# 2. Modelling changes

This chapter describes any changes that were done to the modelling from the 2000-version to the 2009-version of LIBEMOD. For a full description of the 2000-version of the model see Aune et al. (2008).

## 2.1 Countries

For most activities, countries are divided into three groups. First, the group of all model countries (endogenous countries); these are 29 countries in Europe (Austria, Belgium incl. Luxembourg, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Great Britain, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, The Slovak Republic, Slovenia, Spain, Sweden, and Switzerland). Second, a group of five countries that are not members of the European Economic Area (exogenous countries); Algeria, Belarus, the remaining part of former Yugoslavia, Russia and Ukraine. Finally, the group of all other countries, referred to as row (rest of world). For natural gas supply, we also need a group of five large suppliers; Algeria, The Netherlands, Norway, Russia and the UK, as well as a country group that is the single supplier of LNG, henceforth referred to as row2.

## 2.2. Fuel supply

In LIBEMOD 2000 the modelling of extraction of fuels, and also imposed functional forms, differ somewhat between fuels. In the present model we harmonize the modelling by assuming that the following first-order condition for production (price equal to marginal cost) applies for a number of countries and fuels:

 

Here, *m* is an index for countries and *j* is an index for goods.  is the producer price,  is the quantity supplied and is the marginal cost of transport.[[1]](#footnote-1) Finally, and  are parameters.

For the model countries, relation applies to oil, steam coal, coking coal, biofuel and biomass. For the group of the five exogenous countries and row, applies to oil, steam coal, coking coal and biofuel.

For natural gas, the model distinguishes between three types of goods, which are perfect substitutes for gas users; (i) natural gas extracted from existing fields (supplied by the five large producers Norway, the Netherlands, the UK, Russia and Algeria), (ii) natural gas extracted from new fields (supplied by all countries, for example, Germany, Norway, Belarus and row), and (iii) LNG (supplied by only one country, namely row2).[[2]](#footnote-2) Relation applies to (i) and also to (ii), except for gas extraction in row. [[3]](#footnote-3),[[4]](#footnote-4) Finally, for extraction of natural gas in row and also for LNG supply in row2, production is determined from

 

where and are parameters.

For lignite, production is set to the observed level of consumption in each country (in the data year 2009). In the model countries, production of lignite is assumed to decline by four percent annually.

For the five exogenous countries and row, production of biomass is exogenous and set equal to the observed 2009 values.

## 2.3. Demand for fuels in exogenous countries

For the five exogenous countries, demand for oil, steam coal, coking coal and gas follows from

 

where  reflects the growth rate of country *m*,  is the income elasticity, and  and  are parameters. Relation also applies for oil, steam coal, coking coal and biofuel in row. Further, the demand relation for gas in row and for LNG in row2 is

 

where  and  are parameters. Finally, as specified above, in the group of five exogenous countries consumption of lignite, biomass and biofuel is exogenous, whereas in row consumption of lignite and biomass is exogenous.

## 2.4 International energy trade

In LIBEMOD 2000, Armington formulations were used to model imports of steam coal and coking coal to model countries. In the new version of LIBEMOD, this approach has been replaced by introducing a world market for each of these goods, see the discussion below.

Whereas the modelling of international electricity trade has not been changed, the modelling of international natural gas trade has been changed in two ways. First, in the new version of LIBEMOD LNG trade is included. In general, LNG is modelled as natural gas, but only row2 supplies LNG. All model countries with a costal line are potential buyers of LNG, and each of these has a country specific regasification capacity of LNG.

Second, in the previous version of LIBEMOD there was a constant (annualised) cost for expansion of natural gas pipes between each pair of countries: Let *r* denote whether the pipe is onshore or offshore, that is,  Further, let  be the (annualized) cost of investment (€ per toe per 100 km), which depends on whether the pipe is onshore or offshore and let be the length of the pipe (measured in 100 km) between country *m* and country *n*. Cost of investment for a pipe between country *m* and country *n* was  where  is investment in a pipe between country *m* and country *n* (measured in toe). In the present LIBEMOD version, cost of investment for a pipe between country *m* and country *n* is  The general idea of  is that the unit cost of investment in pipes is decreasing; ; in the previous version of LIBEMOD this derivative was zero.

