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The role of Carbon Capture and Storage in a future sustainable energy system

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ABSTRACT

This paper presents the results of adding a CCS(Carbon Capture and Storage) plant including an underground CO_2 storage to a well described and well documented vision of converting the present Danish fossil based energy system into a future sustainable energy system made by the Danish Society of Engineers. The analyses point in the direction that in such context a CCS investment is not a suitable way to decrease CO_2 emissions. Other alternatives are more cost effective and will fit better into the long-term implementation of sustainable energy systems. The reason is that CCS investments involve huge construction costs with the expectation of long lifetimes. Consequently, the CCS has to operate as part of large-scale power or CHP plants with high utilisation hours for the CCS investment to come even close to being feasible. However, seen in the light of transforming to sustainable energy systems, the number of utilisation hours of power and CHP plants will have to decrease substantially due to the energy efficiency measures in combination with the inclusion of renewable energy power inputs from wind and similar resources. Consequently, no power or CHP plants exist in future sustainable energy systems with sufficient utilisation hours to justify a CCS plant.

1. Introduction

In recent years, CCS (Carbon Capture and Storage) has been put forward as one of the important technologies to help decrease CO_2 emissions and thereby combat climate change. As an example the IEA sees CCS as an important technology in the BLUE Map scenario in their report from 2010 about perspectives on scenarios and strategies for 2050 [1]. Furthermore, the World Energy Council sees it as an integral part of the scenarios in “Deciding the Future: Energy Policy Scenarios to 2050” [2]. On the European level the European Commission just approved their long-term strategy “A Roadmap for moving to a competitive low carbon economy in 2050” [3] based on a process using “Road Map 2050” as a basis for developing a long-term European framework with various stakeholders. In Roadmap 2050, conducted in 2010 by the European Climate Foundation, CCS is included as an important part of the scenarios for decarbonisation, i.e. it is an integral part of European policy [4]. Also in non-governmental visions one may find proposals to consider CCS. As an example WWF also sees CCS as an option to further decrease emission, but does not include it in the scenario in “The Energy Report, 100% Renewable Energy by 2050” from 2011 [5]. In the Danish case, visions including CCS have also been included in the scenarios in “Power to the People”, published by the Danish Energy Association in Ref. [6]. Very often CCS is considered a way to permit the continued use of fossil fuels [7] and several studies have been made in countries in which coal plays an important role in the present energy supply such as the UK [7], Germany [8] and China [9,10]. However, studies of combining CCS with biomass resources and thereby achieving a negative CO_2 emission have also been analysed [11] as well as CCR (Carbon Capture Recycling) in which the carbon is not stored but recycled instead by reacting with e.g. CH_4 [12].

One of the major barriers for CCS is the substantial investment cost and the energy consumption when operating the technology [7,8] and several studies have focused on the technological development to improve the CC (Carbon Capture) element e.g. by chemical-looping [13], optimising the steam system [14] or similar [15].

Normally, Carbon Capture is expected to be able to decrease emissions by 90–95 percent [7,16], but if an LCA approach is used the efficiency decreases substantially [17].

Typical for the studies mentioned above is that the operation of the CCS plant is seen either on its own or as part of a power supply in which the structure of the production system is not changed radically. However, if CCS is looked upon as part of a future strategy or scenario, it is typically to evaluate the consequences for the CO_2

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emission [18]. Due to the expected long lifetime of the storage, changes in the power supply structure may prove to be very important for the feasibility of the CCS. Consequently, if CCS is seen as part of the implementation of sustainable energy systems, it is of particular interest to examine the feasibility of CCS in a transformation in which the whole energy system, including power supply, heat, industry and transportation, is converted into a coherent sustainable energy system.

This paper presents the results of two analyses of adding a CCS plant to the Danish energy system, one in which the power plant (and consequently also the CCS) is operated in accordance with the requirements of the vision of a future sustainable energy system. With already 20 percent wind and 50% electricity coming from CHP Denmark is one of the frontrunners in the implementation of sustainable energy systems [19].

2. IDA vision of a future sustainable energy system

The framework for this study of the role of CCS in future sustainable energy systems is a vision converting the present Danish fossil based energy system into a future sustainable energy system made initially by the Danish Society of Engineers (IDA) in 2006 as an energy plan for 2030 [20,21] and later on in 2009 as a climate plan [22]. The latter is used in the following as the scenario of transforming the Danish energy supply system into a sustainable energy system by 2050 and is referred to as the IDA Climate Plan 2050.

