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Is electricity more important than natural gas? Partial liberalization of the Western European energy markets

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MEMORANDUM

No 1/2008

**Is electricity more important than natural gas?
Partial liberalization of the Western European
energy markets.**

The seal of the University of Oslo is a circular emblem. It features a central figure of a woman in classical attire, holding a lyre. The text 'UNIVERSITAS OSLOENSIS' is inscribed around the top inner edge, and 'MDCCCXXXIII' is at the bottom. The seal is rendered in a light gray tone.

**Kjell Arne Brekke
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Is electricity more important than natural gas?

Partial liberalizations of the Western European energy markets¹

Kjell Arne Brekke², Rolf Golombek³ and Sverre A. C. Kittelsen⁴

Abstract

The European Union has introduced directives that aim to liberalize and integrate electricity and gas markets in Western Europe. While progress has been made, particularly in electricity markets, there have been setbacks: for example, because of concerns about national interests and security of supply. Thus it is possible that only part of the energy industry in Western Europe will be liberalized. We use a numerical model to assess what types of liberalization – electricity vs. natural gas; domestic markets vs. international trade – are most influential in decreasing prices and increasing welfare in Western Europe. We find that a partial liberalization of electricity markets has greater quantity and welfare effects than a partial liberalization of gas markets, and that liberalizations of domestic energy markets have (overall) greater effects than liberalizations of trade in energy between Western European countries. Finally, the short-run effects primarily parallel the long-run effects, though they are significantly smaller.

JEL classification: C15, C68, Q40, Q48

Keywords: energy markets, liberalization, price discrimination, resource rent

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1. Introduction

Energy networks form a vital part of the infrastructure of society. According to conventional wisdom, facilities in the energy industry should mainly belong in the public sector in order to ensure an uninterrupted and equitable supply of energy. The gas and electricity industries in Western Europe constitute a sizeable share of the economy (3 per cent of value added) and have, as in most parts of the world, typically been characterized by inefficiencies and lack of competition. In Western Europe, there has been market power in production: for example, supply from a single domestic agent or regional monopolies. Furthermore, long-distance transport networks, both nationally and internationally, as well as local distribution networks, have constituted natural monopolies and have therefore not been exposed to competition.

The increasing existence of long-distance transport networks has opened the possibility of competition, since in principle gas and electricity can be bought from distant suppliers. This presupposes the abolition of legal monopolies in production, while regulating the access to, and tariffs of, transmission and distribution networks, since these networks are natural monopolies. While this may be called re-regulation, these policy changes are commonly referred to as liberalization.

Over the last 10 to 20 years some governments in Western Europe have seen the potential of using competition to reduce prices and costs, remove monopoly profits and increase overall welfare. The reforms in England and Wales around 1990 were among the first to harness competition through an unbundling and privatization of supply and distribution in gas and electricity: see, for example, Newbery (2006). Other countries, such as Norway, have sought to separate supply and distribution, introduce competition in supply and regulate transport without necessarily privatizing utilities: see Sioshansi and Pfaffenberger (2006) for a detailed review of electricity market liberalization in a number of countries.

The European Union (EU) is now the main driving force in liberalizing energy markets in Western Europe. Since the late 1980s different EU bodies have worked out proposals/issued directives in order to liberalize the electricity and gas industry in the EU/Western Europe. Milestones were reached in the late 1990s, when EU directives on establishing internal markets for electricity and natural gas were issued. Subsequently,

there have been new directives and regulations, in particular updated versions of the internal energy market directives: see European Parliament (2003a, 2003b).

Earlier studies have shown considerable potential gains from the planned reform: see, for example, Golombek, Gjelsvik and Rosendahl (1995), Amundsen and Tjøtta (1997) and Aune, Golombek, Kittelsen and Rosendahl (2004). However, while progress has been made, particularly in electricity markets, there have been recent setbacks because of concerns about the national interests of major European countries, as well as security of supply in the EU as a whole. So far, the transition from domestic non-efficient energy markets to competitive Western Europe markets has been partial and incremental: see, for example, Commission of the European Communities (2005a, 2005b), European Union (2005) and Lohmann (2006).

The question that then arises is which reforms are the most important for decreasing prices and increasing welfare? Is it more important to liberalize electricity markets than natural gas markets? Is it more important to liberalize domestic energy markets than trade in energy between Western European countries? Even if a full liberalization is the ultimate aim of the EU, what are the effect of each partial step: that is, liberalization of electricity vs. liberalization of gas, and liberalization of domestic energy markets vs. liberalization of trade in energy between Western European countries? Furthermore, does it matter which reforms are introduced first? The answers to all these questions must be based on the specific features of each market.

In this article we try to shed light on the effects of different partial liberalizations. This is achieved by modelling separately the introduction of cost-efficient electricity production, removing market power in domestic electricity retail, removing market power in domestic gas retail, removing market power in international transmission of electricity in Western Europe by imposing perfect third-party access to transmission of electricity and removing market power in international transmission of gas in Western Europe by imposing perfect third-party access to transmission of gas. In order to study the importance of the order of reform, we model both the liberalization of electricity markets before the liberalization of gas markets and vice versa. We also examine short-run effects, when capacities are given, relative to long-run effects, when capacities can be expanded through investment.

We base our analysis on the numerical model LIBEMOD MP: see Aune et al. (2007). The key idea in LIBEMOD MP is to capture all types of market imperfections through a set of cross-subsidies and mark-ups: see Section 2 for a discussion on how to model market imperfections in the Western European energy industry.

LIBEMOD 2000 MP is a multi-market equilibrium model in which each Western European country (the model countries) produces, trades and consumes a number of energy goods. There is trade in electricity and gas between all Western European countries through transmission/pipelines, whereas there are international markets for coking coal, steam coal and oil. In each model country, electricity can be produced by a number of technologies at heterogeneous plants using various fuels and with differing energy efficiencies. In order to capture the variation in demand for electricity, over the year there is trade in electricity in 12 periods, whereas fuels are traded in annual markets: see Sections 3 and 4 for a description of the model.

The model captures the vital inter-linkages between the electricity and fuel markets and so is suitable for examining inter-fuel competition between, for example, gas as an input to electricity production and gas as a good demanded by end users. The use of explicit technical modelling of electricity production instead of smooth supply curves opens for relatively large shifts, particularly over the long run. However, the experience in the energy markets underlines the fact that such large shifts are also a feature of reality: for example, in 1995/6 the annual UK gas price dropped by roughly one-third, mainly because of major changes in the market structure.

