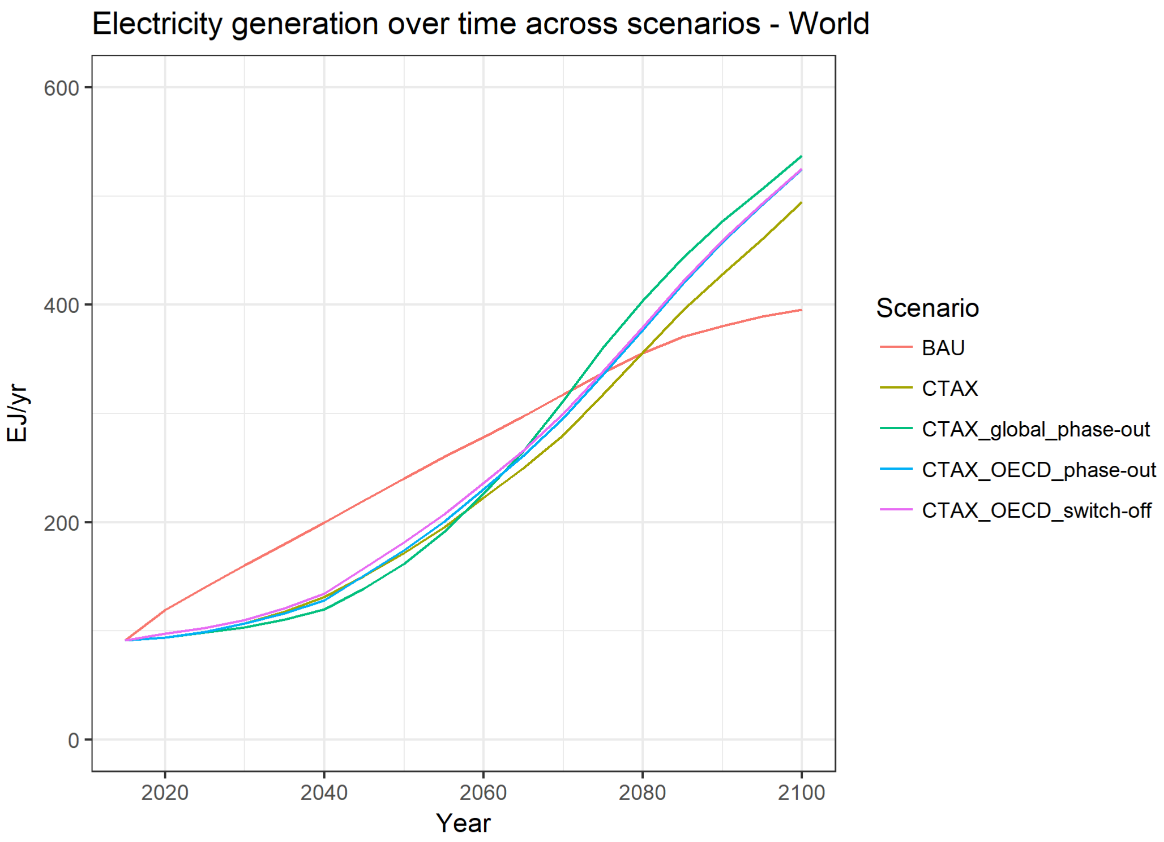

Figure 6 – Global electricity demand across scenarios.

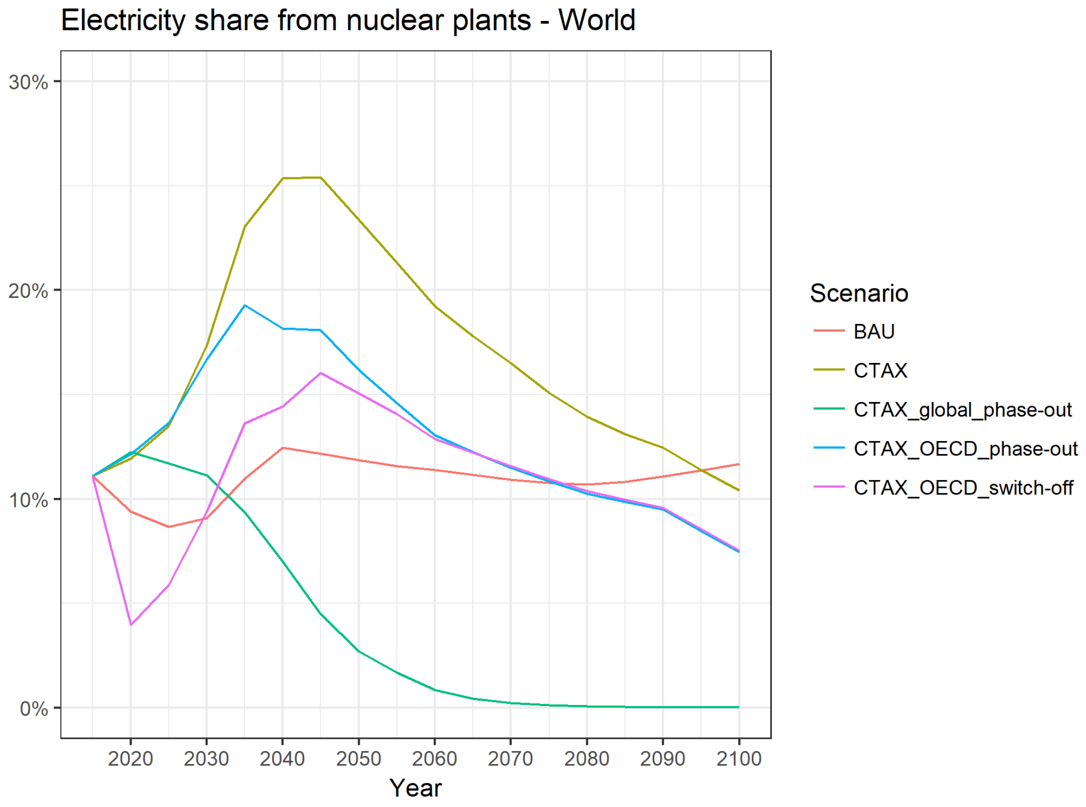

Figure 7 – Global nuclear share across scenarios.

The evolution of the nuclear share in the electricity generation mix (Figure 7) derives from the combination of Figure 4 and Figure 6. The 2015 level of 11% is fairly constant over the century in the BAU scenario, as the nuclear growth is substantially in line with the overall electricity demand growth (around 2% per year). The CTAX_global_phase-out is obviously characterized by a constant decrease to zero, while all the other policy scenarios show a marked increase until around 2040 (to a maximum level which is progressively lower as the stringency of the constraints on nuclear increases, i.e. 25% in the CTAX scenario, 19% in the CTAX_OECD_phase-out scenario, 16% in the CTAX_OECD_switch-off scenario), which is followed by a decrease down to the initial levels towards the end of the century.

This happens because of the tremendous growth of renewables, notably wind and solar PV, which progressively gain market shares and become dominant in the second part of the century. This fact is clearly visible in Figure 8 and Figure 9, which show the evolution of the electricity mix at a global level in four selected years (2025, 2050, 2075, and 2100): the former shows the absolute generation, while the latter shows the relative shares.

