Decarbonisation Strategies Implementing Biochar as a Carbon Capture Technology

by

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Abstract

The energy system is changing since some years in order to achieve the climate goals from the Paris Agreement which wants to prevent an increase of the global temperature above 2 °C [1]. Decarbonisation of the energy system has become for governments a big challenge and different strategies are being stablished. Germany has set greenhouse gas reduction limits for different years and keeps track of the improvement made yearly. The expansion of renewable energy systems (RES) together with decarbonisation technologies are a key factor to accomplish this objective.

This research is done to analyse the effect of introducing biochar, a decarbonisation technology, and study how it will affect the energy system. Pyrolysis is the process from which biochar is obtained and it is modelled in an open-source energy system model. A sensibility analysis is done in order to assess the effect of changing the biomass potential and the costs for pyrolysis. The role of pyrolysis is analysed in the form of different future scenarios for the year 2045 to evaluate the impact when the CO_2 emission limit is zero. All scenarios are compared to the reference scenario, where pyrolysis is not considered.

Results show that biochar can be used to compensate the emissions from other conventional power plant and achieve an energy transition with lower costs. Furthermore, it was also found that pyrolysis can also reduce the need of flexibility. This study also shows that the biomass potential and the pyrolysis costs can strongly affect the behaviour of pyrolysis in the energy system.

1 Introduction

Decarbonisation of the energy sector is one of the main objectives for all governments. The German government has decided recently to re-adapt its climate objectives for achieving climate neutrality in the year 2045 [2]. The expansion of RES together with decarbonisation technologies are a key factor to accomplish this objective. The energy sector is the one who contributes the most to the CO_2 emissions, with an approximate total of 212 million tonnes of CO_2, out of the total 729 emitted in the year 2020 [3].

Therefore, it is of high importance to understand and simulate energy scenarios for upcoming years to appreciate the possible conflicts that may exist in the future network. A simulation with the energy model is performed applying the open source model PyPSA-Eur with the new integration of pyrolysis as a technology which produces simultaneously electricity and biochar. Biochar is a solid material that when it is used as a soil amendment it can reduce CO_2 emissions from the atmosphere.

The aim of this study is to model pyrolysis and assess the effect of having a new technology in the energy system that can reduce emissions and produce electricity. This assessment is done by making different scenarios based on the German government plan for the energy transition for the year 2045. As data for pyrolysis and biomass potential is difficult to find, a sensibility analysis using different values is done to assess the effect of this values in the energy system configuration.

2 Model development

In order to evaluate the effect of biochar into the energy system it has been implemented in the open-source model PyPSA-Eur [4]. Pyrolysis plants have three outputs: oil, biochar and heat. In this model oil is neglected and heat is directly transformed into electricity by the use of another additional technology which is represented by an efficiency factor that is already considered in the efficiency. In short, the output of the modelled pyrolysis plant will be electricity and biochar. Electricity will be used to cover the load and for flexibility measures it can also be used when renewables cannot produce electricity. Regarding the biochar, it will be considered for the model as a carrier which has negative emissions, which means that it can absorb CO_2 from other technologies. This should let other technologies, which produce carbon dioxide, continue emitting further and smooth the energy transition.

The main idea of modelling this new technology is having an input, biomass in this case, and transforming this biomass into electrical energy and biochar. In Figure 1 this main idea is showed.

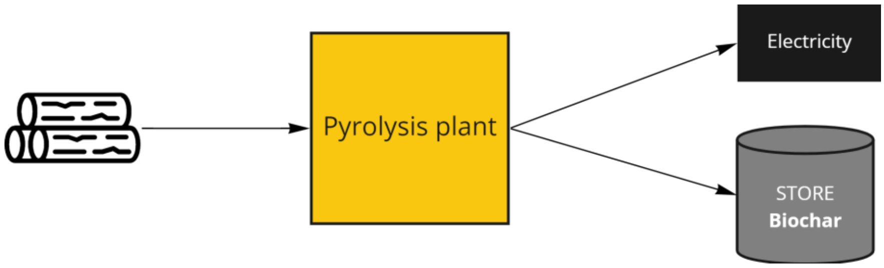

Figure 1: General pyrolysis model.

In order to transform this idea into the energy model system, the following components are needed:

- Store of biomass
  The store of biomass represents the total amount of biomass that is available in each cluster, in other words, how much biomass is available to use for the pyrolysis plant. It is considered that every cluster has its own biomass store and all the stores are completely full at the beginning of the simulation. The store will be optimised and once the simulation is done, the amount of biomass used each hour by the power plant can be tracked.
- Store of biochar and CO_2 carrier
  The biochar store, is where all the biochar output from the pyrolysis plant is going to be kept. With this store it can be tracked how much CO_2 is absorbed from the atmosphere. There is just one biochar store for the whole model, this means that it is not located depending on the clusters. Moreover, all pyrolysis plants will store the biochar output in this same store. This store has attached a new carrier, CO_2 carrier, which has negative emissions and represents the amount of CO_2 that is kept in the product by the production of biochar.
- Link between biomass store and electricity buses and link between biomass store and CO_2 stored
  In order to model the pyrolysis plant, links with their respective efficiency have been used. In this model a link with two possible outputs and two efficiencies has been defined. Moreover, new buses just for the pyrolysis power plant are created, in order to attach the mentioned links and the biomass store to them. One link represents the electricity output, it connects the pyrolysis buses, where the biomass store is attached, with the electrical buses, and they are connected using an efficiency to simulate the transformation of biomass into electricity. The second link represents the biochar output, it connects again the pyrolysis buses to the biochar store by using an efficiency simulating the process that occurs in the pyrolysis plant when biomass converts to biochar. In this component, the marginal cost and capital cost for the pyrolysis plant are set. Figure 2 shows the components explained above and how the model looks like.

