DELIVERABLE No 1.2

Interactions and joint applications between the WITCH and the SWITCH models

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Interactions and joint applications between the WITCH and the SWITCH models

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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 is Prof. Massimo Tavoni, while the Supervisor at UC Berkeley is Prof. Daniel M. Kammen.

The project lasts two years. It started on January 16, 2017 and it will finish on January 15, 2019. The first year is dedicated to the outgoing phase at UC Berkeley, while the second year is 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. 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.

1.3 Note on Work Package 1 and Scope of Deliverable D1.2

According to the proposal, the first year of the MERCURY project (corresponding to Work Package 1 – "Power sector modeling improvements") is dedicated to the improvement of the power sector modeling in the WITCH model, adopting the SWITCH model as a reference. As reported in the previous section, WITCH is the Integrated Assessment Model developed at FEEM, while SWITCH is the detailed energy model developed at the Renewable & Appropriate Energy Laboratory of the University of California, Berkeley. As mentioned, four main aspects are considered in WP1: 1) system integration of Variable Renewable Energies into the electrical system (Task 1.2), 2) electricity storage (Task 1.3), 3) electrical grid (Task 1.4), and 4) electricity trade (Task 1.5). Two deliverables were planned with reference to these activities: the first one (D1.1 – "Power infrastructure modeling improvements in WITCH") was dedicated to Tasks 1.2, 1.3, and 1.4, while the second one (D1.2 – "Electricity trade in WITCH") was dedicated to Task 1.5.

During the first months of the project, however, two issues arose in this context.

First of all, it became clear that a more interactive, two-way collaboration between the two models could be more fruitful than the mere improvement of WITCH referring to SWITCH: on the one hand, as planned, WITCH was improved also taking inspiration from SWITCH (in addition to the IAM literature), but on the other hand more direct interactions between the two models, as well as the possibility to integrate SWITCH in an integrated assessment model framework, were explored.

Additionally, a more in-depth analysis of the issue questioned the actual necessity and value added of implementing electricity trade in the WITCH model. After all, this point is not considered among the priorities in the IAM research community as far as the power sector modeling is concerned.

In this light, Task 1.5 has been diverted accordingly, with a consequent, partial revision of the deliverable plan of the first year. D1.1 has remained the same in terms of content, but it has been renamed "Power sector modeling improvements in the WITCH model". D1.2 is instead dedicated to the interactions between WITCH and SWITCH and is called "Interactions and joint applications between the WITCH and the SWITCH models".

2. The SWITCH model

SWITCH (Solar and Wind energy Integrated with Transmission and Conventional sources)[1] is a linear programming model used to investigate the least cost energy system design to meet specific performance and environmental objectives (Fripp, 2012 and Nelson et al., 2012). Its objective function is to minimize the cost of producing and transporting electricity through the construction and retirement of power generation plants, storage technologies, and transmission grid options between the present day and future target dates according to projected demand. In particular, as regards the grid, SWITCH optimizes both its long-term investments and its short-term operation through the optimization of the hourly generation and transmission dispatch. As regards SWITCH temporal dimension, for each month of the year, two characterizing days are considered: the peak and median load days. For each day, six characterizing hours are included.

SWITCH is normally applied to specific countries or sub-areas of large countries, e.g. Nicaragua (Ponce de Leon Barido et al., 2015), Kenya (Carvallo et al., 2017), and WECC (Nelson et al., 2012)[2]. SWITCH has also been applied to China (He et al., 2016), which is very useful in the MERCURY project perspective as this region is explicitly modeled in WITCH: this allows a direct comparison of the two models, as will be described the next sections.

3. Linking WITCH and SWITCH

D1.1 has already thoroughly described the issue of climate change and the importance of having advanced modeling tools in order to carry out credible research activities in this sector. In particular, describing the characteristics of Integrated Assessment Models, it has been pointed out that these are very effective tools to capture the multi-dimensional nature of climate change, even if, on the other hand, their broad

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[1] https://rael.berkeley.edu/project/switch/

[2] The acronym WECC stands for Western Electricity Coordinating Council, which encompasses fourteen Western states of the United States, the Canadian provinces of Alberta and British Columbia, and the northern portion of Baja California, Mexico.

scope makes it difficult to properly describe specific issues like system integration of Variable Renewable Energies (VRE).

The sense of the collaboration between FEEM and RAEL in the MERCURY project essentially starts from here. As described in Section 2, SWITCH is a detailed electricity model which cannot capture the impacts of the different evolution patterns of this sector on the rest of the energy sector, the economy or climate, but on the other hand it is more able to capture specific details that are missing in IAMs (Collins et al, 2017), and in particular in WITCH (Bosetti et al., 2006 and Emmerling et al, 2016).

The ideal solutions would be to carry out a full integration of the two models leveraging the strengths and compensating the weaknesses of both, but this is beyond the objectives of this research project. In the following, the general guidelines of this possible integration are briefly described, while the next two sections discuss two more extensive examples of joint applications of the WITCH and SWITCH models.

Table 3.1 briefly describes the main features of WITCH and SWITCH.

Feature	**WITCH**	**SWITCH**
Model class	Inter-temporal general equilibrium model	Partial equilibrium electricity system model
Modeling scheme	Inter-temporal optimization with perfect foresight	Inter-temporal optimization with perfect foresight
Temporal resolution	• 5-year time steps (2005-2100) • Average yearly values	• Investments: 10-year time steps (2010-2050) • Dispatch: hourly basis
Spatial resolution	Global (13+ regions)	~ National (+ local load areas)
Electricity demand and fuel prices	Endogenous (model output)	Exogenous (model input)
Model output (among others)	Electricity mix, capacities…	Electricity mix, capacities…

Table 3.1 – Main features of WITCH and SWITCH.