We find in Section 5 that a liberalization of electricity in general has greater quantity and welfare effects than a liberalization of gas, and a liberalization of domestic energy markets has for most variables greater effects than a liberalization of trade in energy between Western European countries. In particular, a liberalization of domestic electricity markets increases production of electricity significantly, leads to significant redistribution from producers to consumers and increases total welfare. The liberalization of trade in energy in Western Europe has only a small impact on quantities and prices, yet the liberalization of international transmission of gas redistributes huge amount of economic surplus from the transmission companies to the gas resource owners.

The different impacts on natural gas and electricity markets reflect the fact that natural gas is an exhaustible scarce resource and thus has limited scope for increased production in the long run. Therefore, natural gas liberalization has a greater effect on the distribution of surplus than on total welfare. Electricity, however, is a produced commodity and the quantity can be expanded considerably without large unit-cost increases.

We also find that the short-run effects primarily parallel the long-run effects, though they are significantly smaller. Finally, the order of liberalization has only a minor impact on the effects of the partial liberalizations.

2. Modelling market imperfections

Traditionally, the natural gas and electricity industry in all Western European countries has been subject to various government regulations and controls. These regulations significantly affected all levels of the industry – extraction, production, import, transport, distribution and prices. The standard approach in economics in modelling markets imperfections is to assume market structure being characterized by monopoly, oligopoly or a (cost-minimizing) cartel. Frequently, oligopoly is modelled as a non-cooperative Cournot game: that is, agents choose quantities simultaneously. This leads to an equilibrium in which quantities, and thus also the market price, lie between the competitive outcome and the monopoly solution.

It seems plausible that the present Western European energy market outcome is somewhere between the competitive equilibrium and the monopoly solution. Yet there is no particular reason to believe that the outcome is identical to (or even close to) the Cournot solution, which is just one of an infinite number of outcomes between the competitive equilibrium and the monopoly solution. If the task is to study a policy change – for example, how an imposed energy or environmental tax will affect Western European energy markets – it would be almost pure chance if the real changes were mimicked by the change in the Cournot solution. As long as the market structure in Western European energy markets is characterized not only by strategic behaviour that tends to lower production (this effect is captured by the Cournot model) but also by factors such as government regulations to protect consumer interests, measures to ensure

security of supply, foreign policy considerations, horizontal and vertical integration, as well as international price bargaining, application of the Cournot model may provide bad predictions.

In addition, it may be hard, or not even feasible, to find the equilibrium in a Cournot game. Typically, papers examining Cournot games assume that there is a simple demand function/system for a single good: see Golombek and Bråten (1994), Bråten and Golombek (1998) and Egging and Gabriel (2006). It is then easy to find the first-order conditions for the strategic agents and these are used to find the equilibrium. In the present paper we have demand from various agents with different behavioural assumptions. Some of the agents demand energy as inputs in electricity production, and these agents are modelled with a set of first-order optimum conditions that are solutions to their own profit-maximization problems, and where corner solutions often appear. The resulting demand system cannot be differentiated and thus we are not in a position to specify the first-order conditions for Cournot players.⁵

An alternative approach to the Cournot model is to let data determine type and degree of market imperfections. Some decades ago, a popular approach was to apply the theory of conjectural variation, whereby each agent conjectured how an increase in his own production would be met by competitors by changed production: see Varian (1992). For example, if all agents believe that competitors will not respond to an increase in their own production, the outcome is the Cournot solution, whereas the competitive equilibrium is the outcome if all agents believe an increase in their own production will be exactly counteracted by the competitors. In principle, data can be used to calibrate the sizes of the conjectural variations and hence determine market structure: see, for example, Dixit (1987).

There are three major drawbacks to the theory of conjectural variation. First, conjectures are related to expected quantity responses from competitors. This might be a useful approach for some agents in the energy industry – for example, producers of gas and electricity – but not for others. It is hard to see how the theory of conjectural

⁵ In addition, some buyers in the fuel markets (e.g. the power producers) will be sellers in another market (i.e. the electricity market) and are large enough to have market power in both markets. It is not obvious how the Cournot conditions should be applied in such a multi-market game and how one could potentially take account of secondary market feedbacks.

variation can be applied to agents in retail markets or to international transmission of electricity and gas. Second, in the conjectural model conjectures are exogenous, whereas ideally they should be endogenous. Third, whereas conjectures should be used within a dynamic setting, the conjectural model is static. The theory of conjectural variation is typically seen as outdated by economists, although it is still used in some applied work. In the present paper we do not apply the theory of conjectural variation. Yet the basic idea of using economic theory and data to calibrate market structure is attractive.

It is well known from economic theory that restrictions facing an agent – for example, a quantity restriction – can (under conditions of no uncertainty and full information) be represented through a set of taxes, subsidies and transfers. We have therefore chosen to mimic the different market imperfections in the Western European energy market through a set of price-cost deviation parameters, henceforth referred to as mark-up factors. These mark-ups influence behaviour in the same way that taxes and subsidies would have done, but without generating a transfer of revenue to or from the government. Instead it is assumed that revenues are kept as surplus by the producer. The cost-price differences that are represented by marks-ups in the model could be consistent with several forms of market power: for example, monopolies, oligopolies or cartels. They could also be consistent with various forms of government intervention: for example, regulations restricting the use of market power, subsidizing coal industries, protecting domestic companies from foreign competition and policies encouraging the use of particular technologies such as green power. For our purposes, the cause of the cost-price differences need not be identified and the magnitudes of the mark-ups are determined by data as discussed below.

Our numerical model specifies mark-ups for:

- electricity producers;
- domestic energy retailers;
- owners of international transmission lines for electricity and gas.

For electricity producers, the standard first-order conditions following from profit maximization with respect to activity level are modified by including mark-ups. These

differ across technologies and model countries, and allow non-profitable technologies to operate at a loss (negative mark-up), while profitable technologies might be penalized (positive mark-up). These mark-ups could be the result of explicit cross-subsidization between different technologies within each country, or they could be the result of explicit or implicit encouragement and discouragement of different technologies by the government. The signs and magnitude of the mark-ups are determined so that the equilibrium levels of production (given the mark-ups) are equal to observed production in the data year of the model.

Under a competitive regime, the difference between end-user prices and producer prices (or marginal producer costs) equals the sum of taxes and the costs of domestic transport and distribution, including losses. We observe, however, that actual user prices less actual producer prices differ from this sum. For retailers of energy, we introduce mark-ups that are equal to the difference between the “net selling price” (i.e., observed user prices less of taxes and costs of domestic transport and distribution), and observed producer prices. These mark-ups are all positive, indicating the use of market power. Furthermore, they differ between user groups, energy goods (electricity and gas) and countries: that is, between users of the same energy good in different countries, and between energy goods for the same user group in the same country. Thus, there is price discrimination in the energy markets. For a detailed discussion of the calibration of the mark-ups, see Aune et al. (2007).

