Consequences of the UK Energy Market Reform on the Development of Carbon Capture, Transport, and Storage

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***Abstract*— To achieve the three main energy policy priorities of competitiveness, energy security and decarbonization, the UK government has recently undertaken a major "Energy Market Reform" (EMR). This paper presents a modeling framework to analyze how the different policy measures of the EMR will shape the future UK electricity generation mix until 2050. We set up a two-sector model where players can invest in various types of generation technologies including renewables, nuclear, and Carbon Capture, Transport, and Storage (CCTS). For a detailed representation of CCTS we also include industry players (iron/steel as well as cement), CO_2 transport, and CO_2 storage including the option for CO_2-enhanced oil recovery (CO_2-EOR). The players maximize their expected profits based on variable, fix and investment costs, as well as the price of electricity, CO_2 abatement, and other incentives, subject to technical and environmental constraints. Demand is inelastic and represented via a selection of representative hours. The model framework allows for regional disaggregation and features simplified electricity and CO_2 pipeline networks. The model uses a mass balance as market clearing for electricity and CO_2. The equilibrium solution is subject to constraints on CO_2 emissions. In this paper we present the model formulation and some preliminary results to illustrate the mechanics of the model. The tentative scenario indicates a diversified technology mix for 2050. The CCTS development is purely triggered by CO_2-EOR; the EMR does not incentives any additional CCTS investments.**

***Index Terms*-- CCS, CO_2, electricity, energy policy, MCP, UK**

I. Introduction and Literature Overview

The UK government decided to undertake a major restructuring of its energy policy framework, called the "Energy Market Reform" (EMR) [1]. The UK-EMR introduces four main policies to support low-carbon technologies: Contracts for Differences (CfD), Carbon Price Floor (CPF), Emissions Performance Standard (EPS) and a Capacity Market (CM). These instruments constitute a major reform to the previous framework of the UK electricity market, which was characterized by a high competitiveness and low market concentration.

The upcoming EMR and its effects have been controversially discussed, e.g. by Pollitt and Haney [2] and Eide et al. [3]. Some critics question the effect the reform might have on the UK electricity market and in particular on the future of low-carbon technologies. Major risks include possible welfare losses as well as possibly breached climate targets due to sunk investments in carbon-intensive power plants (a topic examined by Johnson et al.[4] on a global level). This calls for additional research on low-carbon technologies in the UK. One technology that is particular to the UK's approach is Carbon Capture, Transport, and Storage (CCTS), which has vanished as technology option in most European countries [5]. Existing studies such as Egerer, Kunz and Hirschhausen [6] have concentrated their research on the integration of renewables into the UK electricity market. Their representation of the CCTS technology, however, neglects transportation and storage aspects as well as the possibility of industrial usage of CCTS. Other studies concentrate only on the technical or political feasibility of CCTS (see [7], [8]) or on possible pipeline routing (see [9], [10]), neglecting the integration of CCTS into the rest of the electricity market.

To our best knowledge, there is no study that examines the UK-EMR with respect to its implications for the CCTS technology and the UK electricity market. Therefore, the aim of this paper is to set up a modeling framework to analyze the measures of the UK-EMR (specifically the CPF, EPS and CfD) and how they will influence the construction of new generation capacities. The developed Electricity-CO_2 (ELCO) model calculates regionally disaggregated electricity generation and flows as well as CO_2 transport, storage, and usage for CO_2-enhanced oil recovery (CO_2-EOR) in UK until 2050. Incorporating CO_2 capture by industrial facilities from the iron/steel and cement sectors is another unique feature of this modeling approach. On the one hand, this facilitates the representation of economies of scale along the transport routes while, on the other hand, leading to a higher scarcity of storage options.

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II. Mathematical Representation of the ELCO Model

The ELCO model includes stylized players of the electricity sector, iron/steel and cement industry, as well as CO_2 transportation and storage. All players maximize their respective profits subject to their own as well as overall technical and environmental constraints. Other (external) costs as well as further welfare components are not being analyzed. CfD for low-carbon technologies are set exogenously for 2015 and 2020, and derived endogenously from shadow variables of environmental constraints for later periods. The EPS and the CPF remain exogenous throughout the modeling period. The equilibrium model assumes perfect competition as well as perfect foresight and is solved as mixed complementarity problem (MCP) with the General Algebraic Modeling System (GAMS) software using the PATH Solver. An equilibrium is reached when overall system costs are minimized subject to all constraints. The following notation uses capital letters for parameters and lower case letters for variables and sets.