First of all, both figures highlight that the carbon tax applied in the policy cases is such that the electricity sector is already fully decarbonized by 2050, when only a residual share of gas without CCS still appears in the electricity mix. This obviously does not apply to the BAU scenario, where fossils do not suffer from any constraints and they still maintain almost half of the generation portfolio in 2100, despite a growth in renewables which progressively become attractive even in the absence of the carbon tax.

The behavior of electricity demand has already been discussed above: in 2025 and 2050 demand is higher in the BAU scenario than in the policy ones, in 2075 the levels are similar, while in 2100 the policy scenarios show a much higher demand. It is interesting to note an additional point here: as written above, the overall demand is similar across the policy scenarios, but a more precise observation would highlight that demand grows with respect to the unconstrained CTAX scenario if constraints (phase-out or switch-off) are applied to the OECD countries, and even more if phase-out regards all regions. This happens because the constraints on nuclear imply higher investments in the other low-carbon technologies. Since WITCH features an endogenous technological modeling of the investment cost for renewables – in particular, wind onshore, wind offshore, solar PV, and solar CSP, while this does not apply to hydro and CCS – this implies considerable innovation benefits for wind and solar technologies, that are thus able to reach higher generation levels, which more than compensates the reduction or the absence of nuclear generation. As a result, the aggregated penetration of solar and wind technologies reaches 35% of the electricity mix in 2100 in the BAU scenario, 54% in the CTAX scenario, 59% in the CTAX_OECD_phase-out as well as the CTAX_OECD_switch-off scenarios, and 67% in the CTAX_global_phase-out scenario.

The severe impact that such a considerable penetration of variable renewable energies would have on the energy system is a topical and well-known issue. The stability of electrical grid requires that demand and supply be constantly in balance and this is not trivial if generation comes from plants fueled with a variable energy source. Abstracting from the technical aspects, it is not easy to model this issue in Integrated Assessment Models: these phenomena take place on very small spatial and temporal scales, whereas IAMs generate scenarios which span an horizon of decades, providing average annual quantities and considering large, aggregated regions. It is not within the scope of this paper to thoroughly discuss such an aspect, however. To this purpose, the reader is referred to Carrara and Marangoni, 2017 for further details on the WITCH model and to Pietzcker et al., 2017 for an overview of IAMs. However, one effect, i.e. the deployment of huge storage capacity to sustain the renewable expansion, can be easily highlighted: see Figure 10 which shows the power capacity evolution in the same selected years as Figure 8 and Figure 9.

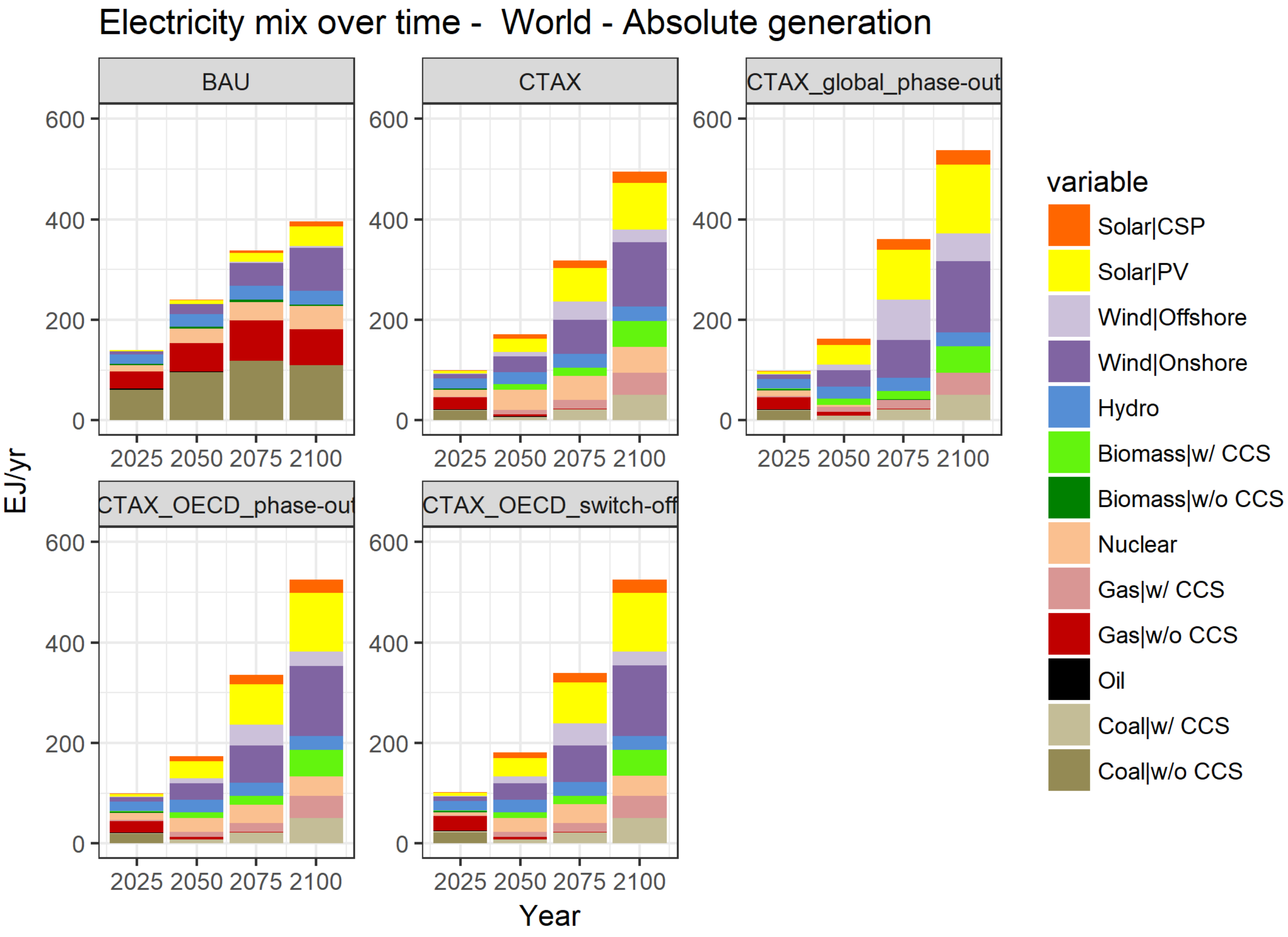

Figure 8 – Global electricity mix over time: absolute generation.