Our approach facilitates the study of partial liberalizations. For example, by removing the mark-ups of electricity producers, keeping other mark-ups constant, we can measure the partial effects of introducing cost efficiency in electricity production. Such a measure will, however, contain large trade effects that are far from plausible. The reason is related to the mark-ups for transmission between countries in Western Europe.

The mark-ups for international trade in Western Europe, which are calculated as the price difference of a good (electricity or gas) between all pairs of model countries net of costs of international transmission and losses, will reflect various (non-economic) regulations and also some cases of gas being transported through a transit country on the way to its final destination in a third country. If domestic mark-ups are removed while mark-ups for international transmission are kept constant, large trade effects occur that

are inconsistent with the reasoning behind the price differences between countries. The simplest way to avoid such trade effects is to impose trade restrictions, requiring all pairs of net exports of gas and electricity between the model countries to be unchanged.

We identify the effects of introducing cost efficiency in electricity production by removing the mark-ups of electricity producers and at the same time requiring all pairs of net exports of gas and electricity between the model countries to be unchanged. Similarly, we identify the effects of liberalizing domestic gas (and/or electricity) retail by removing the mark-ups for gas (and/or electricity) in the retail markets and at the same time requiring all pairs of net exports of gas and electricity between the model countries to be unchanged. Finally, the effects of a liberalization of trade between Western European countries in electricity (and/or gas) are identified by removing the quantitative trade restrictions for electricity (and/or gas), and removing the mark-ups for electricity (and/or gas) transmission between countries in Western Europe. This strategy amounts to imposing perfectly working third-party access to international transmission lines (pipes) in Western Europe. After the latter partial liberalization, tariffs are equal to marginal costs when capacity is not fully utilized, whereas tariffs restrict the demand for transmission services to the available capacity when the capacity would otherwise be insufficient. The identification of effects following on from different types of partial liberalization is the key issue of the present paper and the results are reported in Section 5.

3. The model

Our empirical model, LIBEMOD MP, is a variant of the model LIBEMOD: see Aune et al. (2004, 2008). The main difference between the two models is the market structure. LIBEMOD assumes that all markets are competitive, whereas in LIBEMOD MP most markets are imperfect: that is, several agents have market power. In common with the LIBEMOD 2000 model used in Aune et al. (2008), LIBEMOD MP has a larger set of goods, markets and countries than the earlier model used in Aune et al. (2004), and has 2000 as its data year.⁶

⁶ In addition to the modelling of market structure, the total liberalization results reported here are slightly different from those in Aune et al. (2008), due to a different basis of comparison. The Aune et al. model

LIBEMOD MP specifies seven energy goods: coking coal, steam coal, lignite, natural gas, oil, biomass and electricity. With some exceptions, these are produced, traded and consumed in all model countries, which are the 16 Western European countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, Portugal and the United Kingdom. All countries in the world that are not model countries produce, trade and consume coking coal, steam coal and oil.

Coking coal, steam coal and oil are traded in competitive world markets. For all other energy goods, markets are not competitive. Natural gas and electricity are traded between the model countries. In addition, some of the non-model countries also export (exogenously given quantities of) gas and electricity to the model countries. Regional trade in gas requires pipes running between a node in the export country and a node in the import country. Similarly, regional trade in electricity requires transmission lines running between the node in the export country and the node in the import country. For both gas and electricity, there are capacity constraints in international transmission. These capacities are given in the short run, but are determined in the long-run version of the model. The remaining goods – lignite and biomass – are not traded internationally (domestic markets only), but the model determines how lignite is divided between different domestic users and the amount of biomass used in domestic bio-power production. In each model country, energy is transported and distributed from the country node to the end users at fixed costs and without capacity constraints. These costs differ according to user group and energy good.

There are four groups of users of energy in each model country. First, there is intermediate demand from electricity producers: for example, gas power producers who demand natural gas. Furthermore, there is demand from end users: the household, industry and transport sectors, though the latter demands only oil products. For end users, demand is derived from a nested CES utility function with five levels. The parameters of the utility functions differ between end users and countries. At the top-nest level, there

solutions are compared with a calibrated data set directly; this retains some statistical errors that are not important when discussing the total results of liberalization, but can be of some importance when one is interested in partial liberalizations of individual markets. In this paper we compare instead with an actual model solution with all mark-ups and quantity restrictions in place.

are substitution possibilities between energy-related goods and other forms of consumption. At the second level, consumers face a trade-off between consumption based on the different energy sources. Each of these is a nest describing complementarity between the actual energy source and consumption goods that use this energy source (for example, electricity and light bulbs). Finally, the fourth and fifth levels are specific to electricity in defining the substitution possibilities between summer and winter (season) and between six time periods over the 24-hour cycle. Thus, except for electricity, energy goods are traded in annual markets.

In each model country, there is production of electricity by various technologies: steam coal power, lignite power, gas power, oil power, reservoir hydro power, pumped storage power, nuclear, waste power and wind power. Some of these are not available in all countries. In general, for each technology and each country, efficiency varies across power plants. There are costs related to electricity production: fuel costs, maintenance costs (related to maintained power capacity) and start-up costs (related to additional capacity started in a time period). The power producer obtains revenues either from using his maintained power capacity to produce and sell electricity or by selling all or part of his maintained power capacity to a national system operator, who buys reserve power capacity in order to ensure (if necessary) that the national electricity system does not break down.

Power producers face some technical constraints. For example, maintained capacity should not exceed installed (or invested) capacity, and in each period production should not exceed maintained energy capacity, net of the capacity sold as reserve capacity to the system operator. In addition, there are technology-specific constraints. For example, with reservoir hydro, the reservoir filling at the end of a season cannot exceed the reservoir capacity. Moreover, total use of water cannot exceed total availability of water (the sum of seasonal inflow of water and reservoir filling at the end of the previous season).

Each power producer maximizes his profits within the technical constraints. Under perfect competition, the first-order condition for profit maximization for a producer of electricity requires that the sum of marginal costs (including all shadow prices reflecting constraints faced by the producer) should equal the price of electricity.

In our model, this condition is modified by including a mark-up that differs across technologies and model countries (see discussion above). In the Appendix we give a more detailed discussion of production of electricity.