Table 3.1 indirectly suggests how the potential integration between and WITCH and SWITCH could be developed: WITCH would perform a global optimization, which would yield the electricity demand and fuel prices as model outputs. These parameters are normally exogenous in detailed models like SWITCH: being disconnected from the rest of the energy or economic sector, there is no way to endogenously calculate or optimize them. These parameters would now be used as inputs in SWITCH, which could calculate with higher detail the electricity sector of a region, possibly further disaggregating it into countries or sub-areas. Figure 3.1 summarizes this workflow for a potential application in the European Union (which, of course, would start from the development of the European version of the SWITCH model, that is currently missing).[3]

WORKFLOW

1. Development of SWITCH-EU
2. Run of WITCH

   → Global optimization

Western EU (+ EFTA) and Eastern EU or Europe as a whole
Input: Electricity demand, fuel prices, etc.
Constraint: regional electricity mix

3. Run of SWITCH with a national detail (32 countries)

   → National detail of load, grid, etc.

Figure 3.1 – Integrating WITCH and SWITCH: a potential application to the European Union.[4]

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[3] It is reminded that the EU is divided into two regions in WITCH, oldeuro and neweuro. Runs with an aggregation of the two regions into only one overall EU region can be performed as well.

[4] EFTA stands for European Free Trade Association consisting of the main four Western European states not belonging to the EU, i.e. Iceland, Liechtenstein, Norway, and Switzerland. For the sake of simplicity, these countries are included into the oldeuro region in WITCH.

4. Comparing grid and storage modeling in WITCH with SWITCH

Thanks to its high temporal and spatial resolution, predictions performed by SWITCH about the development of the investment in grid projects can be considered a reliable term of comparison. As a consequence, the first activity where the two models have been used has been the evaluation of the consistence of the results obtained with the new WITCH modeling (described in D1.1 and in Marni and Prato, 2017) – especially focusing on the investments in grid – through a SWITCH based study. As anticipated in Section 2, China has been considered as the reference region, as it is explicitly modeled both in WITCH and SWITCH (He et al., 2016). Thanks to the direct contact with the authors of the article at UC Berkeley, it was also possible to access additional information not reported in the paper.

The aim of this study was to investigate different possible paths for decarbonizing the Chinese power sector in the 2010-2050 time span. In particular, attention was focused on the SWITCH-China IPCC scenario that involves an overall power sector carbon emission target of 80% below the 1990 level baseline in 2050, as proposed in the 2°C scenario suggested by the IPCC (IPCC, 2014). This scenario was chosen because it envisions the highest installation of VREs capacity and one objective in the comparison was specifically to test the behavior of the new WITCH formulation with high shares of VREs. The SWITCH results include the extension planning of the transmission lines between China load areas[5] and its related investments. On the other hand, the distribution related investments are represented just in an approximated way. The distribution network in each area is built to serve the peak load of 2010. In the future, the peak load is assumed to be a liner function of the demand, and so are the related investments. Finally, results also include the electricity production mix and the generation and storage technologies installed capacities in each timestep.

Figure 4.1 shows a comparison of the overall annual grid investments in transmission and distribution as a function of the VRE share between the WITCH and SWITCH results. Three different WITCH scenarios are represented. WITCH CTAX100 is a scenario where a constant carbon tax of 100 $2011/tCO_2$ is applied from 2020. It is shown because in this scenario the CO_2 emissions of the Chinese power sector approximately follow the assumption of the SWITCH IPCC scenario. However, since such a carbon tax is not sufficient in an integrated assessment model like WITCH to significantly transform the generation mix, only a VRE share of 36% can be reached. Therefore, in order to investigate the WITCH results behavior with higher shares of VREs, the CTAX and CTAX2DEG scenarios are also displayed. In the CTAX scenario a

[5] In SWITCH, China is divided into 31 load areas connected by transmission lines.

moderate carbon tax, starting from 30 \$2005/tCO2eq in 2020 and increasing at an annual rate of 3.5%, is applied to carbon emissions; in the CTAX2DEG scenario, a carbon tax is applied to carbon emissions in order to achieve a temperature increase of 2°C in 2100 with respect to the pre-industrial levels with a likely chance. In order to compare it to the previous scenario, this entails an annual growth rate of about 7%. It could be noted that the trend of the overall grid investment as a function of the VRE share is similar in these scenarios as well.

The SWITCH IPCC and the WITCH CTAX2DEG curves are partially diverging at VRE shares higher than 60%. Due to the limited amount of data available from the SWITCH-China study, it has not been possible to better compare the behavior at VRE shares higher than 60%. However, the order of magnitude of the investments is similar, as they increase from 18 bln\$/yr at a 16% VRE share to 99 bln\$/yr at a 66% VRE share for the SWITCH IPCC scenario, while they grow from 55 bln\$/yr at a 13% VRE share to 175 bln\$/yr at a 73% VRE share for the WITCH CTAX2DEG scenario. The higher WITCH values can be explained by the fact that the distribution related costs are described in more detail than in SWITCH, where they just grow linearly with the demand. Moreover, the larger difference at higher shares of renewable can be attributed to the additional investments in grid pooling required in WITCH that at the distribution level cannot be captured by SWITCH due to its not detailed formulation. Finally, it should be highlighted that, while the 66% VRE share is reached already in 2050 in the SWITCH IPCC scenario, in the CTAX2DEG the highest share is obtained only in 2100.

Figure 4.2 reports a comparison of the ratio between the installed capacity of storage technologies and of VREs. The graph highlights that the general trend with growing VRE share is similar for the SWITCH IPCC and the CTAX2DEG scenarios. On the contrary, the behavior of the WITCH CTAX100 and CTAX scenarios, at shares lower than 40%, appears to be really different. This could be explained by the fact that when in WITCH the carbon tax is not high enough (CTAX100 and CTAX before reaching 30% share), it does not foster the installation of high shares of VREs. The model, however, tries to push in this direction installing more storage capacity per unit of VRE capacity.

The higher capacity installation of storage in WITCH with respect to SWITCH can be explained focusing on the purpose of storage technologies in SWITCH. In SWITCH, electric storage contributes to meeting the load and providing operating reserve and capacity reserve margin. Thus, it can store VREs production in order to shift it and meet the load. On the other hand, storage cannot exploit VREs curtailment that is just wasted. Therefore, the installed capacity K_STOR_CURT that can store the VREs curtailment in WITCH (see D1.1) is missing in SWITCH. As a consequence, it probably makes more sense to compare only the storage capacity that is installed in WITCH to supply the peak load with the SWITCH storage capacity (K_STOR_PEAK).