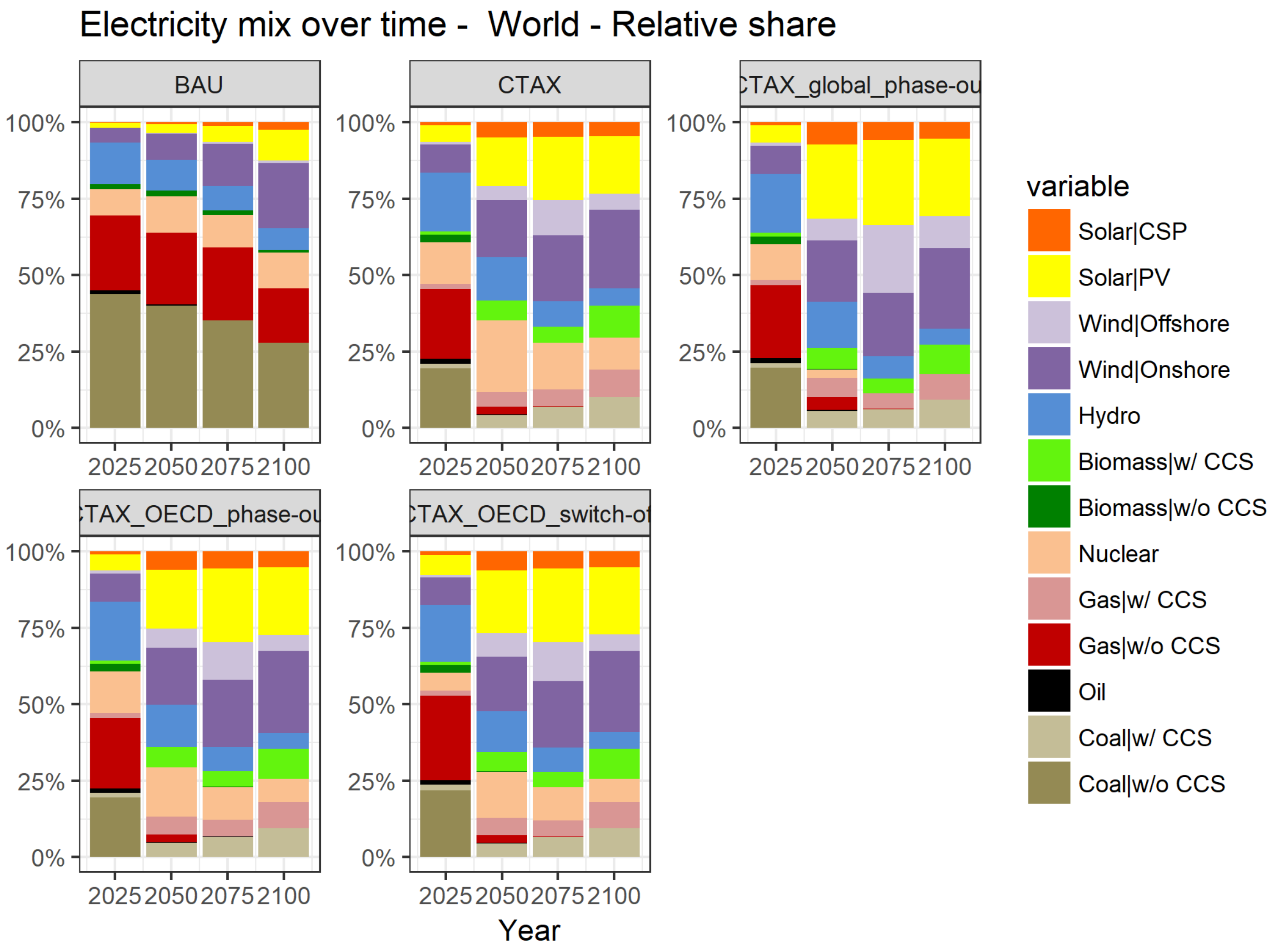

Figure 9 – Global electricity mix over time: relative generation shares.

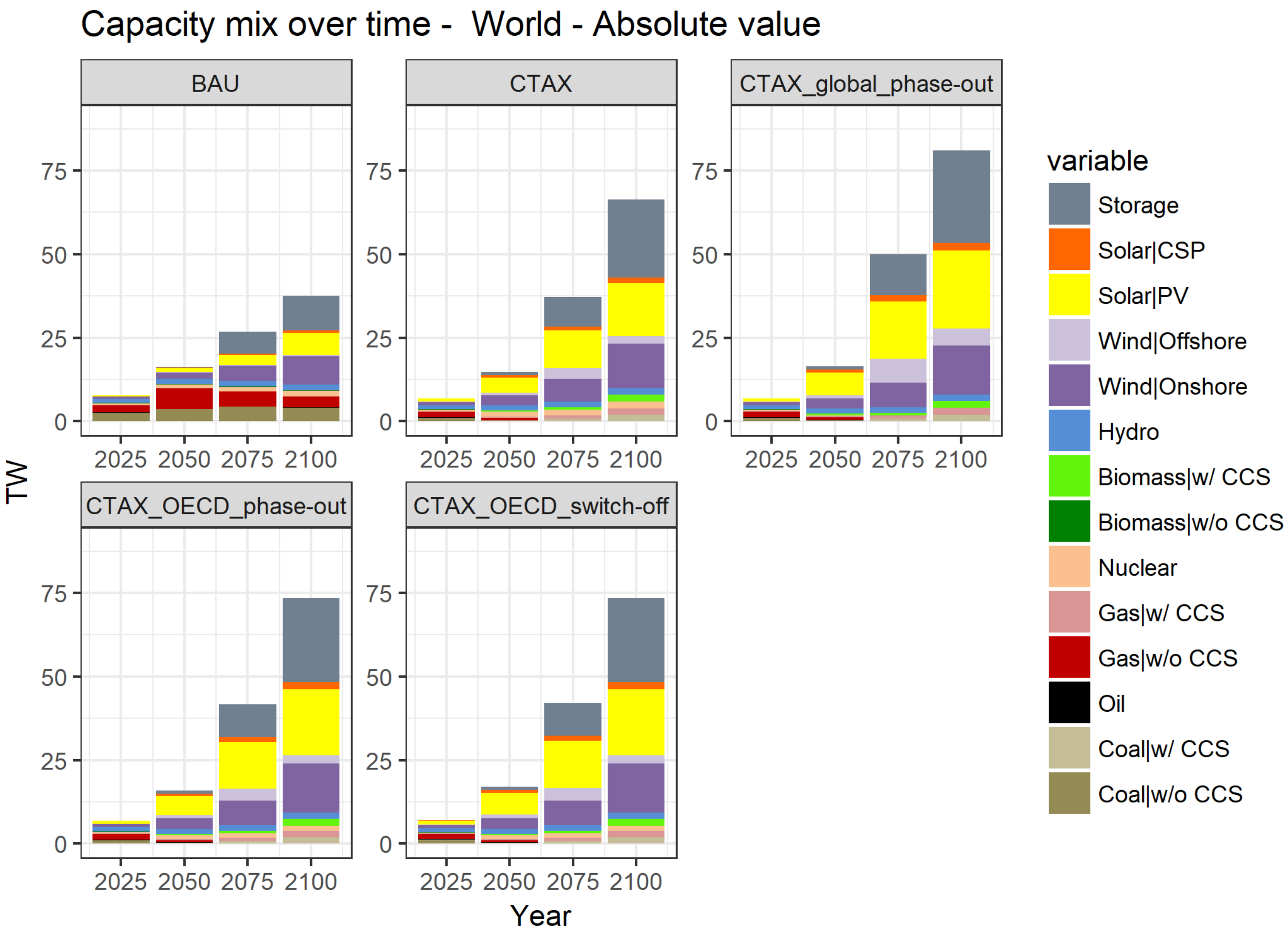

Figure 10 – Global electricity mix over time: capacity.