A. The electricity sector

The ELCO model represents electricity generation from various technologies ($g_{h,n,t,a}$ (g-type): from existing capacities, newly built coal, gas OCGT and gas CCGT; and $g\_cfd_{h,n,t,aa,a}$ (g_cfd-type): from PV, wind on/offshore, hydropower, biomass, CCTS coal/gas, and nuclear). Their objective functions (1) represent the profit functions for different technologies and share the common components of fix costs $FC\_G_{n,t,a}$ and annualized investment costs $INVC\_G_{n,t,a}$, which both depend on the investments $inv\_g_{n,t,a}$ (lowest rectangular segment). The variable costs components and revenue differ: I) For g-type technologies (upper rectangle with upper flat corners), revenue is generated from sales in the electricity market. It consists of the dual variable of the electricity balance (19) $price\_e_{h,n,a}$ and a factor describing the technology's contribution to achieving the environmental target (see (8)). The variable cost function comprises of fuel and O&M costs with a linear and a quadratic term ($VC\_G_{n,t,a}$ and $INTC\_G_t$, respectively), CO_2 costs based on the emission factor EF_t, and the CO_2 certificate price ($CO2\_PRICE\_EU_a$+ CPS_a). II) For g_cfd-type technologies (middle rectangle with rounded corners), revenue is generated from the new CfD scheme. The strike price for a technology depends on the extent to which its generation helps achieving the environmental goals (see (8)). These technologies also incur additional variable costs from possible CO_2 transport and storage, which are passed via the dual variable $price\_co2_{h,n,a}$ and account for CO_2 capture rates CR_G_t. The quadratic cost term can be interpreted as rising integration costs for increasing shares of g_cfd-type generation.

The individual players maximize their profits subject to several constraints. The EPS constraint (2) ensures that newly constructed generation capacities do not exceed the annual allowed CO_2 emissions per GW. The overall emissions are calculated as an annual fuel-specific sum, allowing for combined accounting of new capacities with and without CCTS. The model includes the option for curtailment of excessive (renewable) generation via (3).

$$\Pi^{ELEC}_{g/g\_cfd} = \sum_a DF_a \cdot PD_a$$
$$\left(\sum_h \left(\begin{array}{l} TD_h \cdot \\ \left(\begin{array}{l} g_{h,n,t,a} \cdot \\ \left[\begin{array}{l} price\_e_{h,n,a} + \alpha_{t,a} \cdot \lambda_a^{target\_co2} \\ - \left(\begin{array}{l} EF_t \cdot \left(CPS_a + CO2\_PRICE\_EU_a \right) \\ + VC\_G_{n,t,a} + g_{h,n,t,a} \cdot INTC\_G_t \end{array} \right) \end{array} \right] \\ + \sum\limits_{aa \in USE_{t,a,aa}} \left(\begin{array}{l} g\_cfd_{h,n,t,aa,a} \cdot \\ \left[\begin{array}{l} \left(SP_{t,aa} + \sum\limits_{aaa \in I\_USE_{t,aa,aaa} \text{ and } SP_{t,aa}=0} \alpha_{t,aaa} \cdot \lambda_{aaa}^{target\_co2} \right) \\ - \left(\begin{array}{l} \left(EF_t \cdot \left(1 - CR\_G_t \right) \right) \\ \cdot \left(CPS_a + CO2\_PRICE\_EU_a \right) \\ + EF_t \cdot CR\_G_t \cdot price\_co2_{h,n,a} \\ + VC\_G_{n,t,a} + g\_cfd_{h,n,t,aa,a} \cdot INTC\_G_t \end{array} \right) \end{array} \right] \end{array} \right) \end{array} \right) \end{array} \right) \\ - FC\_G_{n,t,a} \cdot \left(INICAP\_G_{n,t,a} + \sum\limits_{aa \in USE_{t,a,aa}} inv\_g_{n,t,aa} \right) \\ - \left(\sum\limits_{aa \in USE_{t,a,aa}} INVC\_G_{n,t,aa} \cdot inv\_g_{n,t,aa} \right) \right) \quad (1)$$