Like in the previous version of LIBEMOD, a pipe can be used in both directions, but the trade in any direction ( and ) cannot exceed total pipeline capacity ();  where  is the shadow price of the pipeline capacity (There is a similar condition for exports from *n to m*). The first-order condition for investment in transmission capacity now becomes



In the previous version of LIBEMOD there was no international biomass trade. This has been changed by opening up for trade in the same way as for electricity and natural gas, that is, there might be trade between neighbouring countries. However, in contrast to electricity and natural gas where trade cannot exceed a capacity (of an electricity line or a gas pipe running between two countries), no capacity is required to undertake biomass trade. Therefore, trade is simply modelled as a requirement that the price difference between two countries should fully reflect costs of transport () and loss in transport () from exporting biomass from country *m* to country *n*:

 

This corresponds to relation (A.67) in Aune et al. (2008).

## 2.5 Equilibrium

In general, the types of equilibrium conditions are not changed, but for each type of condition the set of goods for which this type applies may have changed. First, for endogenous countries the requirement that consumed quantities, adjusted by a distribution loss factor, are equal to quantities delivered at the central node, that is, the sum of domestic production and net imports, applies to all fuels, now also to biofuel. For electricity a similar equilibrium condition applies, and there is de facto no change except that the set of electricity users have been augmented by the group “services”.

Third, for the five exogenous countries and also row and row2, the domestic equilibrium condition for all fuels requires that demand  should equal production plus imports. In the previous LIBEMOD version, this was a requirement for gas, oil, steam coal and coking coal only. The complementarity variable of this condition is the domestic producer price, but the modeller can impose other prices; as in the previous LIBEMOD version we set the domestic producer price of lignite to 70 percent of the domestic steam coal producer price.

Finally, the equilibrium condition for goods traded in world markets (oil, coking coal, steam coal and biofuel) states that the sum of net imports should equal zero.[[5]](#footnote-5) In the previous version of LIBEMOD this was the case for oil only, whereas in the new version there are world markets for oil, steam coal, coking coal and biofuel. For each of these goods, the difference between the domestic producer price and the world market price reflects costs of transporting the good from the world market node to the country node.

## 2.6 Electricity production and supply

Production of electricity takes place in each model country using various technologies, see listed in table 2.1 in Aune *et al.* (2008); note that in the new LIBEMOD version this set has been augmented by (new) solar power. Corresponding to each of the pre-existing or *old* technologies , there are *new* technologies  which have no initial capacity and which are therefore only relevant in the long run. Since electricity production based on old and new technologies is in principle modelled in the same way, we present them together. Some of the technologies are not available in all countries. Electricity is supplied to markets that are differentiated by time and place. In each endogenous country there are four time periods  defined by the two seasons summer and winter, and two times of day, day and night, each lasting 12 hours; this differs from Aune et al. (2008) where there are six times of day (of varying length). This change reflects that due other refinements of the model, in particular to develop a stochastic version of LIBEMOD, simplifications of the previous version of LIBEMOD was necessary. In addition, whereas the idea of introducing six time periods over the 24 hour cycle was to capture peak periods, we never obtained much equilibrium variation in the price of electricity; in order to capture the observed price variation another modelling strategy would be required.

### 2.6.1 Thermal power

We begin by studying electricity supplied from the combustion of fuels, returning later to the particulars of hydro, wind and solar (The modelling of waste and nuclear power has not been changed, and we therefore do not comment on these technologies). Note that relative to the previous version of LIBEMOD, reservoir hydro has been split into two technologies - reservoir and run-of-river; in the previous version of LIBEMOD reservoir hydro contained both these technologies. Moreover, solar is a new electricity technology.

Like in Aune *et al.* (2008), in each model country there are five old fuel technologies: gas power, steam coal power, lignite power, bio power and oil power, as well as four new technologies using the same fuels (except lignite). In general, for each old technology and each country, efficiency varies across electricity plants. However, instead of specifying heterogeneous plants within each category of electricity production (for old technologies and model countries), we model the supply of electricity from each category as if there were one single plant with decreasing efficiencies, implying increasing marginal costs. For each type of a new fuel-based technology, we assume, however, that all plants have the same efficiency (in all model countries).

There are six types of costs involved in electricity supplied from combustion of fuels. First, there are non-fuel monetary costs directly related to production of electricity, formulated as a constant unit operating cost . When  is the production of power in period *t*, the monetary cost in each period is , which must be summed over all periods to get the total annual operating costs. Second, there are fuel costs, with a fuel input price of and an annual input quantity of .