It can be noted that, whereas considerable storage capacity is required in the second half of the century (in addition to a similar growth in the electric infrastructure, not shown here), this is not the case in the first half, when the moderate renewable growth can be "absorbed" by the remaining generation fleet which provides sufficient flexibility.

Moving the attention on the regional results, Figure 11 shows the evolution of the nuclear share in the unconstrained CTAX scenario in the thirteen WITCH regions (as well as at global level for comparison purposes).

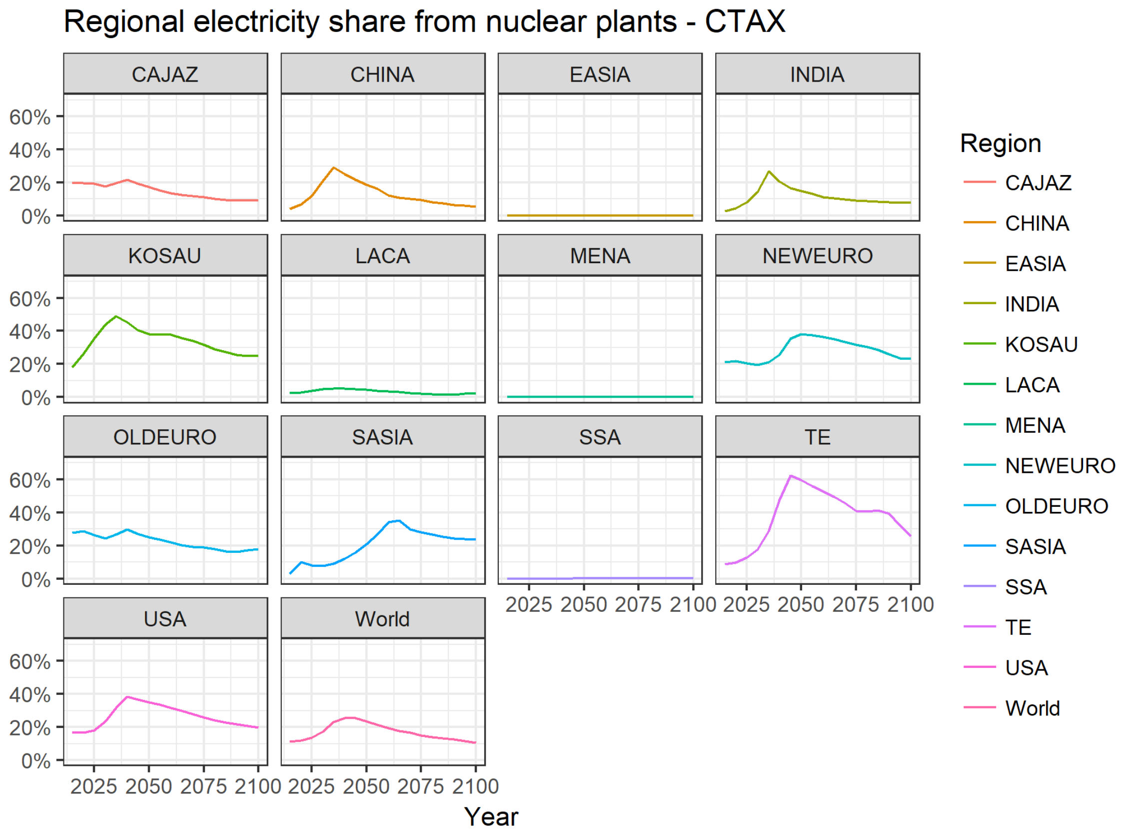

Figure 11 – Regional nuclear share in the CTAX scenario.

For most regions, the optimization model provides results in line with the actual policy landscape and prospects. Nuclear generation remains zero or close to zero in the regions which today have neither reactors nor investments plans, i.e. EASIA and SSA, and in the regions which do have a small nuclear share but do not have any particular expansion plans, i.e. LACA and MENA. The nuclear share instead grows in the regions which have ambitious expansion plans: CHINA, INDIA, KOSAU, SASIA, and TE, at least until mid-century. After that date, as already discussed, nuclear does not stop growing in absolute terms, but it does so at a slower pace than renewables, which gain more and more market shares, so that the relative nuclear share decreases. On the other hand, the nuclear share immediately starts decreasing in those regions which are characterized by critical nuclear prospects, such as CAJAZ and OLDEURO, where decarbonization is mostly carried out via renewables and, for the former, CCS. The only two regions not fully in line with the actual policy landscape are NEWEURO and USA, which show a marked growth despite the present conditions which do not suggest such an evolution for the next decades.

Remaining at a regional level, it is interesting to focus on the European results. Europe is naturally 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 between the two.

First of all, Figure 12 shows the evolution of the nuclear share in Europe. Indeed, the CTAX_global_phase-out, CTAX_OECD_phase-out, and CTAX_OECD_switch-off scenarios, in fact, show a trivial behavior: in the latter, nuclear generation immediately falls to zero in 2020, while in the two phase-out scenarios (which are equivalent for Europe), the share gradually decreases to zero over the next decades. Hence, the main aim is to compare the BAU and the CTAX scenarios, which essentially have the same progress, with a substantial constancy of the nuclear share over time.