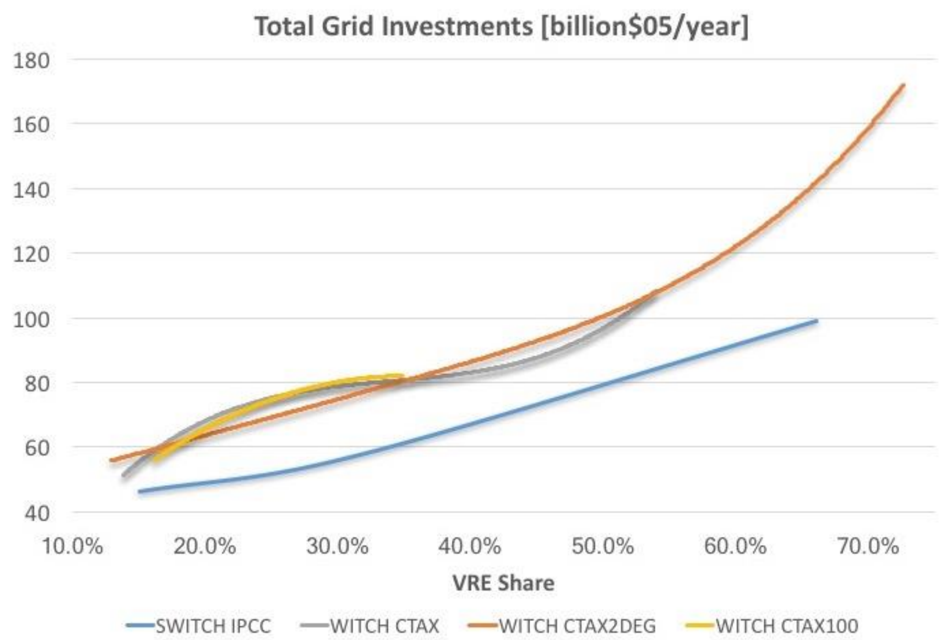

Figure 4.1 – Comparison of total investments in grid as a function of the VRE share (after curtailment for WITCH) in China in the WITCH and SWITCH models.

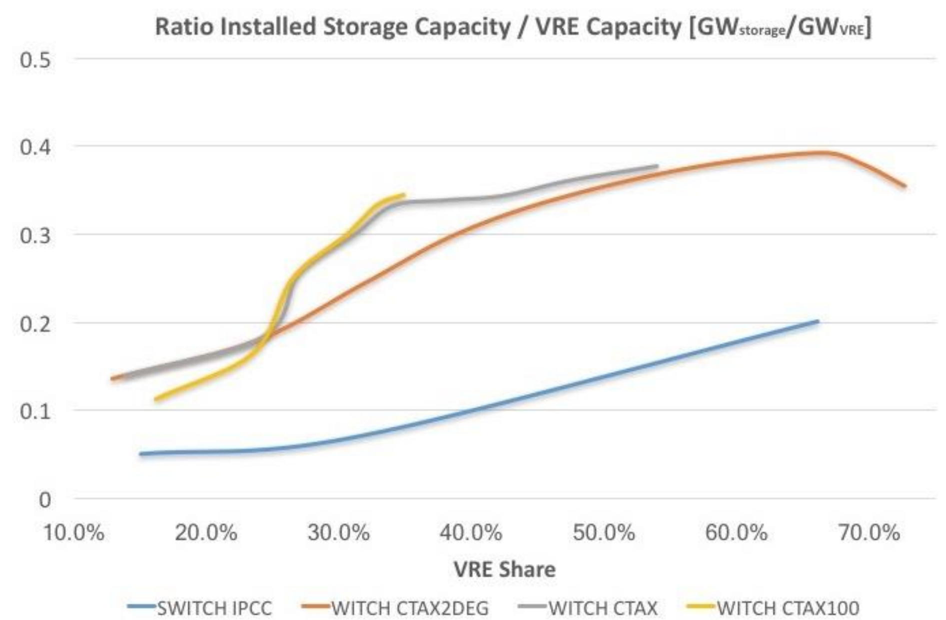

Figure 4.2 – Comparison of the trend of the ratio between the installed capacity of storage and VRE as a function of the VRE share (after curtailment for WITCH) in China in the WITCH and SWITCH models.

Figure 4.3 thus shows this second curve called WITCH CTAX2DEG (Only K_STOR_PEAK) for the CTAX2DEG scenario. Only the SWITCH IPCC and the WITCH CTAX2DEG scenarios are considered here because the highest VREs share is reached in the latter. It can be noted that the gap between the SWITCH and WITCH curves has been reduced considering just the storage capacity type that is modeled also in SWITCH. Moreover, a further observation can be added. In SWITCH, another dispatchable technology whose main aim is to provide operating reserve is represented, i.e. the combustion gas turbine (CGT), which is missing in WITCH. Thus, it could be stated that a portion of the operating reserve required with growing VREs share in SWITCH is provided by CGTs and not by storage. To validate this conclusion, a fourth curve representing the behavior of the ratio between the sum of storage and CGT capacities and VREs one in SWITCH can be seen in Figure 4.3, called SWITCH IPCC (Storage + CGT). Indeed this ratio starts at much higher values than the WITCH storage one at low VREs shares, but this can be explained considering that in 2015 a certain capacity of CGT was already installed in China (PEI, 2015) and at low VREs shares CGT is however a cleaner solution than coal power plants. Then, at high VREs shares it can be noted how the WITCH CTAX2DEG (Only K_STOR_PEAK) and SWITCH IPCC (Storage + CGT) curves converge, meaning that the storage capacity K_STOR_PEAK is well representing the overall dispatchable capacity requirement per unit of installed VREs capacity.