$$0 \le \sum_h AVAIL_{h,n,t} \cdot TD_h \cdot \sum_{\substack{aa \in USE_{t,a,aa}, \\ (t,tt) \in ONE\_FUEL_{t,tt}}} inv\_g_{n,tt,aa} \cdot EMPS_{aa}$$
$$- \sum_h TD_h \cdot \left[\begin{array}{l} \left[g_{h,n,t,a} \cdot \left(EF_t \cdot \left(1 - CR\_G_t \right) \right) \right] \\ + \sum\limits_{\substack{aa \in USE_{t,a,aa}, \\ (t,tt) \in ONE\_FUEL_{t,tt}}} \left[g\_cfd_{h,n,tt,aa,a} \cdot \left(EF_{tt} \cdot \left(1 - CR\_G_{tt} \right) \right) \right] \end{array} \right] \quad (2)$$
$$\perp \quad \lambda_{n,t,a}^{emps} \ge 0$$

$$0 \le \sum_n \left(D_{h,n,a} - RES\_OLD_{h,n,a} \right)$$
$$- \sum_{n,t} \left(g_{h,n,t,a} + \sum_{aa \in USE_{t,a,aa}} g\_cfd_{h,n,t,aa,a} \right) \quad (3)$$
$$\perp \quad \lambda_{h,a}^{curt\_g} \ge 0$$

The generation capacity constraints for conventional generation technologies, $g_{h,n,t,a}$ (4), and newly constructed low-carbon technologies, $g\_cfd_{h,n,t,aa,a}$ (5), differ slightly. A diffusion constraint (6) restricts the maximal annual investment depending on previous generation quantities.

$$AVAIL_{h,n,t} \cdot inv\_g_{n,t,aa} - g\_cfd_{h,n,t,aa,a} \ge 0 \perp \lambda_{h,n,t,aa,a}^{cap\_g\_cfd} \ge 0 \quad (4)$$

$$0 \le AVAIL_{h,n,t} \cdot \left(INICAP\_G_{n,t,a} + \sum_{aa \in USE_{t,a,aa}} inv\_g_{n,t,aa} \right)$$
$$- g_{h,n,t,a} \quad \perp \quad \lambda_{h,n,t,a}^{cap\_g} \ge 0 \quad (5)$$

$$0 \le \left[START\_G_t + \sum_{h,n,aa} TD_h \left(g\_cfd_{h,n,t,aa,a-1} + g\_cfd_{h,n,t,aa,a-2} \right) \right] \quad (6)$$
$$\cdot DIFF\_G_t - \sum_{h,n,aa} TD_h \cdot g\_cfd_{h,n,t,aa,a} \quad \perp \quad \lambda_{t,a}^{diff\_g} \ge 0$$

Another constraint limits total investments depending on a technology-specific maximal potential (7).

$$0 \le MAX\_INV_{n,t} - \sum_{aa \in USE_{t,a,aa}} inv\_g_{n,t,aa} \perp \lambda_{n,t,a}^{pot\_g} \ge 0 \quad (7)$$

Shared environmental constraints for the electricity sector

All players in the electricity sector have to respect shared environmental constraints; a CO_2 target guarantees that the annual dispatch is in line with an exogenously set CO_2 reduction path for the UK (8). Here, $\alpha_{t,a}$ is the difference between the CO_2 intensity of the generation mix induces by an annual CO_2 target and the emission factor of a particular technology which can be both positive or negative.

$$0 \le \sum_{h,n,t}\left(TD_h \cdot \alpha_{t,a} \cdot \left(\sum_{aa \in USE_{t,a,aa}} g\_cfd_{h,n,t,aa,a} + g_{h,n,t,a}\right)\right) \perp \lambda_a^{target\_co2} \ge 0 \quad (8)$$

Many countries have additional renewables targets that could be incorporated via a similar renewables constraint. Such a constraint, however, is not analyzed in this paper.