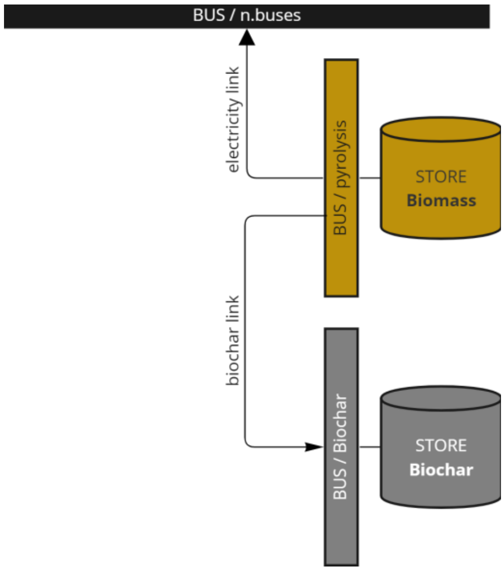

Figure 2: Detailed sketch of the pyrolysis model.

It has been chosen to use stores, links and buses from PyPSA components to recreate a pyrolysis plant because with a normal generator component only one output can be considered. This way, working with more fundamental components, it is possible to keep track of the biochar production and the model can be further developed in a future by adding more similar technologies like Fischer-Tropsch or direct air capture. Moreover, different sectors can also be modelled this way, for example, the heating sector.

3 Definition of the energy model scenarios

Year 2045 will be modelled in this study and a sensitivity analysis will be carried out. A sensitivity analysis consists of evaluating the movement of a specific value under different values of one or more variables. In other words, it studies how various sources of uncertainty in a mathematical model contribute to the model's output. The scenarios are based on the "Easter package on the energy transition" [2] from Germany. The simulation will reproduce climate neutrality by year 2045 considering that flexibility technologies are successfully integrated into the energy system, in this case hydrogen (electrolysis and fuel cell) and batteries. The sensibility analysis will study the changes of the marginal and capital cost of pyrolysis and biomass potential.

The configuration of all scenarios, including reference scenario and sensibility scenarios will have the same characteristics that are mentioned in this paragraph. All scenarios have a time span of 1 hour and model one whole year. The numbers of clusters are 3, which means that whole Germany is disaggregated in 3 regions. For the purpose of this study a small number of clusters is enough, because regionality is not going to be assessed. The renewable energies considered in the system are off wind-ac, off wind-dc, on-wind, run of river (ror) and solar. The conventional carriers considered in the system are: oil, Open Cycle Gas Turbine (OCGT), Combined Cycle Gas Turbine (CCGT), coal, lignite, geothermal and biomass for the scenarios of year 2045. In theory, if the "Easter package on the energy transition" takes place, coal and lignite will not exist anymore by the year 2045. However, for research purposes these two technologies are considered to see whether the model decides to use them or not. Finally, an emission price of 200€/t CO_2 is considered in all scenarios.

The data used to model the pyrolysis power plant is based on literature and adapted to make the sensibility analysis. The biomass potential refers to the amount of biomass available to use for this process. In order to study different options and potentials three different quantities of biomass potential are considered (high, medium and low) [5]. The difference between them is the consideration of different types of biomass.

Table 1: Biomass potential in MWh/year for Germany.

iomass store	Energy content
High	$7.5 \cdot 10^8$ MWh/year
Medium	$2.52 \cdot 10^8$ MWh/year
Low	$2.28 \cdot 10^7$ MWh/year

The data used for the pyrolysis plant is shown in Table 2 [6–8]. There is a big difference between the two groups of values, this way the different behaviour in the energy system can be seen more clearly. Lastly, but not less important the CO_2 sequestration potential for biochar can have different values depending on the biomass type that is used and many other conditions. For this model the CO_2 sequestration potential for biochar considered is -0.215 t CO_{2eq}/MWh [9].

Table 2: Pyrolysis plant data.

Pyrolysis plant	Pessimistic	Optimistic
Capital cost	1300 €/MW	55.3 €/MW
Marginal cost	26.38 €/MWh	9.5 €/MWh
Lifetime	20 years	
Electrical efficiency	32%	
Biochar efficiency	36%	

4 Results and discussion

In this section the scenarios results are going to be analysed and discussed. The role of pyrolysis is going to be analysed and the changes on the power plants layout, costs and emissions is going to be assessed by always comparing the result to the reference scenario.

4.1 Reference scenario

In this scenario the CO_2 limit is 0 and it is assumed that fuel cell, electrolysis and batteries are going to be successfully introduced into the energy system by the year 2045. The reference scenario does not consider pyrolysis in the energy system.

Power plants layout

If the electrical generation from the energy system is analysed, it can be observed in Figure 3 that only RES participate in the generation of electricity. This is due to the fact that the network must not have any emissions and there is not any technology that can compensate the emissions of the conventional power plants. On wind and off wind-dc are the generators which produce more energy followed by solar. With less amount of energy produced there is off wind-ac, ror and finally a slightly amount of biomass.