There are other differences between WITCH and SWITCH that can clarify why there is a gap between the installed storage capacity in the two models and why the CGT is partially preferred in SWITCH, however. The storage capacity shown in Figure 4.3 for SWITCH just refers to NaS (Sodium–sulfur) batteries with a round-trip efficiency of 76.7%, well lower than the 85% characterizing the Lithium-ion batteries modeled in WITCH. Moreover, in SWITCH the capacity of PHES (Pumped Hydro Energy Storage) is maintained constant at the initial value, while CAES (Compressed Air Energy Storage) is not considered at all. Therefore, modeling the use of Lithium-ion batteries with higher efficiency may make the battery technology more convenient because it would entail lower losses; the introduction of CAES and the possibility of future projects for PHES (since this technology is still characterized by a big potential in China) should also be taken into account because they may foster the installation of storage capacity (for more details see D1.1 and Marni and Prato, 2017).

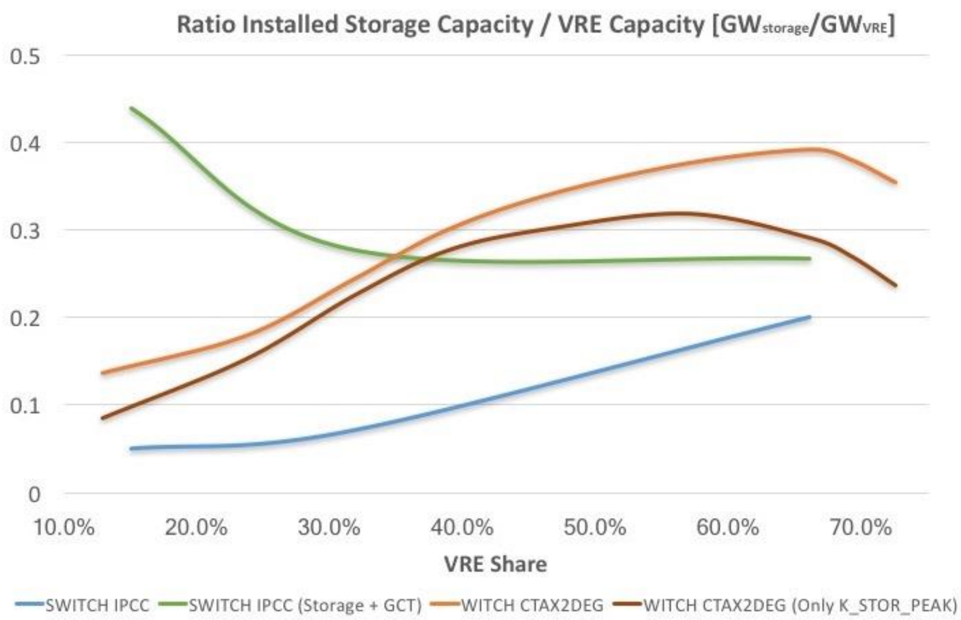

Figure 4.3 – Comparison of the trend of the ratio between the installed capacity of storage and VRE as a function of the VRE share (after curtailment for WITCH) in China in the WITCH and SWITCH models considering only K_STOR_PEAK for the former and storage plus the capacity of combustion gas turbines for the latter.

5. Dynamics of decarbonization

The second activity where the WITCH and SWITCH models have been tested is the so called dynamics of decarbonization. The objective is to study the effects that different carbon price levels can have in defining technological deployment patterns in the power sector. Again, the idea is to compare how this is captured by a detailed electricity model like SWITCH and a more general Integrated Assessment Model like WITCH, always taking China as the reference country/region. The activity started during the outgoing period at UC Berkeley and it is still at its early stage. The first series of scenarios have been run and the preliminary analysis of the results has been performed: this will be discussed in this document. In the next months the collaboration with RAEL at UC Berkeley will continue and the activity will be further developed.

The scenario matrix is very simple: eleven scenarios have been run implementing a constant carbon tax applied from 2020 to 2050[6] and set at increasing values in the different scenarios: 10 \$2011/tCO_2, 20 \$2011/tCO_2, …, up to 100 \$2011/tCO_2.[7] These scenarios have been complemented by the benchmark scenario with no carbon tax (baseline or Business-as-Usual, BAU).

Figures 5.1 and 5.2 show the evolution of carbon dioxide emissions from the electricity sector in the different scenarios according to the two models. The emission patterns are quite similar, even if emissions in the baseline scenario are a bit higher in WITCH. Both models project that emissions will become zero in the high tax scenarios, even if in SWITCH this level is reached quite early (i.e. in 2030), with a constant behavior afterwards, while WITCH shows a more regular decrease. However, the main point that leaps to the eye is the evident distance between the 30 \$/tCO_2 and 40 \$/tCO_2 scenarios in WITCH. Indeed something similar happens in SWITCH as well, even if it is less marked and is more referred to the 20-30 \$/tCO_2 scenarios.

Figures 5.3 and 5.4 report the cumulative amount of emissions in the period 2010-2050: in addition to the obvious decrease of this quantity at increasing levels of carbon tax, a clear discontinuity in the slope is visible in correspondence of the abovementioned tax values, especially in WITCH but also in SWITCH.

What leads to this emission pattern? Figure 5.5 shows the different electricity mix as optimized by the two models in four selected scenarios: BAU, TAX 20, TAX 50, TAX 100. First of all it is reminded that the electricity demand is exogenous in SWITCH, and it is kept practically constant across scenarios (achieving about 57 EJ/yr in 2050). This means that the electricity mix changes, but the overall demand does not change (if not negligibly, due to VRE curtailment and other technical aspects). WITCH instead endogenously optimizes this quantity. In particular, the demand in WITCH is higher than in SWITCH in the BAU scenarios (it is 66 EJ/yr in 2050), then it progressively diminishes, being significantly lower in the TAX_100 scenario (slightly more than 42 EJ/yr in 2050). Both WITCH and SWITCH project a dominance of coal in the baseline scenario. The implementation of higher and higher carbon taxes then results in a deeper and deeper decarbonization: this takes place more thanks to nuclear and CCS (Carbon Capture& Storage) in SWITCH, while renewables (especially wind) have the lion's share in WITCH.

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[6] It is reminded that, whereas WITCH covers the whole 21st century, the SWITCH temporal horizon is limited to 2050.

[7] For the sake of simplicity, the indication of the year (2011) will be avoided in the following.