B. *The industry sectors*

Two industry sectors are represented: iron/steel as well as cement. The objective function of these sectors is limited to the abatement costs linked to exogenous CO_2 emissions. It includes the options of either paying the $CO2\_PRICE\_EU_a$ or investing into the CCTS technology with its variable costs $VC\_CO2_{n,i,a}$, and annualized investment costs $INVC\_CO2_{n,i,a}$. The additional costs of the potential transport and storage of CO_2 are passed on from the CO_2 sector via the dual variable $price\_co2_{h,n,a}$.

The industry sectors maximize their objective function (9) subject to constraints similar to those of the electricity sector.

$$\Pi^{IND} = \sum_a DF_a \cdot PD_a \cdot \left(-\sum_h \left[TD_h \cdot \begin{pmatrix} \left(CO2\_IND_{h,n,i,a} - co2\_c_{h,n,i,a}\right) \\ \cdot CO2\_PRICE\_EU_a \\ + co2\_c_{h,n,i,a} \cdot price\_co2_{h,n,a} \\ + co2\_c_{h,n,i,a} \cdot VC\_CO2_{n,i,a} \end{pmatrix} \right] - \left(INVC\_CO2_{n,i,a} \cdot \sum_{aa \in USES_{i,a,aa}} inv\_co2\_c_{n,i,aa} \right) \right) \quad (9)$$

A diffusion constraint (10) restricts the maximal annual investment depending on previous investments.

$$0 \le \left(START\_CO2_i + \sum_n \sum_{aa<a} inv\_co2\_c_{n,i,aa} \right) \cdot DIFF\_CO2_i - \sum_n inv\_co2\_c_{n,i,a} \perp \lambda_{i,a}^{diff\_co2\_c} \ge 0 \quad (10)$$

The annual capturing quantity is restricted by the amount of previous investments (11) as well as the total emissions per node and technology (12).

$$0 \le \sum_{aa \in USES_{i,a,aa}} inv\_co2\_c_{n,i,aa} \cdot CR\_IND_i - co2\_c_{h,n,i,a} \quad \perp \quad \lambda_{h,n,i,a}^{cap\_co2\_c} \ge 0 \quad (11)$$

$$0 \le CO2\_IND_{h,n,i,a} \cdot CR\_IND_i - co2\_c_{h,n,i,a} \quad \perp \quad \lambda_{h,n,i,a}^{max\_ind} \ge 0 \quad (12)$$

C. *The storage sector*

$$\Pi^{STOR} = \sum_a DF_a \cdot PD_a \left(\sum_h \left[TD_h \cdot co2\_s_{h,n,s,a} \cdot \begin{pmatrix} EFF\_CO2 \cdot OILPRICE_a \\ price\_co2_{h,n,s,a} \\ -VC\_CO2_{n,s,a} \\ -co2\_s_{h,n,s,a} \cdot INTC\_CO2_s \end{pmatrix} \right] - \left(INVC\_CO2_{n,s,a} \cdot \sum_{aa \in USES_{s,a,aa}} inv\_co2\_s_{n,s,aa} \right) \right) \quad (13)$$

Offshore saline aquifers, depleted oil and gas fields (DOGF), and fields with the opportunity for CO_2-EOR are identified as possible storage locations. Onshore storage is not included in the examination due to limited geological potential and rising public resistance. The objective function of the storage sectors (13) represents the costs linked to the underground storage of CO_2. For CO_2-EOR sites it includes returns from oil sales at $OILPRICE_a$. The storage costs consist of variable costs $VC\_CO2_{n,s,a}$, the quadratic cost term $INTC\_CO2_s$, and annualized investment costs $INVC\_CO2_{n,s,a}$. The dual variable $price\_co2_{h,n,a}$ is used to pass on the overall storage costs (or in case of CO_2-EOR also possible returns) to the CO_2 transport sector.