LIBEMOD MP is available in two versions. In the short-run version, all capacities in power production and all capacities for international transmission lines/pipes are given. In the long-run version, all capacities are endogenously determined by the model. By comparing revenues and costs associated with expanding each type of capacity, the model determines optimal investment, given all mark-ups.

The model determines all energy quantities – production, trade, consumption and possibly investment – and all energy prices, both producer prices and end-user prices. If some or all of the mark-ups are changed, a new equilibrium is computed, and the difference in outcome is due to the shift in the mark-ups. Because mark-ups are zero in a competitive equilibrium, the effect of liberalizing a sector is identified by comparing the observed 2000 outcome with a new equilibrium where all mark-ups in the sector are eliminated.

4. Data and calibration

Much of our data build on statistics published by international organizations such as OECD/IEA, UNIPED, UCPT and NORDEL, supplemented with national sources when necessary. In general, demand elasticities differ between countries and goods, whereas supply elasticities for fuels generally differ between goods and regions. Elasticities differ between the short-run version of the model and the long-run version. All elasticities build on a number of studies, including econometric studies: see Aune et al. (2007) for a full data documentation. The data year of the model is 2000.

As explained in Section 3, the mark-ups are calibrated so that the model fits the observed data. The main calibration challenge is to determine a country-specific ‘system price’ of electricity, which is needed in order to separate the effects of liberalizing electricity production, liberalizing retail and liberalizing trade. The system price in the model is the opportunity cost of electricity for the suppliers at the central node in each country and is the price that international traders can buy or sell at, as well as the basis on which all mark-ups to end users are calculated.

The total profit margin is different for each country, technology and end-user/trading partner. The separate specification of a system price allows the decomposition of this margin into two terms. The first term is the cross-subsidization parameter, which is calibrated as the difference between the system price and the marginal cost of each technology in each country. The second term is, for each user group in each country, a mark-up which is calibrated as the difference between the end-user price (net of taxes and distribution costs) and the system price, and for each transmission line a mark-up which is calculated as the difference (net of transmission costs) between system prices in the connected countries. The way in which this system price is calibrated thus has consequences for the calculated mark-ups in international trade and in domestic retailing, and therefore also for the separate effects in each partial liberalization step. It does not, however, have consequences for the fully liberalized outcome.

Ideally, the system price should be the marginal cost of producing one additional unit of electricity within the country. However, this is not well defined in our data, as we observe that many technologies – at the same point in time – have different marginal costs and produce at less than full capacity. There are alternative interpretations of this observation: for example, there may be an implicit system of cross-subsidies, in which case the system price should be a weighted average of the marginal costs for different technologies. Alternatively, market imperfections restrict production from technologies with the lowest marginal costs and hence impose implicit taxes on these technologies. In the latter case, the system price will be the marginal cost of the most expensive technology.

We have chosen the latter interpretation, with one modification. In many countries there are technologies with very small market shares: for example, nuclear power in Norway, where capacity is installed purely for research purposes. Similarly, in the data year 2000 there were small-scale experiments with environmental technologies in many countries. These technologies clearly do not represent the system price and have thus been treated as exogenous in the calibration of the model. This is done to avoid the system price being determined by, for example, small-scale experiments.

The main reason for setting the system price equal to the highest observed marginal cost (given that the technology is not too small) is to obtain a reasonable

assessment of the effect of a liberalization in electricity production. When mark-ups in electricity production are removed, the system price in a liberalized market will equal the marginal cost of the most expensive technology that is actually used. If the initial system price had been estimated as the average marginal cost (see above), moving to a cost-efficient composition of production across technologies would have increased the system price and reduced consumer surplus. As we do not judge this to be a likely outcome, we have chosen to use the marginal cost of the most expensive technology as the system price.

5. Results

In this section we report the results of different partial liberalizations in the energy industry in Western Europe. For gas and electricity we consider the effects of liberalization of *domestic markets* and *international trade* between countries in Western Europe separately. For domestic electricity markets, we also consider the effects of liberalizing production and retail separately. In contrast, for gas supply there are no competing technologies and hence no potential efficiency gains from liberalizing production, as we assume cost efficiency in supply of gas in each country also prior to liberalization. The order of liberalization is as given in Table 1, where electricity is liberalized first, but we will return to check the soundness of this assumption.

In all cases we consider the effects of liberalization both in the *short run* (pre-existing capacities) and in the *long run* (endogenous determination of capacities for power production, international transport of gas and international transport of electricity between model countries). The long-run scenarios assume the same income levels as in the calibration year 2000 and are therefore not predictions of the future, but they may be regarded as a comparative static analysis of how the different agents would have adapted had the liberalization been announced quite a few years before 2000.

According to the calibration of the numerical model, in the data year 2000 there were market imperfections in the gas and electricity markets in Western Europe, as well as some small imperfections in the international coal markets. In the present paper, the common starting point for examining liberalizations of electricity and gas is that international coal markets have already been liberalized: this only causes minor

deviations in prices and quantities from the initial calibration outcome. In order to avoid results that are too detailed, we focus on the group of all model countries (not each model country) and the group of non-model countries.

For each group of countries, there are four types of agent: consumers of energy, producers of energy, the government (receives taxes) and international traders in energy. For traders, we do not know their country of origin, which within our model means that we do not fully know how the ownership of each international electricity transmission line and each international gas pipeline is distributed between countries. In what follows we have assumed that 50 per cent of each international electricity line and 50 per cent of each international transmission pipe is owned by the importing (or exporting) country. The main welfare results of the present paper are robust relative to this assumption.

The main welfare effects: domestic electricity markets

As can be seen from Table 1, in the short run a full liberalization increases annual consumer surplus in the model countries by \$59 billion (\$59,000 million), reduces annual producer surplus in the model countries by \$47 billion, increases annual welfare in the model countries by \$6 billion and increases annual global welfare by \$12 billion. In the long run, these effects are enhanced, with an increase of annual consumer surplus in the model countries of \$80 billion, a reduction of annual producer surplus in the model countries of \$56 billion, an increase in annual welfare in the model countries of \$16 billion and an increase of annual global welfare of \$20 billion. Roughly 90 per cent of these effects are due to the liberalization of domestic electricity markets in the model countries: that is, the combined effect of liberalizing electricity production and domestic electricity retail. We will therefore focus mainly on the effects of the liberalization of domestic electricity markets.

In order to see what is driving the large changes following on from the liberalization of domestic electricity markets, consider the price and quantity responses reported in Table 2. There is a significant increase in production of electricity, particularly in the long run (18 per cent), and a corresponding reduction in the long-run average end-user electricity price of 31 per cent. In both the short and long runs, the increase in production of electricity – following the liberalization of domestic electricity

markets – is mainly due to increased production in steam coal-fired plants. The effects on electricity supply of other types of liberalization are small.