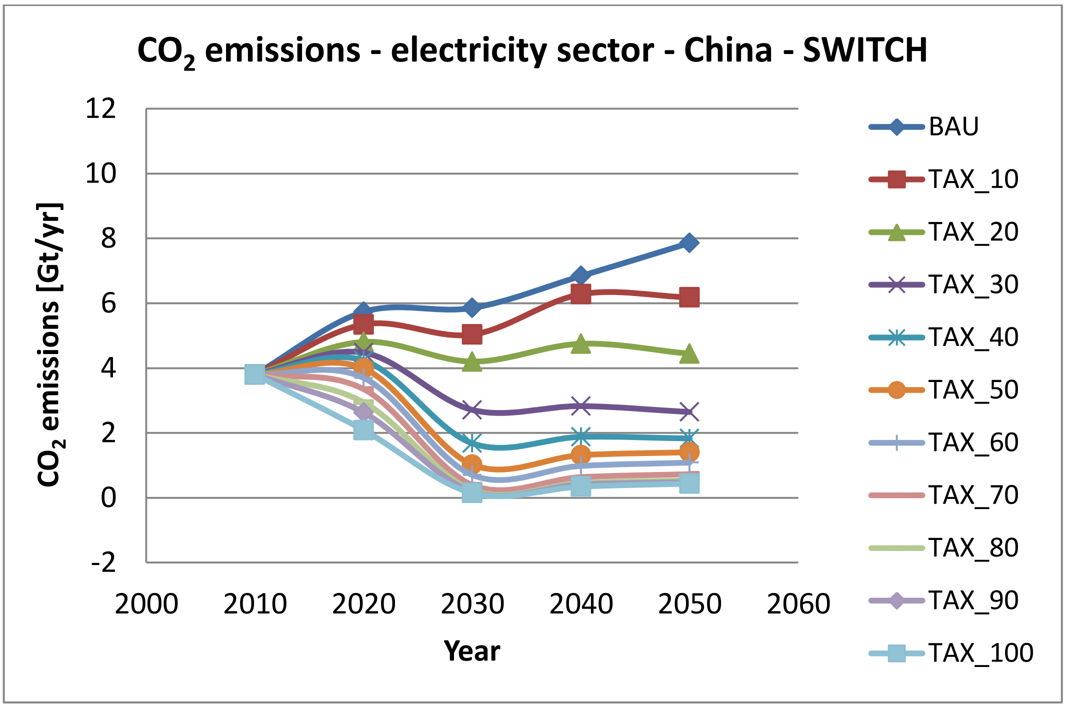

Figure 5.1 – Carbon dioxide emissions in the electricity sector in China in SWITCH.

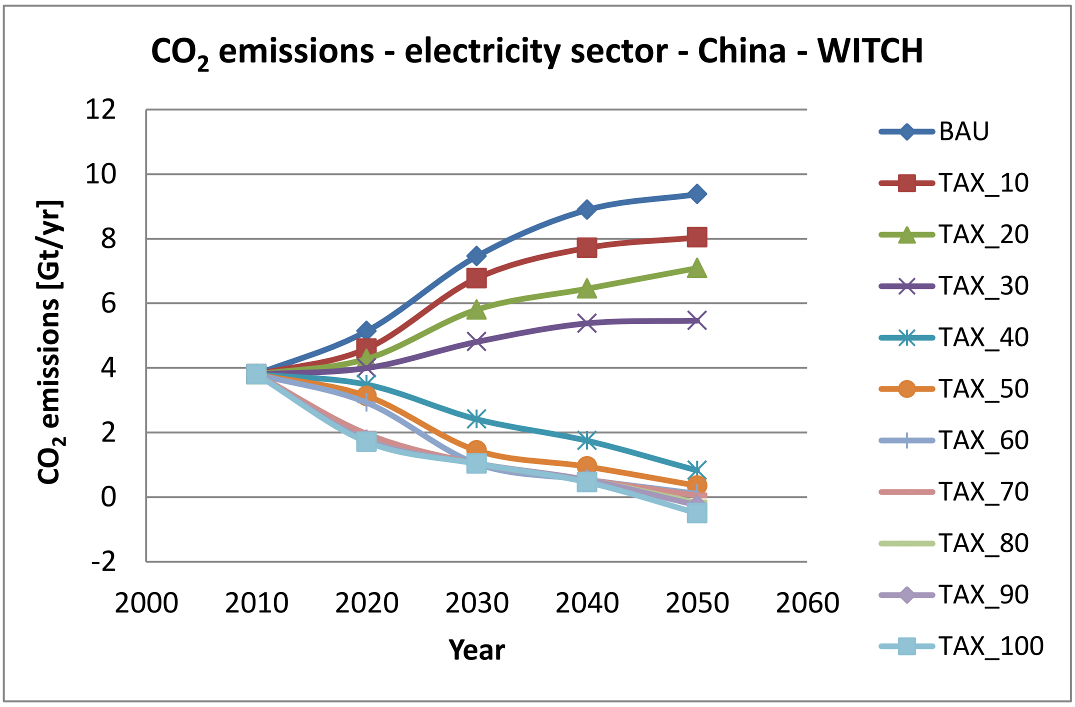

Figure 5.2 – Carbon dioxide emissions in the electricity sector in China in WITCH.