The storage entities maximize their objective function subject to a respective diffusion constraint (14), which limits their maximal annual investment:

$$0 \le \left(START\_CO2_s + \sum_n \sum_{aa<a} inv\_co2\_s_{n,s,aa} \right) \cdot DIFF\_CO2_s - \sum_n inv\_co2\_s_{n,s,a} \perp \lambda_{s,a}^{diff\_co2\_s} \ge 0 \quad (14)$$

Further constraints restrict the annual storage quantities, depending on previous investments (15) as well as the overall maximal storage quantity per node and technology (16).

$$0 \le \sum_{aa \in USES_{s,a,aa}} inv\_co2\_s_{n,s,aa} - co2\_s_{h,n,s,a} \perp \lambda_{h,n,s,a}^{cap\_co2\_s} \ge 0 \quad (15)$$

$$0 \le MAX\_STOR_{n,s} - \sum_{aa \le a} PD_{aa} \cdot \left[\sum_h \left(TD_h \cdot co2\_s_{h,n,s,aa} \right) \right] \quad \perp \quad \lambda_{n,s,a}^{max\_stor} \ge 0 \quad (16)$$

D. *The electricity TSO*

The objective function of the electricity TSO is shown in (17). The CO_2 transportation sector is designed analogously to the electricity TSO and therefore not displayed in this paper. The sum of variable costs $VC\_F\_E_{n,nn}$ and annualized investment costs $INVC\_F\_E_{n,nn}$ equal the price difference between two nodes in case of no line congestion. Possible congestion rents are kept by the TSO as profit. Electricity is treated as a normal transport commodity ignoring Kirchhoff`s 2nd law, as network congestion is not the focus of the ELCO model.

$$\Pi^{TSO\_E} = \sum_{a} DF_a \cdot PD_a \cdot \sum_{n,nn} \left[\begin{array}{l} \sum_{h} TD_h \cdot \left(\begin{array}{l} \left(price\_e_{h,nn,a} - price\_e_{h,n,a} \right) \\ \cdot f\_e_{h,n,nn,a} \\ -VC\_F\_E_{n,nn} \cdot f\_e_{h,n,nn,a} \end{array} \right) \\ -\sum_{aa<a} \left(INVC\_F\_E_{n,nn} \cdot inv\_f\_e_{n,nn,aa} \right) \end{array} \right] \quad (17)$$

The electricity utility maximizes its profits subject to the following line capacity constraint:

$$\begin{array}{l} 0 \le \sum_{aa<a} \left(\begin{array}{l} ADJ\_E_{n,nn} \cdot inv\_f\_e_{n,nn,aa} \\ +ADJ\_E_{nn,n} \cdot inv\_f\_e_{nn,n,aa} \end{array} \right) \\ +INICAP\_F\_E_{n,nn} - f\_e_{h,n,nn,a} \quad \perp \lambda^{cap\_f\_e}_{h,n,nn,a} \ge 0 \end{array} \quad (18)$$

E. *Market clearing conditions across all sectors*

Two market clearings connect the different nodes and sectors in the ELCO model: The first is the energy balance (19) with its dual variable $price\_e_{h,n,a}$.

$$\begin{array}{l} 0 = \sum_{t} \left(g_{h,n,t,a} + \sum_{aa \in USE_{t,a,aa}} g\_cfd_{h,n,t,aa,a} \right) \\ +\sum_{nn} f\_e_{h,nn,n,a} - \sum_{nn} f\_e_{h,n,nn,a} \\ -\left(D_{h,n,a} - RES\_OLD_{h,n,a} \right) \perp price\_e_{h,n,a} \; (free) \quad \forall h,n,a \end{array} \quad (19)$$

The second market clearing is the CO_2 mass balance (20) with its dual variable $price\_co2_{h,n,a}$.

$$\begin{array}{l} 0 = \sum_{nn} co2\_t_{h,n,nn,a} + \sum_{s} co2\_s_{h,n,s,a} - \sum_{i} co2\_c_{h,n,i,a} \\ -\sum_{t} \left(\sum_{aa \in USE_{t,a,aa}} g\_cfd_{h,n,t,aa,a} \cdot EF_t \cdot CR\_G_t \right) \\ -\sum_{nn} co2\_t_{h,nn,n,a} \perp price\_co2_{h,n,a} \; (free) \quad \forall h,n,a \end{array} \quad (20)$$

