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Global electricity technology substitution model with induced technological change

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Abstract

Future energy planning which aims to avoid excessive radiative forcing due to anthropogenic greenhouse gas (GHG) emissions leading to a global warming of more than 2 degrees C is likely to require drastic reductions in greenhouse gas emissions, possibly an almost complete decarbonisation of the current global energy sector. Such a transformation is expected to involve drastic costs, and large uncertainties surround the concept of decarbonisation and as to whether it is feasible economically. The transformation of the energy sector is likely, therefore, to have major consequences on the global economy, and it is difficult to model the energy sector without including its interactions with global economic activity. E3MG is a disaggregated global macroeconometric model which features an electricity technology submodel, involving a powerful combination of top-down and bottom-up approaches to power systems modeling. However, this submodel currently lacks a treatment of natural resources, and does not reproduce adequately some of the important dynamics underlying changes in technology and energy infrastructure.

We propose in this work a novel approach to electricity technology substitution modeling as a development of the electricity submodel of E3MG. As opposed to traditional energy models based on cost optimisation procedures, it focuses instead on the dynamics of technology substitution in connection with induced technological change. Technology costs are influenced by learning-by-doing effects, which lead to strong path dependence. The model is designed to work with several world regions and thus with local energy landscapes. These regions are defined by the availability and costs of natural resources. Preliminary calculations using a single world region are given in order to explore the properties of the model given very simple sets of assumptions. The results highlight how technological change dynamics emerge from the set of equations at the root of this model.

Contents

1 Introduction

The future levels of anthropogenic greenhouse gas (GHG) emissions are the primary unknowns in estimating the rate of climate change in the medium and long term. Anthropogenic GHG emissions depend on human activities, and thus on the structure of the future economic system. They stem primarily from energy use and land use change. Global energy systems have been modeled for several decades (see for instance the models IMAGE/TIMER (Bouwman et al., 2006), MESSAGE (Messner and Strubegger, 1995), MARKAL (Seebregts et al., 2001)). The problem of GHG emissions reductions requires changes to be made to the structure of global energy use. Since the latter lies at the very core of the world's economy, these changes have deep implications and effects felt in all aspects of society. Therefore, a simulation of GHG emissions cannot easily be separated from simulations of the economy.

A large part of the mitigation effort is likely to be applied to reductions in energy demand and supply, through improvements in the efficiency of energy use. However, reductions of emissions to low levels are not likely to be obtained through demand reductions alone. Rather, they must occur also through a transformation of the electricity production sector, by changing highly emitting technologies associated with fossil fuels towards low emission systems based on other types of energy sources, notably renewable energy sources. Therefore, deep structural changes to this sector are required, and are not likely to be simple to achieve. Since large additional investments in new technologies are required, there is likely to be an ever growing interaction between the economy and the energy sector. According to several studies, such a transformation of the energy sector may not necessarily be detrimental to the global economy, since it has the potential to generate additional employment in several sectors of the economy (the most comprehensive review being Stern (2006), and references therein, notably Barker et al. (2006)).

In this report, we propose the structure of a new theoretical representation of the global electricity sector, as the main sub-model of a larger global energy sector, each section of which are based on a similar theoretical basis. This model is intended to be used as part of a larger framework which simulates the global economy, E3MG. E3MG is a highly disaggregated macroeconomic model representing 20 world regions, 12 energy carriers, 19 energy users, 28 energy technologies, 14 atmospheric emissions and 42 industrial sectors. It calculates energy demand through the level of economic activity within its various sectors. The model presented here is designed to determine how this demand may be met by the supply of electricity produced by a mix of different technologies. These technologies possess different characteristics, such as varying levels of GHG emissions, differing investment and operation costs and potentials of energy production based on resource availability and use, defined locally for 20 world regions. The choice between the various energy production technologies is done through market competition represented by a set of coupled logistic differential equations, which simulates how various competing technologies interact in regional markets.

Reductions of greenhouse gas emissions to low levels requires a radical, but gradual, transformation of the way with which energy is produced and used. Currently, the power sector is dominated by fossil fuel based electricity production methods, on average less expensive than most other energy sources. Following policy aimed at phasing out such technologies, or through the gradual depletion of some of the fossil resources, technological transitions should naturally arise. Such transitions are driven by evolving cost differences between alternatives which occur through many processes, but are studied under two grouping principles, termed induced technological change and technology diffusion. Market shares of competing technologies for many types of completely different systems have been shown to follow S-shaped curves, appropriately described by the logistic family of functions (Grubler et al., 1999; Pan and Koehler, 2007). There exists an extensive literature where logistic systems of equations have been used in the analysis of growth and competition in markets (Bass, 1969; N. and Kabir, 1976; C., 1989; Morris and Pratt, 2003), and specifically in energy markets (Marchetti and Nakicenovic, 1978). The subject has been explored more recently by Anderson and Winne (2007), where they introduce a family of coupled differential logistic equations. Such systems of equations are generally inspired from the general theory of population growth in biological systems. Of particular note is the model by Lokta (Lotka, 1925) and Volterra (Volterra, 1939), widely used for the study of predator-prey type of biological systems, and widely used for competition in markets (see for instance Morris and Pratt (2003)).

Technological improvements are likely to take an important role in future choices for energy technologies. It is not realistic to omit technological change for any simulation projecting energy systems into the future further than a decade or two. Learning here is taken in the sense of improvements to current technologies, which bring down their costs. In this work, we are interested in simulating GHG emission reductions up to 2100, where in most studies of future emission scenarios, these are assumed to be stabilised (IPCC, 2007, 2000). Thus an important aspect of this model is the assumption of technological learning-by-doing, which occurs with the deployment of technology. It produces a highly non-linear system, where technologies with high rates of deployment see their costs reduce rapidly, whereas those with slow deployment rates see very little change in their costs. Lowering costs favours even more deployment, which again triggers additional lowering of the costs, and so on. This effect is of primordial importance, since it is one which governments and firms may use in order to generate change in the energy system. This may be done through sustained support for new technologies, which are expected to become more affordable even with modest deployment, as opposed to mature technologies which see very little improvements even for large amounts of new investment. As we show in this work, the combination of the concepts of learning-by-doing with a set of coupled logistic differential equations to represent market competition leads to the generation of technological transitions strikingly similar to those observed in history, as explored by Grubler et al. (1999) and by Marchetti and Nakicenovic (1978).

The solution to GHG emissions does not lie in changing the whole energy system towards a single low emitting energy source. Many reasons lie behind this, the most important being that such massive deployment of one resource is probably not cost effective.

Although many types of renewable energy sources have been reported large enough to cover the energy requirements of the world many times over (Lu et al., 2009; Hoogwijk et al., 2004, 2005, 2009; Hoogwijk, 2004; UNDP, 2000a,b), some of these statements fail to take into account the cost of such massive use of resources (for instance, the World Energy Assessment (UNDP, 2000a,b), and work by Lu et al. (2009)). The value of so-called 'economic' potentials inherently depends on the cost and level of use of every alternative, making it a concept difficult to interpret. Costs of resources must be viewed as functions of their level of use, and the level of use must be determined through competition with other alternatives. This may be done using a formalism involving cost-supply curves, described extensively in this work, widely used in energy modeling, made popular primarily by Rogner (1997) for his work on fossil fuels, and taken again by Hoogwijk et al. (2004, 2005, 2009); Hoogwijk (2004) for their assessments of wind, solar and biomass global energy potentials. This framework enables the system to remain stable and produce solutions which lie within realistic bounds of future resource use. Although it has been discussed extensively elsewhere, we include a description for completeness.

Finally, the transformation of the global economy towards low GHG emissions is likely to be possible only through their appropriate pricing. Global warming stems from a market failure, where GHG emissions correspond to an externality which affects everyone, and requires to be appropriately penalised, or priced, in order to remove existing market distortions (see for instance Stern (2006) and Perman et al. (2003)). Such pricing on an international level may be done through an emissions trading scheme similar to the EU-ETS in the European Union. Additional carbon costs must be taken into account by investors when choosing between energy technologies. It represents the tool to generate a drive for change in a system which is likely to remain relatively the same otherwise. In this simulation, the pricing of GHGs gives rise to a wealth of phenomena and to many differing future energy landscapes. It is therefore very interesting, even if only for academic purposes, to analyse the results the model produces for different sets of assumptions.

The model was built in view of representing energy markets in 20 regions of the world. However, the results presented here are calculated using a world model only, based on a single world energy market. This is not meant to be realistic, but rather it is done in order to explore the properties of the set of equations at the root of the model for a simple case. Therefore, in these simulations, all electricity technologies compete on equal grounds with global cost-supply curves, and a single price for electricity is assumed to exist. In a model featuring a more realistic disaggregation of the world into several regions, not all types of energy resource should be available in all regions, making the competition in various local markets limited to a restricted number of options. Energy demand also varies between regions, and is not likely to correspond closely to the availability of energy sources in each of these regions. Therefore, price differences and trade are expected to occur between world regions. As in the real world, energy resource scarce regions find it cost-effective to buy electricity from neighbouring energy rich regions. Therefore, the intended use of this model is likely to be much more complex than that represented in the results of a single region model as presented here. It is, however, critical to analyse the behaviour of the set of equations at the core of this model under different assumptions. We defer to later work the analysis of this model when it features 20 regions which coincide with those of E3MG, trading energy amongst each other, where a wealth of new phenomena is likely to be observed. Moreover, the hard-linking of this model with a macroeconomic simulation implies continuous feedback between the two, where energy use generates evolving carrier prices, which affect energy demand, and feeds back into energy use through the complete set of cost-supply curves and the depletion of resources. Economic activity within the macroeconomic model being susceptible to strong influence from energy prices which are affected by policy decisions, energy demand reductions can be generated, providing the missing key part of the problem of decarbonisation.