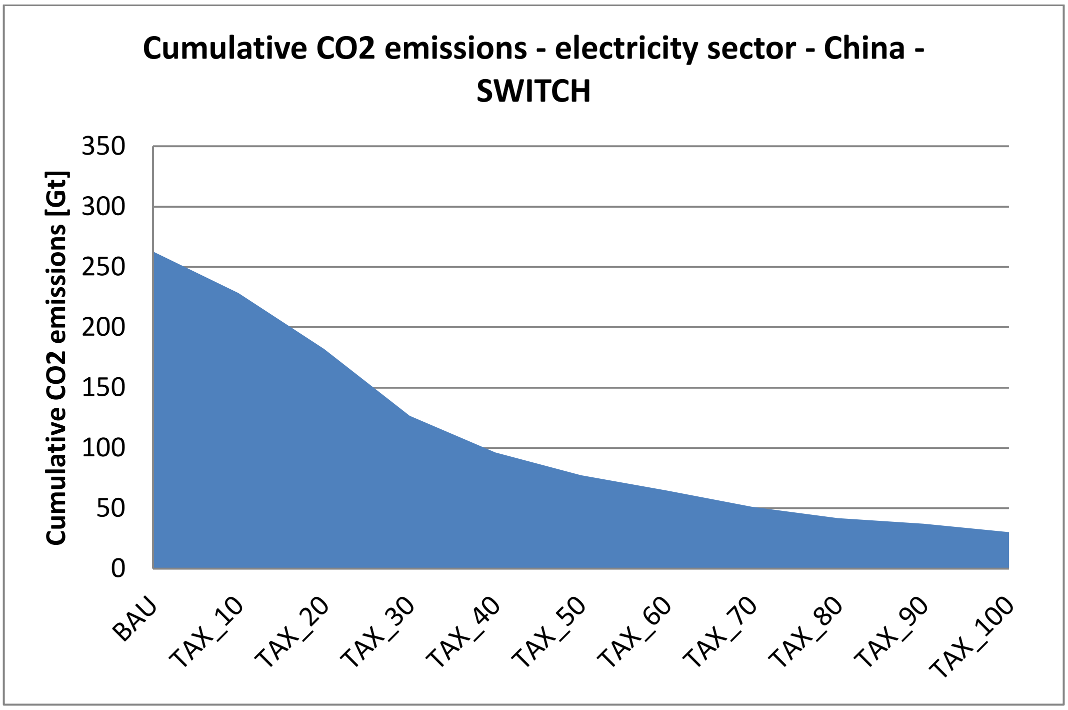

Figure 5.3 – Cumulative CO_2 emissions in the electricity sector in China in SWITCH.

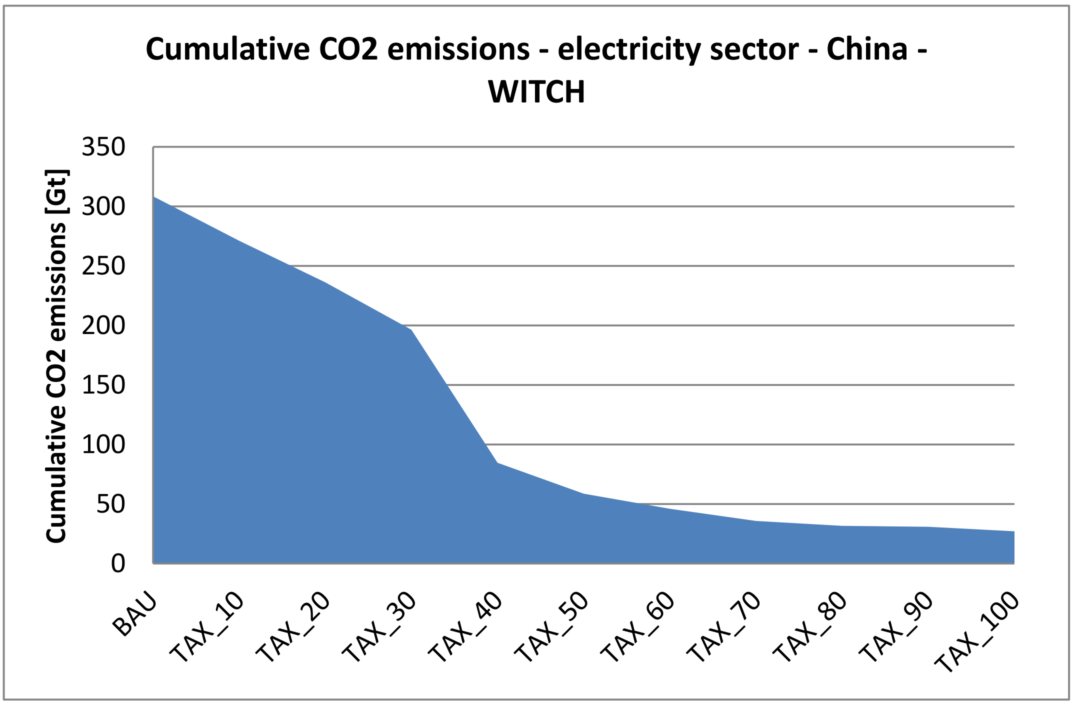

Figure 5.4 – Cumulative CO_2 emissions in the electricity sector in China in WITCH.

