Evaluating demand side measures in simulation models for the power market

Ove Wolfgang	SINTEF Energy Research Sem Sælandsvei 11 NO-7465 Trondheim Norway email: ove.wolfgang@sintef.no
Gerard Doorman (corresponding author)	Norwegian University of Science and Technology Department of Electric Power Engineering NO-7491 Trondheim Norway telephone: +47 73 59 72 90 fax: + 47 73 59 72 50 email: gerard.doorman@elkraft.ntnu.no

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.

Keywords: Energy efficiency, power systems, economic surplus, simulation models

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. Among others, 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 partial models for the electricity market. 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], [6], [7] and [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] and [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] and [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 partial models that only include the electricity market, while spill-over effects from other markets are studied as exogenous shifts.

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. The method that can be used to adjust the economic surplus consistently 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] and [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 Section 3 and Section 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 benefit.

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]). 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 Figure 1.

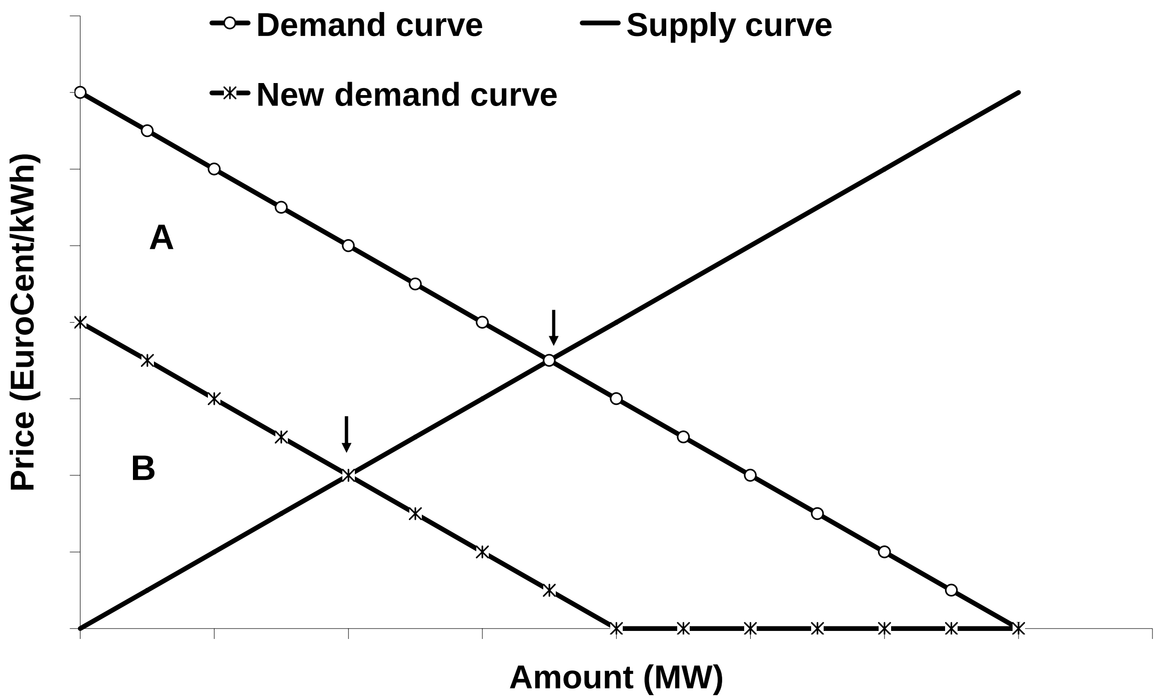

Figure 1 The effect of reduced demand on total economic surplus in optimization models

The total economic surplus (sum of consumer surplus and producer surplus) is given by the area under the demand curve minus 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. E.g. 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 Figure 2.

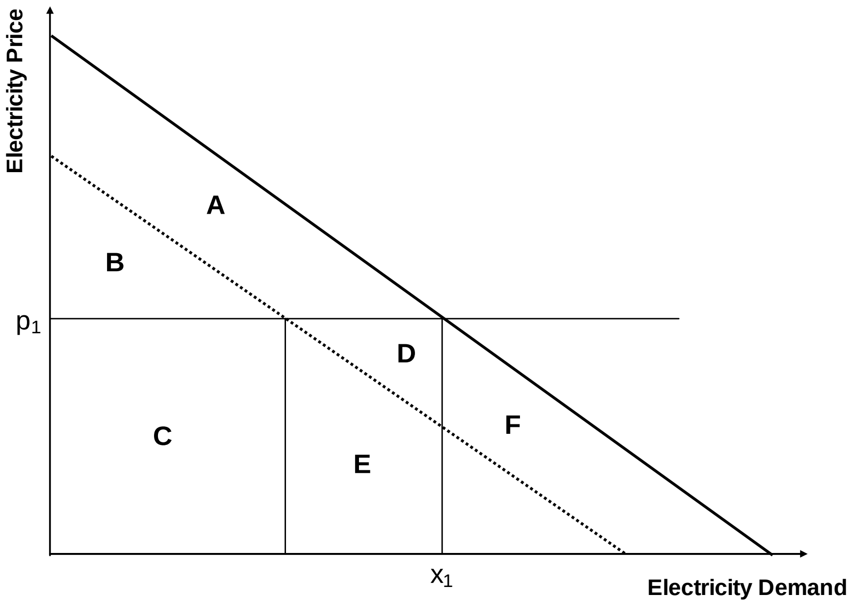

Figure 2 Example demand curve for electricity

The cost and maximum quantity for the alternative to electricity are shown by the horizontal line-segment in Figure 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.

If the electricity price is reduced the demand for electricity increases in accordance with the demand curve. When the price level reaches p_1, the consumers will shift from the use of the alternative to electricity. As long as the price is p_1 the consumers are indifferent to the use of either electricity or the alternative energy source. Therefore, the marginal value of electricity consumption does not decline in the domain where this shift occurs (it is constant and equal to the cost of the alternative fuel), even if electricity demand is increasing. When the price drops below p_1, electricity is used instead of the alternative energy source.