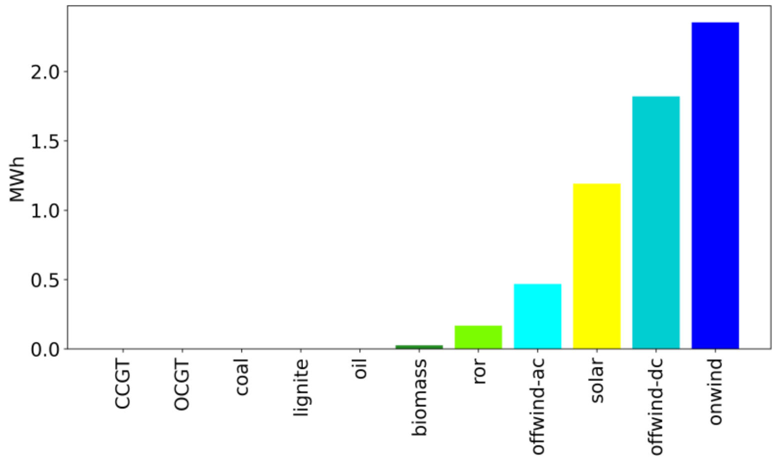

Figure 3: Annual electrical generation – reference scenario 2045.

Regarding the unit commitment, two representative days for winter (February) and summer (July) are plot in Figure 4. In both months, solar generation is used during the day while at non-sunny hours on wind is being used in combination with the other technologies. In both cases ror produces constantly but mostly in February.

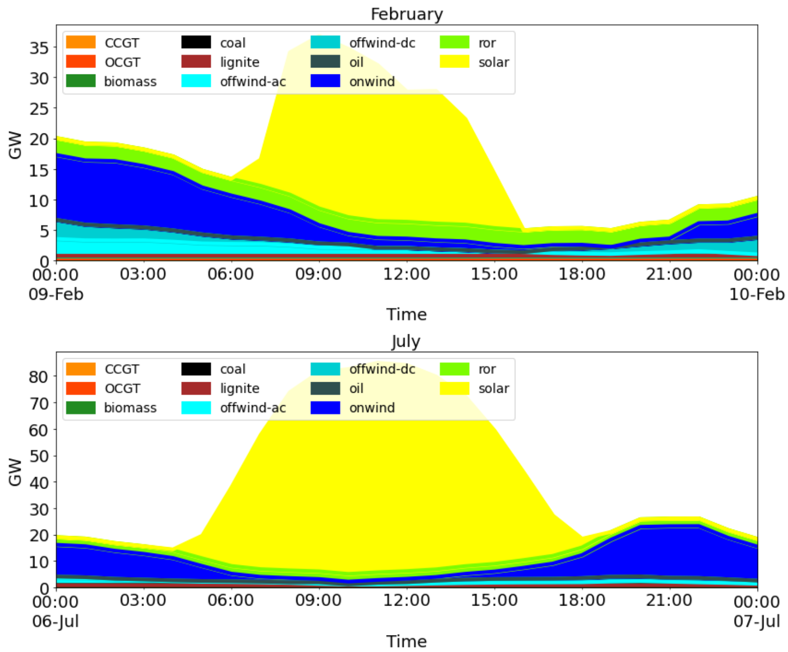

Figure 4: Unit commitment for two representative days in winter and summer – reference scenario 2045.

Flexibility technologies

Regarding the flexibility technologies, in this scenario hydrogen and battery are being used. The optimised capacity for the battery store is 3.36 GWh and for the hydrogen it is 13 TWh. Hydrogen is optimised with higher values and when it comes to the optimised energy production of the links it is also significantly higher. Hydrogen is used more in the network because it has higher maximum hours of storing compared to the battery. Moreover, battery is also more expensive to install.

CO_2 emissions and costs

The CO_2 emissions of this network is 0, as only RES are being used and the total costs are 53 billion euro.

4.2 Sensibility analysis

In order to analyse the role of pyrolysis some parameters are going to be changed to study the impact. First, the pessimistic cost scenario is going to be analysed and it is followed by the optimistic cost scenario where the three different potentials of biomass are also going to be assessed.

- **Pessimistic scenario (higher costs)**

If the capital cost is really high and the CO_2 limit is 0, pyrolysis is being used to compensate the emissions of conventional power plants. With the configuration of this scenario it is just installed the exact amount of pyrolysis that is needed in order that CCGT can run and the costs are lower than the reference scenario (without pyrolysis) and the accumulative emissions are zero at the end of the year. The amount of biomass used in this scenario is smaller than the low biomass potential, therefore in this scenario there is no need to use the medium and high biomass potential

Power plants layout

The annual electrical generation is different if compared to the reference scenario because CCGT can come into play, as can be seen in Figure 5. In this figure, the generation over a year is showed and divided into the different technologies. Moreover, on wind produces more energy but off wind-ac less, compared to the reference scenario. Solar, ror and biomass have similar production values.