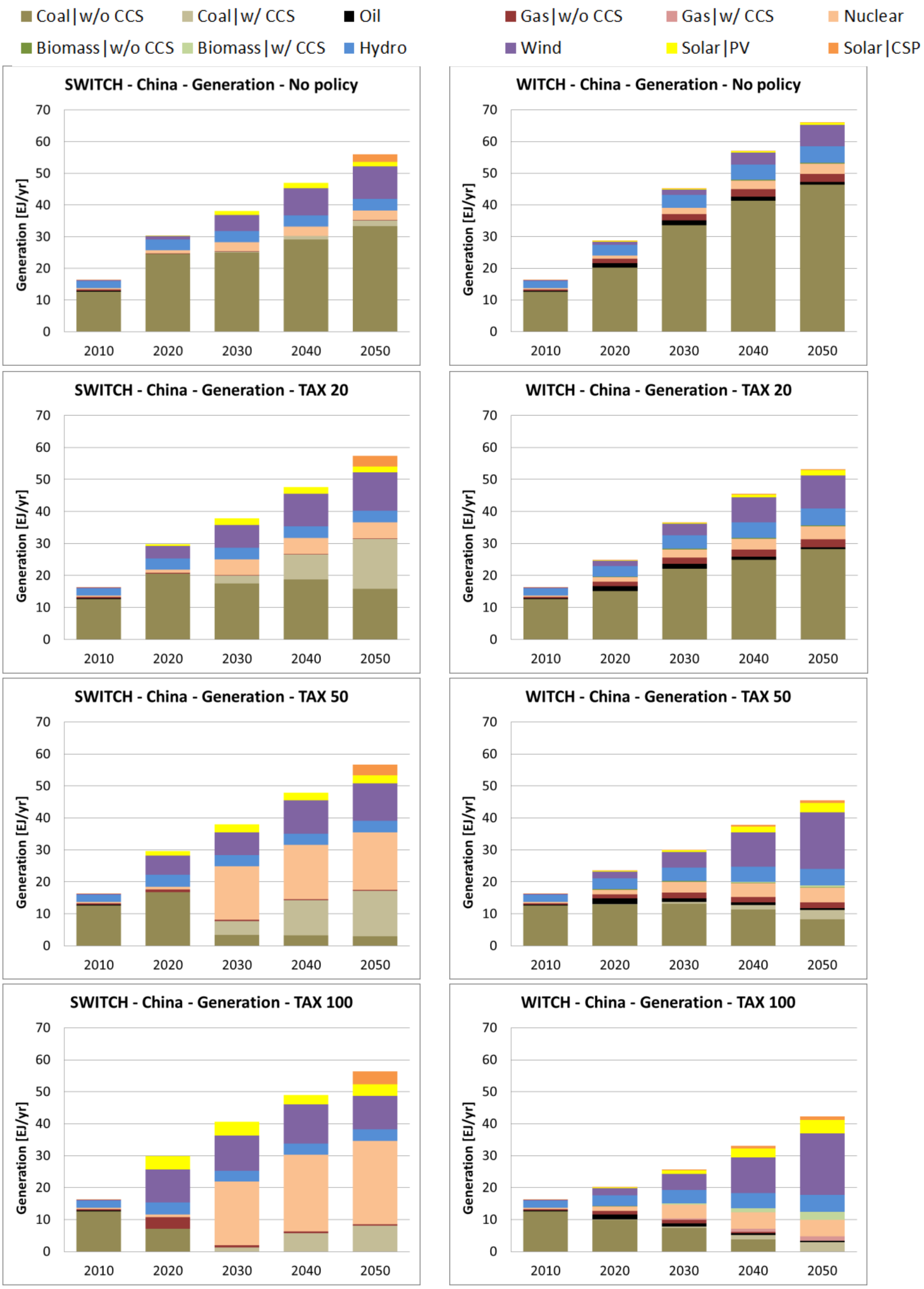

Figure 5.5 – Electricity mix in China in SWITCH and WITCH in selected scenarios.

In WITCH, in particular, a marked change is visible between the TAX_20 and TAX_50 scenarios (Figures 5.2 and 5.4 indeed show that the actual jump is between the TAX_30 and TAX_40 scenarios, as already noted).

This sort of transition is better shown in Figures 5.6 and 5.7, which essentially summarize the sense of the dynamics of decarbonization: the graphs show the "marginal" change in the penetration of one technology with respect to the previous carbon tax level in percentage terms. In SWITCH the behavior is quite smooth, even if the "discontinuity" highlighted in Figures 5.1 and 5.3 between the 20 $/tCO$_2$ and 30 $/tCO$_2$ levels can be noted: this is the level where coal without CCS shows the strongest reduction (even if it does not disappear in the highest carbon tax levels), while nuclear has the strongest increase. In WITCH the discontinuity is more dramatic, and Figure 5.7 shows it quite clearly: coal without CCS is almost completely phased out passing from 30 $/tCO$_2$ to 40 $/tCO$_2$, while coal with CCS enters the electricity mix. Indeed, in absolute terms the penetration of the latter technology, as already pointed out, will be quite negligible: the mix will progressively be dominated by renewables, which show a more regular but constant growth, especially at low levels of carbon tax (see also Figure 5.8 which reports the very same results as Figure 5.7, but with a better focus on the low values on the y-axis)

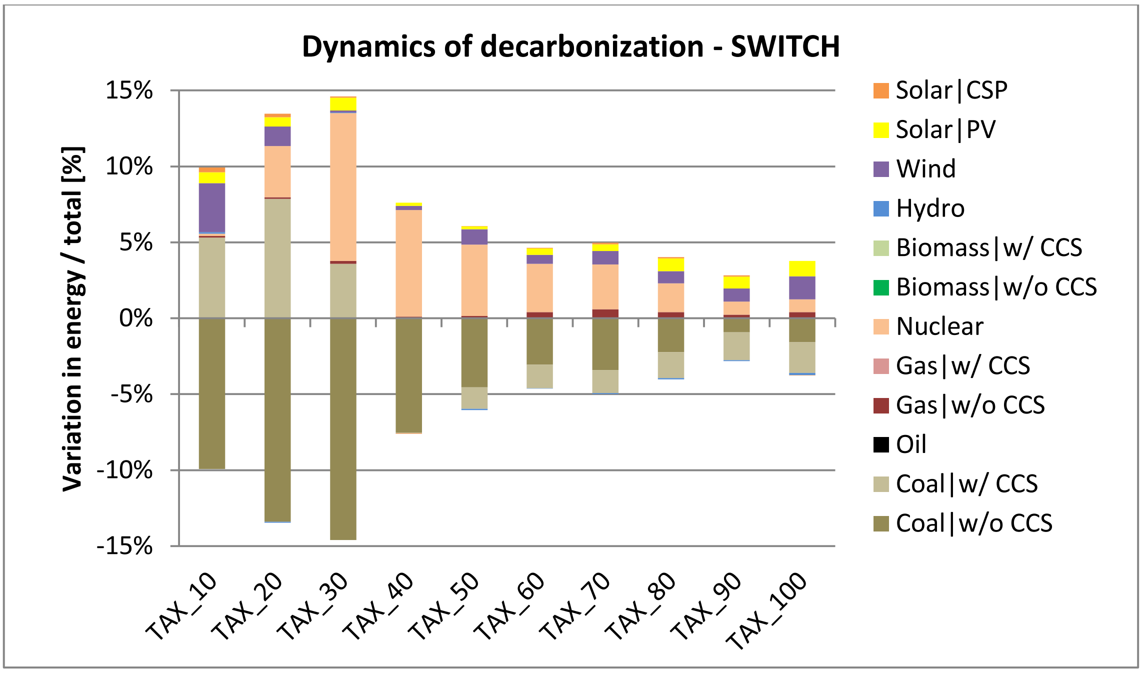

Figure 5.6 – Dynamics of decarbonization in the electricity sector in China in SWITCH.