We introduce the model in this report using the following progression. We first construct a representation of electricity technology substitution through a market shares equation based on a set of dynamic coupled logistic differential equations, given in section 2. We then present in section 3 a number of simple rules which constrain the shares equation in order to produce a realistic energy system in terms of various technical properties, where power demand fluctuations can be met appropriately without losing system stability. We then introduce in section 4 our representation of natural resource availability, use and depletion through cost-supply curves. We then finish with section 5 by giving numerical results for a world model featuring a single region given various sets of assumptions.

2 Dynamics as a set of differential equations

2.1 The logistic equation as a basic framework

We define an ensemble of electricity producing technologies which compete with one another in the electricity market. We define the central variable, the capacity U_i of technology labeled i, measured in GW:

$$U_{tot} = \sum_i U_i, \tag{1}$$

where U_{tot} is the total capacity. These units of generating capacity produce each year a certain amount of electricity generation G_i, according to the set of capacity factors CF_i, defined as the ratio of time over which a technology produces its rated capacity as electricity output:

$$G_i(t) = U_i(t) CF_i(t), \tag{2}$$

which is measured in GWh/y[1]. The total generation is required to match exactly the demand of electricity $D(t)$ at every instant:

$$\sum_i G_i(t) = D(t) \tag{3}$$

The problem we pose is the following. How does the electricity sector evolve as the market environment changes? As the demand $D(t)$ varies, and units of capacity come to the end of their lives, decisions are going to be made by investors regarding new units of capacity. In order to decarbonise the global electricity sector, investors will attempt to replace current polluting capacity by new units with low or no greenhouse gas emissions. Thus our effort at modeling the electricity sector is one of mimicking the decision-making of investors.

Markets of competing technologies have been modeled in the past using logistic functions. The approaches that have been taken follow closely the general theory of population growth, for instance by using the Lotka and Volterra equations of predator-prey biological systems (Lotka, 1925; Volterra, 1939), which are part of the logistic family of equations. Bass (1969) has introduced in an influential paper the use of a logistic equation to describe the penetration of several durable consumer goods, such home freezers and black and white television sets, into the market. Several authors have developed the use of the Lotka-Volterra set of differential equations to competition in markets and technological substitution (see for instance the work of N. and Kabir (1976), C. (1989) and Morris and Pratt (2003)). Logistic equations have been used by Grubler et al. (1999) to describe technological transitions in various types of goods, services, processes or types of infrastructure. We will discuss in more detail the subject of technological transitions related to induced technological change again in section 5.4.

We thus start with a mathematical analogy using a simple biological system made up of an individual specie, say, a type of bird in an isolated system, which can only nest on a

[1] CF includes a factor of 8760, the number of hours per year, in order to maintain appropriate units.

certain type of tree, of which there is a limited number. If the bird has a fertility factor b, then at any time the change in the fraction of trees occupied by birds $N(t)$ is the following:

$$dN(t) = bN(t)\big(1 - N(t)\big)dt,$$

where the term $bN(t)$ refers to the fertility growth of the specie, while the term $1 - N(t)$ corresponds to the fraction of unoccupied trees left. This is the well known Verhulst equation used in biological systems of individual species. Thus as the amount of possible nesting places decreases, this model assumes that a fraction of each new generation perish through competition for space. The solution to this model is the logistic equation,

$$N(t) = \frac{e^{bt}}{1 + e^{bt}},$$

which features an exponential increase at low population, and saturation where the value of N approaches 1.

In the case where two types of birds competing for the same nesting opportunities completely occupy the system, a similar description may be used. Assuming the variables N_1 and N_2 being the fraction of trees occupied by these two species, and the factor b representing the ability of the first specie to overtake space at the expense of the second, the change in the fraction of space occupied by the first specie is

$$dN_1(t) = bN_1(t)N_2(t)dt = bN_1(t)\big(1 - N_1(t)\big)dt,$$

which has the same solution. It thus indicates that if b is positive, specie 1 gradually overtakes the whole space and specie two perishes, while if it is negative, the reverse occurs.

We aim to apply the same reasoning for an ensemble of competing electricity generating technologies. The variable in use in this case is the share of the market, defined by the share of electrical capacity

$$S_i(t) = \frac{U_i(t)}{U_{tot}(t)}.$$

In the construction of a set of differential equations which describes the replacement of units of a technology by another, the substitution parameters must be determined, and their definition is critical for defining the properties of the system.

2.2 The shares equation

The substitution parameters may be defined based on probabilistic arguments. We may determine what is the probability that a technology, denoted i, possesses a lower energy production cost than another, denoted j. From the observation of recent occurrences of construction of electricity generation units, statistics can be performed in order to determine probability distributions for the cost of various systems. In a recent survey done by the IEA on recent energy capacity constructions (IEA, 2010a), upon which much

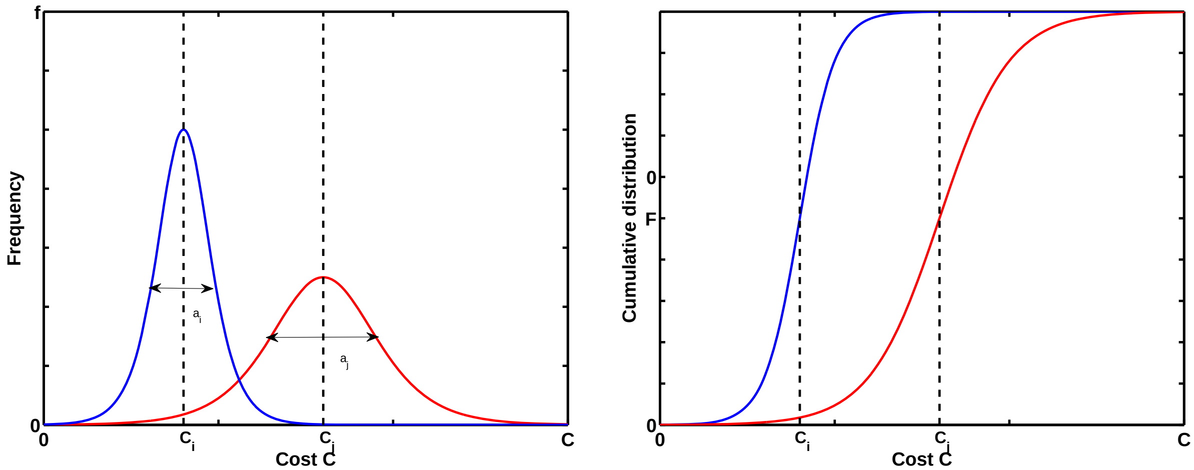

Figure 1: *Left* Distribution of costs for two different energy technologies, denoted i and j. These have median costs C_i,C_j and widths a_i,a_j. *Right* Cumulative cost distributions. These correspond to the fraction of potential units with cost below threshold C.

of this work is based, one can observe that even for specific geographical locations, the costs are distributed over a certain range of values. This reflects that, on the ground, a large number of factors influence the final cost of producing electricity. Thus, for two technologies possessing each their respective cost distribution, even though one may be on average cheaper than the other, individual units of the more expensive option are likely to turn out cheaper than some units of the less expensive, possibly even cheaper than its *average* (or *median*)[2] cost.

This is depicted in figure 1. The normalised cost distribution of technology i is represented in blue in the left panel, with median cost value C_i, which we denote $f(C, C_i, \sigma_i)$, were σ_i corresponds to its standard deviation. Meanwhile, technology j is shown in red, with median C_j. It can be observed that a range of units of j are situated at cost values below the median of i, reflecting factors on the ground which we are unable to specifically represent in a model that attempts to simplify the complexity of reality. Thus interpreting cost distributions as probabilities is a very useful tool for simplification. Note that such a framework can also be interpreted to represent investor behaviour which is not purely rational, but which is rational on *average*.

Associated with $f(C, C_i, \sigma_i)$ is a cumulative distribution $F(C, C_i, \sigma_i)$ that represents the probability that the technology comes out cheaper than the arbitrary cost value C. We thus frame the problem by asking the following question, based on cost distributions for technologies i and j: what is the probability that, when building a unit of i, the cost turns out cheaper than the median value of the cost of j? It is the cumulative distribution function $F(C_j, C_i, \sigma_i)$. Meanwhile, we may ask the converse question: what is the probability that j comes out cheaper than the median value of i, for which the answer

[2]For the case where the distribution is not symmetric.

is $F(C_i, C_j, \sigma_j)$. These two probabilities, quite unrelated in reality, depend solely on both distributions, and are both positive and non-zero. By centring these distributions at their median value, we observe that they can also be expressed as a function of the difference in cost ΔC_{ij}, and we thus denote these probabilities as $F_i(\Delta C_{ij})$ and $F_j(\Delta C_{ji})$, where $\Delta C_{ij} = C_j - C_i$.

Assuming rational investor behaviour on *average*, the probability of substitution between i and j is related to the probability of the first being cheaper than the second, and the reverse, but also to the rate at which one technology is able to replace the other in a competing market. We express the problem in terms of shares of the market S_i and S_j, where units of shares are exchanged between i and j. These exchanges occur in all directions for a variety of reasons on the ground, expressed by the probability distributions, but give rise to a general average trend which we can calculate. We thus define two distinct processes, one whereby shares of technology j flow towards technology i, and the second the reverse.