III. DATA

Electricity generation capacities as well as data for investment cost, variable cost, fix cost, availability, and lifetime assumptions are taken from DECC ([11], [12]). For investment costs, we assume cost reduction over time according to Schröder et al. [13]; variable and fixed costs remain constant. The costs are independent from power plant location, but the availability of renewables does vary. Industrial CO_2 emissions and their locations are taken from various studies concentrating on CCTS adoption in the UK industry sector ([14], [15]). Capturing costs in the industry sector as well as costs for CO_2 storage and CO_2-EOR application are taken from Mendelevitch [10]. Fix costs are included in the variable storage costs. We assume a simplified electricity grid, neglecting congestion in between nodes. In addition, no exchange with the neighboring countries is allowed. CO_2 pipelines can be constructed endogenously between the nodes.

The CPF consists of the Carbon Price Support (CPS) which is 18 £/tCO_2 (around 25 €) in 2015 and the ETS price. We assume a continuous increase of the CO_2 price due to the effects of the structural reform of the ETS. The CPS, however, probably drops, resulting in a constant CPF of 35 €/t CO_2 until 2030. From 2030 onwards the CPF rises linearly to 70€ in 2050. All technologies under the CfD receive the proposed strike prices for 2015 and 2020 [16]. From 2025 onwards, an endogenous auctioning system will set an equal financial support for all CfD technologies. The EPS remains at its current level of 450g/kWh throughout the modeling process. The annual CO_2 target induces a reduction of CO_2 emissions in the electricity sector leading to a 90% decrease in 2050 compared to 1990. The discount rate is 5% for all players. The oil price is expected to remain at its current level of 65 €/bbl.

The annual UK load duration curve is approximated by five weighted representative hours, assuming a demand reduction of 20% until 2050 (base year 2015). This simplification does not allow for demand shifting nor energy storage in between periods. CO_2 emissions of the cement as well as iron/steel industry are assumed to be reduced by 40% until 2050. The lifetime of generation units varies by technology between 25 (most renewables), 40 (gas), and 50 (coal, nuclear, hydro) years; construction periods vary between 0 (PV) and up to 10 (CCTS, nuclear) years.

IV. SCENARIO RESULTS

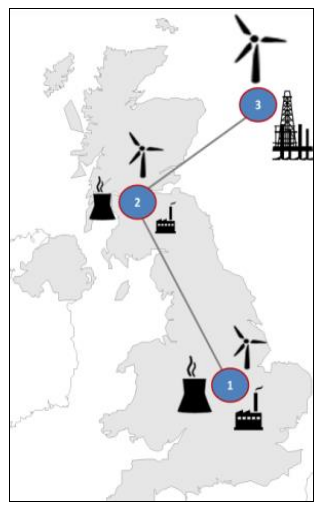

Figure 1. Set-up of simplified 3 nodal network

The simplified network used for this paper consists of three nodes (c.f. Fig. 1). Nodes 1 and 2 represent the Southern and Northern part of the UK, with their respective power plants and industrial facilities. The third node resembles possible locations for offshore wind parks as well as CO_2 storage facilities both with and without CO_2-EOR. We assume electricity and CO_2 pipeline connections to be between nodes 1 and 2, as well as between node 2 and node 3. This simplified case was created to show the characteristics and features of the ELCO model. Its results should not be over-interpreted; they should rather give an idea of the potential of the model once its complete data set is calibrated.

This scenario run indicates a diversified electricity portfolio in 2050: renewables (47%), gas (25%), nuclear (14%), and CCTS with CO_2-EOR (14%). As shown in Fig. 2, Investment activity has two peaks: one early (2015) and diversified which is due to exogenous the strike prices; and one later (around 2040) with renewables and gas. Less favorable regional potentials and technologies such as PV are increasingly used in later periods. The implemented incentive mechanism is comparable to an auctioning system where the last bidder sets the price. The resulting endogenous payments for low-carbon technologies are in the range of 90 €/MWh, but depend strongly on the assumptions for learning curves and technology potentials.