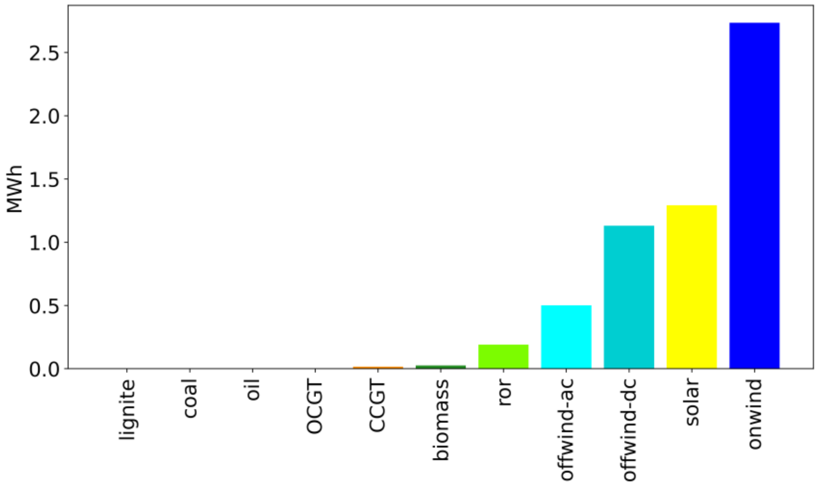

Figure 5: Annual electrical generation – scenario 2045, sensibility analysis.

Figure 6 shows the unit commitment of the generators and the electricity produced from pyrolysis for two days in winter and summer, it can be observed that in February CCGT is used when there is no solar generation. CCGT only participates in winter days where the solar generation is less. Moreover, pyrolysis electrical generation is really low as can be observed. In summer, the generation comes from RES only, specifically from solar, on wind, ror and off wind.

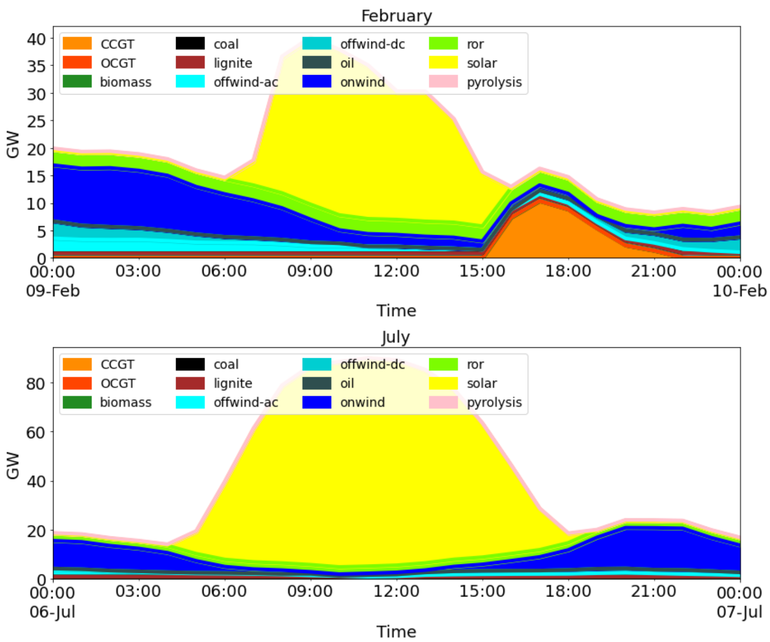

Figure 6: Unit commitment – scenario 2045, sensibility analysis.

<u>Flexibility technologies and pyrolysis</u>

With regard to the flexibility technologies, only hydrogen is being used in this network. Battery is being neglected while in the reference scenario it is being used. Hydrogen as a flexibility measure for power generation was preferred over pyrolysis because not a lot of pyrolysis is being installed due to its high capital cost. In addition, pyrolysis is used constantly during the whole year at its maximum, so that at the end of the year the sum of all biochar can avoid the CO_2 emissions produced by CCGT.

CO_2 emissions and costs

The CO_2 emissions of the network are 0 and the costs are 51.3 billion euros. The costs compared to the reference scenario are almost 2 billion euros cheaper. In Figure 7 the accumulative emissions over the year can be observed. It can be seen how in the first months the emissions are positive and after three months it starts to go down, this is because in the beginning of the year CCGT is being used more than in summer. Moreover, the production of biochar is constant, as said before, pyrolysis produces constantly, so at the end of the year the total amount of biochar produced will be exact to get 0 emissions.

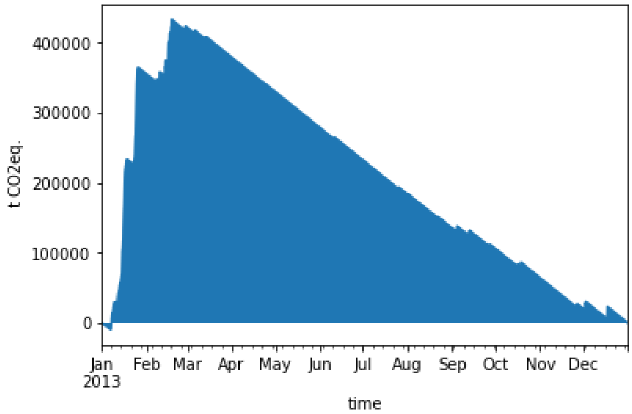

Figure 7: Accumulative emissions – scenario 2045, sensibility analysis.

- **Optimistic scenario (lower costs)**

With this configuration a difference between the biomass potentials must be done in order to analyse the effect of it.