In the first case, the probability of one unit of S_j flowing towards i is proportional to the rate at which units of j are replaced, which occurs once every lifetime τ_j of each unit of j, the total being S_j/τ_j. However, this probability is also proportional to the rate at which units of i can be built, the total being S_i/t_i, t_i being the time of construction. We thus postulate the following principle: the number of shares of j flowing towards i is proportional to the following probability:

$$\Delta S_{j\rightarrow i} \propto \frac{S_i}{t_i}\frac{S_j}{\tau_j}F_i(\Delta C_{ij})\Delta t. \tag{4}$$

Similarly, even if technology i may be on average cheaper than j, there is probably still a number of units of j that will be built instead of i, giving rise to an independent flow of units from i towards j:

$$\Delta S_{i\rightarrow j} \propto \frac{S_j}{t_j}\frac{S_i}{\tau_i}F_j(-\Delta C_{ij})\Delta t.$$

We are interested in the general trend, which is given by the total flow $\Delta S_{j\rightarrow i} - \Delta S_{i\rightarrow j}$ and represent the exchanges, which may be positive or negative:

$$\Delta S_{ij} = S_i S_j \Big(A_{ij}F_i(\Delta C_{ij}) - A_{ji}F_j(-\Delta C_{ij})\Big)\Delta t,$$

where the lifetimes and construction times have been expressed as a matrix A_{ij}, which may be labelled the substitution frequency matrix. Finally, we observe that the change in S_i will be made of contributions from all other technologies, which may be added to yield the general shares equation

$$\Delta S_i = \sum_j S_i S_j \Big(A_{ij}F_i(\Delta C_{ij}) - A_{ji}F_j(-\Delta C_{ij})\Big)\Delta t. \tag{5}$$

Note that this equation respects the share conservation requirements that $\sum_{ij} \Delta S_{ij} = 0$ and $\sum_i S_i = 1$, provided by the symmetry of the expression.[3] This set of coupled

[3] This is verified by substituting i for j and obtaining the same form again.

dynamic logistic differential equations is the core of the energy technology substitution model developed in this work. As one expects for such a type of problems, it has no analytical solution, but it is straightforward to calculate numerically.

2.3 Properties of the shares equation

We show in this section how the shares equation previously defined behaves with various sets of parameters. We expect that shares of an expensive technology should decrease with time depending on the cost difference. Similarly, cheap technologies should expand. This is indeed what is observed, shown in the top left panel of fig. 2. Market domination was given to a technology which is 30% more expensive than the cheapest alternative. Two other technologies were defined with costs 10 % and 5% more expensive than the cheapest. The result is a gradual replacement of the marker technology, by all alternatives at first, however the market is eventually overtaken completely by the cheapest option. In a second example (top right panel), we have used the same parameters, but gave a head start to the second most expensive alternative. We observe that this option initially comes to dominate the market, due to its better ability to reproduce itself given its large initial share. In time, however, it is overtaken by the cheapest alternative. This thus captures the logistic behaviour we require, and indicates that, given a set of constant non-identical cost values, the system always converges towards the cheapest option.

We carry on further by analysing the behaviour of the shares equation when we change either the distribution variances or the substitution parameters. We once again gave 97% of the market to the marker technology, which this time is 30 % more expensive than all other alternatives, which have identical costs. In the first case, we used cost distributions of widths 2, 3 and 4 times larger than the marker for the alternatives. We observe that the system converges towards different stable shares for all the alternatives, which is higher the higher when the cost distribution is sharper. In the second case, we used substitution parameters of the alternatives relative to the maker which are 2, 3 and 4 times larger than they were originally. We observe again different stable shares for the alternatives, which are larger when the associated matrix element is larger.

2.4 Investment in new generation technology

The evolution of the shares through the shares equation corresponds to new investment in generation technology. Thus generation G_i, associated to capacity U_i, may be expressed as

$$G_i(t) = U_{tot}(t) S_i(t) CF_i(t), \tag{6}$$

such that when summed in order to obtain the demand $D(t)$, we have

$$D(t) = U_{tot}(t) \sum_i S_i(t) CF_i(t) = U_{tot}(t) \overline{CF}(t), \tag{7}$$

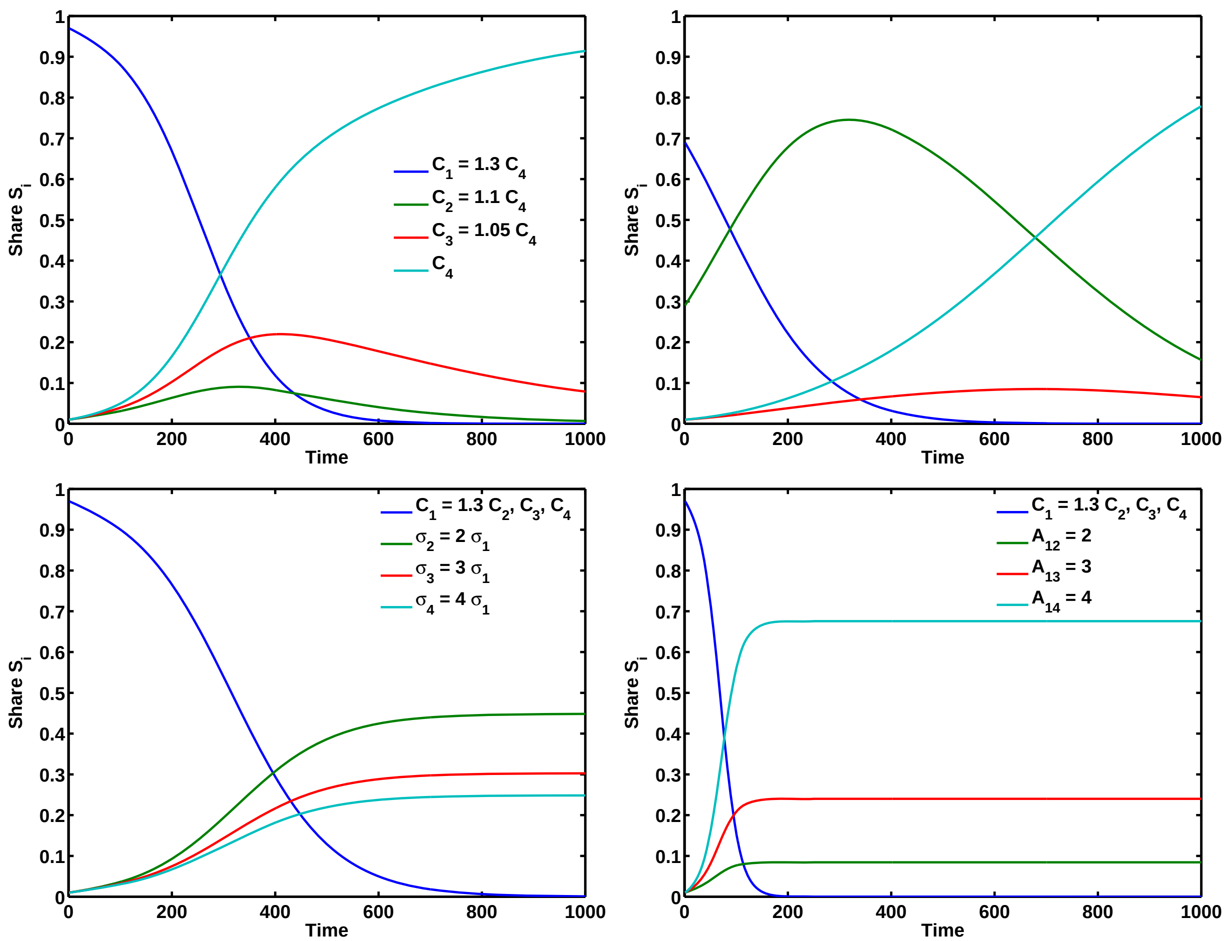

Figure 2: *Top Left* First example where a marker technology possesses 97% of the market, but is 30 % more expensive than the cheapest alternative, while the cost of the other two are 10 % and 5% more expensive. *Top Right* Same situation, where a head start of 29 % of the market is given to the technology which is 10 % more expensive than the cheapest. *Bot. Left* Situation where a marker technology possesses 97% of the market and is 30 % more expensive than all other alternatives, which have different cost distributions. *Bot. Right* Same situation, however where different substitution parameters relative to the marker were used.

where $\overline{CF}$ is the capacity factor averaged over all type of systems. The capacity may be determined from S_i, CF_i and D using

$$U_i(t) = \frac{S_i(t)D(t)}{\overline{CF}(t)}. \tag{8}$$

Changes in capacity may be obtained by differentiating U_i:

$$\frac{dU_i(t)}{dt} = \frac{S_i(t)}{\overline{CF}(t)}\frac{dD(t)}{dt} + \frac{D(t)}{\overline{CF}(t)}\frac{dS_i(t)}{dt} - \frac{S_i(t)D(t)}{\overline{CF}(t)^2}\frac{d\overline{CF}(t)}{dt}, \tag{9}$$

which possesses three types of contributions: from changes in demand, shares or capacity factors. The changes in demand correspond mostly to demand growth, while changes in shares correspond to changes in the composition of the system. Finally, changes in capacity factors reflect the efficiency at which the whole system is used, where for instance in a static system, more capacity could be built to be used at lower capacity factors for a constant demand. The positive changes in capacity are associated with investment $I_i(t)$:

$$I_i(t) = \begin{cases} C_i(t)\left(\frac{dU_i(t)}{dt} + \delta_i U_i(t)\right), & \frac{dU_i(t)}{dt} > 0 \\ C_i(t)\delta_i U_i(t), & \frac{dU_i(t)}{dt} \leq 0 \end{cases}, \tag{10}$$

where δ_i is a rate of decommission, resulting in capacity to be replaced, and $C_i(t)$ is the investment cost of technology i.