In the IDA Climate Plan 2050, the Danish energy system is transformed into being based 100 percent on renewable energy. When analysing 100 percent renewable energy systems, energy savings, efficient conversion technologies and the replacement of fossil fuels with renewable energy are essential elements to consider [23,24]. The design of 100 percent renewable energy systems has two major challenges: One is to integrate a high share of intermittent resources into the energy system, especially concerning electricity supply [25–27]. The other is to include the transportation sector in the proposed strategies [28,29].

In the IDA Climate Plan 2050, the possibilities of reducing the emission of greenhouse gases by 90 percent are analysed by using only renewable energy sources and related socio-economic feasibility studies are presented. The analyses include: transport, the agricultural and industrial parts of greenhouse gas emissions, the potential for increased exports as well as domestic job creation, and the total effects on health costs. Electricity market trade analyses and sensitivity analyses are also included. The vision thus presents technical energy system analyses of the total system with a multitude of interrelated technologies as opposed to just one technology or one category of effects. The final year of analysis is 2050, while two intermediate years, 2015 and 2030, are also analysed. The methodology includes hour by hour simulations leading to the design of flexible energy systems with the ability to balance electricity supply and demand and to exchange electricity production on the international electricity market.

The vision is thoroughly described in Refs. [20,22,30]. The paper [20] describes the process, analyses and results of the IDA Climate Plan 2050 by the Danish Society of Engineers (IDA) which was completed in August 2009. As a point of departure, the latest business-as-usual projection to 2030 from the DEA (Danish Energy Authority) has been used. Utilising the same methodology, a business-as-usual projection has been extended towards 2050 in the IDA Climate Plan 2050. The analyses of the IDA Climate Plan 2050 build on previous experience and analyses of 100 percent renewable energy systems [21,23,28]. However, the technical and economic analyses are more comprehensive and include a short-term target year, a business-as-usual projection to 2050, as well as the first estimates of the socio-economic costs of a 100 percent renewable energy system for Denmark. Job effects and effects on health costs are also analysed.

3. Methodology, assumptions and validation of model

In the study of the IDA Climate Plan 2050 as well as the study of adding CCS technology to the system, presented in the following, the analyses have been done by analysing the system hour by hour in the energy system analysis tool EnergyPLAN. A model of the Danish energy system has been made and used for technical system analyses as well as estimates of economic consequences [31]. The model is an input/output model that performs annual analyses at intervals of 1 h. Inputs are demands, capacities of the technologies included, demand distributions, and fluctuating renewable energy distributions. A number of technologies can be included enabling the reconstruction of all elements of an energy system and allowing the analyses of e.g. wind integration technologies as well as the interrelation between the electricity and the heat supply with high penetration of CHP. The model makes it possible to use different regulation strategies putting emphasis on heat and power supply, imports/exports, ancillary services, grid stability and excess electricity production. Outputs are energy balances, resulting annual production, fuel consumption, and imports/exports. The EnergyPLAN tool is particularly suitable for analysing radical changes in energy systems and renewable energy systems with a high intermittency [32].

The computer tool EnergyPLAN has been used for several similar modelling studies at national and regional levels in various countries. In the review paper [33] EnergyPLAN has been compared to a number of similar tools. In accordance with the definitions used in the review paper, the modelling of a national system by the use of the EnergyPLAN tool can be characterised as a bottom-up hourly simulation model which can calculate the consequences of a given operation of a given national energy system in terms of annual fuel demand, costs and CO_2-emisions, among other things.

The validation of such kind of simulation models has been discussed in the paper [34] in which the models are considered as miniature scientific theories. In Ref. [34] the validation is discussed in relation to different philosophical positions including Rationalism, Empiricism and Positive Economics emphasising a discussion of the objectivist approach versus the relativist approach – foundationalism versus anti-foundationalism. On one side an extreme objectivist believes that model validation can be divorced from the model builder and its context and that validation is an algorithmic process which is not open to interpretation or debate. By contrast, an extreme relativist believes that the model and model builder are inseparable and validation is a matter of opinion.

The authors [34] argue that most practitioners have instinctively adopted a middle ground in this debate and they compare the validation of simulation models to the situation in a court house. The prosecutor does not have to prove the guilt in any foundationalist sense but rather "beyond reasonable doubt". Extending the court house metaphor, the authors argue that "*The model builder would be free to establish and increase the credibility of the model through any reasonable means. This process would also involve other model stakeholders, such as model users and referees of journal articles*" [34].

In the process of defining *reasonable*, one may refer to papers such as [35,36] in which the purpose of the model is highlighted as essential, i.e. if the model is acceptable for its intended use.

Following such guidelines, it should initially be highlighted that the purpose of the model used in this study has been to calculate the consequences of adding a certain technology (in this case CCS)