High biomass potential

When the biomass potential is high, conventional power plants participate in the energy system, flexibility disappears and pyrolysis covers a big part of the electrical load, in general, the production of power plants (RES and conventional) is lower. As a side effect, as pyrolysis is being used that much, negative emissions are achieved.

Power plants layout

When it comes to the electricity generation, the production from power plants also differs a lot if compared to the reference scenario. As can be seen in Figure 8, CCGT, OCGT and lignite produce electricity while in the reference scenario only RES produce electricity. Moreover, the total generation for one year from the generators is 397 TWh, whereas in the reference scenario it was 603 TWh. This reduction of generation is, as said before, due to the high energy production of pyrolysis, the rest of the load is cover by the electricity coming from pyrolysis.

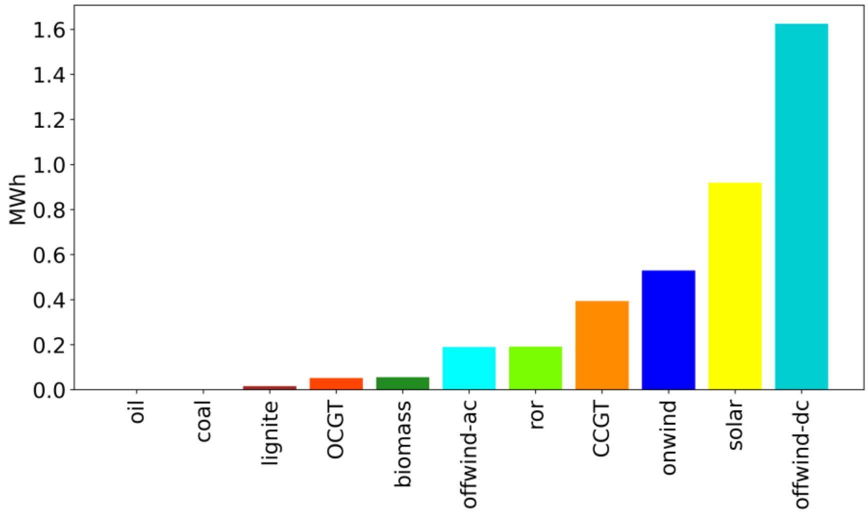

Figure 8: Annual electrical generation – scenario 2045 (with flexibility), sensibility analysis.

Observing the unit commitment for two different days (Figure 9) it can be seen when the model uses conventional power plants and the electrical generation from pyrolysis. In February, which represents a typical day from winter, CCGT is being used almost constantly together with pyrolysis and OCGT and lignite are used when there is no solar production. On the other hand, in July, which represents a typical day from summer, only CCGT is being used during times when there is no solar production, as well as, electricity that comes from pyrolysis. This unit commitment is really different compared to the reference scenario because pyrolysis produces a lot of energy and conventional power plants can participate in this energy system.

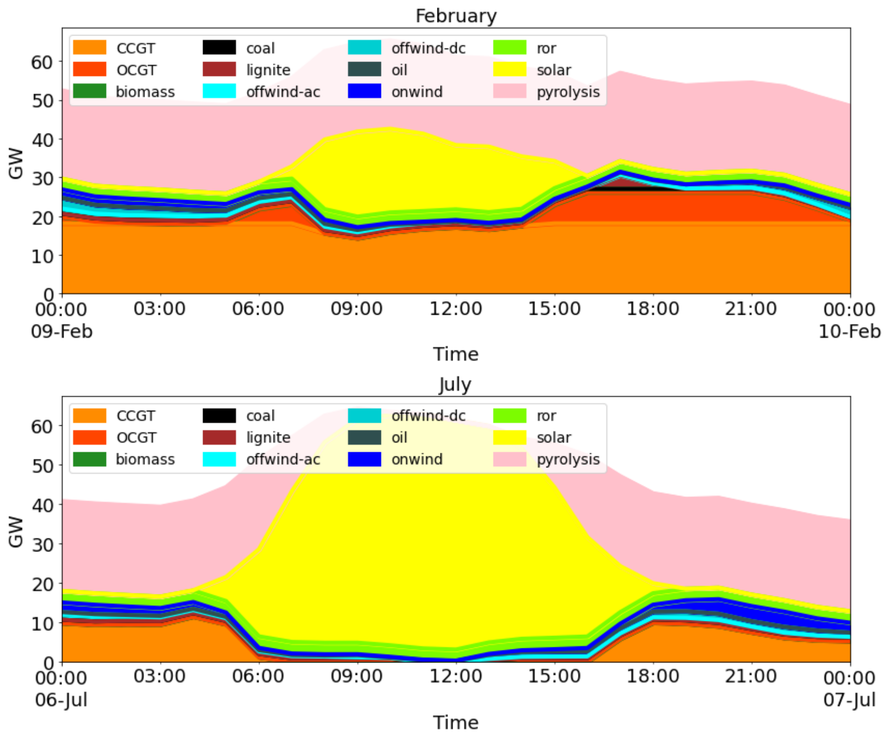

Figure 9: Unit commitment – scenario 2045 (with flexibility), sensibility analysis.

Flexibility technologies and pyrolysis

With this configuration, flexibility technologies are not used. With regard to pyrolysis, it produces a total of 113 TWh and the capacity installed for pyrolysis is 71130 MW. This value is quite high because the amount of biomass available is high as well.