One final variable should be defined here, the emissions of CO_2. Each technology is characterised by an emission factor α_i, which is zero in the case of non-fossil technologies. The emissions E_i are proportional to electricity generation:

$$E_i(t) = \alpha_i G_i(t). \tag{11}$$

Cumulative emissions can be obtained simply by integrating $E_i(t)$ from $t = 0$ up to an arbitrary time t', summed over all technologies:

$$E_{tot}(t) = \int_0^t \sum_i \alpha_i G_i(t')dt'. \tag{12}$$

2.5 Technological learning-by-doing

The repetitive production of identical goods is known to produce reductions in production costs. This stems from both improvements in production methods and the development and expansion of industries which lead to economies of scale. Wright (1936) noted that the production of an airplane frame was a decreasing function of the total number N of airframes of the same type previously produced, and that that function is proportional to $N^{-1/3}$. As discussed by Arrow (1962), the observation from which predictions can be made regarding the savings generated by technological improvements lies in a functional form

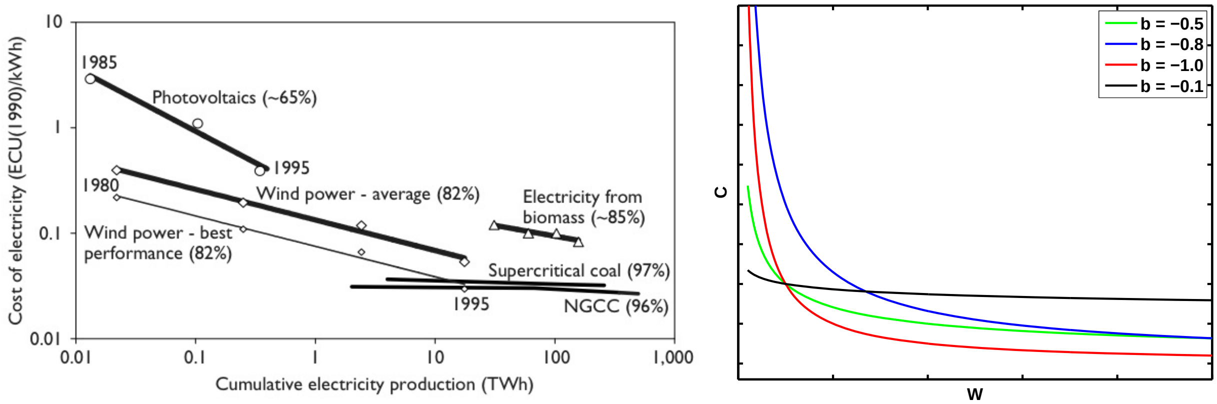

Figure 3: *Left* Technological learning curves for several electricity generation technologies, calculated by the IEA (IEA, 2000). Progress rates are given in brackets. The exponents b_i are related to the progress rates a_i through $b_i = \ln(1 - a_i)/\ln(2)$. *Right* Learning curves plotted on a linear scale for various exponents.

which has been empirically observed in many different types of goods sold on the market. This applies in particular to electricity production technologies, as shown in figure 3, right panel. The cost of units generally obeys a power law as a function of the total number of units sold since the first one was produced. In other words, these quantities appear as a linear relation on a log-log plot, and it is often obeyed over several orders of magnitude (McDonald and Schrattenholzer, 2001; IEA, 2000).

We express this phenomenon with the following equation,

$$C_i(t) = C_0(t)\left(\frac{W_i(t)}{W_0}\right)^{-b_i}, \tag{13}$$

where $W_i(t)$ is the cumulative investment, W_0 its value at the start of the simulation, and b_i the learning exponent, obtained from the slopes in fig. 3. The changes in cost associated with learning may be expressed as

$$\frac{dC_i(t)}{dt} = -b_i \frac{C_i(t)}{W_i(t)} \frac{dW_i(t)}{dt}. \tag{14}$$

We observe that two parameters control how learning proceeds, the initial value of cumulative investment and the exponent.

Learning-by-doing gives rise to a highly non-linear behaviour and path dependence for any type of simulation. This is due to the fact that, as observed in the real world, investment in a technology generates reductions of its own cost, which in turn stimulates sales and more investment. Once a technology begins a descent along the learning curve, it is likely to continue, while it often requires a push at the start, which may be done using subsidies to overcome large initial costs, or the so-called 'valley of death' (Murphy and Edwards, 2003). This can lead to avalanche effects which would not have happened if the technology had not succeeded in crossing this 'valley of death'. This is the motivation underlying subsidies given to new expensive technologies, some of which have the potential to replace components currently in place.

Technology categories for learning and those represented in a model may not necessarily coincide, and thus a certain amount of mixing, or knowledge *spillover*, may have to be included. In other words, particular sets of categories may be closely related technologically and a learning spillover matrix B_{ij} should be defined in order to calculate W_i from incremental positive capacity additions:

$$W_i(t) = \sum_j B_{ij} \begin{cases} \int_0^t \left(\frac{dU_j(\tau)}{d\tau} + \delta_j U_j(\tau) \right) d\tau, & \frac{dU_j(\tau)}{d\tau} > 0 \\ \int_0^t \delta_j U_j(\tau) d\tau, & \frac{dU_j(\tau)}{d\tau} \leq 0 \end{cases}, \tag{15}$$

therefore insuring that knowledge is shared between related technologies [4]. There exists an extensive literature on learning and progress rates for all sorts of goods beyond the electricity sector (For instance Koehler et al. (2006); Pan and Koehler (2007); Grubler et al. (1999)). Within the power sector, learning rates have been compiled by both the IEA (2000) and McDonald and Schrattenholzer (2001).

2.6 The levelised cost of electricity

The way investors take decisions regarding which energy technology in which to invest is not a simple matter. An evaluation of the unit cost of electricity must be made, which involves combining several types of costs spread over the lifetime of the generating capacity. This is generally done using the framework of the levelised cost of electricity (LCOE), which involves equating the result of two net present value calculations. The first of these is the net present value of all the costs during the lifetime of the power plant,

$$NPV_C = \sum_{t=0}^{\tau_i} \frac{I_i(t) + OM_i(t) + F_i(t) + C_i^{CO_2}(t)}{(1+r)^t},$$

where I_i is the overnight investment cost, OM_i is the operation and maintenance cost, F_i is the fuel cost, $C_i^{CO_2}$ is the carbon cost in the case of a trading scheme being in place and r is the discount rate. The power plant expects to generate income over its lifetime by selling the electricity. The total amount of earnings can be discounted to the present:

$$NPV_I = \sum_{t=0}^{\tau_i} \frac{E_i P_E}{(1+r)^t},$$

where E_i is the electricity sold and P_E its price, which, for the sake of this calculation, are assumed constant in time. If we equate these two equations in order to find the minimum

[4] Technologies with knowledge spillover include for instance coal and biomass gasification, offshore and onshore wind, combined cycle gas turbines (CCGT) and integrated gasification combined cycle (IGCC). These connexions can arise for instance through the use of similar mechanical parts that involve similar production methods, susceptible to economies of scale.

price at which the electricity should be sold in order to just break even in terms of cost and revenue, we obtain the equation for the LCOE:

$$LCOE_i(t) = \frac{\sum_{t=0}^{\tau_i} \frac{I_i(t)+OM_i(t)+F_i(t)+C_i^{CO_2}(t)}{(1+r)^t}}{\sum_{t=0}^{\tau_i} \frac{CF_i(t)}{(1+r)^t}}. \tag{16}$$

Note that if the costs in the numerator are expressed per unit of energy, the energy term in the denominator becomes the capacity factor CF_i. This capacity factor is that which is expected for the new generation capacity considered.

Investors use the LCOE in order to inform their investment decisions, by projecting all cost values over the lifetime of the power plant, and choosing a discount rate according to their prediction of future profits likely to be generated by their company. Thus the value of the LCOE strongly depends on the assumptions made by the investors and their view of what the future might hold. The use of the LCOE is appropriate in a simulation of the energy sector because it imitates the behaviour we expect of investors. Similarly, appropriate projections of the future are required to be made by the simulation at every step, without referring to the actual value of the exogenous variables in the future. This may generate decision errors, just like investors are prone to in a highly uncertain world. Thus in this work we use the LCOE as a way to compare different energy technologies by using this value within the shares equation.

Of particular interest here is the carbon component of the LCOE, denoted here $C_i^{CO_2}$. It is related to the CO_2 emission rates α_i. Since these costs are in dollars per unit energy, and the emissions E_i as given by eq. 11 are proportional to the electricity G_i, the factor G_i cancels out and the cost is simply the price of carbon $P^{CO_2}(t)$ (in \$/t CO_2) times α_i (in t CO_2/GWh),

$$C_i^{CO_2}(t) = \alpha_i P^{CO_2}(t). \tag{17}$$

2.7 Discussion

The shares equation, as defined in this section, always produces as a result one candidate dominating the market, given enough time, and it is that which possesses the lowest levelised cost. In a world where all options of the market are exactly equivalent, this should always be true. However, we observe that the energy sector is not dominated by a single electricity production technology, and may ask why this is the case.

Firstly, electricity originates from the transformation of matter from high to low energy states. It completely depends on the availability of natural resources with high energy content, and this varies widely across the various regions of the world. Thus the electricity sector is dominated first and foremost by the local landscape of available natural resources. This is reflected by the fact that the LCOE is a quantity that varies across regions due to the inclusion of the cost of resources, if available at all. The cost of these resources moreover changes as they are exploited. We thus introduce in this work a simple method to include the resource landscape and use into the framework of the LCOE, in section 4.

Secondly, electricity production methods possess different technical characteristics which enable them to fulfil different tasks. The daily energy demand features a profile in time which varies rapidly. In order to keep the electricity grid balanced and functional, the demand must be met exactly by the supply at every instant. The demand is then divided amongst the various available technologies as a function of their own capacity to change the magnitude of their electricity output. There is only a small subset of these which is able to provide the requested flexibility, a fact which is reflected by a higher electricity price where the demanded quantity varies the most, at peak demand times. Thus the demand is distributed according to the cost of production, by increasing order, using the expensive options as a last resort, where flexibility is rewarded by a higher price of electricity. This system is called the merit order (see, for instance, IEA (2010a)).