Table 1 Partial liberalization of energy markets: electricity is liberalized first; effects on welfare of each step (\$2,000 billion)

	Consumer surplus in model countries	Producer surplus in model countries	International trader surplus	Sum model countries ¹	Sum all countries ²
Short run Partial liberalization in:					
Electricity production	11.1	-6.4	-0.9	3.9	0.8
Domestic electricity retail	42.6	-35.3	1.8	4.7	9.9
International electricity trade	4.4	-2.3	-1.3	0.6	0.7
Domestic gas markets	3.5	-1.8	-1.3	-1.0	0.4
International gas trade	-2.4	-0.7	-3.3	-2.7	0.3
Total effect	59.2	-46.5	-5.1	5.5	12.0
Long run Partial liberalization in:					
Electricity production ³					
Domestic electricity retail	73.0	-51.7	-1.4	17.0	17.9
International electricity trade	-3.5	3.6	0.3	0.1	0.1
Domestic gas markets	10.7	-9.7	1.2	1.2	1.9
International gas trade	0.2	1.4	-9.6	-2.2	0.2
Total effect	80.4	-56.4	-9.5	16.2	20.2

¹ Sum of consumer surplus, producer surplus and tax revenues to the government in the model countries, plus half the international trader surplus on each transmission connection.

² Sum of consumer surplus, producer surplus, tax revenues to the government and international trader surplus in all countries.

³ In the long-run version of the model, it is only possible to identify the combined effect of the liberalization of electricity production and the liberalization of domestic electricity markets.

Table 2 Partial liberalization of energy markets: electricity is liberalized first; changes in electricity supply, gas consumption and average end-user prices for electricity and gas (percentage)

	Electricity supply		Electricity price		Gas consumption		Gas price	
	short run	long run	short run	long run	short run	long run	short run	long run
Partial liberalization in:								
Electricity production ¹	2.6		-4.3		0.0		0.4	
Domestic electricity retail	6.9	17.9	-21.6	-31.2	0.0	3.2	8.0	1.6
International electricity trade	0.2	-1.2	-1.2	1.6	0.0	0.2	-2.3	0.3
Domestic gas markets	-0.1	0.6	0.1	-1.2	0.0	5.0	-3.6	-9.1
International gas trade	-0.1	0.4	0.2	-0.4	-0.7	1.9	2.1	0.9
Total effect	9.4	17.7	-26.8	-31.2	-0.7	10.3	4.6	-6.3

¹ In the long-run version of the model, it is only possible to identify the combined effect of the liberalization of electricity production and the liberalization of domestic electricity markets.

In the data year 2000, due to market imperfections in each model country, total supply of electricity was not efficient, and also the composition of electricity technologies was non-optimal. In our model, these imperfections are taken into account through a set of mark-ups in electricity production and a set of mark-ups in electricity retailing: see the discussion in Section 2. When examining the liberalization of domestic electricity markets, technically we eliminate these mark-ups. Technologies with initially

high positive mark-ups will then gain and thus output from these technologies will increase. Steam coal power had high mark-ups, but after liberalization this technology enjoys low production costs. The rise in production depends on the price of steam coal, other costs elements for steam coal plants, the distribution of fuel efficiency for steam coal plants and the price of electricity. Relative to other fuels, steam coal is cheap, but this effect is to some extent modified by rather low efficiencies in steam coal plants. Overall, marginal costs of production are quite low for steam coal power.

Note that due to increased steam coal power, the user-price of steam coal (average over all model countries and all user groups) increases by 25 per cent in the short run. The significant short-run price effect reflects low supply elasticities of steam coal, whereas in the long run the price increase is moderate (3 per cent) due to high supply elasticities. This is one reason why the short-run increase in steam coal power (39 per cent) is lower than the long-run response (84 per cent). In addition, in the long run there is profitable investment in steam coal power. These effects explain the larger welfare effects in the long run.

Also production from gas-fired plants increases due to the liberalization of domestic electricity markets (see above), but measured in quantity (TWh) it is only about a quarter of the increase in steam coal power. In both absolute and relative numbers, we find the largest increases in electricity production – due to the liberalization of domestic electricity markets – in the United Kingdom (increased steam coal power and gas power) and in Italy (mainly steam coal power, but also some gas power), but there are also significant increases in Germany (mainly increased steam coal power) and in France (steam coal power). Note that there is a simultaneous reduction in oil-based thermal power (particularly in Italy), which after liberalization suffers from high costs.

Increased electricity production explains a substantial part of the welfare gain. There is, however, also an effect of equalizing net electricity prices (end-user prices less transport losses, costs of domestic transport, costs of distribution and taxes) across end users in a model country, which is part of the effect of liberalizing domestic electricity markets. Note from Table 3 that in the short run, the entire reduction in electricity prices due to the liberalization of electricity retail is enjoyed by households, whereas there is no reduction in prices to industry. In the long run it is not possible to separate the effects of

production efficiency and distribution efficiency of electricity (due to the way the long-run model is calibrated), but the combined effect is a reduction in prices for both user groups, though the reduction is much larger for households than for industry. The model simulations thus indicate significant price discrimination between end users of electricity in 2000, with corresponding welfare gains when the price discrimination is removed.

Natural gas

We have already identified that one effect of liberalizing domestic electricity markets is increased gas power production. Demand for gas from gas-fired plants therefore increases. Because total extraction of gas is given in the short run (per assumption), the end-user price of gas – average over all model countries and all user groups – increases in the short run (by 8 per cent: see Table 2) due to the liberalization of domestic electricity markets. As seen from Table 3, the short-run percentage increase for household (5 per cent) is lower than that for the other user groups of gas (11 and 18 per cent), reflecting the high costs of distribution to households (which do not change as part of the liberalization).

Table 3 Partial liberalization of energy markets: change in average end-user prices for electricity and gas by groups (percentage)

	Electricity				Natural gas					
	Households		Industry		Households		Industry		Gas Power	
	short run	long run	short run	long run	short run	long run	short run	long run	short run	long run
Partial liberalization in:										
Electricity production ¹	-3.2		-7.4		-1.0		2.3		3.7	
Domestic electricity retail	-29.4	-36.9	-0.6	-16.3	6.0	1.1	9.7	2.5	13.9	2.4
International electricity trade	-1.0	1.5	-1.9	1.9	-1.3	0.1	-3.7	0.8	-4.0	0.3
Domestic gas markets	0.2	-0.9	0.2	-1.8	-8.5	-12.3	4.8	-2.4	5.0	-4.1
International gas trade	0.1	-0.4	0.3	-0.6	2.3	1.3	3.7	0.2	-1.1	0.2
Total effect	-33.3	-36.7	-9.4	-16.8	-2.5	-9.8	16.8	1.1	17.5	-1.2

¹ In the long-run version of the model, it is only possible to identify the combined effect of the liberalization of electricity production and the liberalization of domestic electricity markets.