CO_2 emissions and costs

The CO_2 emission for this network are -8.94 million tonnes and the costs are 38.87 billion euros. As can be seen in Figure 10, in the beginning the emissions for this network are posisitive, because there is not enough biochar produced to compensate the emissions. However, at the end of the year the emissions are negative because the total amount of CO_2 captured by using biochar is bigger than the emissions from the conventional power plants. The emissions get a negative value because pyrolysis is being optimised mainly for its electricity output and the negative emissions from biochar are a side effect. Pyrolysis is cheap and it has a lot of biomass available, then the model decides to use this cheap energy to reduce the production from the other power plants and cover the load.

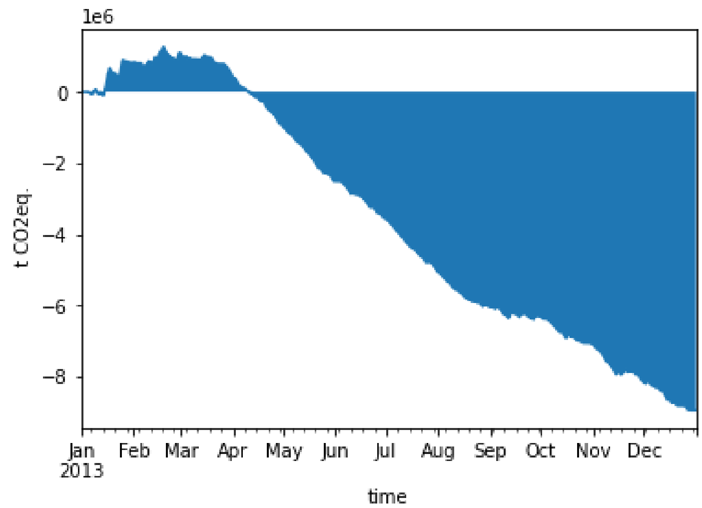

Figure 10: Accumulative emissions – scenario 2045 (with flexibility), sensibility analysis.

Medium biomass potential

When the biomass potential is medium and the costs are low, all the biomass is used and pyrolysis lets conventional power plant participate because it can compensate the emissions.

Regarding the electrical generation in one year, the power plants layout is the same as in Figure 8. The only difference is that the total electricity produced by power plants in one year is higher, 440 TWh. The unit commitment of the two chosen days follows also the same patterns just with the difference of energy production (see Figure 9).

Flexibility technologies and pyrolysis

With pyrolysis and medium biomass potential there is no need any more of battery but hydrogen is still being used. The total electricity produced by pyrolysis during one year is 80.7 TWh.

CO_2 emissions and costs

The total CO_2 emissions from the network is 0 and the costs are 34.81 billion €. The emissions are the same compared to the reference scenario but the costs are much lower with the introduction of pyrolysis in the network. The CO_2 emissions represent 20 million tonnes and come from CCGT, lignite and OCGT. Biochar is able to sequestrate exactly the same amount of carbon dioxide. The accumulative emissions of the network considering the emissions from power plants and the biochar sequestration can be observed in Figure 11. In the beginning of the year the emissions reach positive values till end of March, this is because in winter months the RES generation is less and the biochar production was still not enough to cover the emissions. However, from April the emissions are going down. In October and December there is again positive emissions because in that moment conventional power plants need to be used to cover the load. However, at the end of the year, the accumulative emissions from this network are 0 because biochar is able to compensate all those emissions.

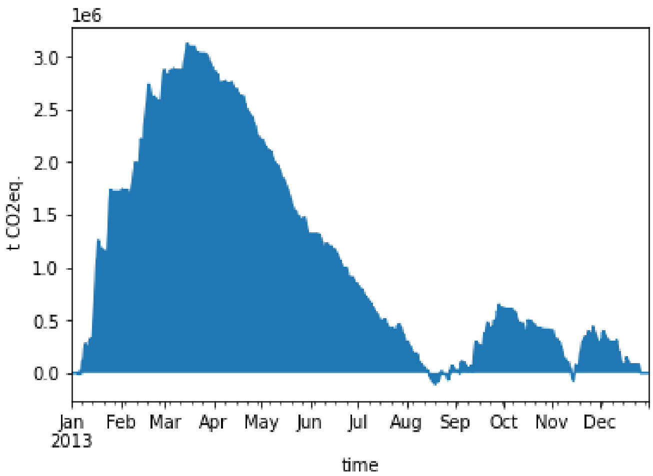

Figure 11: Accumulative emissions – scenario 2045 (with flexibility), sensibility analysis.

Small biomass potential

If costs are low and the biomass potential is small, pyrolysis will run and it will compensate the emissions of CCGT. Moreover, in this network battery and hydrogen are used.

Power plants layout

If the total annual generation is analysed (see Figure 12), it can be observed that CCGT is being used, while in the reference scenario only RES are allowed to run. The total generation from power plants is 580 TWh and the rest is covered by pyrolysis. CCGT can be used even though there is a 0 emissions limit because pyrolysis is compensating the emissions. The rest of technologies used are RES which do not emit CO_2 to the atmosphere, off wind-dc, solar and on wind are the dominant ones.