In this work, we have tried to avoid constructing a simulation of the merit order, as this can become extremely complex, and not necessarily very useful. Instead we defined a simple set of rules which govern which systems are used to cover the demand, and imitates the behaviour of the merit order. This leads us to more restrictions of the shares equation, producing a more realistic simulation. This is presented in section 3.

3 Technical constraints

3.1 Share value restrictions

We attempt in this section to replicate simply the operation of the power sector, often called the merit order, which decides which power plants cover which part of the demand. The merit order devises the optimal way to cover the demand by ranking in terms of cost all the capacity available (see for instance IEA (2010a)). It explains why some types of old power plants are sometimes kept for use during extreme demand peaks. Since the simulation of the merit order involves calculating the price of electricity at every instant of the day, which depends on the magnitude and changes in demand as well as on the availability of capacity and flexibility in the electricity system, it may become much too complicated for our purpose, without much benefit. We thus replace the merit order calculation by a simple rule, which possesses slightly different properties, but provides us with a major simplification.

The daily demand for electricity is characterised by strong variations, the amplitude of which can be of the order of one third of the average demand. Thus approximately one third of the capacity may have to be switched on or off on demand. Meanwhile, some energy technologies, such as nuclear or coal power stations, do not work efficiently or at all when used in that particular way. Additionally to that, some types of renewable sources, such as wind and solar energy, produce an uneven output which cannot be controlled since it depends on natural variations of the resource, but the grid generally guarantees to buy their full output, and therefore have an inflexible uneven power production. Matching a specific demand profile with the inflexible part of the supply requires a certain amount of capacity of flexible systems, such as gas turbines or diesel generators, which can vary their output from zero to their full capacity within time scales of hours or minutes. However, energy storage systems exist, which help smooth out demand and generation variations, and can be substituted to flexible generation capacity. It must be noted however that it does not produce 'new energy', but displaces energy generation from one time of day to another with an efficiency loss. Given enough storage capacity and generation, none of these problems would arise, however the amount of storage required would be very large.

We define the total shares of capacity of three types of energy systems:

$$\begin{aligned}
&S_{Base} = S_{Nuclear} + S_{Coal} + ...\\
&S_{Var} = S_{Wind} + S_{Solar} + S_{Marine} + ...\\
&S_{Flex} = S_{Gas} + S_{Oil} + S_{Hydro} + ...\\
&S_{Base} + S_{Var} + S_{Flex} = 1.
\end{aligned}$$

We define an average daily power demand curve $U_D(t_D)$, where t_D refers to the time of day, expressed in units of capacity, GW, illustrated in the left panel of figure 4. From this function, we define an average value for the daily energy demand,

$$\overline{D} = \int_0^{T_D} U_D(t_D) dt_D,$$

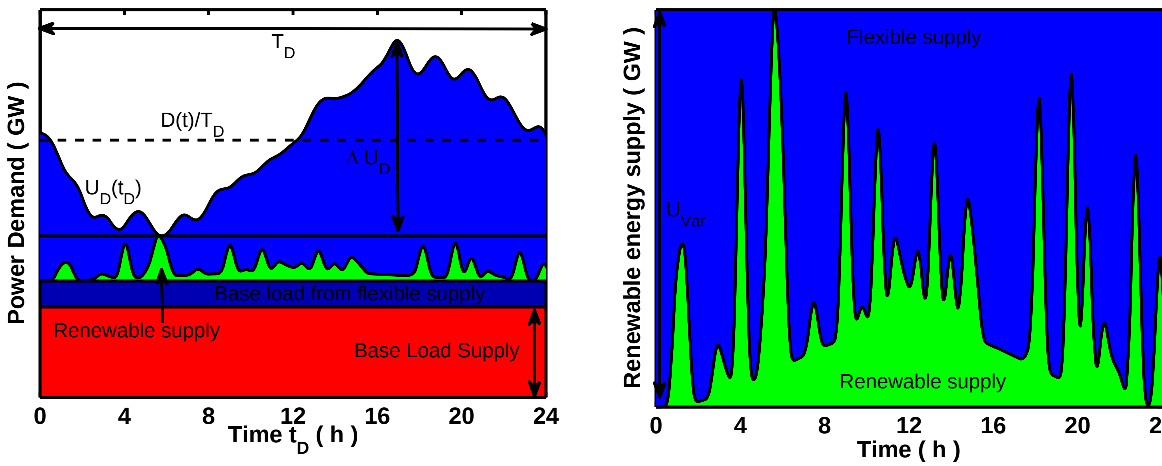

Figure 4: *Left* Sketch of a hypothetical profile of daily power demand as a function of the time of day $U_D(t_D)$, expressed in capacity units (GW), and how it might be met by various types of supply. The time integral of the demand function yield a daily energy demand, where energy quantities correspond to areas in the plot. The area within the red rectangle corresponds to the base load energy supply, while its height is the base load capacity times the capacity factor. The green area is the supply of variable renewable energy, while its maximum height corresponds to its total rated capacity. The blue area above the horizontal black line is the peak load energy supply, while the distance between the maximum value of $U_D(t_D)$ and its minimum is the peak load capacity ΔU_D. The area between the renewable energy supply and the horizontal black line is the amount of energy which must be supplied to cover for times when the renewable capacity does not produce energy. Thus, the light blue area is the minimum energy which must be produced by flexible sources of energy, since the required capacity varies between zero and $\Delta U_D + U_{Var}$ throughout the day, and thus cannot be supplied by base load systems. However, flexible sources may also act as base load sources, using their full capacity factors, represented by the dark blue rectangle. *Right* Zoom into the renewable energy supply, composed here of solar and wind energy.

We assume that this average corresponds to the yearly demand previously discussed, $D(t)$. We furthermore define a power demand variation, which is a daily periodic oscillation $\Delta U_D(t_D)$ equal to the distance between the maximum and the minimum of $U_D(t_D)$. ΔU_D is associated with the peak load energy demand, ΔD and is represented as the area between $U_D(t_D)$ and its minimum, shown with a horizontal black line.

Since we deal with extremes of power demand, we assume that $\Delta U_D(t_D)$ is the daily demand variation observed during the most demanding days of the year, where the largest variations of demand are observed. However, the average of $U_D(t_D)$ is assumed to correspond to $D(t)/T_D$. [5] This is done in order to simplify the number of parameters used to define the problem. Two independent parameters emerge, the ratio of peak to base power demand, $\Delta U_D/U_D$ and the ratio of peak to base energy demand, $\Delta D/D$. [6]

We then turn our attention to the uncontrollable generation coming from variable renewable sources, shown in both panels of fig. 1 as green areas. In order to put this energy generation to good use, two conditions must be met. Firstly, since there exists at every hour of the day the possibility that this energy generation is zero, an equal reserve capacity from a flexible or storage source must be kept,

$$U_{Flex} \geq U_{Var}.$$

Secondly, the amount of energy missing between the bursts of generation from the renewables must be produced by this flexible source. This corresponds to the blue shaded area of the right panel of figure 1.

Finally, the rest of the generating capacity is assumed to act as base load. This does not necessarily mean only base load type of capacity as defined by S_{Base}, since flexible type of capacity can also act as base load energy generation (for example, CCGT or hydro). Figure 1, left panel, shows the base load generation as two rectangles, the red one produced by U_{Base} and the dark blue one produced by a fraction of U_{Flex}. This is an important subtlety, since it allows the system to be run without any nuclear or coal capacity, or in other words, by having $U_{Base} = 0$.

We frame the complete problem in the following way. Two independent requirements have to be met, one for energy and one for capacity. Firstly, the peak energy demand plus the missing energy from renewables must be covered by the sum of flexible energy generation and energy storage, denoted E_s:

$$G_{Flex} + E_s \geq \Delta D + U_{Var}T_D - G_{Var}. \tag{18}$$

Secondly, the total capacity of flexible source plus storage generation capacity (U_s) must at least be able to cover for possible variations of power demand and renewable output:

$$U_{Flex} + U_s \geq \Delta U_D + U_{Var} \tag{19}$$

[5] Thus in the construction of $U_D(t_D)$, the variation is taken independently to its offset.

[6] These are related through the area under the curve of $U_D(t_D)$; however by defining these two parameters independently, we can avoid specifying this particular curve.

For simplicity, we assume that the amplitude of ΔU_D scales with the average of $U_D(t_D)$ and that ΔD is similarly proportional to $D(t)$. Thus the problem can be expressed in terms of the constant parameters $\Delta U_D/U_{tot}$ and $\Delta D/D$. These equations are then transformed into

$$S_{Flex}CF_{Flex} + S_{Var}CF_{Var} \geq \overline{CF}\left(\frac{\Delta D}{D} + \frac{U_{Var}T_D}{D} - \frac{E_s}{D}\right),$$

$$S_{Flex} - S_{Var} \geq \left(\frac{\Delta U_D}{U_{tot}} - \frac{U_s}{U_{tot}}\right). \tag{20}$$

Thus the shares equation must be forced to meet these restrictions. In the next section, we devise a way with which the share values in the shares equation may be restricted to maximum or minimum values. These share limits can then be connected together using the pair of inequalities derived here.