In the long-run version of the model, we assume cost-efficient extraction of natural gas in each model country, both in the calibration of the model and in each type of partial liberalization. In the calibration, extraction in each model country is set equal to the observed level of extraction in 2000, whereas in all other cases we assume that the

level of extraction is determined by competitive supply functions. As is well known, a change in market structure from imperfections/collusion in 2000 to competitive supply tends to increase supply. Therefore, in the long run increased demand for gas due to the liberalization of domestic electricity markets is counteracted by increased supply of gas. The net effect of the liberalization of domestic electricity markets is a modest increase in the long-run average user prices for gas for all groups (1–3 per cent: see Table 3).

In both the short and long run, the liberalization of international transmission has marginal impact on the average gas price. On the other hand, the liberalization of domestic gas markets, which is the same as the liberalization of domestic gas retail as we have assumed no cost inefficiencies in domestic supply of gas (see discussion above), lowers the average end-user price of gas, particularly in the long run (9 per cent decrease: see Table 2). In 2000 there was price discrimination in the domestic gas market, as net prices differed across user groups. When eliminating the mark-ups in domestic gas retail, households benefit significantly as – within each model country – gas is moved from the industry sector and gas power production to the household sector, thereby equalizing net prices.

Price variations

Liberalizing the markets removes price discrimination and should equalize net prices across different users in the same country. Hence one effect of liberalizing domestic retail is that in each country (and for each energy good) end-user prices less domestic losses, cost of domestic transport, cost of distribution and taxes – the producer prices – should not differ across groups.

The dispersal of prices can be measured by the coefficient of variation: that is, the standard deviation relative to the average. As seen from Table 4, the short-run effect of liberalizing domestic retailing of electricity is a drop in the coefficient of variation for the national electricity producer prices from 0.45 to 0.35. Because the coefficient of variation is zero within each country after domestic retail has been liberalized, the estimate of 0.35 reflects remaining differences in electricity producer prices between countries. Similarly, the short-run coefficient of variation for the national producer prices of gas drops from 0.37 to 0.27 due to the liberalization of domestic gas retail.

Table 4 Partial liberalization of energy markets: coefficient of variation across countries for national producer prices for electricity and gas

	Electricity		Natural gas	
	short run	long run	short run	long run
Partial liberalization in:				
Calibration (estimated producer prices)	0.45	0.44	0.28	0.17
Electricity production ¹	0.46		0.58	
Domestic electricity retail	0.35	0.22	0.40	0.25
International electricity trade	0.27	0.12	0.37	0.24
Domestic gas markets	0.27	0.13	0.27	0.17
International gas trade	0.24	0.11	0.09	0.03

¹ In the long-run version of the model, it is only possible to identify the combined effect of the liberalization of electricity production and the liberalization of domestic electricity markets.

When liberalizing international trade in Western Europe, energy is moved from high-price countries to low-price countries in order to obtain arbitrage profits. However, due to the costs of international transmission, as well as capacity constraints in international transmission, producer prices are not completely equalized across countries. As seen from Table 4, the liberalization of international gas transmission lowers the short-run coefficient of variation for national producer prices of gas from 0.27 to 0.09. Thus in the short run most of the price differences between countries are eliminated. Moreover, in the long run, when transmission capacity can be expanded, almost all price differences between countries are eliminated as the liberalization of international gas transmission lowers the coefficient of variation for national producer prices of gas from 0.17 to 0.03.

For electricity, however, we see that a significant variation in the national producer prices remains even after a complete liberalization. In the short run, the relatively high coefficient of variation after a complete liberalization (0.24) mainly reflects binding capacity constraints in international transmission. In the long run, the strictly positive coefficient of variation (0.11) reflects the fact that it is not profitable to expand electricity transmission lines to the extent that all differences in net prices between countries are eliminated.

Because the liberalization of international transmission lowers the coefficient of variation for national producer prices, one might guess that the coefficient of variation for national end-user prices would also drop. This is the case for electricity, but not for natural gas. Our calculations reveal that the partial effect of liberalizing international

transmission of gas is an increase in the short-run coefficient of variation for national end-user prices of gas (from 0.25 to 0.31). In fact, the accumulated effect of all partial liberalizations is an increase in the short-run coefficient of variation for national end-user prices of gas from 0.26 (in 2000) to 0.33. The increase reflects the fact that in 2000 there was a tendency for negative correlation on the country level between end-user prices of gas and producer prices of gas. Hence countries with high end-user prices for gas had low producer prices and vice versa. When the difference in producer prices between countries is reduced, which roughly means that initially high producer prices are lowered (as are end-user prices in the same countries), and initially low producer prices are raised (as are end-user prices), the coefficient of variation for end-user prices of gas actually increases due to the initial negative correlation of producer and end-user prices.

Redistribution: gas vs. electricity

Liberalization causes important redistributions of economic surplus. As can be seen from Table 1, the net welfare effects of liberalizations (for all agents in all countries) differ between electricity and gas. First, there are significant net welfare gains and redistribution (transfer from producer surplus to consumer surplus) from liberalizing domestic electricity markets: that is, liberalizing electricity production and domestic electricity retail. The net welfare and redistribution effects of liberalizing domestic gas markets are much smaller, though qualitatively similar. These differences mainly reflect the fact that the total amount of electricity increases much more than the total amount of gas (total supply of gas is per assumption given in the short run). This mirrors the fact that gas is a scarce natural resource in limited supply, whereas electricity is a produced commodity with suboptimal supply in 2000 due to market imperfections. The differences in quantity response imply that the average price of electricity drops much more than the average price of gas.