Because the capital cost of the installed power capacityis sunk, it should not affect behaviour, and it will therefore be disregarded in our model. On the other hand, there will be costs related to the maintenance of capacity. In addition to choosing an electricity output level, the producer is assumed to choose the level of power capacity that is maintained, , thus incurring a unit maintenance cost  per power unit. Fourth, if the producer chooses to produce more electricity in one period than in the previous period in the same season, he will incur start-up or ramping up costs. In LIBEMOD these costs are partly expressed as an extra fuel requirement (and therefore included in the fuel costs above), but also as a monetary cost per unit of started power capacity () in each period.

For investments in *new* power capacity, , there are annualised capital costs  related to investments in *new* power capacity . Finally, for new plants there are costs related to connect to the grid; these reflect that either the site of the plant is not located at the grid and/or connection to the grid requires upgrading of the grid, and these costs may partly be borne by the plant. Under the assumption that the distance to the grid is increasing in the number of new plants, that is, increasing in the new capacity, and/or costs of upgrading the grid is increasing and convex, the cost of grid connection, , is also increasing and convex. Note that the last type of cost was not present in the previous version of LIBEMOD. Hence, the first-order condition for investment therefore differs between the present version of LIBEMOD and Aune *et al.* (2008).

The short-run variable cost equation is therefore:

 

where *T* is the set of time periods.

The revenue of the power producers come potentially from two sources. First there is the regular sale of electricity produced in each time period, which reflects that the electricity price  varies over time. Second, each agent can also sell capacity that is used as reserve power capacity  for which he receives a price  from the system operator. The profit of each power producer is then the two revenue sources less the short run variable costs and any costs of new investments:

 

The producer maximises profits given several constraints. Below, the restrictions on the optimisation 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  should be less than or equal to total installed power capacity :

 

 where  is the shadow price of installed power capacity. Not all pre-existing capacity need be maintained, but if it is maintained it incurs a cost  pr GW.

Second, in each period maintained capacity can be allocated either to production of electricity or to reserve power. Since production is measured in energy units (TWh) while maintained and reserve capacity is measured in power units (GW), this can best be expressed by a constraint that production should be bounded by the energy equivalent of maintained power capacity net of reserve power capacity, i.e., the number of hours available for electricity production in each period, , multiplied by net power capacity  in that period:

 

All power plants need some down-time for technical maintenance. Therefore, total annual production cannot exceed a share () of the maintained capacity:

 

Notice that this is an annual constraint, so the producer may choose in which period(s) the technical maintenance will take place.

Fourth, as mentioned above, start-up and ramping up costs are incurred if electricity production varies between periods in the same season. This cost depends on the additional capacity that is started at the beginning of each period, that is, on the difference between capacity use in one period and capacity use in the previous period in the same season. The start-up capacity () must therefore satisfy the following requirement:

 

where is actual capacity used in period *t* and is actual capacity used in the previous period *u=t-1* in the same season. Each produced quantity is thus involved in two inequalities, one for period *t* and one for period *t+1*, which together imply two different non-negative start-up capacities. Note that the maximum value of is , and hence  can never exceed .

We now turn to the fuel requirement, which consists of two parts. The first is related to the quantity of electricity produced by the direct input requirement function , which is the quantity of fuel needed to produce the given quantity of electricity and which captures the energy efficiency of the transformation process. In LIBEMOD the direct input requirement function is quadratic:

 

The second part is the additional fuel required to start extra capacity, or ramp up an already started power plant, which is assumed proportionate to the start-up capacity by a factor :

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For fuel power technologies, the Lagrangian of the optimisation problem is:

 

where the period *u* is the previous period in the same season as period *t*. In addition to the production of electricity in each period , each electricity producer chooses the amount of reserve power capacity to sell in each period , the quantity of fuel to buy , the capacity to maintain , the capacity to start up each period , and, for new technologies only, the level of investment .

After insertion of the cost equation in the Lagrangian , the first-order condition with respect to produced electricity in each period is:

 

where *u* is the period *following t* in the same season, and  is the marginal inverse efficiency in period t. Hence, in each period positive electricity production  requires that the difference between the price of electricity  and the marginal operating cost of production  should be equal to the sum of suitably weighted shadow prices. The first term in this sum is the shadow price of the periodic available energy capacity restriction , where  reflects that increased production in period *t* is not possible for given maintained capacity net of reserve power . Outside of optimum, if the left hand side of is greater than the right hand side and the restriction is not binding, it may be possible to increase maintained capacity to facilitate increased electricity production. Once optimum is reached, and holds, increasing maintained capacity is either not possible or not worth it.