The maximum quantity of electricity that can be substituted by the alternative energy source is equal to $x_b - x_a$. The reason that this is a limited quantity is typically that the consumers can use the alternative (e.g. oil) to substitute electricity only for some purposes (e.g. for heating) but not for all alternatives (e.g. lights).

3.2 Informal, graphical analysis

To give an intuitive understanding of the approach, we start with an informal, graphical analysis. We will show how the consumer surplus is changed in a partial analysis of the electricity market if the cost of the alternative to electricity consumption is reduced. The change in the demand curve and the consumer surplus for the three possible cases is illustrated in Figure 3. For clearness we use a linear demand curve in these figures, but this is not generally required for the analysis.

Figure 3(a) shows the shift in the demand curve when the price of the alternative to electricity is reduced. The solid line shows the demand curve before the price-reduction, while the dotted line shows the demand curve after this change. The size (integral) of the area marked A is exactly equal to the cost-reduction for the alternative energy multiplied with the maximum consumed amount.

Figure 3(b) shows the consumer surplus before and after a price-reduction for alternative energy in the case where the electricity price is higher than the initial price for alternative energy. Since the surplus is B in both cases, the consumer surplus is apparently unaffected by the price-reduction. But this cannot be correct: the alternative energy is utilized at maximum in both cases, and total expenditures are therefore reduced by the price-reduction times the maximum consumed amount for the alterative energy (i.e. by the area between the two demand curves). Thus one has to add area A to the new consumer surplus to get the correct estimate of the value of this price-reduction for the consumer.

Figure 3(c) shows the consumer surpluses in the case where the electricity price is below the new lower price for the alternative to electricity. The calculated consumer surplus is the area A+C prior to the cost-reduction and only area C after this change. However, in this case the alternative energy is unused in both cases because of the low price of electricity, and the true consumer surplus is therefore unaffected by the price-reduction. Again we have to add the area A to the new consumer surplus to get a correct calculation of the total change in the surplus.

Figure 3(d) shows the consumer surplus in the case where the electricity price is between the old and new price for alternative energy. The consumer surplus is D+E prior to the price-reduction and only area D when the price has been reduced. So apparently the consumer surplus is reduced by area E. The real effect of the reduced cost for the alternative fuel is however that some of the electricity is substituted with the alternative fuel and this reduces the costs with the area F. We therefore have to add F+E, i.e. area A, to the new consumer surplus to get a correct calculation of the change.

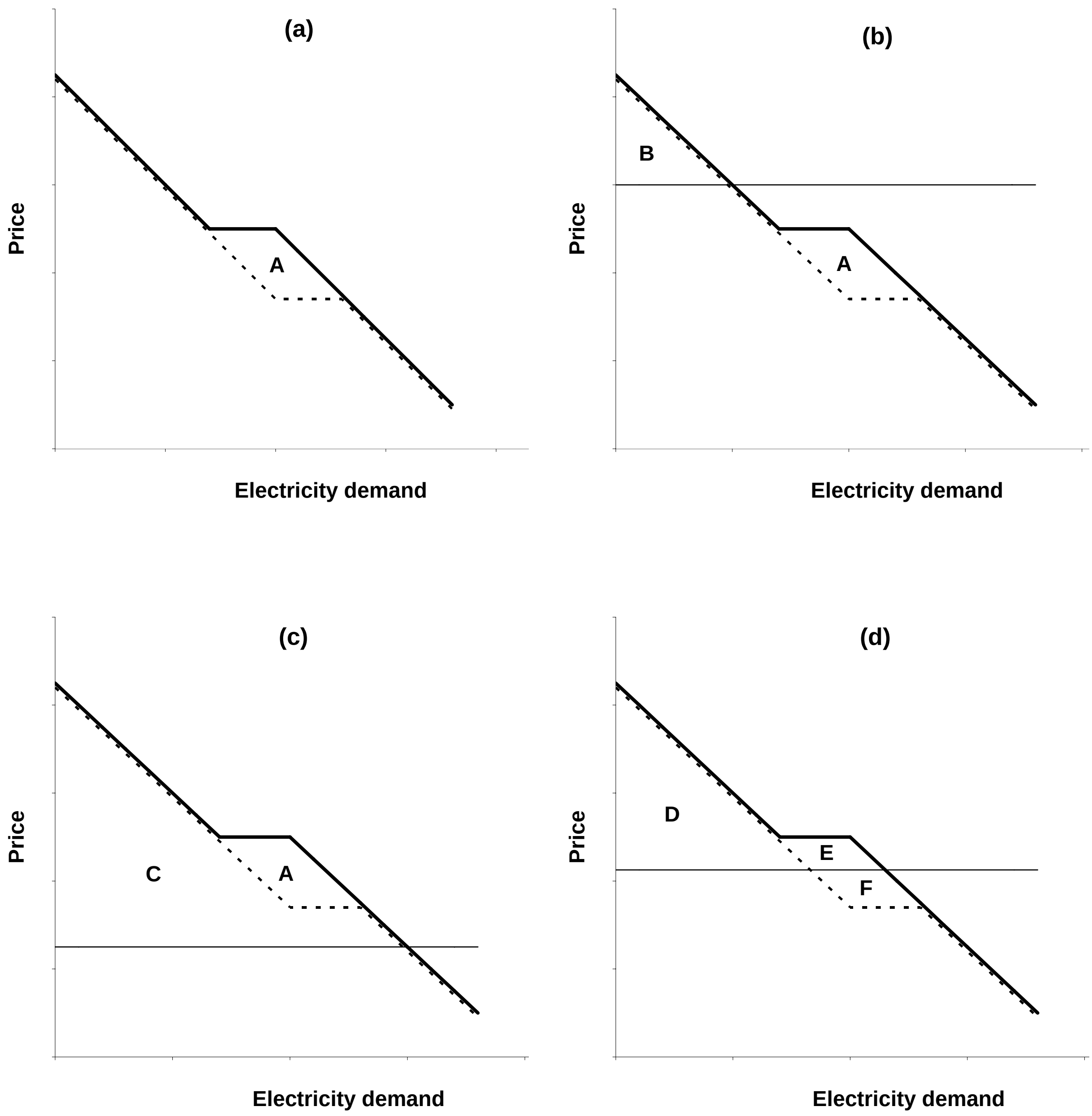

Figure 3 Changed consumer surplus when the price of an alternative to electricity is reduced

For the three possible cases we have showed that, in a partial model for the electricity market, we have to add the area between the old and new demand curve for electricity to the new consumer surplus when we analyze how a price-reduction for alternative energy affects consumer surplus. In the next section we will show this result in a formal mathematical analysis.