Second, there is a considerable redistribution from traders to producers when international gas transmission is liberalized, as this type of liberalization allows the gas producers to sell directly to the end users in the model countries. Under this partial liberalization, the difference between national producer prices of gas is almost eliminated because all arbitrage profits in international gas transmission are exhausted: see the

discussion above. Hence international traders in gas suffer significant losses, as in the new equilibrium national producer prices are almost equalized. For example, Norway as a gas producer benefits from liberalization of international gas transmission, whereas Norway as an owner of international transmission pipes loses. Note that presently much of the gas is sold on long-run contracts, yet such contracts are not incorporated into our model. LIBEMOD MP may thus overestimate this redistribution, especially in the short run, when contracts are still valid and end-user prices of gas increase because of increased demand. In addition, if there are no legal constraints in international agreements, the importing countries may counteract this transfer of rent to the gas producers by taxing the use or imports of gas. This policy alternative is not analysed within the model.

Whereas there are significant redistribution effects when liberalizing international gas transmission, there are only small redistribution effects when liberalizing international electricity transmission. What explains this difference between gas and electricity? As natural gas is a scarce natural resource, there is a resource rent related to selling natural gas. In general, the distribution of the resource rent depends on the market structure. When a gas transmission company has a monopoly on transmission, the resource owner can obtain access to the market only through the transmission company, which may cut into the resource rent through a mark-up on transmission. Liberalizing gas transmission removes the mark-up and enables the resource owner to keep the resource rent, thereby shifting significant amounts of money from the transmission sector to the gas resource owners.

In contrast, electricity is a produced good and so there is no resource rent ('extra profits') to be distributed. This is one reason why the value of trade between the model countries in 2000 was much higher for gas than for electricity. In addition, trade flows between model countries (measured, for example, as a share of total consumption) were significantly lower for electricity than for gas, reflecting the fact that electricity is a good being produced in all countries, whereas a large fraction of total extraction of gas takes place in a limited number of countries. Finally, while the liberalization of international gas transmission eliminates almost all differences in the national producer prices of gas and thus removes the source of making profits in international gas transmission, there are

significant differences in national producer prices for electricity even after a complete liberalization: see the discussion above. These factors explain the difference in profit shifting between gas and electricity.

Robustness

We have examined the case when electricity is liberalized before gas. The effects of a partial liberalization may, however, depend on the order in which different markets are liberalized. To analyse the impact of the order of liberalization, we compare the case in which *gas* is liberalized before electricity to the (initial) case in which *electricity* is liberalized before gas. In both instances, domestic markets are liberalized before international transmission. The welfare effects of the different stages of liberalization are shown in Table 5, where the effects are reported in the same order as in Table 1 (the order of liberalization when electricity is liberalized first) to make the comparison easier.

Table 5 Partial liberalization of energy markets: gas is liberalized first (G) and electricity liberalized first (E); effects on welfare of each step (\$2,000 billion)

		Consumer surplus in model countries		Producer surplus in model countries		International trader surplus		Sum model countries ¹		Sum all countries ²	
		G	E	G	E	G	E	G	E	G	E
Short run	Partial liberalization in:										
	Electricity production	7.5	11.1	-2.4	-6.4	0.1	-0.9	4.1	3.9	0.6	0.8
	Domestic electricity retail	43.7	42.6	-36.6	-35.3	-3.5	1.8	2.9	4.7	10.5	9.9
	International electricity trade	3.6	4.4	-3.0	-2.3	0.6	-1.3	0.7	0.6	0.7	0.7
	Domestic gas markets	5.5	3.5	-2.9	-1.8	-1.9	-1.3	-0.8	-1.0	0.4	0.4
	International gas trade	-1.0	-2.4	-1.6	-0.7	-0.2	-3.3	-1.4	-2.7	0.0	0.3
	Total effect	59.2	59.2	-46.5	-46.5	-5.1	-5.1	5.5	5.5	12.0	12.0
Long run	Partial liberalization in:										
	Electricity production ³										
	Domestic electricity retail	69.9	73.0	-48.4	-51.7	-2.8	-1.4	16.9	17.0	19.0	17.9
	International electricity trade	1.6	-3.5	-0.2	3.6	0.5	0.3	1.0	0.1	0.5	0.1
	Domestic gas markets	8.9	10.7	-9.8	-9.7	2.4	1.2	0.2	1.2	1.1	1.9
	International gas trade	0.1	0.2	2.0	1.4	-9.6	-9.6	-1.9	-2.2	-0.4	0.2
	Total effect	80.4	80.4	-56.4	-56.4	-9.5	-9.5	16.2	16.2	20.2	20.2

¹ Sum of consumer surplus, producer surplus and tax revenues to the government in the model countries, plus half the international trader surplus on each transmission connection.

² Sum of consumer surplus, producer surplus, tax revenues to the government and international trader surplus in all countries.

³ In the long-run version of the model, it is only possible to identify the combined effect of the liberalization of electricity production and the liberalization of domestic electricity markets.

As can be seen from Table 5, the order of liberalization has in general little impact. For short-run effects, the largest difference is found in the distribution between consumers and producers in the model countries when electricity production is liberalized. For this type of partial liberalization, the effects on consumer surplus and producer surplus are largest when electricity markets are liberalized first. Note also that liberalizing domestic gas markets has a greater short-run redistributive effect from producer surplus to consumer surplus when gas is liberalized first. More generally, in the short run there is a slight ‘diminishing returns’ effect with respect to domestic market liberalizations: that is, the partial effect of liberalizing gas is highest if gas is liberalized before electricity, and the partial effect of liberalizing electricity is highest if electricity is liberalized before gas. This is roughly the case for price and quantity responses, as well as for redistribution between consumers and producers.

The long-run effects of liberalizing domestic markets on consumer and producer surpluses, as well as the impact on global welfare, are, however, independent of the order of liberalization. In fact, for consumer surplus the effect of liberalizing domestic gas markets is actually slightly larger when gas is liberalized *after* electricity.

6. Concluding remarks

Earlier studies have considered the effects of a complete deregulation in Western Europe of either gas markets – see Golombek et al. (1995) – or electricity markets – see Amundsen and Tjøtta (1997) – or the gas and the electricity markets – see Aune et al. (2004, 2008). By contrast, in the present paper we focus on the effects of partial liberalization, posing the questions: in which markets does liberalization yield large benefits, and where are the benefits smaller?

We find that a liberalization of electricity has stronger quantity and welfare effects than a liberalization of gas. Although this partially reflects the fact that the electricity market is approximately three times as large as the gas market, the welfare effects of electricity liberalization are roughly ten times as large as those of gas liberalization. Furthermore, we find that the liberalization of domestic energy markets has (overall) stronger effects than a liberalization of trade in energy between Western European countries. In particular, the liberalization of domestic electricity markets

increases production of electricity significantly, leads to significant redistribution from producers to consumers and increases global welfare. The liberalization of trade in energy in Western Europe has a small impact on prices and quantities, yet the liberalization of international gas transmission redistributes huge amounts of money from the transmission companies to the gas resource owners. To summarize, liberalization increases economic welfare in Western Europe by around \$16 billion per year, which corresponds to about 7 per cent of gross value added in the energy industry in Western Europe.