3.2 Limiting the shares equation

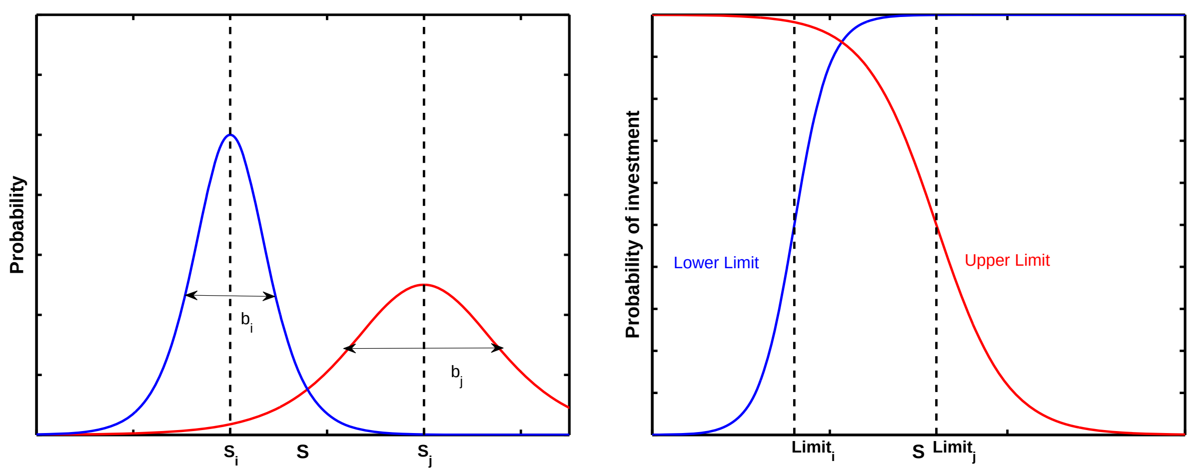

Figure 5: *Left* Sketch of probability distributions associated with the value of the shares. *Right* Cumulative probability distributions which correspond to the probability of share limits not being exceeded, which is equal to the probability of investing.

In this section, we devise a way to modify the shares equation in order to limit the share value of various technologies in order to respect the pair of inequalities 20. We thus want to impose both possible upper and lower limits to each technology. Where such a limit is exceeded, the electrical grid would become unstable, and thus present a risk to investors of either blackouts or or seeing their capacity unused. However, investors do not necessarily know accurately how much capacity is currently working, and thus may feel inclined to slow down investment even before the limit is reached.

This can be expressed simply by imposing a probability distribution to the actual value of the shares of various technologies as seen by investors, $g(S_i, \hat{S}_i, b_i)$, where $\hat{S}_i$ is the share limit and b_i is the width of the distribution. This is shown in the left panel of figure 5. Thus, given this uncertainty, the probability of investing should be equal to the probability of not having passed the limit, which is

$$\begin{aligned} G_i^{max}(S_i, \hat{S}_i) &= \int_0^1 1 - g_i(S_i, \hat{S}_i) dS_i \quad \textit{Upper limit} \\ G_i^{min}(S_i, \hat{S}_i) &= \int_0^1 g_i(S_i, \hat{S}_i) dS_i \quad \textit{Lower limit}, \end{aligned}$$

as shown in the right panel of figure 5. Each technology may possess both limits for simplicity. Thus the number of shares flowing from technology j towards i, as given by equation 4, is modified:

$$\Delta S_{j\to i} \propto \frac{S_i}{t_i}\frac{S_j}{\tau_j} F_i(\Delta C_{ij}) G_i^{max} G_j^{min} \Delta t,$$

using G_i^{max} and G_j^{min} since i increases and j decreases during this process. The reverse process is similar but involves G_j^{max} and G_i^{min}. Consequently, the complete shares equation may be rewritten as the following:

$$\Delta S_i = \sum_j S_i S_j \bigg(A_{ij} F_i(\Delta C_{ij}) G_i^{max} G_j^{min} - A_{ji} F_j(-\Delta C_{ij}) G_j^{max} G_i^{min} \bigg) \Delta t. \qquad (21)$$

Note that this equation still respects the conditions $\sum_{ij} \Delta S_{ij} = 0$ and $\sum_i S_i = 1$. [7]

3.3 Properties of the limited shares equation

We carry on with a description of the numerical properties of the limited shares equation, in a similar spirit as in section 2.3. It is trivial to show numerically that equation 21 falls back onto eq. 5 when the shares are nowhere near the limits, which we do not demonstrate here. We show numerically here the effect on the shares of reaching fixed limit, in other words, which are not yet connected to one another.

Figure 6 presents two examples where the situation described in section 2.3 was used, shown in figure 2, left panel. We impose one technology as a marker with 97% of the market, but 30% more expensive than the cheapest alternative, while two other technologies are 10 and 5 % more expensive than the cheapest. We add two restrictions, where the cheapest technology is restricted to 20% of the market, and the second cheapest alternative is restricted to shares of 30%. We observe that these saturate when they reach their limit. This produces kinks into the curve of the share of the marker technology, at which it slows down its decline. The market is eventually overtaken by the second most expensive technology, since it is not limited, while the marker is phased out. Note that given the way the shares equation was built, the shares saturate at a value slightly lower than the limit. This can be controlled by the choice of the distribution function $g(S_i, \hat{S}_i, b_i)$.

[7]The symmetry of the shares equation is maintained.

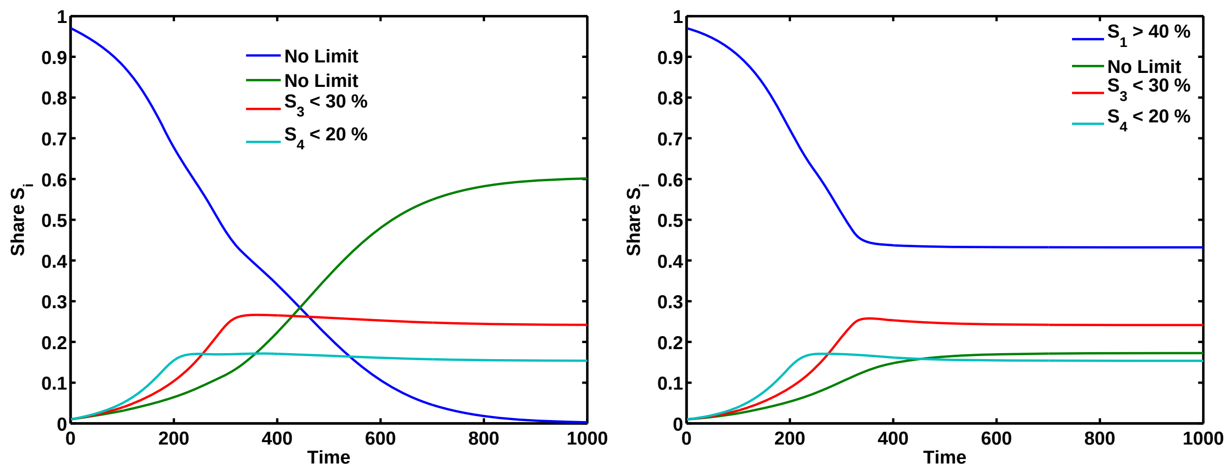

Figure 6: *Left* Numerical example where two technologies possess an upper limit to their shares of 20 and 30 % for the light blue and red curves. *Right* Similar example, with an additional lower limit to the marker technology, in dark blue.

In a second example, shown in the right panel of fig 6, we added one more restriction, which requires the marker to stay above 40%. We then observe that as the marker reaches its lower limit, all four technologies become stable, since all degrees of freedom were taken away.

3.4 Connecting the share limits to one another

The previous two sections allow us to connect the share limits to the values of the actual shares. Both inequalities 20 dictates regions where shares may be allowed to exist, as expressed by a greater or equal symbol ($\geq$). Thus the system may not always be on the limit, and it is possible to encounter situations where ineq. 20 are respected without invoking the probabilities of investing $G_i^{max}(S_i, \hat{S}_i)$ and $G_i^{min}(S_i, \hat{S}_i)$. However, when on the limit, inequ. 20 become equations and investment decisions become limited in some way. In such a situation, the shares of flexible sources become dependent on the shares of variable capacity, demand and storage.

In the general case, the limit of each technology must be calculated from the shares of all other technologies. This is done as follows:

$$\hat{S}_i = \pm\left[\left(\frac{\Delta U_D}{U_{tot}} - \frac{U_s}{U_{tot}}\right) + S_{Var} - S_{Flex}\right] + S_i, \qquad (22)$$

where the sign of the first term is positive if i refers to flexible output and negative if i refers to a variable renewable source. For example, it can be used to find the upper limit for the share of wind power given the current amount of gas, hydro and storage:

$$\hat{S}_{Wind} = S_{Gas} + S_{Hydro} + S_{Oil} + ... - \overline{CF}\left(\frac{\Delta U_D}{D} - \frac{U_s}{D}\right) - S_{Solar} - S_{Marine} - ...$$

Similarly, the minimum share of gas may be obtained from the shares of wind, solar, marine, hydro and oil energy as follows:

$$\hat{S}_{Gas} = S_{Wind} + S_{Solar} + S_{Marine} + ... + \overline{CF}\left(\frac{\Delta U_D}{D} - \frac{U_s}{D}\right) - S_{Hydro} - S_{Oil} - ...$$

Thus the limits to all energy sources must be determined in turn in this way. This is true for all except base load technologies, which simply take up the rest of the demand not covered by flexible of variable renewable sources through the normal shares equation, the sum of which must equal one.

3.5 Evolution of the capacity factors due to restrictions

One last issue was not yet discussed in relation to the limitation of the shares, which regards the evolution in time of the capacity factors when the system is limited. All flexible capacity which is not used for base load generation sees its capacity factor decrease below the maximum rated. This is simply another way of expressing the fact that when flexible systems follow the demand curve or cover for variable renewables, they are only used for a fraction of the time. This occurs only for flexible systems, since in general grids guarantee to buy the full amounts of energy produced by variable renewable energy sources, and base load systems always run on their rated capacity factors by definition.