3.3 Mathematical analysis

First we define the following symbols:

x_{alt} Consumed amount of substitute for electricity.

x_{el}	Consumed amount of electricity.
x_{max}	Maximum quantity of electricity that can be substituted with the alternative energy.
x	Sum energy consumption (electricity and substitute).
p_{el}	Electricity price.
p_{alt}	Price of substitute for electricity.
$u(x)$	Utility of energy consumption measured in money. As commonly assumed, the derivative is $u'(x)\geq 0$, while the second derivative is $u''(x)<0$.
CS_{el}	Consumer surplus evaluated in a partial analysis of the electricity market.
CS	Consumer surplus, also including the surplus of consuming alternative energy.
δ	Price-reduction for alternative energy (zero initially), $\delta\geq 0$.
Δ	Symbolises optimal change for a variable as a result of a price reduction for the alternative energy. The symbol is put in front of a variable that is changed, e.g. Δx_{el}.
λ	Shadow-price (dual value) of energy consumption constraint
$\overline{\mu}$	Shadow-price (dual value) for maximum use of alternative energy
$\underline{\mu}$	Shadow-price (dual value) for minimum use of alternative energy

The consumer surplus is the utility of energy consumption measured in money minus expenditures for electricity and alternative energy. For any given prices the consumer will choose the composition of energy-goods that maximizes consumer surplus. In the following we assume an inner solution for electricity demand (not restricted by zero or a maximum consumed amount). Therefore, the consumer surplus is given by:

$$\begin{aligned} &CS = \max_{x,x_{el},x_{alt}} \left\{ u(x) - p_{el}x_{el} - p_{alt}x_{alt} \right\} \\ &s.t. \quad x_{el} + x_{alt} \geq x \\ &s.t. \quad 0 \leq x_{alt} \leq x_{max} \end{aligned} \tag{1}$$

The Lagrangian function to this optimization problem is

$$L = u(x) - p_{el}x_{el} - p_{alt}x_{alt} + \lambda(x_{el} + x_{alt} - x) + \overline{\mu}(x_{max} - x_{alt}) + \underline{\mu}x_{alt} \tag{2}$$

Kuhn-Tucker optimality conditions are:

$$u'(x) - \lambda = 0 \tag{3}$$
$$-p_{el} + \lambda = 0 \tag{4}$$
$$-p_{alt} + \lambda - \overline{\mu} + \underline{\mu} = 0 \tag{5}$$
$$\lambda(x_{el} + x_{alt} - x) = 0 \tag{6}$$
$$\overline{\mu}(x_{max} - x_{alt}) = 0 \tag{7}$$
$$\underline{\mu}x_{alt} = 0 \tag{8}$$

In addition we know that all shadow prices are non-negative, $\lambda, \overline{\mu}, \underline{\mu} \geq 0$.

Combining (3) and (4) gives:

$$u'(x) = p_{el} \tag{9}$$

The total use of energy is therefore only a function of the electricity price. In the following we will study the effect of reducing the price of alternative energy with δ for a given price of electricity. From (9) we know that this will not affect the total energy consumption.

$$\Delta x = \Delta x_{alt} + \Delta x_{el} = 0 \tag{10}$$

As a consequence, the reduced price for alternative energy will only affect consumer surplus through the reduction in total expenses, which can be written as:

$$\begin{aligned} \Delta CS &= -p_{el}\Delta x_{el} - p_{alt}\Delta x_{alt} + \delta\left(x_{alt} + \Delta x_{alt}\right) \\ &= \left(p_{el} - p_{alt}\right)\Delta x_{alt} + \delta\left(x_{alt} + \Delta x_{alt}\right) \end{aligned} \tag{11}$$

Equation (9) shows the real change in the consumer surplus when the price of the substitute to electricity is reduced by δ. However, in the Appendix it is shown that the price reduction for alternative energy will affect the calculated consumer surplus in the partial model for the electricity market by:

$$\Delta CS_{el} = -\delta\left(x_{\max} - x_{alt} - \Delta x_{alt}\right) - \left(p_{alt} - p_{el}\right)\Delta x_{alt} \tag{12}$$

When we compare this with the real change in consumer surplus in (11) we find:

$$\Delta CS_{el} - \Delta CS = -\delta x_{\max} \tag{13}$$

Equation (13) shows that the calculated change in the consumer surplus in the partial analysis of the electricity market is δx_{max} too low. This is exactly equal to the area between the old and new demand curve for electricity when the price of the alternative energy source declines.

4 Increased energy efficiency

4.1 Assumptions for the increase in energy efficiency

If the isolation of buildings is improved so that their demand for electricity for heating is reduced or some electronic equipment is made more efficient, the use of electricity can be reduced without any welfare-reductions. An industrial consumer that uses electricity in the production process can reduce the use of electricity without reducing the produced amount if the energy efficiency is increased. In the following we will analyse a case where the amount of electricity that is needed to obtain a given utility is reduced by a given quantity. We will again start with an informal analysis.

4.2 Informal, graphical analysis

If the isolation of buildings is improved, the whole demand curve for electricity shifts to the left, cf. Figure 4.