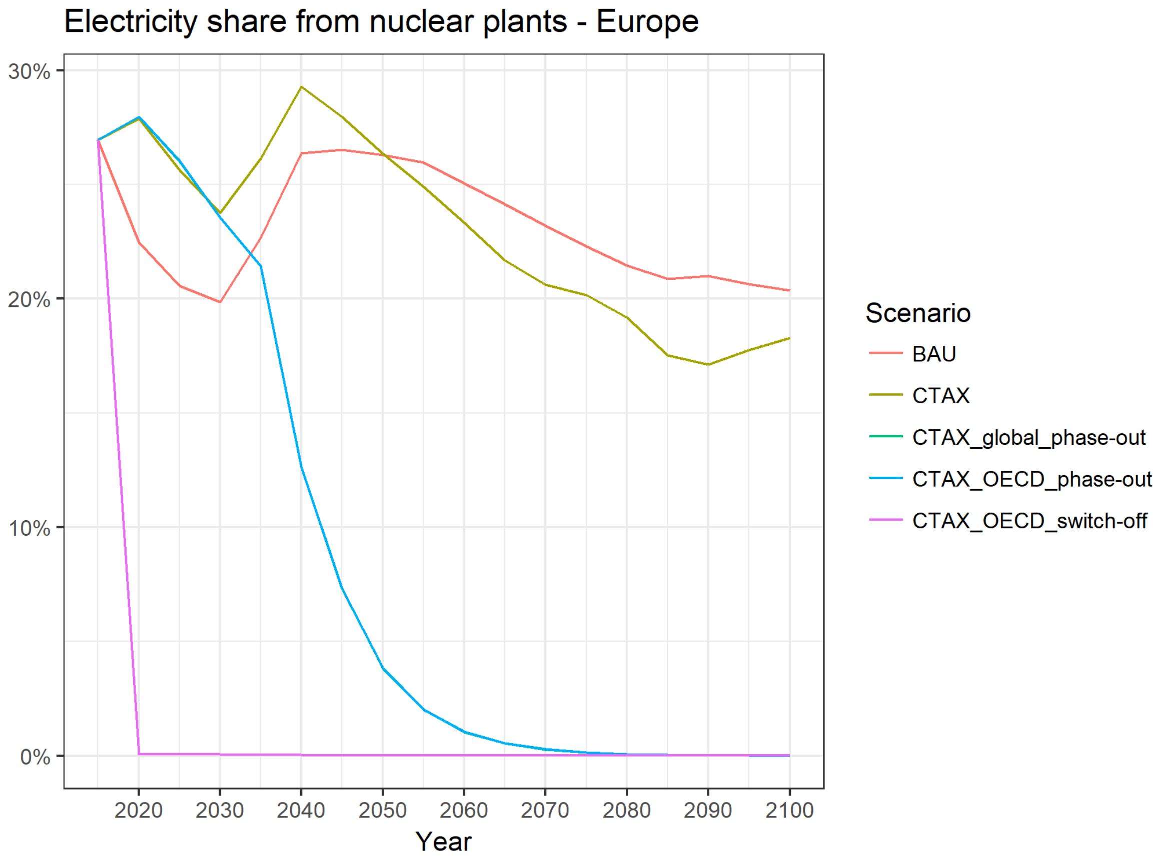

Figure 12 – European nuclear share across scenarios.

Figures 13, 14, and 15 show the generation (in absolute and relative values) and the capacity mixes in the four selected years for the five scenarios for Europe. Two major differences emerge compared to the global results. First, renewable penetration is considerable already in the BAU scenario, where fossils have a marginal role even in the absence of a climate policy. Therefore it is not surprising that these technologies dominate (with nuclear) the power landscape in the mitigation scenarios. Second – and related to the first point – CCS penetration is negligible: this is due to the low availability of storage sites and, again, to the high potential and technology maturity that renewables have in this region. The enormous penetration of solar and wind is such that a corresponding very high amount of storage capacity is needed to ensure grid stability, as clearly shown in Figure 15.

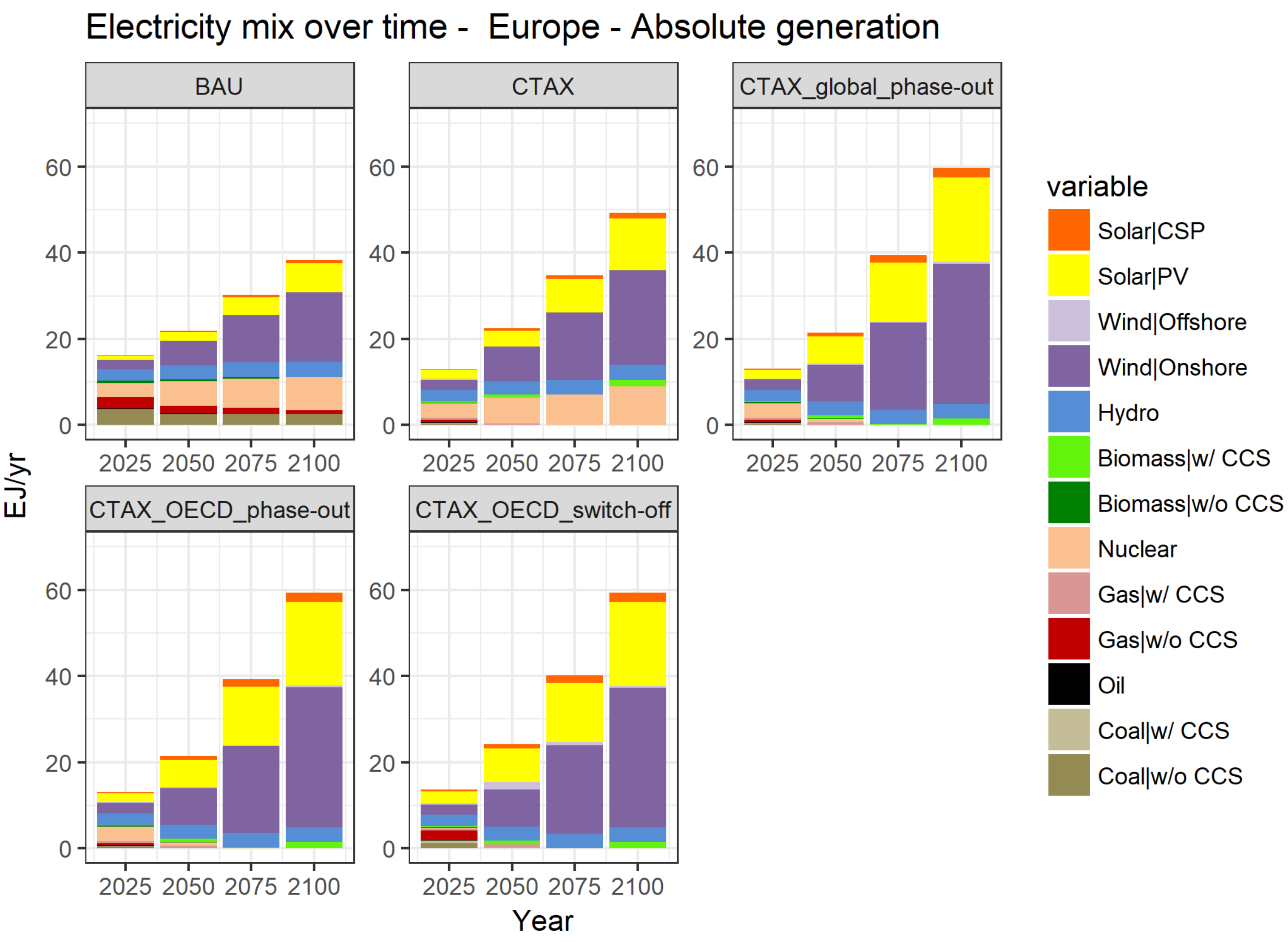

Figure 13 – European electricity mix over time: absolute generation.

