**Carbon flows in macro energy planning: The case of the Swiss energy system**

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**Highlights**

* Macro energy systems planning by prospective optimization modeling based upon Energyscope.
* Complete carbon flow chain from *cradle to grave* in different scenarios.
* Exploration of the role of CCUS (carbon capture, utilization and sequestration) and a broad set of Power-to-X technologies in energy transition.
* Analysis on the quasi-neutrality of carbon emission.

**1. Introduction**

Decarbonation as one of the core objectives delivered by Paris Agreement [1] in 2015, is expected to be approached by: 1) massive introduction of renewable energy sources; 2) deployment of CCUS technologies. Some prospective energy models declare that the anthropogenic carbon emissions in Switzerland in 2050 could be optimized to below 5-10 Mt/year, which is however difficult to get further mitigated taking into consideration the emissions during construction periods in the perspective of a Life Cycle Analysis (LCA).

Compared to intermittent renewables, the emission of biomass technologies in construction period is trivial, despite relatively important emissions during the operational periods, which is yet possible to be recovered by applying carbon capture technologies. The captured GHG (Green House Gases) could be either sequestrated directly underground, or take the role as a storage medium for intermittent electricity from renewables, e.g. by participating in electrolysis and methanation processes known as Power-to-Gas. Up to now, merely 4% [2] of fossil carbon is used in non-energy use to make products in Switzerland. Therefore, it is promising to produce chemical products such as plastics, commodity chemicals and energy carriers free from fossil CO2 by carbon reutilization technologies. This article aims at estimating the possible carbon demand for different usage in long terms, and exploring the optimal configuration of carbon flows by linking the carbon sources and carbon sinks in techno-economic and ecologic perspectives.

**2. Methods**

The methodology of the research is categorized into 3 steps: first the carbon sources and carbon sinks in Switzerland are identified, including the demand for carbon-related chemical products; then a broad set of conversional technologies are modelled and integrated based upon existing technologies and newly added biomass and CCUS technologies in Swiss Energyscope (SES) [3], an open-source MILP (Mix Integer Linear Programming) optimization tool for energy system developed by EPFL. The model takes a “snapshot” of the optimized Swiss energy system in 2050, with the objective of minimizing the total cost subjected to various constraints [4] such as supply-demand, availability of resources, as well as the potential of conversional technologies. CCUS technologies are categorized into CC (carbon capture), CCS (carbon storage) and CCU (carbon utilization) in order to precisely depict the carbon flows. Each technology within its corresponding category is associated with a specific cost and an energy penalty coefficient. In this model, the carbon sources are divided into two branches: carbon-intensive energy industries, such as fossil-based power plants, cements etc., and carbon from the atmosphere. It is assumed that only the DAC (Direct Air Capture) technology could be applied to atmospheric carbon capture. The total Global Warming Potential (GWP) is then expressed as a trade-off between the carbon emissions and the reduction by deploying CCUS, which is subjected to an ε-constraint limiting the upper bound of GHG emissions. The third step lies in scenario generation for understanding the impact of different pathways of carbon flows into the energy system.

**3. Results and discussion**

The energy system will become inevitably more expensive by increasing carbon mitigation. Carbon flows Sankey diagrams illustrate the carbon sources and sinks and the corresponding conversional technologies. In a low carbon scenario with high penetration of renewables, more biomass technologies are used to produce bio-diesel or synthetic natural gas for satisfying in principle the mobility demands. The CCUS technologies do not appear until the total emission threshold reaches 5 - 10 Mt/year, where amine gas treating becomes dominant among carbon capture technologies. Carbon sequestration is less competent compared to carbon utilization contributing to reduce the total cost by decreasing chemical products import expenses.

**4. Conclusions**

The study sheds light on the optimized configuration of carbon flows in the horizon of 2050 for Switzerland, displaying the importance of biomass in the future energy system as the dominant carbon source in operation. CCUS implementation is obligatory in order to realize quasi-neutrality of carbon emission: the results demonstrate that the total GWP emission in the point of LCA could be controlled within 4 - 6 Mt and 0 - 3 Mt respectively in the absence and presence of CCUS technologies, respectively.

**References**

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