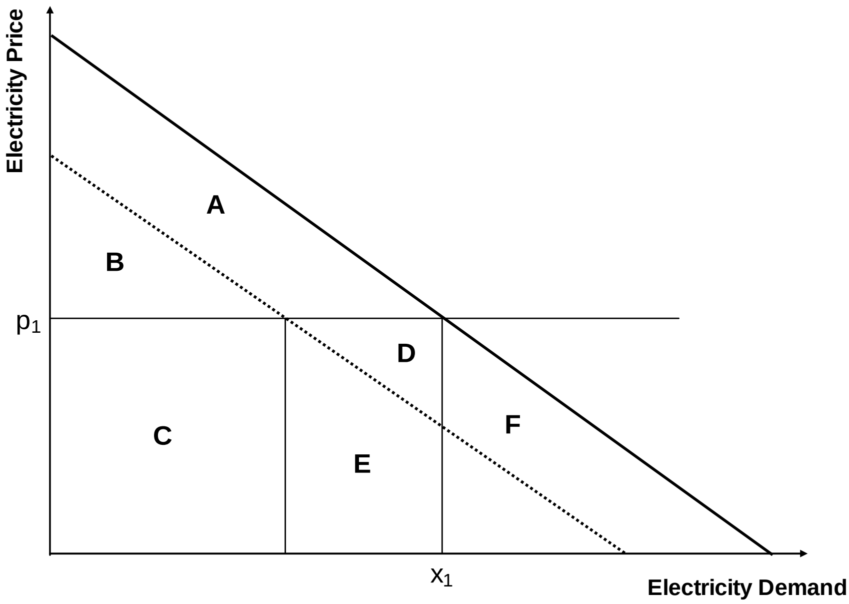

Figure 4 Changed consumer surplus when energy efficiency is increased

The dotted curve shows the new demand curve after the shift. The consumer surplus is given by A+B before the shift and area B after the shift. There is an apparent reduction in the consumer surplus with the area A. However, since the demand curve reduces the consumed amount with the size of the shift, the utility of the electricity consumption is by assumption the same. Moreover, the consumers save costs corresponding to the area D+E compared with the situation before the shift. If we want to calculate how the increase in energy efficiency affects consumer surplus we must therefore add area A+D+E to the new consumer surplus. Area E is identical to area F since triangles E+G and F+G are identical. Thus, we have to add the amount A+D+F to the new consumer surplus, and this is the area between the old and new demand curve.

4.3 Mathematical analysis

The result from the previous section is now shown analytically. In this case the consumer surplus is given by:

$$CS = \max_{x_{el}} \left\{ u\left(x_{el}\right) - p_{el} \cdot x_{el} \right\} \tag{14}$$

We assume $x_{el} > 0$ in the optimal solution. Therefore, the first-order condition is

$$u'\left(x_{el}\right) = p_{el} \tag{15}$$

Because of increased energy efficiency, the total utility is the same if the consumed amount is reduced by the amount $\theta > 0$. We assume $x_{el} > 0$ also after the increase in energy efficiency. The new utility-function $v(x_{el})$ is

$$v\left(x_{el}\right) = \left\{ u(x_a) : x_a = x_{el} + \theta \right\} \quad \forall x_{el} > 0 \tag{16}$$

It follows that

$$v'\left(x_{el}\right)=\left\{u'(x_a):x_a=x_{el}+\theta\right\}\quad \forall x_{el}>0 \tag{17}$$

The new first-order condition for use of electricity is

$$v'\left(x_{el}\right)=p_{el} \tag{18}$$

From equation (17) it follows that the use of electricity that satisfies the first order condition is θ smaller in (17) than in (15), and therefore, from (17), the total utility of electricity consumption is the same as prior to the change in energy efficiency. The consumer surplus is however increased because of the saved costs, i.e.

$$\Delta CS=p_{el}\theta \tag{19}$$

Investment costs for improved isolation are not included in the analysis. We now look at the calculated consumer surplus in a partial analysis of the electricity market. When setting limits to integrals we denote the initial optimal amount by x_{el}^{*}. The optimal amount after increased energy efficiency is $x_{el}^{*}-\theta$. The apparent change in the consumer surplus in the partial analysis of the electricity market is therefore

$$\Delta CS_{el}=\left(\int_{x_{el}=0}^{x_{el}^{*}-\theta} v'(x_{el})dx_{el}-p_{el}\left(x_{el}^{*}-\theta\right)\right)-\left(\int_{x_{el}=0}^{x_{el}^{*}} u'(x_{el})dx_{el}-p_{el}x_{el}^{*}\right) \tag{20}$$

The total area under the demand curve to the right from the respective optimal amounts are identical before and after the horizontal shift (by definition of the shift), i.e.

$$\int_{x_{el}=x_{el}^{*}-\theta}^{x_{el}:v'(x_{el})=0} v'(x_{el})dx_{el}=\int_{x_{el}=x_{el}^{*}}^{x_{el}:u'(x_{el})=0} u'(x_{el})dx_{el} \tag{21}$$

We add the left hand side of (21) and subtract the right hand side of (21) from (20) and this gives

$$\Delta CS_{el}=\int_{x_{el}=0}^{x_{el}:v'(x_{el})=0} v'(x_{el})dx_{el}-\int_{x_{el}=0}^{x_{el}:u'(x_{el})=0} u'(x_{el})dx_{el}+p_{el}\theta. \tag{22}$$

Using (19) and (22) we can compare the real change in consumer surplus with the change that is calculated in a partial analysis of the electricity market.

$$\Delta CS_{el}-\Delta CS=\int_{x_{el}=0}^{x_{el}:v'(x_{el})=0} v'(x_{el})dx_{el}-\int_{x_{el}=0}^{x_{el}:u'(x_{el})=0} u'(x_{el})dx_{el}. \tag{23}$$

Equation (23) shows that we have to add the total integral between the demand curve before and after the shift to the new consumer surplus when the benefit of increased energy efficiency is calculated.

5 Revealing underlying elasticity

5.1 Consumer prices for electricity

Although it plausible that some of the electricity consumption respond little to prices, at least in the short run, it is unreasonable to believe that demand is completely inelastic to varying prices. The major issue in power markets is not that demand would not react on prices, but that demand is not exposed to varying prices [14]. If consumers had been exposed to varying prices, the underlying price elasticity had been revealed, and demand would probably respond more to varying market prices.

Hourly metering as is now installed or underway in several countries. If this is followed by more dynamic tariffs that reflect marginal costs in the power system, it would be up to consumers to either pay the occasional high prices or to reduce demand.