This change in capacity factors for flexible sources makes the system more complex than might have been anticipated until now. It is however an important effect which must be taken into account. It becomes topical for instance if the amount of wind power increases significantly in a power system. We should thus observe that a lot of gas turbines are used for a fraction of the time to run when the wind does not blow, and not if it does so. This in turn would decrease their profitability enormously if it was not compensated by a higher price of electricity during peak time. However we have until now made good efforts to avoid the full modelling of the merit order. Thus we are required to find a simple solution to this problem.

We first assume that the changes in capacity factors do not influence the decision-making which is reproduced by the shares equation using the levelised cost of electricity. The LCOE is calculated using rated capacity factor values, as if the flexible capacity was completely used for base load generation. This is done in order to avoid the simulation of the price in a merit order system, which depends on demand and supply at every hour of a day. Secondly, we assume that the price during peak times is such that it compensates flexible system owners the same amount as if they had used these for base load generation, in other words the base load rate divided by the capacity factor. This is a reasonable assumption since it is consistent with the fact that the real decision making is always done without complete knowledge of the future capacity factor, and assumptions have to be made in any case. This also signifies that the cost of using more system flexibility is passed on to consumers, a fact which is most likely to be the case in general. We furthermore assume that the reduced time of operation is shared equally by all flexible generation sources available, which means that they must all have equal capacity factors.

Thus the capacity factor for flexible generation must be recalculated at each step of the simulation. It can be obtained from noting that the capacity factors do not change for variable or base load generation technologies. We divide the generation from flexible sources into two categories, one which generates electricity as if it was in the base load category, using the maximum rated capacity factors, and the other the fraction which is used to cover variations,

$$\begin{aligned} U_{Flex} &= U_{Flex}^{Base} + U_{Flex}^{Peak} \\ G_{Flex} &= G_{Flex}^{Base} + G_{Flex}^{Peak}. \end{aligned} \tag{23}$$

The capacity and generation which covers for variations are constrained as discussed previously in the inequalities 18 and 19,

$$\begin{aligned} G_{Flex}^{Peak} &= \Delta D + U_{Var} T_D - G_{Var} - E_s \\ U_{Flex}^{Peak} &= \Delta U_D + U_{Var} - U_s, \end{aligned} \tag{24}$$

where we are dealing with equations here, given this further subdivision of flexible sources. The capacity factors for the flexible capacity which operates as base load are known. Thus the flexible capacity may be expressed in terms of the generation by all other sources,

$$G_{Flex}^{Base} = D - G_{Base} - G_{Var} - G_{Flex}^{Peak}.$$

Replacing expression 23 for U_{Flex}, we obtain

$$U_{Flex} = \frac{D - G_{Base} - G_{Var} - G_{Flex}^{Peak}}{CF_{Flex}^{Base}} + U_{Flex}^{Peak}.$$

Replacing both expressions 24 leads to

$$\frac{S_{Flex} D}{\overline{CF}} = \frac{D - G_{Base} - \Delta D + E_s - U_{Var} T_D}{CF_{Flex}^{Base}} + \Delta U_D + U_{Var} - U_s$$

$$S_{Flex} = \overline{CF} \left(\frac{1 - S_{Base} \frac{CF_{Base}}{\overline{CF}} - \frac{\Delta D}{D} - \frac{U_{Var} T_D}{D} + \frac{E_s}{D}}{CF_{Flex}^{Base}} \right) + \frac{\Delta U_D}{U_{tot}} + S_{Var} - \frac{U_s}{U_{tot}},$$

where CF_{Base} and CF_{Flex}^{Base} are capacity averaged over those categories of systems,

$$CF_{Base} = \frac{\sum_{Base} S_i CF_i}{\sum_{Base} S_i}, \quad CF_{Flex}^{Base} = \frac{\sum_{Flex} S_i CF_i^{Rated}}{\sum_{Flex} S_i}.$$

Isolating $\overline{CF}$, we obtain:

$$\overline{CF} = CF_{Flex}^{Base} \left(\frac{S_{Flex} + S_{Base} \frac{CF_{Base}}{CF_{Flex}^{Base}} - S_{Var} - \frac{\Delta U_D}{U_{tot}} + \frac{U_s}{U_{tot}}}{1 - \frac{\Delta D}{D} - \frac{U_{Var} T_D}{D} + \frac{E_s}{D}} \right).$$

The average capacity corresponds to

$$\overline{CF} = S_{Flex}CF_{Flex} + S_{Base}CF_{Base} + S_{Var}CF_{Var},$$

and therefore the capacity factor for flexible sources can be isolated:

$$CF_{Flex} = \frac{1}{S_{Flex}}\left(\frac{S_{Flex} + S_{Base}\frac{CF_{Base}}{CF_{Flex}^{Base}} - S_{Var} - \frac{\Delta U_D}{U_{tot}} + \frac{U_s}{U_{tot}}}{1 - \frac{\Delta D}{D} - \frac{U_{Var}T_D}{D} + \frac{E_s}{D}} - S_{Base}CF_{Base} - S_{Var}CF_{Var}\right) \quad , \qquad (25)$$

where $\frac{\Delta D}{D}$, $\frac{E_s}{D}$, $\frac{\Delta U_D}{U_{tot}}$ and $\frac{U_s}{U_{tot}}$ are dimensionless numbers between 0 and 1.

This equation provides a connexion between the capacity factors and the shares, changing the capacity factors from independent to dependent variables. Therefore, this eliminates the third term of the differential of U_i, eq. 9. The real world allows in principle a less efficient energy sector where more units are used with even lower capacity factors. This solution however provides a very simple approximation of the full merit order, and therefore a much lighter load in terms of calculation power.

4 Natural resource use and depletion

4.1 Restricting the shares equation

This section addresses two issues related to the energy system. The first is to find out which types of energy systems might be found in which areas of the world. In particular, the model must take into account in some way which types of energy systems are unlikely to be found in some parts of the world, as for example hydroelectricity in North Africa or solar energy in northern countries such as Norway. This stems from the origin of the natural resource, and where it is distributed around the planet. The second issue is depletion of natural resources. All types of resources, even renewables, are exploitable only up to a certain economic potential, at which the use of an additional unit becomes uneconomical compared to alternatives. This section thus describes a methodology that enables the shares equation to take into account how natural resources might restrict the size of certain branches of the energy sector.

As described in section 2, choices made by investors may be modelled formally using a combination of the shares equation and the levelised cost of electricity. All issues which may influence the choice of investors which do not stem from technical constraints of the grid, as described in the previous section, should be represented within the equation for the LCOE. Resource availability influence the LCOE inasmuch as some of its internal cost components are affected by scarcity. This may appear simply in fuel costs for fuel based technologies, in particular fossil fuels, however, it may also appear in less obvious factors such as the capacity factor for some renewables, or investment costs for other capital intensive sectors such as hydro. We thus construct in this section a general framework that we can apply to all technologies, which enables the LCOE calculation to represent realistically which resource is available where, how it may evolve as these resources are exploited, and orient the behaviour of investors through the shares equation.

4.2 The cost-supply curve framework

The cost-supply curve framework has been used by various people in the past (Rogner, 1997; Hoogwijk et al., 2004, 2005, 2009; Hoogwijk, 2004; de Vries; Bert J. M. et al., 2001). It aims at representing the costs of extracting new units of natural resources as a functions of the number of units extracted in the past. Since this framework applies to both renewable and stock (exhaustible) resources, the units of the variables may change. Thus, potentials for renewables are expressed in units of $energy\ flows$, GWh/y, while the potentials for exhaustible resources correspond to finite amounts of $energy$, GWh.

It is widely debated currently when the world might run out of fossil fuels, but studies exist that evaluate approximately how much of these resources are left to use around the planet (UNDP, 2000a,b; Rogner, 1997; IEA, 2008, 2005). In contrast, renewables are often perceived as infinite sources of $energy$, since they are continually replenished, as for example by the sun. They are however limited in that the amount of capacity for their extraction that can be built is limited by space or by the number of productive sites

