***Designing a highly renewable decarbonized energy system; the sector-coupling effect***

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## Overview

In the wake of the Paris agreement, France has set a zero net greenhouse gas emission target by 2050. This target can only be achieved by rapidly decreasing the share of fossil fuels and accelerating the deployment of low-carbon technologies. While decarbonization of electricity sector has long been studied and the literature over limiting the CO2 emissions in the power sector is very reach, an energy system-wide analysis including technical details of carbon removal technologies and energy storage technologies and detailed trade-offs between different vectors of energy has not gained enough attention in the literature.

We develop a detailed model of the energy system including power, gas and heat vectors to satisfy the demands in residential, tertiary, industry, agriculture and transport sectors. We study the role of different low emission and negative emission technologies in the French energy mix, as well as the endogenous energy vector choice for different sectorial demands and we identify the role of different electricity, gas and heat generation and storage technologies, as well as the negative emission technologies and the vector change options for various values of the social cost of carbon (SCC).

## Methods

We develop the EOLES (Energy Optimization for Low Emission Systems) model. The EOLES model optimizes the investment and operation of the energy system in order to minimize the total cost while satisfying energy demand. It minimizes the annualized energy generation and storage costs, including the cost of connection to the grid, in order to account for a precise dispatch with a correct dimensioning of storage technologies and the seasonal and intra-daily variability of demand and power production from renewable resources, a full year with hourly time-steps is considered as the optimization period. It includes six power generation technologies: offshore and onshore wind power, solar photovoltaics (PV), run-of-river and lake-generated hydro-electricity, nuclear power (EPR, i.e. third generation European pressurized water reactors), three gas production technologies: natural gas, methanization from anaerobic digestion and pyro-gasification of solid biomass, and two heat production technologies: centralized and decentralized solar thermal collectors. The sector coupling is enabled by vector change technologies: open-cycle gas turbines (OCGT) and combined-cycle gas turbines (CCGT) equipped with post-combustion carbon capture and storage (CCS) technologies are used to convert gas to electricity. Vector change from electricity to gas is enabled by electrolysis (power to hydrogen to inject into the gas network with a volume share limit) and methanation (hydrogen production from electrolysis of water and Sabatier reaction of produced hydrogen with green CO2 to produce synthetic methane) as power-to-gas options. Similarly, centralized and decentralized boilers and heat pumps are used to produce heat from gas and centralized and decentralized heat pumps and resistive heat production technologies are used to produce heat from electricity. The model includes two electricity storage technologies (Li-Ion batteries and pumped hydro storage), the existing gas network as the gas storage option and two heat storage technologies (centralized and decentralized hot water tanks). This model also allows the transport demand to choose endogenously from electric vehicles and internal combustion engine vehicles. Direct air carbon capturing and storage (DACCS) and direct air carbon capturing and utilization (DACCU) are considered separately to both provide negative emissions and provide green CO2 for methanation.

We study a wide range of social cost of carbon (from 0 to 500€/tCO2) to account for both the emission tax and the negative emission remuneration.

## Results

In the absence of social cost of carbon, power system consists of roughly 85% of renewable energies (~75% VRE), while nuclear power and natural gas together account for less than 15% of power production. By introducing the first SCC value of 100€/tCO2, natural gas provides 7% of power production, and the part of nuclear power increases to more than 25% in electricity mix. by the increase of SCC, the overall share of electricity in the energy supply side increases (from 26% without SCC to up to 85% for a SCC of 500€/tCO2). This happens mainly because of replacement of the gas-to-heat options by power-to-heat options in residential and tertiary sectors, and the fall in fossil gas share in the overall gas production. While increasing the SCC value leads to an increase in the part of nuclear power in the electricity mix, it never surpasses 30% of the overall electricity mix.

The renewable gas production technologies do not appear in the absence of an SCC value, but by 100€/tCO2 of SCC, the share of fossil gas in the gas supply side falls to 72% and the remaining is provided by pyro-gasification of biomass, and from 300€/tCO2 of SCC on, natural gas is phased out and completely replaced by the renewable gas production technologies. Similarly, by the appearance of the smallest carbon tax, heat production from gas-to-heat technologies (such as boilers and gas heat pumps) is replaced by power-to-heat options (except the industrial sector where high temperatures from combustion are needed, which is already introduced as gas demand to the model). Methanation becomes cost efficient from 200€/tCO2 of SCC value on, and CCGT power plants combined with CCS are used to provide negative emissions.