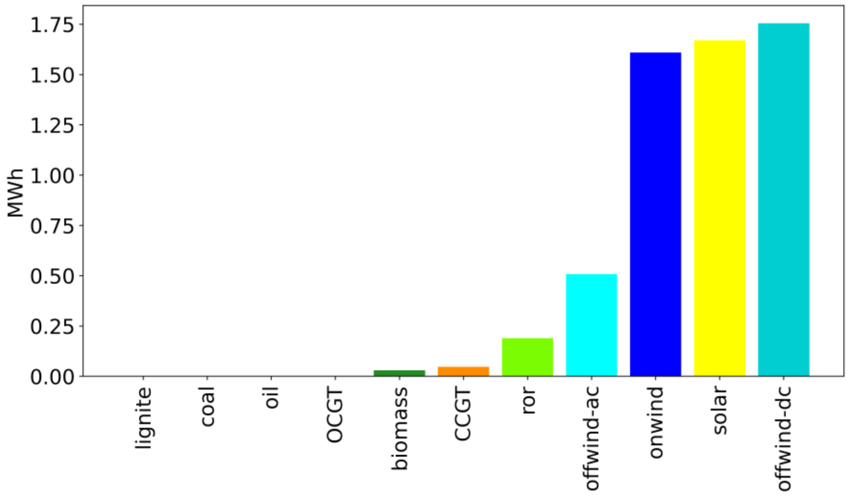

Figure 12: Annual electrical generation – scenario 2045 (with flexibility), sensibility analysis.

To analyse when pyrolysis and the rest of technologies work during a typical day of winter and summer Figure 13 can be analysed. If the unit commitment of the two different days is compared, it can be observed that pyrolysis is used strongly in February, when the RES production is lower. On the other hand, in summer most of the production comes from RES. Moreover, CCGT is used in winter only to support when there is no renewable generation.

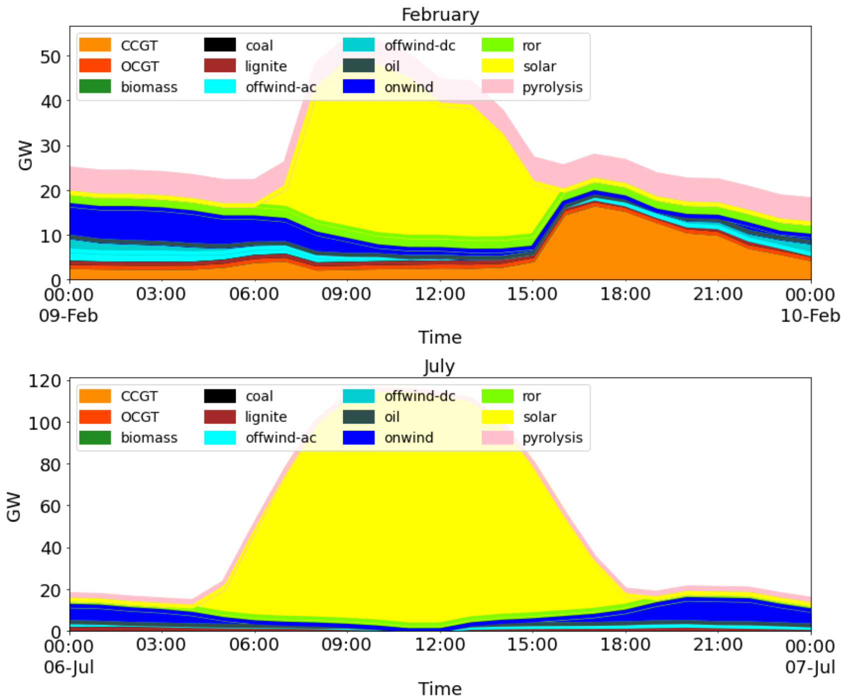

Figure 13: Unit commitment – scenario 2045, sensibility analysis.

With this configuration, battery and hydrogen are needed for flexibility reasons. However, battery is used less than hydrogen technologies, because battery has higher costs and less storage hours. Moreover, hydrogen and battery are optimised with lower capacity compared to the reference scenario, this is due to the fact that pyrolysis is also producing electricity and CCGT too.

<u>CO_2 emissions and costs</u>

The CO_2 emissions of this network are 0 and the costs are 47.53 billion €. The costs compared to the reference scenario are 5.49 billion € less and still the same goal of 0 emissions can be achieved. This is due to the role of pyrolysis, it produces electricity and with the CO_2 compensation it allows CCGT to produce electricity that can be used when there is no RES generation. In Figure 14 it can be observed how the emissions at the end of the year arrive to zero, however until July they do not start to decrease.

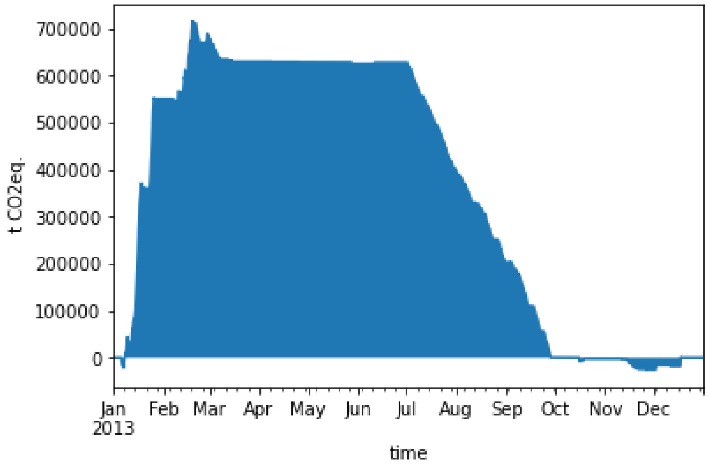

Figure 14: Accumulative emissions – scenario 2045 (with flexibility), sensibility analysis

4.3 Summary of the results

A summary of the different scenarios can be found in Table 3. The costs and emissions values are shown together with the main conclusions from the scenarios.