The sum of shadow prices also contains the shadow price of the annual energy capacity , and the difference (measured per hour) between the shadow price of capacity used in this period and in the following period, where  reflects that production in period t cannot be increased for given . The final term  reflects the value of fuel input needed to produce an extra unit of electricity.

Second, the first-order condition with respect to reserve power capacity sold in each period is:

 

so that for positive reserve power sales the reserve power price must equal the shadow value of increasing the power capacity available to produce electricity. The marginal unit of power capacity should be worth the same either it is sold as reserve power () or used to produce electricity () expressed in value per power unit (MUSD/GW).

Third, the first-order condition with respect to fuel input demand is:

 

which trivially states that at positive input demand, the shadow price of the input is equal to its market price.

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

 

that is, the cost of increasing maintained capacity marginally – the sum of the maintenance cost () and the shadow price of installed capacity () – should be equal to the value of increased annual production following from this policy (or maintained capacity should be zero). Because increased maintained capacity raises both potential periodic electricity production and potential annual electricity production, in each period the value of increased production (per hour) is the sum of the shadow price of periodic energy capacity () and the shadow price of the annual energy capacity adjusted by the maximum operating time ().

Fifth, the first-order condition with respect to the start-up capacity is:

 

that is, in each period the shadow price of start-up capacity , which reflects the benefit of increased start-up capacity through higher production, should be equal to the sum of the monetary start-up cost  and the cost of the extra fuel input , or alternatively, the start-up capacity should be zero.

Equations and imply that *if* a plant is producing in one period, costs will increase if the plant does not also produce in the previous period because the plant will incur a start-up cost. By the same token, if the marginal benefit of a start-up is positive in the period after the one we examine (), then this allows a greater benefit of a start-up in this period since if capacity is already used in this period, we can also use it in the next period without incurring additional start-up costs. Hence, the start-up component tends to smooth out production from a plant over the day. However, smooth production combined with high demand during the day and low demand at night will lead to increased price variation between day and night.

The final FOC with respect to a decision variable is for investment. Using the fact that for new technologies total capacity will be equal to investment, , the investment criteria can be written as

 

Relation implies that if investment is positive, the total annualised investment cost must equal the shadow price of installed capacity, i.e. the increase in operating surplus resulting from one extra unit of capacity.

In addition to the FOCs with respect to the decision variables, that is, -, the FOCs with respect to the multipliers recover the original optimisation restrictions -.

### 2.6.2 Hydro power

We now turn to *pumped storage power.* This is when a producer buys electricity in one period (e.g. during the night) and uses that energy to pump water up to the reservoir in order to produce electricity in a different (higher-price) period (e.g. during the day) by letting the water flow down through the generator again. For this technology, the Lagrangian is similar to , except that the pumped storage producer uses electricity (and not fossil fuels) as an input.

The *reservoir hydro power* producer has two additional restrictions in his optimisation problem. First, total use of water, that is, total production of reservoir hydro power in season *s* () plus the reservoir filling at the end of season *s (*) should not exceed total supply of water, that is, the sum of the reservoir filling at the end of the previous season () andthe seasonal inflow capacity () expressed in energy units:

 

Second, the reservoir filling at the end of season *s* cannot exceed the reservoir capacity:

 

These two restrictions have the following impact on the first-order conditions. First, the sum of the shadow prices in should include the shadow price of the inflow capacity  instead of the cost of fuel input . As increased production will reduce the available amount of water,  is often termed the *water value*. Second, an additional first-order condition (related to reservoir filling) requires that the shadow price of reservoir capacity in season *s* should be equal to the difference in water values between this and the other season (or the reservoir should be empty at the end of season *s*):

 

In Aune *et al.* (2008) the *run-of-river hydro power* technology was incorporated in the reservoir hydro technology, that is, the magnitude of the reservoirs reflected the reservoir hydro technology only because per definition run-of-river does not have a reservoir. For run-of-river hydro power restriction therefore does not apply and is modified, partly because there is no reservoir, and partly because the adjusted restriction applies for each time period (not each season). Hence, for run-of-river we have

 

where  is the magnitude of water available for run-of-river electricity production in time period *t*.

### 2.6.3 Wind power

The energy capacity for wind power varies across periods, but there is no storage possibility. Thus, in each period, production from pre-existing wind power capacities is exogenous (equal to observed supply in the data year).[[6]](#footnote-6) The stochastic nature of wind power makes it unsuitable for reserve power. Hence, in the short-run version of LIBEMOD the producer determines only how much of the predetermined capacity that is maintained.