While the system cost increases with the SCC, sector-coupling decreases the overall energy system cost by more than 30% in comparison with the separate modelling of each energy vector; particularly, the endogenous choice of electricity and gas for satisfaction of transport and heat demand and enabling the interactions between electricity and gas networks lead to this high synergy. In the absence of an emission tax/remuneration (internalization of SCC), the yearly CO2 emissions of the whole system is 250MtCO2. Comparing to the 2017 statistics (325MtCO2), we already observe a lower emission with no SCC implication thanks to highly decarbonized electricity and heat coming from cheap VRE technologies. A big proportion of this emission comes from the transport sector where all the demand is satisfied by internal combustion engine (ICE) vehicles. Introducing an SCC value of 100€/tCO2 decreases the emissions by a factor of 2, mainly by replacing gas-to-heat technologies by power-to-heat technologies and decreasing the part of natural gas from 100% to 72% in the gas supply side. An SCC value of 300€/tCO2 leads to a carbon neutral energy system, increasing the social cost of carbon leads to negative emissions and for SCC values of 400€/tCO2 and 500€/tCO2 these negative emissions reach 61MtCO2/year.

The unit price of electricity does not surpass 50€/MWhe (compared to actual price of 60-70€/MWhe) and it decreases drastically for an SCC value of 300€/tCO2 or more, but the unit prices of gas and heat increase with the SCC value. Since the negative emission remuneration is only applied to CCGT power plants with CCS and DACCS, but not to any gas production technology directly, the remuneration of negative emissions is only visible in the electricity price, and that’s why a lower electricity cost is observed for high SCC values. On the other hand, since this negative emission remuneration is not applied to gas and heat costs, increasing the SCC value results in higher unit costs and respectively prices of gas and heat. While the system-wide average levelized cost of gas production stays around 50€/MWhth for low SCC values of 100€/tCO2 and 200€/tCO2, it increases drastically to 90€/MWhth for high SCC values. Similarly, the heat production becomes more expensive by increasing the SCC value but it never surpasses 40€/MWhth thanks to low electricity production cost.

Although shift in SCC value leads to remarkable changes in the system-wide levelized cost of each energy vector, the average yearly market prices for electricity and transport sectors stay roughly constant, with ~51±2€/MWhe and ~28±1€/1000.km. On the other hand, the average market price of heat goes from 17€/MWhth to 29€/MWhth and the average market price of gas increases by a factor of more than 4, from roughly 30€/MWhth to 130€/MWhth.

## Conclusions

Keeping diverse options open in the national energy planning targets can be an important enabler in efficient exploitation of each technology. Moreover, the integrated modelling of the whole energy system enabling sector coupling for the prospective studies can lead to more accurate prospective representation of the energy sector, leading to lower costs and more efficient decarbonization of energy sector. Therefore, a very important finding of this study is the efficiency of sector-coupling for transport and heat demands when they are defined endogenously to choose freely between electricity and gas networks instead of setting the share of each vector exogenously. We find a very high electrification of energy by introduction of smallest SCC value (100€/tCO2), from 26% in the absence of SCC to more than 80% for the SCC of 500€/tCO2.

The CO2 market (the gap between the technical cost of the system and the cost including SCC) accounts for 24bn€/year (~36% of the technical cost) for a social cost of carbon of 400€/tCO2, which highlights the importance of this market and the support schemes for negative emissions. This gap also shows the importance of carbon businesses which can take place for high SCC scenarios, where the main incentive for negative emission technologies can be mainly to generate negative emissions, but not so much to produce electricity. The increasing average market and levelized cost for gas and heat sectors (while the average electricity cost decreases) by increasing SCC also necessitates a better allocation of the negative emission remunerations among different energy sectors than only remunerating directly where negative emissions occur (CCS which is considered as an electricity technology).