All the different types of partial liberalization increase global welfare, in both the short and long run. There is one exception: namely, the liberalization of international gas transmission in the short run. Due to pre-existing taxes, a liberalization of international gas transmission tends to increase the differences in marginal willingness to pay for gas across countries in the short run. This type of result is known from the literature on the second-best outcome: if a change (liberalization of all markets) that raises total welfare is split into several steps (several partial liberalizations), then each step (a partial liberalization) may not be welfare-improving – see, for example, Dixit (1975).

Throughout the paper we have neglected the fact that liberalization causes higher emissions of CO₂ through increased use of fossil fuels, particularly in coal-fired power plants. Is there a net welfare gain of liberalization when this externality is taken into account? A complete liberalization increases global emissions by 315 Mt CO₂ in the long-run version of the model, which – according to our model – amounts to roughly 8 per cent of CO₂ emissions in Western Europe. However, as long as the social cost of CO₂ is less than \$64 per ton CO₂, the change in global welfare is positive. Typically, the international carbon permit price is estimated to be below \$10 per ton CO₂ in the Kyoto period: see, for example, Springer and Varilek (2004). This suggests that a radical liberalization of the electricity and natural gas markets in Western Europe will raise global welfare. In addition, by (hypothetically) imposing efficient instruments like a uniform carbon tax, emissions will decrease and the net gain in global welfare will be enhanced.

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Appendix: Production of electricity

As explained in Section 3, a producer of electricity maximizes his profits, given some technical constraints and a mark-up on production, which is a (positive or negative) tax. Below we specify the maximization problem of the electricity producer and also derive the first-order conditions.

In order to simplify matters, we consider only one technology (gas power) and two types of cost, disregarding investment in new capacity. We also consider production in only one country. While efficiency varies across gas power plants in this country, instead of specifying heterogeneous plants we model the supply of electricity *as if* there were one single plant (producer) with decreasing efficiency. Let $x(y_t)$ be the amount of gas required to produce the amount y_t of electricity in period t , that is, the input requirement function. $x'(y_t) > 0$ is then the marginal fuel use, and by assumption this is increasing in electricity production ($x''(y_t) > 0$), which reflects decreasing efficiency – less efficient plants are phased in as production increases. Then fuel costs in period t are given by $x(y_t)P^g$, where P^g is the (annual) user price of gas.

In addition to fuel costs, the producer chooses the level of power capacity that is maintained (K^M), thus incurring a unit maintenance cost c^M per power unit. In the short run (given capacity), total costs are thus given by:

$$C = \sum_t x(y_t)P^g + c^M K^M \quad (1)$$

The income from gas power production is:

$$I = \sum_t (P_t y_t + P_t^R K_t^R) \quad (2)$$

The income consists of two parts: income from ordinary sales of electricity and income from sales of capacity to the system operator, who ensures that there is always a reserve power capacity available. Ordinary income in period t is given by $P_t y_t$, where P_t is the price of electricity in period t . Moreover, the producer sells K_t^R of his (maintained) capacity to the system operator at the price P_t^R in period t .

The producer faces some constraints. Below, the restrictions on the optimization problem are given in solution form, where the Kuhn-Tucker multiplier – complementary to each constraint – is also indicated. The first constraint requires that maintained power capacity (K^M) should be less than or equal to total installed power capacity (K_0):

$$K^M \leq K_0 \perp \lambda \geq 0, \quad (3)$$

where λ is the shadow price of installed power capacity.⁷

Second, in each period, production of electricity is constrained by the maintained energy capacity, net of the capacity sold as reserve capacity to the system operator. This net energy capacity equals the net power capacity ($K^M - K_t^R$) multiplied by the number of hours in the period (ψ_t):

$$y_t \leq \psi_t (K^M - K_t^R) \perp \mu_t \geq 0. \quad (4)$$

Finally, we introduce the mark-up factor $s^{MP} \sum_t y_t$, which is our way to model market imperfections.

The producer maximizes his profits: that is, income (2) less costs (1), given the constraints (3) and (4) and the mark-up factor $s^{MP} \sum_t y_t$ with respect to period production of electricity, sale of reserve capacity and maintained capacity. The Lagrangian of the gas power producer is:

⁷ In general, the notation $a \leq 0 \perp b \geq 0$ is shorthand for $a \leq 0$ and $b \geq 0$ and $ab = 0$, where a is the derivative of the Lagrangian w.r.t. b .

$$\begin{aligned}
L = & \sum_t (P_t y_t + P_t^R K_t^R) - \sum_t x(y_t) P^g - c^M K^M \\
& - \lambda \{K^M - K_0\} - \sum_t \mu_t \{y_t - \psi_t (K^M - K_t^R)\} - s^{MP} \sum_t y_t
\end{aligned} \tag{5}$$

The first-order condition with respect to produced electricity is:

$$P_t \leq x'(y_t) P^g + \mu_t + s^{MP} \perp y_t \geq 0. \tag{6}$$

Hence, in each period an internal solution requires that the price of electricity (P_t) should equal the sum of marginal input costs of production ($x'(y_t) P^g$), the shadow price of the periodic energy capacity (μ_t) and the mark-up factor (s^{MP}). In the full model, the mark-up factor differs across technologies and countries, and is determined so that the equilibrium levels of production are equal to the observed production levels in the data year 2000.

The first-order condition with respect to sale of reserve capacity is:

$$P_t^R \leq \mu_t \psi_t \perp K_t^R \geq 0 \tag{7}$$

that is, the income from selling one more unit of power capacity to the system operator (P_t^R) should (in an internal solution) equal its opportunity cost, which is the value of increased production due to a higher energy capacity (μ_t) being available for electricity production during all hours in the period (ψ_t).

Finally, the first-order condition with respect to maintained capacity is:

$$\sum_t \psi_t \mu_t \leq c^M + \lambda \perp K^{PM} \geq 0. \tag{8}$$

Hence, in an internal solution the cost of increasing maintained capacity marginally – the sum of the maintenance cost (c^M) and the shadow price of installed capacity (λ)⁸ – should be equal to the value of increased annual production following from this policy, which is the shadow price of energy capacity (μ_t) times the number of hours in the period (ψ_t), summed over all periods.

⁸ If $\lambda > 0$, then increasing the maintained capacity marginally requires that also the installed capacity is raised.