Table 3: Summary of the results.

Scenarios	Biomass potential			Costs (billion €)	Emissions (Mt CO_2eq)	Conclusions
	High	Medium	Low			
Reference				53.01	0	- Hydrogen and battery are used.
High costs	X	X	X	51.31	0	- Reduction of costs. - Pyrolysis compensates emissions to use CCGT. - Only hydrogen is used.
Low costs	X			38.87	-8.94	- Negative emissions and lower costs. - Pyrolysis as a generator – more conventional power plants used. Less generation in general. - Hydrogen and battery are not used. - Not all biomass available used.
Low costs		X		34.81	0	- Reduction of costs. - More conventional power plants used. Pyrolysis compensates emissions. - Hydrogen and battery are not used. - All biomass available used.
Low costs			X	47.53	0	- Reduction of costs. - Compensate emissions to use CCGT - Hydrogen and battery are used. - All biomass available used.

4.4 Comparison between the scenarios

In order to compare and summarise the results of this study three different questions are analysed. The questions analysed are:

- Is pyrolysis used?
- What is the main purpose of pyrolysis? Produce electricity or compensate emissions?
- Is flexibility being used less when pyrolysis is running?

When the CO_2 emissions are set to 0 and pyrolysis is available, it is always used. It depends on the costs if the model decides to use the whole amount of biomass available or not.

To prove what is the main purpose of pyrolysis, whether to produce electricity or compensate CO_2 emissions, the energy production and the energy layout from the other power plants need to be analysed. Pyrolysis is used to produce electricity when the rest of power plants reduce their energy generation and pyrolysis covers the load. In this case, electricity is the output that is mostly optimised and biochar is a side product from pyrolysis. When this happens, negative emissions in the energy system can be achieved. On the other hand, CO_2 compensation refers to the fact that pyrolysis is being used so that other power plants which emit carbon dioxide can work and biochar compensates those emissions. In the year 2045 only in one scenario pyrolysis is used to produce electricity, when the biomass potential is high and the costs are low. In this case, there is a lot of cheap biomass available and the model decides to use this technology to cover the load, and as a consequence, the generation from other power plants is reduced. In the rest of the scenarios, pyrolysis compensates the CO_2 emissions of the conventional power plants that can run. CCGT is always used more because the CO_2 emission factor is low and the marginal cost is also low, however when more than one conventional power plant can run it is always followed by OCGT. This technology has the same CO_2 emission factor but higher marginal cost compared to OCGT. And finally, lignite is also used in one of the scenarios configurations. Lignite has higher CO_2 emissions compared to OCGT and CCGT and also compared to oil, but the marginal cost from oil is really high. Therefore, the model decides to use lignite which is cheaper, as it always optimises finding the best cost optimal solution.

Finally, the last question is whether flexibility is being used less when pyrolysis is introduced in the energy system. It can be said that if pyrolysis is used, it can reduce the need of flexibility. An example is when pyrolysis is added to the network with high costs, only hydrogen is used while in the reference scenario battery and hydrogen are used. Moreover, when the costs are low the necessity of having hydrogen or battery disappears completely.

5 Conclusions

The study successfully integrates biochar in an open-source energy system model by the simulation of a pyrolysis plant and assess the effect of it in the energy system by using different future scenarios. With the sensibility analysis different conclusions can be drawn and results obtained in this study give an insight of how can pyrolysis affect the energy system in a future.

It has been found that depending on the data used for pyrolysis the model optimises two different outputs, electricity or biochar. Pyrolysis will be used to produce electricity when the biomass potential is high and the costs are low. The model chooses to generate energy by using pyrolysis and reduce the energy production of all other power plants. Biochar will be produced at the same time and as side effects, the system will have negative emissions. On the other hand, in the rest of scenarios pyrolysis is used to compensate carbon dioxide emissions from conventional power plants in order to achieve the limit of zero emissions.

It was also found that by using pyrolysis the need of flexibility can be reduced. Pyrolysis produces biochar and electricity simultaneously and this energy can be used to cover the load at the moment when there is not enough renewable generation, for example.

To summarise all the information, it can be said that conventional power plant could run longer thanks to the emissions compensation from biochar. Moreover, it was also found that pyrolysis can reduce the need of flexibility as it can produce energy whenever it is needed. This study also shows that the biomass potential and the pyrolysis costs can affect a lot the behaviour of pyrolysis in the energy system.

The limits of this study are the data related with biomass and the costs from pyrolysis. Some assumptions have been made and further investigation for these values should be done. Regarding the modelling of pyrolysis, in a future work the biomass potential should also be applied for the conventional biomass power plant. In this study, the conventional biomass power plant has infinite potential and only the pyrolysis biomass is limited. Lastly, the influence of pyrolysis in flexibility technologies could also be investigated with more detail by doing more specific scenarios.

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