5.2 Graphical analysis of the effect of exposing consumers to varying prices

Unless consumers are exposed to price-variations in the short term, demand will be completely inelastic for market prices and thus it is not possible to calculate the consumer surplus. However, even when consumers are not facing wholesale prices, we know that the cost of reducing demand is not infinite. At a certain price, demand will be reduced and the demand curve is no longer vertical. It is well-known that the cost of load shedding differs significantly between consumers. It is however impossible in most power systems today to differentiate rationing between consumers. Therefore often the average level of the cost of rationing is used and defined as the Value of Lost Load (VOLL). With this approach, the demand curve becomes vertical up to VOLL, and horizontal from this point down to zero demand. For this case the calculated consumer surplus is the area between the price and VOLL, cf. area "A" Figure 5(a).

We assume that there is no real change in the consumers' utility function, but because of the introduction of more varying consumer prices the real elasticity becomes visible in the market. In the following we assume that hourly metering is implemented and that consumer prices respond fully to wholesale prices.

When the price for electricity is fixed, the willingness to pay is revealed only for the fixed price. The willingness to pay for electricity is in general lower for larger quantities and higher for smaller quantities. For the case where consumption is exposed to prices we therefore rotate the demand curve at the initial price and quantity, cf. the dotted curve in Figure 5(b).

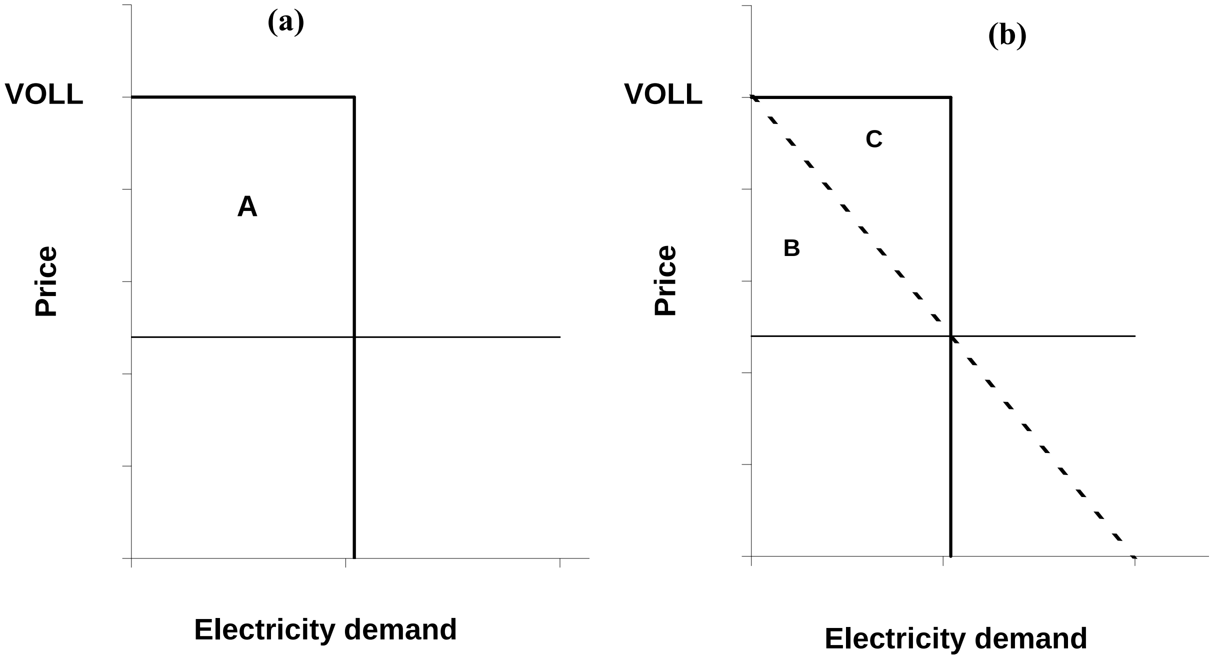

Figure 5 Changed consumer surplus when the demand elasticity is revealed

In general, a fixed consumer price may deviate from wholesale electricity prices. This creates inefficiencies because there is no link between generation costs and willingness to pay for electricity. This inefficiency is however not our major concern here. In the following we therefore compare the calculated consumer surplus in a case where the fixed consumer price equals the wholesale electricity price.

From Figure 5 (a) and (b) we can see that the calculated consumer surplus is reduced from area "A" to area "B" when consumers are exposed to prices. However, this cannot be correct, because these are the same consumers consuming the same quantity and paying the same price. The true consumer surplus is equal to B also without hourly monitoring. Thus, we overestimated the consumers' surplus by area "C" in the first case. The true consumer surplus is area "B" also without hourly monitoring.

6 Examples

6.1 Reduced price for a substitute to electricity

In this section we will illustrate the concepts in Section 3 and 4 with two simple examples. We first look at the case with reduced cost of an alternative energy source. We assume a small power market, and look at demand and supply in a specific period (e.g. hour). Supply and demand in this market are given in Figure 6.