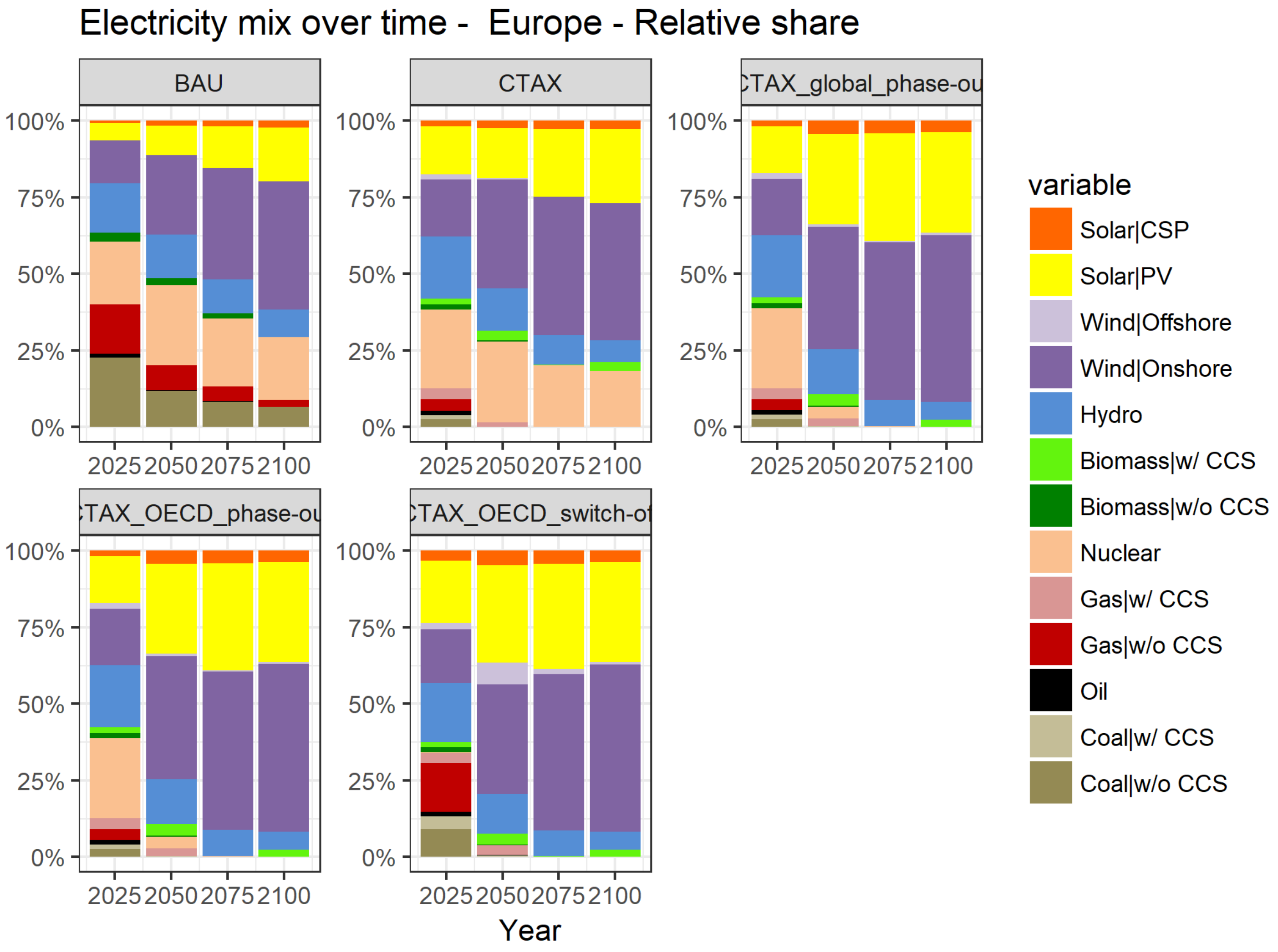

Figure 14 – European electricity mix over time: relative generation shares.

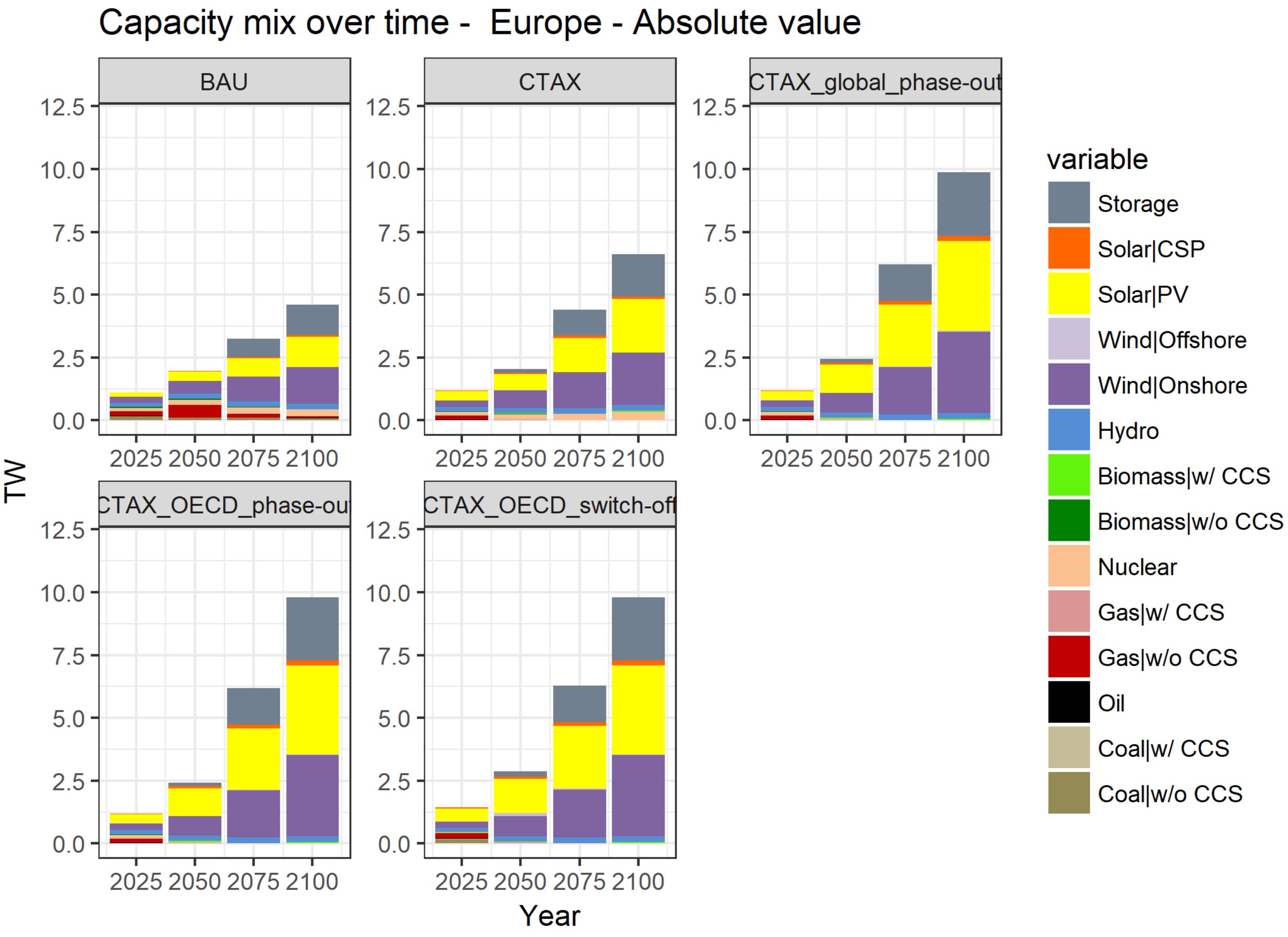

Figure 15 – European electricity mix over time: capacity.

