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Energy system analysis of utilizing hydrogen as an energy carrier for wind power in the transportation sector in Western Denmark

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Abstract

Hydrogen is an energy carrier that can potentially be used for introducing renewably generated electricity into the transportation sector. This paper presents a methodology for an overall energy system analysis of a hydrogen infrastructure, which meets a transportation hydrogen demand profile. The methodology starts by building a mathematical model for optimizing the economic operation of electrolyzers on the electricity market by use of Genetic Algorithms. Demand profiles from the optimization are then included in an overall energy system analysis model studying the electricity market and power balance system effects. A sample 2030 scenario analysis of Western Denmark is presented to demonstrate the applicability of the devised methodology. It is shown that Genetic Algorithms is a flexible tool that can be adapted to optimization problems involving energy storage. On the other hand, it is found that the ability of Genetic Algorithms to find a solution is highly dependent on initial variables and the storage constraint. Further analysis is required in order to test and expand the methodology and scenario results.

Keywords: Genetic Algorithms; Operational optimization; Electricity market

1. Introduction

Wind energy provided 22% of the electricity consumption in Western Denmark in 2006. The installed wind turbine capacity of 2400 MW already exceeds the local demand at certain hours of the year (Energinet.dk, 2007). On the other hand, transportation has almost entirely relied on products derived from oil (DEA, 2005). The operational costs of a thermally dominated electricity system (such as in Denmark) are expected to increase with an increasing share of fluctuating wind power (Meibom et al., 2007a). While foreign exchange can contribute to balancing fluctuating power, having local flexible technologies is essential for the development of a renewable energy market (Hvelplund, 2006). Various technological alternatives have been analyzed for increasing the system flexibility and economically allowing the integration of higher shares of wind power in the Danish electricity system (Andersen and Lund, 2007; Lund and Münster, 2006; Meibom et al., 2007b; Østergaard, 2005).

A transportation fleet based on electricity is expected to have a positive technical influence on the electricity system flexibility and stability at high wind power penetration (Lund, 2007; Mathiesen and Lund, 2008). The introduction of renewable energy into the transportation sector requires an energy carrier that meets the performance characteristics demanded by modern societies. Electrolytic hydrogen produced from wind and solar power is a potential carrier that has received considerable research attention during the previous decade (EHFCTP, 2006; EC, 2004; USDOE, 2007; IEA, 2004).

Several studies have analyzed various aspects of a future energy system with hydrogen as an energy carrier in the transportation sector in Denmark. Sørensen et al. (2004) constructed 2030 scenarios for Denmark with centralized and decentralized hydrogen production. The scenarios sought to maximize the utilization of wind power and study the impact on the storage size and hydrogen transportation problem. The study concluded that both centralized and decentralized

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Nomenclature

GAs	Genetic Algorithms
P_m	Electricity bought on the market
P_w	Specific wind power production
P_e	Electrolyzer power consumption
η_{tot}	Total electrolyzer efficiency
C_m	Electricity market cost
C_w	Wind power cost
K_{oc}	Operational cost
K_{loss}	Leakage coefficient from the storage tank
N_{chr}	Number of chromosomes per population
P_{emax}	maximum electrolyzer power capacity
P_{emin}	minimum allowable electrolyzer operation power
$\dot{Q}_{H_2}$	Hydrogen production by the electrolyzer system up to storage
$\dot{Q}_{H_2loss}$	Hydrogen static loss from the storage tank
$\dot{Q}_{H_2T}$	Hydrogen demand by the transport sector
S	Storage energy content
S_{max}	Maximum storage capacity
S_{min}	Minimum storage limit

scenarios are technically feasible, and that the mismatch between intermittent renewable energy sources and electricity demand can be offset by using hydrogen storage. The study, however, did not address the interaction between electricity prices and hydrogen electrolyzer operation.

One of the studies of the operational system effects of electrolytic hydrogen production in Western Denmark was performed by Pedersen and Eriksen (2005). In the mentioned study, a futuristic hydrogen scenario is simulated. The electrolyzer operation strategy is based on a fixed maximum electricity purchase price on the spot market. The study concludes that electricity prices are highly unlikely to fluctuate enough to allow for the utilization of the produced hydrogen in stationary applications. This is due to the fact that the Danish system is interconnected with the Scandinavian system, which is characterized by relatively high hydropower capacities. It is thus recommended to utilize the produced hydrogen in the transportation sector where tax benefits could potentially allow hydrogen to compete with oil on an energy unit basis. The study, however, puts no restraints on the hydrogen storage capacity or hydrogen demand, and this gives a relatively large storage capacity and has a minor impact on electricity system prices.

The problem of optimizing the operation of energy storage on the day ahead spot market such as the NordPool market poses a modeling challenge. In his work, Korpås models a hydrogen system with a limited grid connection and local wind power generation (Korpås, 2004). An economic optimization method considering wind speed and electricity market prices is presented. The study, however, assumes a deterministic electricity price time series. On a large scale, the hydrogen system would inevitably influence the operation of the electricity market itself.

2. Scope

This paper builds on the work of Pedersen and Eriksen (2005) and aims at developing a methodology for incorporating limited storage and fixed hydrogen demand profiles in the simulation of electricity system prices and power balance. The methodology is modular and utilizes an existing energy system analysis model (SIVAEL), while building an external module for optimizing the operation of the electrolytic hydrogen fuelling stations using Genetic Algorithms (GAs). A Western Denmark 2030 scenario is used in order to test the methodology's applicability. The methodology consists of an iterative two-phase process:

- Micro analysis phase which utilizes a deterministic price time series derived from an overall system analysis for optimizing the economic operation of hydrogen fuelling stations.
- Macro analysis which incorporates the electrolyzer operational results of the micro analysis in an overall system analysis model that generates endogenous electricity prices.

3. Micro analysis

The micro analysis consists of a mathematical model and an operational optimization of the electrolyzers' economic operation by use of GAs.

3.1. Mathematical model

A mathematical model of a hydrogen fuelling station is constructed as shown in Fig. 1. The model differentiates between power bought on the market (P_m) and power from specific wind farms (P_w). This distinction is made in order to make possible the prioritizing of renewable energy for hydrogen production. The sum of wind and market power constitutes the electrolyzer power (P_e). The grid connection is also used for selling excess wind power on the spot market.

The electrolyzer plant's model includes an AC/DC conversion, electrolyzer stack including auxiliary apparatus, and the compressor. Each component is represented by a conversion efficiency (η), while the total electrolyzer efficiency (η_{tot}) is the product of the individual efficiencies. The total efficiency typically drops at lower operational power relative to the nominal power (Korpås, 2004). A minimum electrolyzer power is set to determine the point below which the losses become relatively high and the electrolyzer shuts down. For the purpose of this analysis, the efficiency is assumed to vary linearly in the operational range.

The produced hydrogen $\dot{Q}_{H_2}$ is placed in the storage whose level is kept within a minimum and maximum level. During storage, hydrogen leakage $\dot{Q}_{H_2\text{loss}}$ is, for reasons of simplicity, assumed to be only proportional to the storage size. The remaining hydrogen is used for meeting a certain transportation hydrogen demand $\dot{Q}_{H_2T}$, which is a user-specified deterministic time series.