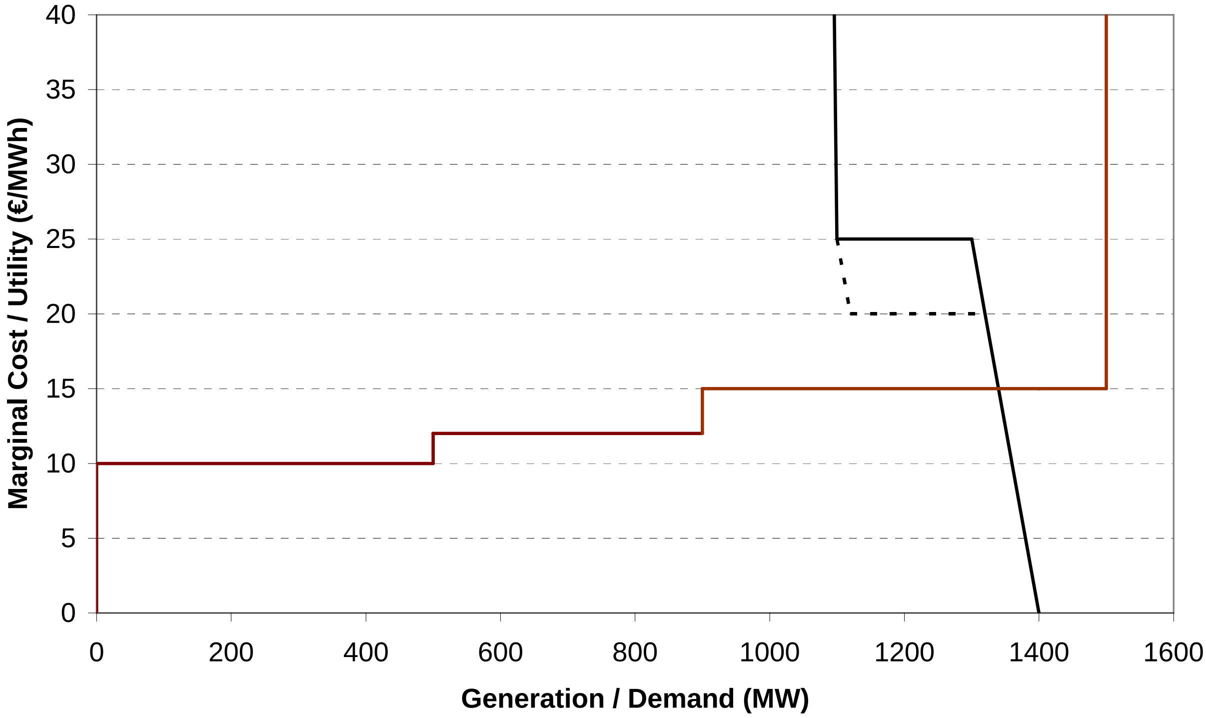

Figure 6 Supply and demand in small power market with alternative energy source

The demand curve is similar to those in Figure 3, but quite inelastic below 1100 MW. At a price of 1000 €/MWh (VOLL, cf. Section 5) demand is assumed to be reduced to 1000 MW. The cost of the alternative energy source is initially 25 €/MWh, but this is subsequently reduced to 20 €/MWh as indicated by the dotted lines. The maximum quantity that can be supplied by the alternative energy source is 200 MW. Electricity supply exists of 3 generators with a capacity of 500, 400 and 600 MW respectively. The first two generators have marginal costs of 10 and 12 €/MWh respectively, while for the third generator three alternative cases are analyzed, 15, 22.5 and 30 €/MWh (only the 15 €/MWh case is shown in Figure 6). We therefore evaluate the outcome of this market for 6 different cases (2 prices for alternative energy for each of the 3 marginal costs for third generator).

Maximization of total economic surplus is a simple quadratic programming problem in this case. It can be seen from the figure that the price always will be equal to the marginal cost of generator 3. The results are shown in Table 1 for the three different marginal costs of generator 3 before and after the reduction of the cost of the alternative energy source.

Table 1: Results for small power market with alterative energy source

Case	MC 3rd (€/MWh)	p_{alt} (€/MWh)	Demand (MW)	TS_{el} (€)	PS_{el} (€)	CS_{el} (€)	ΔCS_{el} (€)	correction (€)	ΔCS (€)
1	15	25	1 340	1 040 650	3 700	1 036 950	-	-	-
2	15	20	1 340	1 039 650	3 700	1 035 950	-1 000	1 000	0
3	22.5	25	1 310	1 037 462	10 450	1 027 013	-	-	-
4	22.5	20	1 110	1 036 962	10 450	1 026 513	-500	1 000	500
5	30	25	1 099.5	1 035 451	17 200	1 018 251	-	-	-
6	30	20	1 099.5	1 035 451	17 200	1 018 251	0	1 000	1000

The columns TS_{el}, PS_{el}, CS_{el} show total economic surplus, producer surplus and consumer surplus respectively. The consumer surplus is relatively high because the value of lost load is used to calculate marginal value for the inelastic demand. It can be argued that this gives an overestimation of the consumer surplus, but ΔCS would not change if we had chosen a lower marginal value of lost load.

The column "ΔCS_{el}" shows that there is an apparent reduction in consumer surplus after the reduction in the price of the alternative energy source from 25 to 20 €/MWh when the marginal costs for the 3rd generator is below 25 €/MWh. We apply a correction equal to the integral of the area between the demand curves before and after the change as derived in Section 3 (equal to $200 \cdot (25 - 20) = 1000$ €) and calculate the real change in consumer surplus (including the effect of reduced expenses for the use of the alternative fuel). The result is shown in the final column. The change in the real consumer surplus is positive only if the alternative is used after the price has been reduced.

6.2 Increased energy efficiency

Now we look at the case of improved energy efficiency. The demand and supply for the example system are given in Figure 7. The supply side is the same as in the previous example, but for the sake of the example a very simple demand curve with unrealistic elasticity is used. (We could easily have use a demand curve similar to the previous case, but this would have made the example less straight forward.) Initially demand is zero when the price reaches 100 €/MWh, while demand is 1400 MW when the price is zero as shown by the solid line. We assume that an increase in the energy efficiency reduce demand by 100 MW for all prices, which is illustrated by the dotted line. As a result of this shift, demand becomes zero when the price equals 92.86 €/MWh. We look at the solution for 4 cases: prior to and after the increase in energy efficiency and for two different marginal costs for the third generator (15 and 30 €/MWh).