It is finally interesting to assess the economic impacts of the different scenarios, and in particular the policy costs. These costs are evaluated as the cumulative GDP loss over the century with respect to the cumulative GDP of the baseline case, considering a yearly discount factor of 2.5%. First of all, Figure 16 shows the policy costs in the different regions in the unconstrained CTAX scenario, which is the benchmark of the mitigation scenarios portfolio.

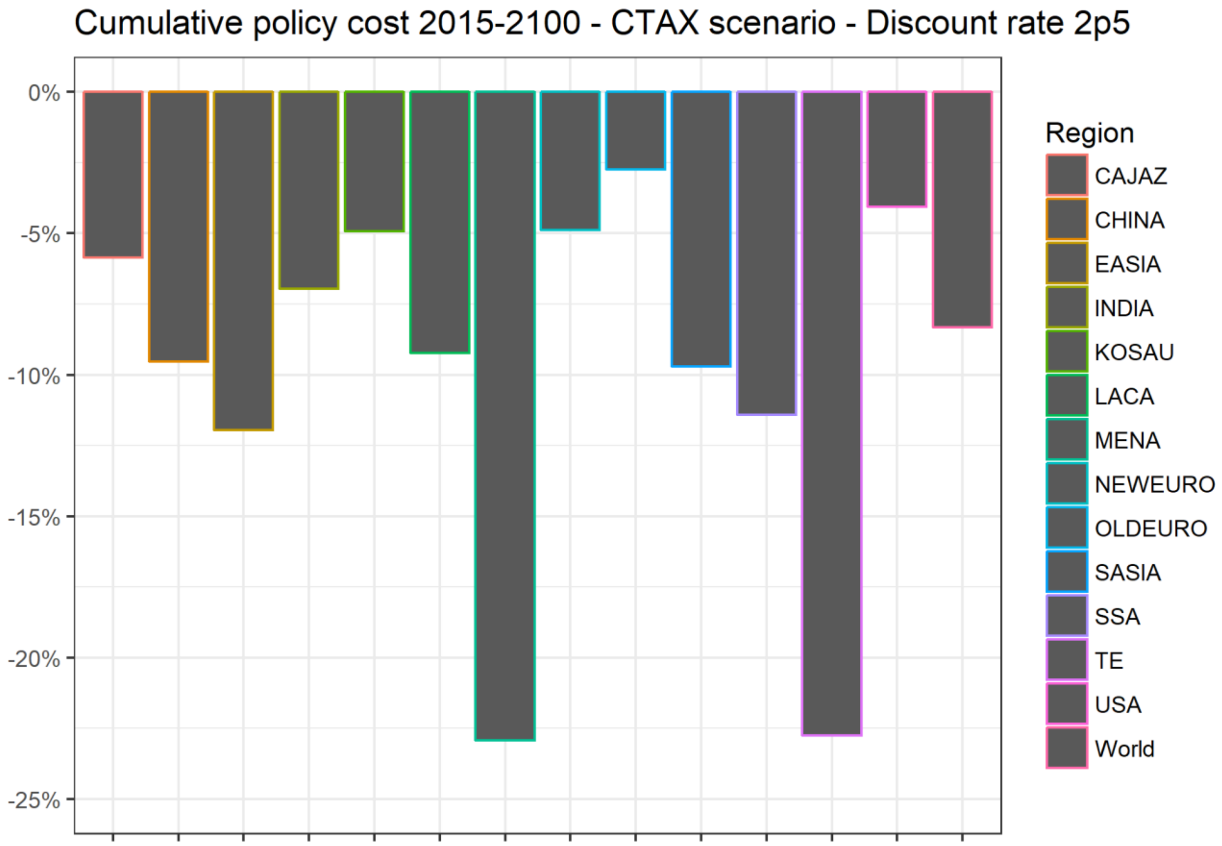

Figure 16 – Regional policy costs in the CTAX scenario.

The average global GDP loss is 8.3%. However, marked differences are found across regions. MENA and TE are the two regions which by far are affected most by the mitigation policies: the GDP loss amounts to about 23% here. This result is unsurprising, as these regions are the two main exporters of fossil fuels: the implementation of the carbon tax results in a global drop of fossil consumption and so happens to the economic performance of these regions, which is added to the lower domestic consumption that the policy allows. On the other end, OLDEURO is the region which is affected least by the mitigation policy: GDP loss is less than 3% here. This result is also unsurprising, as the previous figures have shown that a considerable decarbonization already takes place in the BAU scenario in this region, i.e. the economic optimization per se leads to a low-carbon portfolio without the implementation of a carbon policy, which simply expands this tendency.

Focusing on the economic impacts of the nuclear phase-out or switch-off policies, a previous paper (De Cian et al., 2011) explored this aspect highlighting a point that has already been mentioned in the previous pages: the innovation benefits regarding the technologies which undergo learning (signally wind and solar), as well as the overall efficiency of the energy sector, result in lower costs (investment costs for renewables and for the energy sector in general) which essentially compensate the phase-out costs. But what happens at regional level? And what are the impacts of differentiated policies? Figure 17 shows the policy costs in the remaining three mitigation scenarios, highlighting the difference with respect to the unconstrained CTAX scenario in percentage points. This is done in order to abstract from the effects of the mitigation policy, and focus on the pure effects of the nuclear policy.