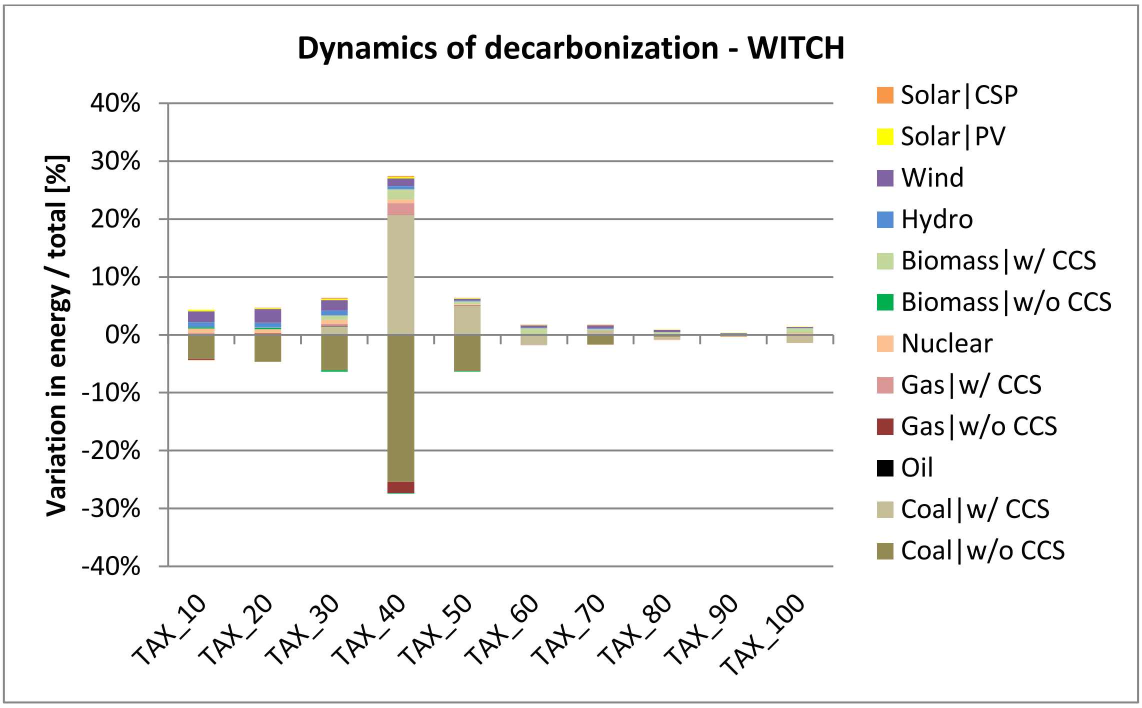

Figure 5.7 – Dynamics of decarbonization in the electricity sector in China in WITCH.

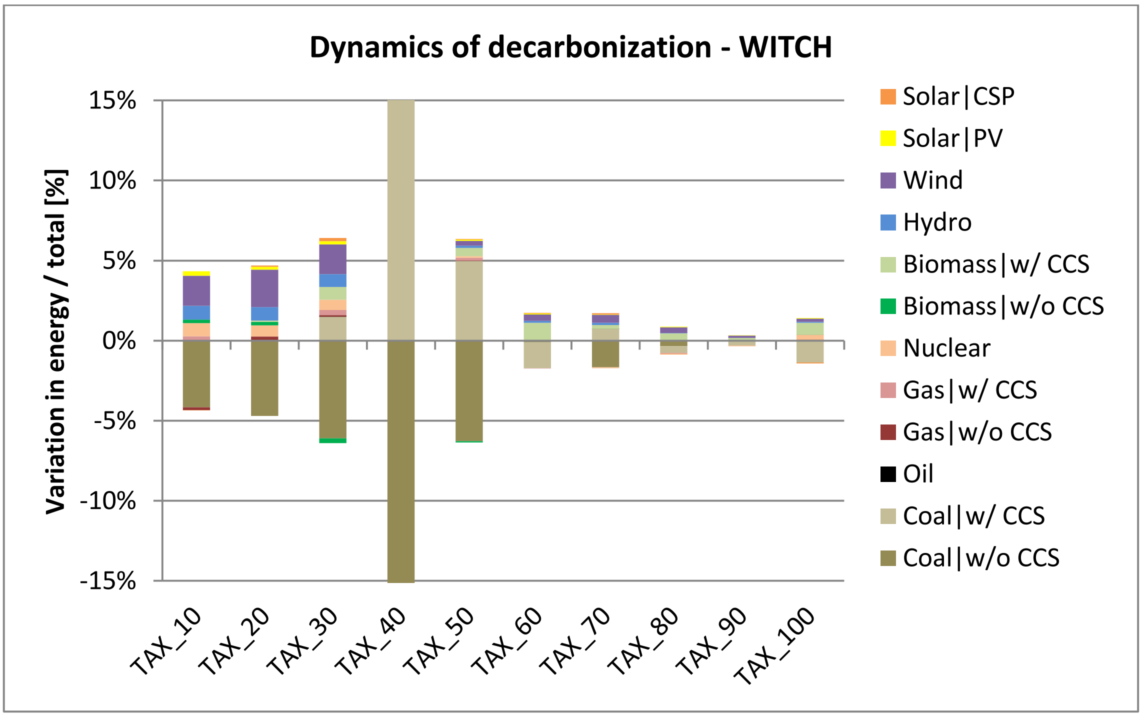

Figure 5.8 – Dynamics of decarbonization in the electricity sector in China in WITCH (closer view at low values on the y-axis).

In conclusion, the analysis has highlighted a non-linear (or non-smooth) behavior resulting from a set of "tipping points" in decarbonization pathways. This behavior suggests that a carbon tax calibrated on the specific conditions of the electricity system should be implemented in order to achieve decarbonization in an effective and efficient way. It is in fact clear that in WITCH a carbon tax of 40 $/t$CO_2$ triggers a regime shift, while higher and higher levels of carbon tax have only marginal effects. On the other hand, it must be underlined that carbon prices define innovation pathways for power systems that may be mutually exclusive: this implies the possibility of locking into sub-optimal low-carbon solutions.

As discussed at the beginning of this section, these are just preliminary results, however. The dynamics of decarbonization will be further explored in the second year of the project, also analyzing the role of storage and grid.

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