We now present the modelling of wind power in the long-run version of the model, that is, when investment is endogenous. This modelling departs from the one in the previous version of LIBEMOD; the difference reflects how scarcity of attractive wind power sites is treated.

We assume that the best site for wind power (in terms of annual wind hours) is used for wind power production before the second best site is developed, and so on. This is formalized by, which shows average number of wind hours as a decreasing function of aggregate capacity of wind power plants. Because production of wind power depends on the amount of capital that is maintained,  annual energy capacity of wind power is . [[7]](#footnote-7) Here we have assumed that technical maintenance of wind power plants take place in periods without any wind; this assumption reflects that the number of wind hours at the best site is by far below the total number of hours in a year.

From the discussion above it follows that production of wind power in period *t* cannot exceedwhere  is the (expected) share of annual number of wind hours in period *t*. We thus have a restriction on maximum production of wind power in each period. The restriction on annual production of wind power due to technical maintenance during the year is still captured by .[[8]](#footnote-8)

We have captured the scarcity of attractive sites through  This means that we can model investment in the same way as we did for fuel-transforming technologies, that is, cost of investment is simply . In LIBEMOD,  is decreasing over time due to technological progress, see Section 3.

The Lagrangian of the optimizing problem of a new wind power plant is:

 

The first-order condition for produced electricity in each period is:

 

This is similar to except that the last three terms in are not present in ; the wind power producer never shuts down the plant when it blows, he has no fuel input and he cannot adjust his start-up capacity.

The first-order condition for maintained capacity is now:

 

Like in the case of fuel-transforming technologies, the cost of increasing maintained capacity marginally – the sum of the maintenance cost () and the shadow price of installed capacity () – should (in an interior solution) be equal to the value of increased annual production following from this policy. Increased maintained capacity raises potential periodic and annual electricity production. Therefore, the value of increased production is i) the shadow price of periodic energy capacity () weighted by the wind share in this period () and summed over the year, when the effect on annual production of wind power due to increased maintained capacity  is taken into account, plus ii) the value of increased potential annual production, which is the shadow price of the annual energy capacity times the maximum number of operating hours during the year  Finally, the first-order condition for investment is given by .

Calibration of wind power parameters

We impose a linear function on :

 

Because  shows average number of wind hours as a decreasing function of aggregate maintained capacity,  should be interpreted as the number of wind hours at the best site (in a country). We have determined the value of this variable by using information from Hoefnagels et al. (2011).

In order to determine the value of , we use information from Eerens and Visser (2008). This report provides information on the potential of onshore wind energy in 2020 and 2030 for European countries for three different cost classes: cost of production (measured in 2005 €ct/kWh) at 0.048 or lower (termed “competitive” in the report), cost of production between 0.05 and 0.07 (termed “most likely competitive” in the report), and finally cost of production exceeding 0.07 (termed “not competitive” in the report). While this information is sufficient to estimate a marginal cost curve for onshore wind power, such a relationship cannot be used directly in our model because we work with - the average number of wind hours as a decreasing function of aggregate maintained capacity. We now explain how we can use the information from Eerens and Visser (2008).

We assume that the amount of wind power production is determined by profit maximization. To simplify, we assume that maintained capacity is equal to invested capacity. We also assume that the price of electricity is constant over the year. This implies that we have only one restriction on wind power production; this restriction is related to total annual production of wind power. The Lagrangian of the optimizing problem of a new wind power plant is now:

 

Note that relative to the real decision problem of a wind power producer, see , we have removed costs of grid connection () because the price of electricity in is measured at the production node.

The first-order condition for annual produced electricity is:

 

Further, the first-order condition for investment is:

 

The corresponding restriction on investment is:

 

Relations , and are three relations that determine and In the calibration all these three variables will be strictly positive, implying that we have equality in (30) and (31), and (32) simplifies to .

We assume that all costs in Eerens and Visser (2008) are measured 2008 values. Based on the data in the Eerens and Viser study we know the amount of profitable potential wind power production in 2030 (in a country) if the price of electricity is constant over the year and equal to 0.07 €ct/kWh in 2030 (measured in 2008 values). However, actual wind power production is only a small share of potential wind power production because most sites suitable for wind power are not available for production. It is hard to estimate this share, which may increase over time, but in this study we assume the share is 10 percent in 2030. This gives us annual wind power production in 2030,  if the annual price of electricity is , which we assume is 0.07 €ct/kWh in 2030.