Fig. 2 and Fig. 3 show the dispatch and the CO_2 stream for 2015, 2030, and 2050. The share of coal-fired energy production is sharply reduced from 46% in 2015 to 0% in 2030 due to a phasing-out of the existing capacities. Investment in conventional fossil-fueled capacities only occurs for OCGT and CCGT, which are built from 2030 onwards. EPS hinders the construction of any new coal-fired power plants. Sensitivity analysis shows that a change of its current level of 450 g/kWh in the range of 400-500 g/kWh has little effect, since gas-fired power plants would still be allowed sufficient run-time hours while coal-fired plants would remain tightly constrained. The share of renewables in the system grows continuously from 22% in 2015 to 47% in 2050. Wind off- (38% in 2050) and onshore (26% in 2050) are the main renewable sources.

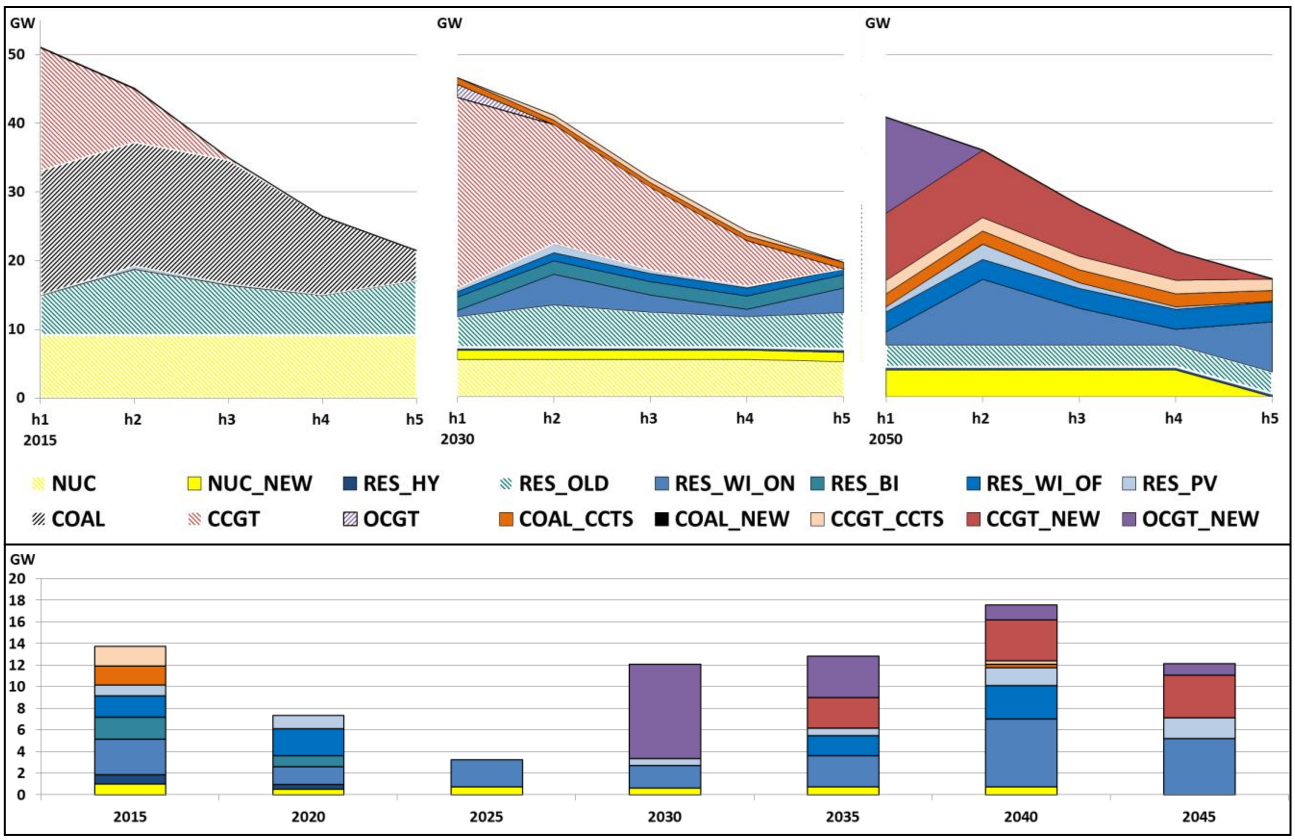

Figure 2. Dispatch by technology type and representative hour for 2015, 2030, and 2050 (top); and annual investments by technology type (bottom).

