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Evaluating demand side measures in simulation models for the power market

Ove Wolfgang [a], Gerard Doorman [b,*]

[a] SINTEF Energy Research, Sem Sælandsvei 11, NO-7465 Trondheim, Norway
[b] Norwegian University of Science and Technology, Department of Electric Power Engineering, NO-7491 Trondheim, Norway

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ABSTRACT

Increased energy efficiency is one of the pillars for reducing CO_2 emissions. However, in models for the electricity market like unit commitment and dispatch models, increased efficiency of demand results in a paradoxical apparent reduction of the total economic surplus. The reason is that these are partial models for the electricity market, which do not take into account the effect of the changes in other markets. This paper shows how the calculation of the consumer surplus in the electricity market should be corrected to take into account the effect in other markets. In different cases we study shifts in the demand curve that are caused by increased energy efficiency, reduced cost for substitutes to electricity and real-time monitoring of demand, and we derive the necessary correction. The correction can easily be included in existing simulation models, and makes it possible to assess the effect of changes in demand on economic surplus.

1. Introduction

Increased energy efficiency is commonly seen as one of the main pillars for reducing the dependency on fossil fuels and reducing CO_2 emissions. This is clearly demonstrated by EU's goal to increase energy efficiency by 20% within 2020 [1]. Reducing demand is challenging, and targeted policy measures will be necessary. The effects of such measures are hard to foresee, but simulation models can be used to give quantitative predictions. However, simulating the effect of changes in demand is not a trivial task. In this paper we demonstrate that the evaluation of the benefits of demand side policies easily leads to false answers when this is analyzed in, e.g. unit commitment and dispatch models. Subsequently we propose a solution to this problem.

The literature on energy efficiency is exhaustive, ranging from improvement of specific industrial or residential applications, analyses to study the impact of increased energy efficiency on energy systems in general, studies of the effect of real-time monitoring, and policy analyses and recommendations. Two examples of the latter categories are Stadler et al. [2] who study the effectiveness of technologies and/or efficiency measures using a new simulation tool and Farinelli et al. [3], who simulate policies and measures using technical-economic models of the well-known MARKAL family.

Electricity consumption is also expected to be increasingly influenced by the accelerating introduction of Advanced Metering Infrastructure (AMI). This development can make it attractive for consumers to react on short-term variations in prices, and it also provides a basic infrastructure for load control. General customer response on price changes is described in for example [5–8]. Recently also the US Federal Energy Regulatory Commission has issued a report on demand response [9]. More specific load control of water heaters is discussed in [10,11].

In theory, consumers increase their energy efficiency and react on prices if it is profitable for them to do so. However, it is well-known that there are many barriers that prevent such behaviour, cf. [2–3,9,12]. An overview over the challenges for demand side management in the electricity sector is given in [13].

Studies of the electricity sector often require a considerable degree of detail in the modelling. Demand response on high prices during peak load, can for example not be assessed without a model that represents peak load conditions. As a consequence it is common to use models that only include the electricity market like unit commitment and dispatch models. Effects from other markets, e.g. increased demand caused by a transition from gas-based heating to heat pumps, are studied as exogenous shifts in demand.

In for example generation dispatch models, it has been common to have a cost-minimization objective. There is a fixed, price-inelastic demand that must be covered at the lowest cost. However, with demand becoming more price-elastic, cost minimization is no longer the obvious criterion: naive cost minimization would imply minimizing demand by serving only its inelastic share. Although other approaches are viable, an obvious alternative is the maximization of economic surplus, the sum of consumer and producer surplus, a well-known principle in economic theory. The advantage of this approach is that the economic effect on consumers implic-

* Corresponding author. Tel.: +47 73 59 72 90; fax: +47 73 59 72 50.
E-mail addresses: ove.wolfgang@sintef.no (O. Wolfgang), gerard.doorman@elkraft.ntnu.no (G. Doorman).

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itly is taken into account, resulting in a solution that maximizes the sum of the benefits for producers and consumers.

Unit commitment and dispatch models can be called "partial models for the electricity market", because they only model one single market (for electricity), and not all markets for energy or the whole economy. In partial models, "spill-over" effects on other markets are not taken into account, and in some cases this leads to wrong results. In this paper we explain why the analysis of energy efficiency measures is an analytical problem in partial models for the electricity market, and we propose a method to correct the apparent inconsistency that occurs when the effect on total economic surplus is calculated straightforwardly. This is important for modellers and users of relevant models widely used in the power sector, because such models increasingly are used to analyze the consequences of policies targeted at the demand side.

The proposed method is general, and is applicable to many models that are used for the analysis of energy efficiency and demand response measures. Models that include the whole energy sector (e.g. [2,3]) do include the effect of changes in the demand for one energy source on other energy sources, but also in these models there are challenges with respect to energy efficiency measures.