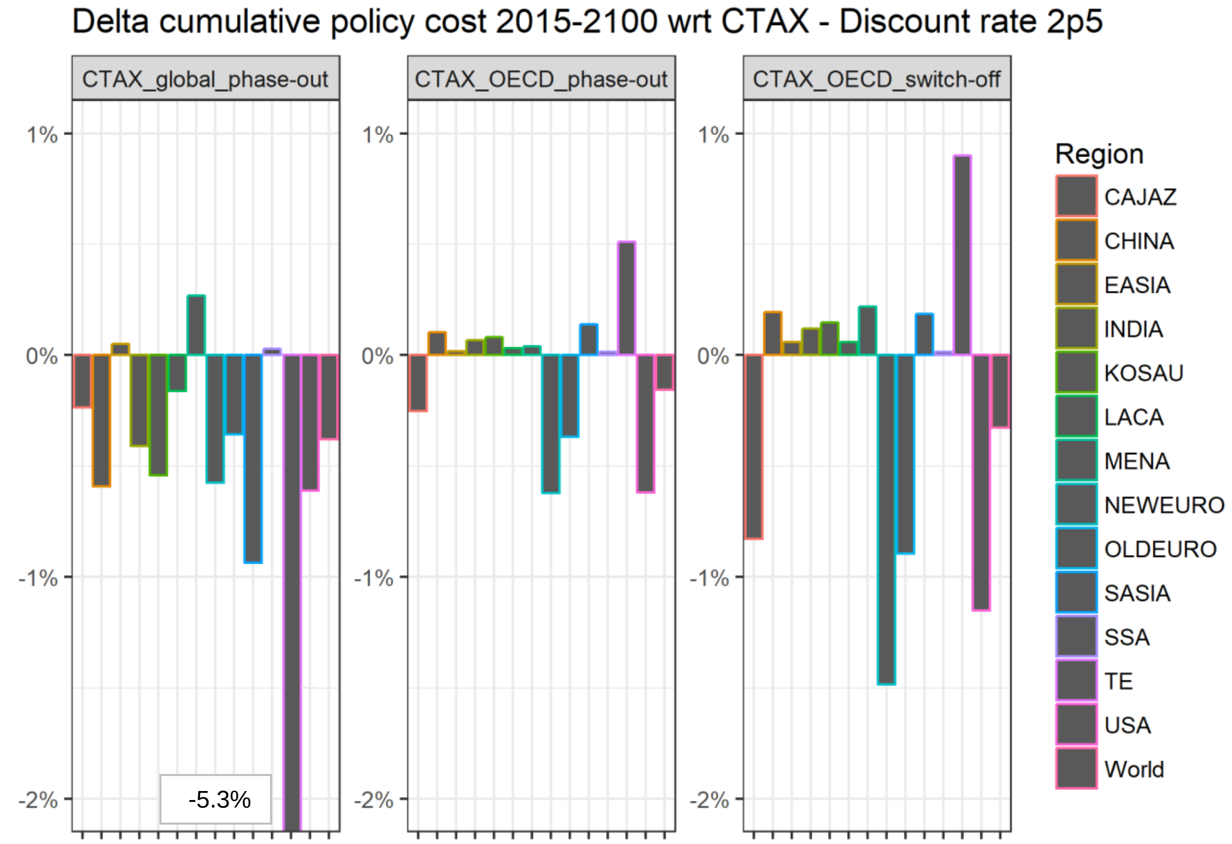

Figure 17 – Regional policy costs in the mitigation scenarios: difference with respect to the CTAX scenario.

The TE result immediately emerges in the CTAX_global_phase-out scenario: the additional GDP loss is 5.3%, markedly more than any other region in all the considered scenarios. Considering that the GDP loss in the CTAX scenario is already equal to 23%, this means an overall loss of more than 28%. The reason must be found in Figure 11: TE is the region that would invest more in nuclear, and the innovation benefits related to renewables are completely insufficient to compensate the absence of a technology that, in the unconstrained CTAX scenario, would almost reach 60% of the generation share towards mid-century. All the other regions are not extraordinarily affected by the global phase-out (the additional losses are within 1%). The specific results, however, depend on the nuclear penetration that would be achieved in the unconstrained scenario, therefore it is not surprising that SASIA, CHINA, INDIA, and NEWEURO show the highest additional losses and that the three regions where nuclear would not be deployed anyway, i.e. EASIA, MENA, and SSA, even gain (although quite marginally) from the global phase-out. MENA, in particular, can benefit from the slightly higher gas demand, to be used in CCS plants, which translate into higher exports. The global additional GDP loss is less than 0.4%, again highlighting the almost total compensation of the policy cost via the innovation benefits. To put this number in perspective, an equivalent scenario with a constraint applied to CCS instead of nuclear would entail a 5%-growth in the policy cost (Carrara, 2019), which is even more remarkable considering the lower average share over the century that CCS would achieve in the unconstrained policy scenarios with respect to nuclear.

If the phase-out is limited to the OECD regions (CTAX_OECD_phase-out), a clear polarization is found. The OECD regions show the economic loss of renouncing nuclear, even if being the only regions which phase out nuclear does not cause any additional costs with respect to the global phase-out scenario (i.e. the additional GDP loss in the OECD regions is practically the same in the central and in the left-hand graphs). The non-OECD regions show very marginal benefits (apart from TE, for the reasons described above), essentially related to the lower costs of uranium deriving from the OECD phase-out.

Finally, the CTAX_OECD_switch-off shows the same qualitative behavior as the CTAX_OECD_phase-out scenario, even if results are quantitatively more marked, given the higher stringency of the technological constraint. The OECD regions show an additional GDP loss which is averagely around 1%, while the relative gain in the non-OECD regions is averagely 0.2% (almost 1% in TE), i.e. losses and gains approximately double.

6. Conclusions

Nuclear is expected to be one of the key technologies in the future power landscape, especially if mitigation policies are implemented. Its main advantage consists in generating electricity with a consolidated and well-known technology without emitting carbon dioxide. However, many issues, and especially public acceptance, hinder its deployment in many areas of the world. This is added to concerns about nuclear proliferation and waste management, the shortage of qualified workforce in the reactor construction and high or uncertain costs.

The nuclear landscape is very polarized between OECD and non-OECD countries. The former feature the most numerous fleets, but most reactors are approaching the end of their operational life and governmental policies are in most cases against further nuclear development and only consider dedicated investments for the lifetime extension of existing reactors. The latter instead, apart from some regions which do not feature and do not intend to invest in nuclear, show higher momentum and more ambitious expansion plans, especially China, India, and Russia.

This work has explored the techno-economic implications of policy-relevant nuclear scenarios, designed on the actual prospects for this technology in the world regions, i.e. mainly differentiating policy constraints between OECD and non-OECD regions.

Results show that global nuclear generation is expected to grow in all unconstrained scenarios (BAU and CTAX), with a higher growth in the policy case, as in this scenario nuclear partly compensates the retirement of fossil plants. If constraints (phase-out and switch-off) are applied to nuclear in the OECD regions, nuclear growth is more moderate and is in line with the BAU scenario. Naturally, in the CTAX_global_phase-out, nuclear generation globally tends to zero over few decades. The considerable growth in terms of generation does not correspond to an analogous marked growth in terms of share in the electricity mix, as the overall electricity demand grows accordingly. Indeed, in the policy scenarios the share does significantly increase in the first decades, but then it approximately returns to the 2015 levels, in correspondence of the huge expansion of renewables (notably wind and solar PV) which prevail on nuclear and CCS in the mitigation portfolio. The huge expansion of variable renewable energies entails the deployment of a substantial storage capacity, which is needed to ensure grid stability.

The electricity landscape is not very different in Europe. However, this region is characterized by low availability of CO_2 storage sites and by high renewable potential and technology maturity, which hinder the penetration of CCS technologies. Therefore, power generation is dominated by wind and solar without major alternatives.

The implementation of a mitigation policy has well-known negative economic effects (the cumulative global GDP loss over the century is about 8% with respect to the baseline scenario), especially in the fossil exporting countries (23% GDP loss in MENA and TE), as the need for decarbonization implies a strong reduction in fossil consumption. The additional policy costs related to the nuclear constraints, however, are not substantial, as most regions have an additional GDP loss of less than 0.5% (0.4% at a global level): this happens because the phase-out costs are almost completely compensated by the innovation benefits in the renewable and the overall energy efficiency areas stimulated by nuclear phase-out. TE shows an additional 5%-loss, being the region that would have the highest nuclear penetration in the unconstrained scenarios. If constraints are applied to the OECD regions only, no additional losses are found in these regions with respect to the global phase-out scenario, while the non-OECD regions slightly benefit from the lower uranium costs. The CTAX_OECD_switch-off scenario simply exacerbates these results: the average additional GDP loss in the OECD regions and the average GDP gain in the non-OECD regions approximately double.

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