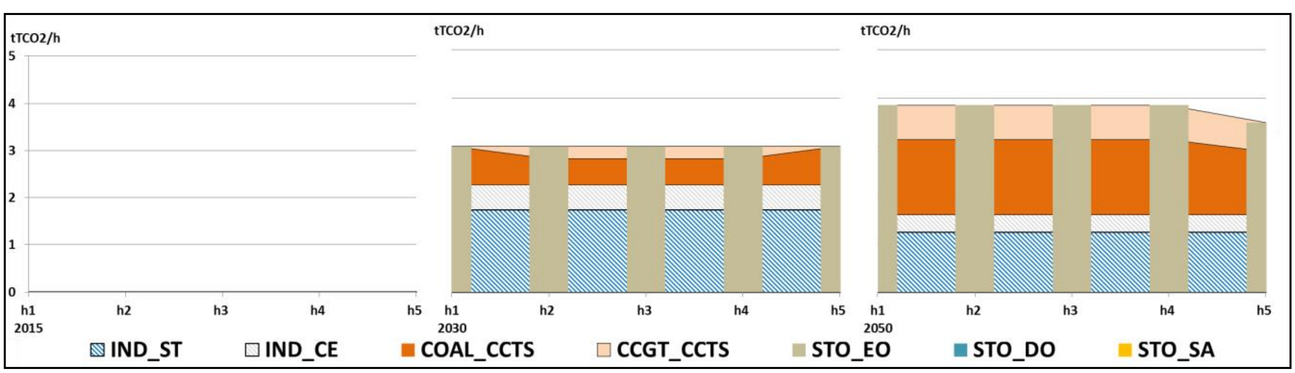

Figure 3. CO_2 capture and storage by type of orgin and sink.

CO_2-EOR creates returns for CCTS through additional oil production. These profits trigger investments in CCTS power plants regardless of additional incentives from the energy market. The maximum share of CCTS in the energy mix is 14% in 2050. The combination of assumed ETS and oil price also triggers CCTS deployment in the industry sector from 2020 onwards. The industrial CO_2 capture rate, contrary to the electricity sector, is constant over all representative hours (c.f. Fig. 3). The storage process requires a constant injection pressure. This shows the need for intermediate CO_2-storage to enable a continuous storage procedure and should be more closely examined in further studies. 90% of the annual emissions from iron/steel and cement industries are captured from 2030 onwards. There is no investment in CCTS without the option of CO_2-EOR as cheaper low carbon technologies are available.

V. Conclusion

The results described in section IV present a showcase of our model framework. It incorporates the unique combination of a fully represented CCTS infrastructure (Carbon Capture, Transport, and Storage) and a detailed representation of the electricity sector in UK. The instruments of the UK Energy Market Reform (EMR), like Emissions Performance Standard (EPS), Contracts for Differences (CfD), and Carbon Price Floor (CPF) are integrated into the framework. We also take into account demand variation in representative hours, the availability of favorable locations for renewables, the limits of their annual diffusion, and an annual CO_2-target. This paper is used to describe the different features and potentials of the ELCO model, though its quantitative results should not be over-interpreted. For further development, we need to test the robustness of the equilibrium results with sensitivity analysis while increasing the regional and time resolutions of the model. The tentative scenario suggests that the EMR does not provide additional incentives for CCTS outside CO_2 use for CO_2-EOR.

The next steps are to compare the costs of different incentive schemes and to analyze their effects on the deployment of different low-carbon technologies with a special focus on CCTS, with and without the option for CO_2-EOR. The role of industry CCTS needs to be further considered in this context. In addition to studying the feedback effects between the CfD scheme and the electricity price, we plan to investigate the incentives of the government, which acts along the three pillars of energy policy: cost-efficiency, sustainability, and security. We want to use our results to draw conclusions and possible policy recommendations for low-carbon support schemes in other countries.

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