The following section will explain the problem in detail. In subsequent sections we will present a solution on each of three variants of the problem:

- Reduced costs for alternatives to electricity consumption, e.g. changed prices for biomass or oil.
- Increased energy efficiency, e.g. more efficient electronic equipment or better isolation of houses.
- Dynamic pricing for electricity that reveals the underlying, already existing elasticity.

The analysis is based on an informal graphical method as well as a formal mathematical approach. In each of these cases social welfare will apparently decrease as the result of the shift of the demand curve. This paper will show how to correct for this effect in a consistent way. In the first two cases there are real changes in the marginal willingness to pay for electricity. These cases will be analyzed in Sections 3 and 4 respectively. In the third case there is no real change in the marginal willingness to pay for electricity. However, the real demand curve is revealed by real-time monitoring and pricing. This case is analyzed in Section 5. The final section gives the conclusions.

2. Short description of the problem

The objective is to ensure the correct calculation of the economic benefit of increased energy efficiency or demand response when a quantitative model for the electricity market is used. Typically, one would run an analysis with the original demand model and an analysis with the alternative demand model and compare the economic surplus.

Traditional power system models, e.g. unit commitment models, often use a cost minimization approach. Obviously, costs are reduced when demand is reduced. But cost-benefit studies can also be carried out by considering the effect on total economic surplus, which is the sum of consumer and producer surplus (see, e.g. [15] and for modelling of the consumer benefit in the optimal power flow [16]). In cost-minimization models the total surplus can be post-calculated. Other models use total economic surplus as the objective to be maximized. However, this criterion does not give the correct results in cost-benefit studies for demand side changes, which is illustrated in Fig. 1.

The total economic surplus (sum of consumer surplus and producer surplus) is given by the area under the demand curve minus

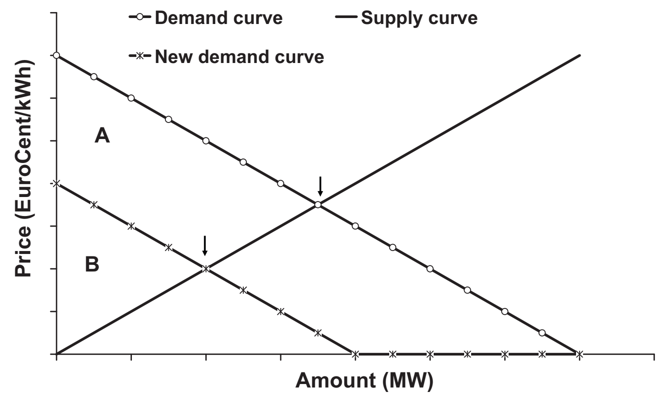

Fig. 1. The effect of reduced demand on total economic surplus in optimization models.

the area under the supply curve. It is well-known that total economic surplus is maximized when the marginal utility of demand equals the marginal cost of supply, i.e. at the point marked with the right arrow. For the initial demand curve the total economic surplus in the optimal solution is given by area "A" plus area "B". However, after the shift in the demand curve (e.g. because of a policy measure) total economic surplus is only "B". Thus, the calculated total surplus is reduced as a consequence of, e.g. increased energy efficiency. This is obviously a false answer.

The underlying problem is the fact that models that simulate the power market are *partial* models. They describe only a part of the economy or even of the energy sector. For example, a shift from electrical heating to biomass apparently reduces total economic surplus if the electricity market is the only market included in the model. The theoretically best approach would be to include other markets in the same model. However, this is impractical in many modelling contexts. In this paper we will propose a solution to the paradox that has been described in this section.

3. Reduced costs for alternatives to electricity consumption

3.1. Demand curve for electricity and a substitute

In general, we are concerned with the calculation of total economic surplus, i.e. the sum of consumer surplus and producer surplus. The full change in the total surplus after an exogenous shift in the demand curve can be divided into two separate parts. The first part is the change in consumer surplus evaluated at the initial price. It is the first part of this calculation we address in this paper. The second part is the change in surplus for consumers and producers because of a different price in the new equilibrium (this affects the surplus for consumers and producers). This second part is consistently accounted for using the original supply curve and the new demand curve. Thus, without loss of generality, in the following we do not include production, but only consider the calculation of consumer surplus at a given price.

In a well-functioning electricity market, the demand curve shows the marginal value of consumption. This marginal value is partly given by the consumers' willingness to pay for energy, and partly by the cost of alternative energy carriers and partly by the technologies that are available for the consumer. Alternative energy can typically be used for heating purposes in households and industries. This is illustrated in Fig. 2.

The cost and maximum quantity for the alternative to electricity are shown by the horizontal line-segment in Fig. 2. The cost of the alternative energy source is assumed to be p_1. If the price of electricity is above p_1, the consumers buy the alternative fuel plus the amount of electricity that is shown on the horizontal axis.