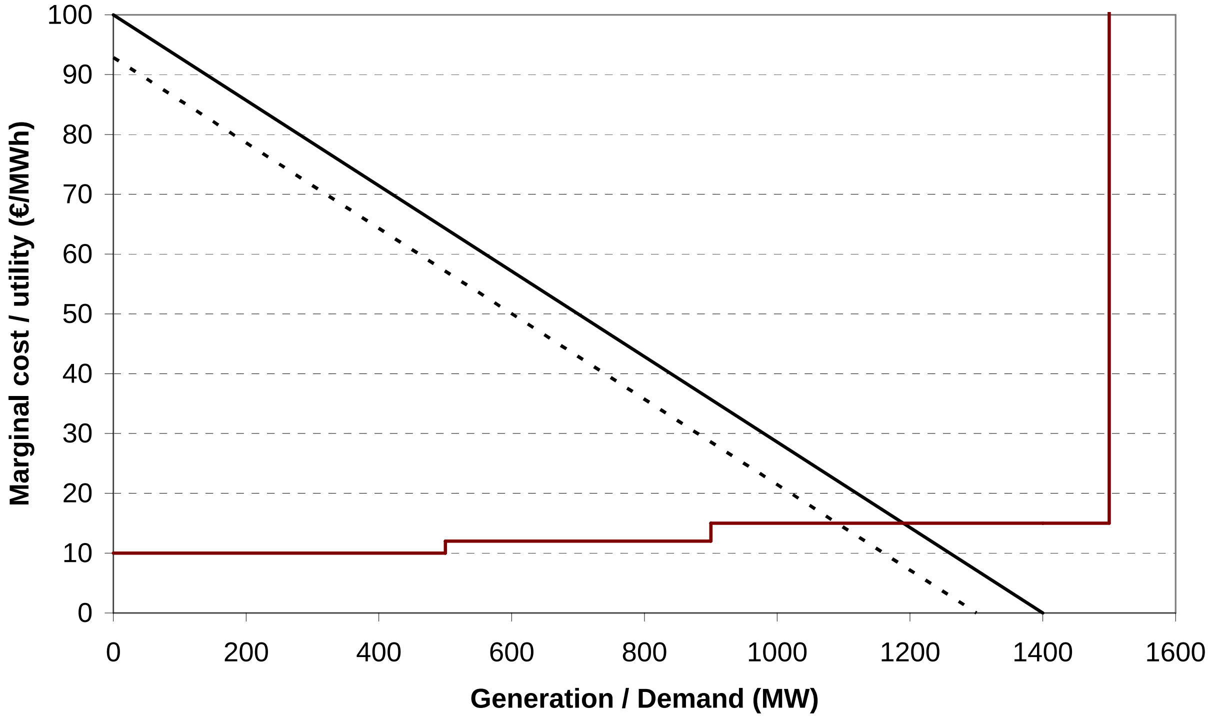

Figure 7 Supply and demand in small power market with increase in demand efficiency

Table 2 shows the result for two different marginal costs of generator 3 (only the 15 €/MWh case is shown in Figure 7).

Table 2: Results for small power market increase in demand efficiency

Case	MC 3rd (€/MWh)	Demand curve	Demand (MW)	TS_{el} (€)	PS_{el} (€)	CS_{el} (€)	ΔCS_{el} (€)	correction (€)	ΔCS (€)
1	15	Original	1 190	54 275	5 950	48 325	-	-	
2	15	New	1 090	46 132	5 450	40 682	-7 643	9 643	2 000
3	30	Original	980	51 500	4 900	46 600	-	-	
4	30	New	900	44 843	4 500	40 344	-6 256	9 643	3 386

Like in the first example, we see an apparent decrease in consumer surplus after the increase in efficiency, caused by the reduction in demand. A correction must be applied given by the area between the demand curves, which is equal to $0.5 \cdot (100 \cdot 1400 - 92.86 \cdot 1300) = 9643$ €. After applying this correction, the real result is an increase in consumer surplus. The increase is higher when the marginal cost of generator 3 and therefore the price is high. This shows that increased energy efficiency is more profitable when prices are higher.

7 Conclusions

In partial models for the electricity market it is necessary to adjust the calculated change in the consumer surplus when the value of exogenous changes in the demand curve is assessed. The approach is basically the same for all cases – the consumer surplus must be corrected with the integrated difference between the old and new demand curves.

In the cases where the demand curve shifted because of a reduced price for a substitute to electricity or because of increased energy efficiency, the change in the consumer surplus must be adjusted with the area between the old and new demand curve. In the case the demand curve shifted because consumers are exposed to varying prices, it is necessary to adjust the change in consumer surplus with the area between the demand curves on the left of the consumed amount

The proposed approach can easily be included in existing simulation models, and makes it possible to assess how changes in demand affect the total economic surplus compared e.g. to increased generation.

References

[1] EU, Commission of the European Communities, COM(2006)545 final, Action Plan for Energy Efficiency: Realising the Potential

[2] M. Stadler, L. Kranzl, C. Huber, R. Haas, and E. Tsioliaridou, "Policy strategies and paths to promote sustainable energy systems-The dynamic Invert simulation tool," Energy Policy, vol. 35, pp. 597-608, 2007.

[3] U. Farinelli, T. B. Johansson, K. McCormick, L. Mundaca, V. Oikonomou, M. Ortenvik, M. Patel, and F. Santi, ""White and Green": Comparison of market-based instruments to promote energy efficiency," Journal of Cleaner Production, vol. 13, pp. 1015-26, 2005.

[4] Eurelectric, The Role of Electricity – A new path to secure, competitive energy in a carbon-constrained world, 2007

[5] I. Graabak, O. S. Grande, J. Ikaheimo, and S. Karkkainen, "Establishment of automatic meter reading and load management, experiences and cost/benefit," Piscataway, NJ, USA, 2004, pp. 1333-8.

[6] S. Valero, M. Ortiz, C. Senabre, C. Alvarez, F. J. G. Franco, and A. Gabaldon, "Methods for customer and demand response policies selection in new electricity markets," IET Generation, Transmission & Distribution, vol. 1, pp. 104-10, 2007.

[7] P. Wang, Y. Ding, and Y. Xiao, "Technique to evaluate nodal reliability indices and nodal prices of restructured power systems," IEE Proceedings-Generation, Transmission and Distribution, vol. 152, pp. 390-6, 2005.

[8] C. Wen-Chen, C. Yi-Ping, and L. Tzu-Hao, "The competitive model based on the demand response in the off-peak period for the Taipower system," IEEE Transactions on Industry Applications, vol. 44, pp. 1303-7, 2008.

[9] FERC, Assessment of Demand Response and Advanced Metering, December 2008

[10] G. C. Heffner, C. A. Goldman, and M. M. Moezzi, "Innovative approaches to verifying demand response of water heater load control," IEEE Transactions on Power Delivery, vol. 21, pp. 388-97, 2006.

[11] D. S. Sowmy and R. T. A. Prado, "Assessment of energy efficiency in electric storage water heaters," Energy and Buildings, vol. 40, pp. 2128-32, 2008.

[12] M. Harmelink, L. Nilsson, and R. Harmsen, "Theory-based policy evaluation of 20 energy efficiency instruments," Energy Efficiency, vol. 1, pp. 131-148, 2008.