Using the system , , and , we treat  as an exogenous variable (equal to ), we set and the parameter  is exogenous (see discussion above). Then this system determines  (from ), and . This is our procedure to determine the parameter  for each country in the year 2030.

### 2.6.4 Solar power

The main solar power technologies are Centralized Solar Power (CSP) and Photovoltaics (PV). The latter is a method of generating electrical power by converting solar radiation into direct current electricity by using solar panels containing photovoltaic material. We have chosen to model PV, which, based on available cost estimates, seems to be the most promising technology.

The PV technology requires land to produce electricity. Let  be *actual* use of land to produce solar power in a country in a year (measured by ). Under ideal conditions, the PV technology requires  to produce 1 kW momentarily, and therefore  is the momentarily production of electricity (KW per m2) under ideal conditions. The actual (momentarily) production capacity of solar is therefore  (measured in GW). Further, let  be the amount of land available to solar power (in a country in a year) where . Then maximum (momentarily) production capacity is and obviously we must have

 

We now derive measures for annual energy capacity of solar power. First, let  be annual solar irradiance per  in a country. Then  measures received energy by the solar panels throughout a year. Second, let be the share of energy received by the solar panels that is transformed to solar power. Annual energy capacity of solar power (TWh) is then  Alternatively, annual energy capacity can be expressed by where z measures annual efficient solar hours (the unit is kh), defined from the identity

 

So far we have implicitly assumed that each solar panel receives the same amount of energy. However, sites differ wrt. solar irradiance. We now assume that there is a continuum of sites (in a country) and these can be ranked according to their solar irradiance. We further assume that as time evolves, more and more land is available for solar power, but due to regulations the distribution of available sites (the share of each type of site) does not differ over time. Further, we assume that the best sites are used first, so the more solar power that is developed, the lower is the average amount of energy received by the solar panels. This mechanism is captured by letting the measure of solar irradiance, , be a downward sloping function of the capacity utilization: . Note that  should be interpreted as the average solar irradiance.

Using the identity , we now define our measure of annual efficient solar hours:

 

By letting  be the share of annual efficient solar hours in period *t*, we have a measure of energy capacity of solar power in this time period: . Here we have substituted actual production capacity () by maintained production capacity () because production takes place only in those panels that are maintained and we assume that producers always maintain the panels at the best sites. Finally, we assume that solar power is not used as reserve power capacity by the system operator due to its intermittency.

For solar power, the Lagrangian of the optimisation problem is:

 

Here, the term  reflects relation , and  reflects condition . Further, using the expression for periodic solar power energy capacity the term  reflects when solar power capacity can only be used to produce power (not sold as reserve power capacity) , and finally  reflects . Like in the case of wind power, will never bind, that is,  because even at the best sun site the number of efficient solar hours is far below 

The first-order condition for maintained capacity is

 

Finally, the first-order condition for investment is given by

 

1. The interpretation of *MCT* depends on the good. For oil, steam coal, coking coal and biofuel, *MCT* is the cost of transporting the good from the world market node to the country node, whereas for biomass *MCT* is zero because this good is not traded at a world market but bilaterally between countries; see discussion below. [↑](#footnote-ref-1)
2. For the group of large gas suppliers, total extraction is defined as the sum of extraction from old and new fields. [↑](#footnote-ref-2)
3. For natural gas, *MCT* should be interpreted as the cost of transporting the gas from the extraction site to the country node. [↑](#footnote-ref-3)
4. Note that the parameter *d* is strictly positive only for gas extracted from new fields among the five large gas producers (Norway, the Netherlands, the UK, Russia and Algeria) and for biomass supplied by each model country. [↑](#footnote-ref-4)
5. Biomass, electricity and natural gas are traded between pairs of countries, whereas there is no international trade in lignite. [↑](#footnote-ref-5)
6. This requires that the price of electricity exceeds the (very low) variable cost of wind power production. [↑](#footnote-ref-6)
7. We assume that if the installed capacity of some (new) wind power plants is not maintained, then these plants are located at sites with the lowest number of annual wind hours. This assumption will be fulfilled if producers maximize profits, as wee assume. In fact, with profit-maximizing wind producers the entire invested capacity will be maintained. [↑](#footnote-ref-7)
8. Because the number of wind hours during the year at the best site is by far below  hours, will never bind. [↑](#footnote-ref-8)