[13] G. Strbac, "Demand side management: benefits and challenges," Energy Policy, vol. 36, pp. 4419-26, 2008.

[14] S. Stoft, Power system economics, IEEE Press / Wiley, 2002

[15] J. P. Quirk, Intermediate microeconomics. Chicago: Science Research Associates, 1987.

Appendix: Demand curve for electricity and a substitute

Equation (11) in Section 3 shows the real change in the surplus when the price of the alternative fuel changes. If the same energy-bundle is purchased, consumer-surplus changes by $\delta \cdot x_{alt}$. Therefore, the true consumer surplus is changed by at least this amount. The calculated consumer surplus in a partial model for the electricity market is however the area under the demand curve for electricity minus expenses for purchasing electricity. In the following we will derive this amount.

The demand for alternative energy x_{alt} follows from (5) combined with (4), (7) and (8), and the optimal solution is:

$$x_{alt} = \begin{cases} 0 & | \quad p_{el} < p_{alt} \\ [0, x_{\max}] & | \quad p_{el} = p_{alt} \\ x_{\max} & | \quad p_{el} > p_{alt} \end{cases} \tag{A.1}$$

The optimal demand for electricity is therefore solved implicitly by

$$u'\left(x_{el} + \begin{cases} 0 & | \quad p_{el} < p_{alt} \\ [0, x_{\max}] & | \quad p_{el} = p_{alt} \\ x_{\max} & | \quad p_{el} > p_{alt} \end{cases} \right) = p_{el} \tag{A.2}$$

Equation (A.2) shows that the demand curve for electricity (electricity price on vertical axis, electricity demand on horizontal axis) consists of three different parts. This is also illustrated in Figure 2. At electricity prices above p_{alt} the demand curve is given by the downward-sloping function $u'(x_{el} + x_{\max})$. At the price p_{alt} there is a flat segment of length x_{max}, and at prices below p_{alt} the curve is downward-sloping and given by the function $u'(x_{el})$. We will utilize this when we calculate the consumer surplus for the electricity market. We start by defining quantity of electricity where the marginal value of energy equals the electricity price if the alternative energy is used at maximum:

$$x_{el}{}^{a} \equiv \left\{ x_{el} : u'(x_{el} + x_{\max}) = p_{el} \right\} \tag{A.3}$$

Second we define the variable α as the consumer surplus for the quantity up to $x_{el}{}^{a}$ in the partial model for the electricity market:

$$\alpha \equiv \int_{x_{el}=0}^{x_{el}{}^{a}} u'(x_{el} + x_{\max})\, dx_{el} - p_{el} x_{el}{}^{a} \tag{A.4}$$

Since x_{el}^{a} is a function of p_{el} and $x_{\max}$, it follows that α also is a function of these two parameters and therefore a constant in the analysis.

We will now calculate the consumer surplus for the three possible cases: $p_{el} > p_{alt}$, $p_{el} = p_{alt}$ and $p_{el} < p_{alt}$.

Case 1: $p_{el} > p_{alt}$.
In this case $x_{el} = x_{el}^a$, cf. equation (A.2) and (A.3), and therefore, from equation (A.4), $CS_{el} = \alpha$.

Case 2: $p_{el} = p_{alt}$.
In this case the use of electricity is x_{el}^a plus some additional amount that substitutes a share of the alterative energy, cf. (A.2). But the last part does not contribute to the consumer surplus since $p_{el} = p_{alt}$, and therefore $CS_{el} = \alpha$ in this case too.

Case 3: $p_{el} < p_{alt}$.
In this case the use of electricity can be divided into three separate parts: the first downward-sloping part of the demand curve $u'(x_{el} + x_{\max})$ plus the flat segment at p_{alt} where alternative energy is substituted plus an additional amount on the second downward-sloping part of the demand curve $u'(x_{el})$. The first part is given by

$$x_{el}{}^b \equiv \{x_{el} : u'(x_{el} + x_{\max}) = p_{alt}\} \tag{A.5}$$

Now we can write the consumer surplus as

$$CS_{el} \equiv \int_{x_{el}=0}^{x_{el}{}^b} u'(x_{el} + x_{\max})\,dx_{el} + \int_{x_{el}=x_{el}{}^b}^{x_{el}{}^b + x_{\max}} p_{alt}\,dx_{el} + \int_{x_{el}=x_{el}{}^b + x_{\max}}^{x_{el}{}^*} u'(x_{el})\,dx_{el} - p_{el}x_{el} \tag{A.6}$$

The symbol x_{el}^* on the last upper integral limit denotes the optimal value x_{el}. The only difference between the two curves $u'(x_{el} + x_{\max})$ and $u'(x_{el})$ is that the latter is located $x_{\max}$ at the right for the former. Therefore,

$$\int_{x_{el}=x_{el}{}^b + x_{\max}}^{x_{el}{}^*} u'(x_{el})\,dx_{el} = \int_{x_{el}=x_{el}{}^b}^{x_{el}{}^* - x_{\max}} u'(x_{el} + x_{\max})\,dx_{el} = \int_{x_{el}=x_{el}{}^b}^{x_a} u'(x_{el} + x_{\max})\,dx_{el} \tag{A.7}$$

In the latter equality we have utilized that x_{el}^* must be equal to $x_a + x_{\max}$ that follows directly from (A.2) and (A.3):

$$u'(x_{el}^*) = p_{el} = u'(x_a + x_{\max}) \tag{A.8}$$

Substituting (A.7) into (A.6) gives

$$CS_{el} = \alpha + (p_{alt} - p_{el})x_{\max} \tag{A.9}$$

For all of the three possible cases, the consumer surplus in a partial analysis of the electricity market is therefore given by

$$CS_{el} = \alpha + \left(p_{alt} - p_{el}\right)\left(x_{\max} - x_{alt}\right) \tag{A.10}$$

The right hand side is reduced to α in the first and second case since $x_{alt} = x_{\max}$ and $p_{alt} = p_{el}$ respectively, while it is reduced to $\alpha + \left(p_{alt} - p_{el}\right)x_{\max}$ in the third case since $x_{alt} = 0$. The change in this consumer surplus if the price of the substitute to electricity is reduced by δ is given by Equation (12).