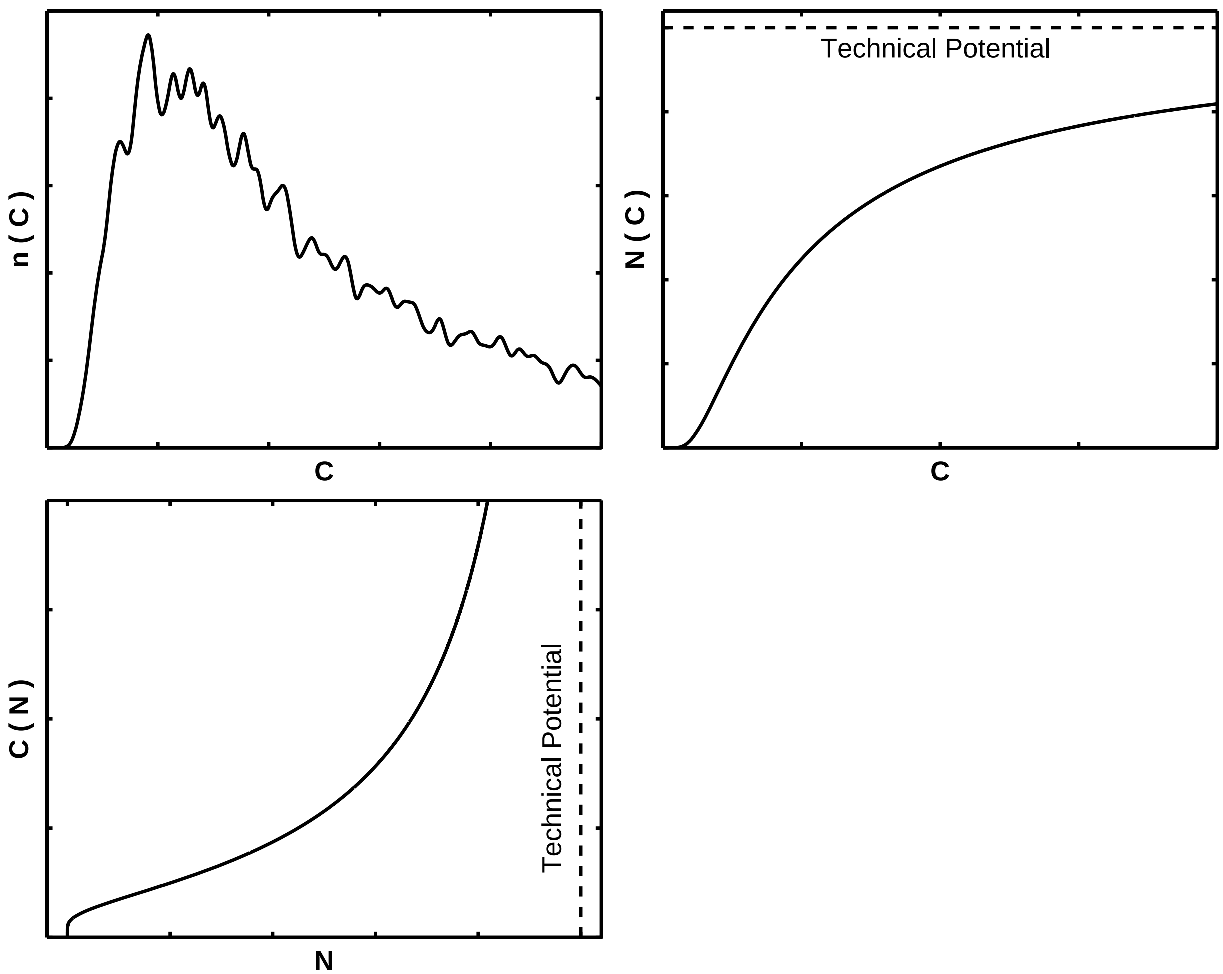

Figure 7: *Top Left* Histogram of energy or energy flow units as a function of cost of extraction. *Top Right* Cumulative distribution of energy or energy flow units as a function of cost of extraction. *Bottom Left* Cost of extraction as a function of all units that have been extracted in the past (energy units) or that are being extracted (energy flows), denoted the cost-supply curve.

that exist. There is a finite number of locations where, for instance, wind turbines, solar panels or hydroelectric dams can be constructed and produce energy profitably. These then produce a finite amount of energy per year, even though they may, with appropriate maintenance and repairs, produce energy for as long as nature provides wind, sunlight and rainfall. At the point where a large capacity has been built, additional units may start to require more funds than they are likely to generate, and thus alternatives will be sought.

We formalise this treatment by defining a distribution, or histogram, of energy (stock resource) or energy flow (renewable resource) available at a various costs of production, denoted $n_k(C)$, where k represents the kth type of resource. This function decreases towards zero at high and low values of C. This is depicted in figure 7, top left panel.

In order to find the number of units that may be extracted below an arbitrary cost C, the cumulative sum must be calculated up to C, which yields the cumulative distribution function $N_k(C)$, shown in the top right panel of figure 7. $N_k(C)$ converges at high values of C towards a constant, which is equal to the total area under $n_k(C)$, and corresponds to the total technical potential. From the point where this number of units has been extracted, it is clear that any additional unit must cost more than C. Thus the cost may be expressed as a function of the number of units of energy that have been extracted up to this point in time or of energy flows that are being extracted, $C = C_k(N)$, shown in the bottom left graph, where the axes have been simply exchanged for one another. The cost-supply curve $C_k(N)$ diverges at the total technical potential, expressing the fact that lower and lower density occurrences of resources lead to higher and higher extraction costs, as for example would happen with the installation of a diverging number of wind turbines on a large number of sites with vanishingly low average wind speeds, producing a finite amount of energy, but requiring an infinite amount of investment.

Finally, we note here that this model makes the explicit assumption of perfect ordering in natural resource use and depletion. This is clearly a broad simplification of reality, but provides an extremely simple framework based on a functional form, and can be used in multiple instances, for instance as required by a model such as E3MG that features 20 world regions, along with 9 types of natural resources of regional nature, plus 4 of global nature, totaling therefore 184 independent cost-supply curves. Energy extraction however does not occur in perfect order of cost, but operates over a certain cost range. This can be described by a framework involving a simple first order differential equation, the subject of possible future theoretical work.

4.3 Evolution of the LCOE with resource depletion

The cost of energy systems are affected in different ways depending on the type of natural resource that they involve. We define three classes of natural resources. The first concerns those which are transformed into fuels for electricity production in thermal power plants. This includes fossil, nuclear and biomass fuels, and the cost affected is the fuel term in the LCOE. The second class corresponds to types of renewable energy sources which are affected by the local quality of the resource, such as wind, solar and wave power. The variable affected in this case is the capacity factor, which influences the investment cost when it is normalised by energy production. The third class includes the remaining types of resources, for which the investment cost changes from site to site. We describe here in more details how these effects are formalised in this work.

In the first class of systems, the LCOE is influenced through the fuel cost term. The origin of the variation of these costs lies in the difficulty of extraction, and involves different types of fuel sources. In the calculation of the LCOE, fossil and nuclear fuel costs correspond to their international price, since these are traded in international markets. Thus, for a system involving several local energy systems, these fuels, as opposed to other types of energy, are considered international resource bases common to and used by every region. Their total potential corresponds to known reserves, and much uncertainty lies with how many new fields or deposits are likely to be discovered in the future.

Systems based on biomass energy behave differently. The origin of the increase of costs with production for biomass lies in the productivity of the land used, and the total potential depends directly on what other land uses might compete with energy production. The exception to this concerns biogas, which depends on waste flows. Not all types of biomass fuels, however, are likely to be traded in international markets. While ethanol and biodiesel may be shipped in the future between countries, solid biomass used in electricity generation, such as wood pellets, are likely to be used locally. Thus, these biomass resources are considered local in this work.

The second class of systems sees its LCOE influenced through capacity factors. These involve wind, solar and wave resource. They have in common that identical capital installations are used over a variety of sites which provide different amounts of energy flows. Thus the capital costs, when calculated per unit of energy produced, increase dramatically as the energy flow decreases. This is expressed by a decreasing capacity factor, which measures the fraction of the time for which the system produces energy at its rated capacity. Logically, the best sites in a locality are generally the first to be developed, and investors gradually work their way down the capacity factor curve. These resources are of course of a local nature, and thus different cost-supply curves may be defined for different regions of the world.

The third class of systems involves hydroelectricity and geothermal energy. These systems are evaluated case by case, since each site is different and involves a different cost of capital. Thus, the cost-supply curve is calculated from a survey of available sites. Potential large hydroelectric dams require the creation of water reservoirs, and the generation capacity depends on the elevation difference that can obtained on a site. Some sites are bound to cost more than others, and the investment cost for each site must be evaluated by engineers. Similarly, geothermal sites involve different underground temperatures, depths and types of rocks to bore through, and require individual studies.

4.4 Cost-supply curve data from the litterature

Cost-supply curves have been evaluated in the past by several people for several types of energy resources. Curves for the remaining fossil reserves were calculated by Rogner (1997) using histograms of known reserves and their cost of extraction, as they were known in 1997, the time of publication. This work is now outdated, but no update has been done to our knowledge.

Curves for wind, solar and biomass energy are more difficult to determine, since they involve knowing what other purposes the land may be used for in the future, and whether these are more profitable than energy production. This is of course particularly true for biomass energy, which is in direct competition with, among other things, food production. Projections of land use are moreover likely to depend strongly on assumptions, or in other words, on the future world scenario considered. Using the four general scenarios defined by the IPCC (IPCC, 2000), Hoogwijk *et al.* were able to evaluate the amount of land available for energy production with wind, solar and biomass systems, using the land use simulation model IMAGE (Hoogwijk et al., 2004, 2005, 2009; Hoogwijk, 2004; de Vries et al., 2006; Bouwman et al., 2006; de Vries; Bert J. M. et al., 2001).

For wind energy, using time series of measured wind speeds and typical power curves for wind turbines, wind energy potentials were evaluated at every onshore point of a grid of the planet (Hoogwijk et al., 2004).[8] Grouping grid points into world regions, histograms were constructed using various ranges of capacity factor values. The cost of wind energy depends mostly on the investment cost, which when normalised by energy production, increases as the capacity factor decreases. However, not only the number of good wind sites affects the cost-supply curve, but land suitability as well, a variable supplied by the land use simulation.

For solar energy, a similar calculation was performed by Hoogwijk (2004). In this case, it is the average solar irradiation which yields a capacity factor that varies across sites, but the land is affected by competing uses in a similar way as for wind. Solar irradiation is affected by average cloud coverage and latitude.

Biomass energy is a more complex system, and is described in Hoogwijk et al. (2005, 2009) and de Vries et al. (2006). Biomass energy potentials were determined both for liquid fuels for transport and for solid biomass for use in electricity production. The authors assumed that energy production does not compete with agriculture for food production; thus only land not already used for food production was considered. This supposes government intervention in land use management in order to keep a sufficient supply of food to support world population, an issue which currently generates much discussion and controversy. [9] Widely different cost curves were obtained for the four IPCC scenarios considered, where a factor of about two was predicted between the amounts of biomass available for electricity in a globalised world as opposed to a regionalised trade, as shown in figure 8. It is clear that these curves should change with time as the world evolves and competing uses of land and the climate change. Reproducing such a phenomenon would require us to run a land use simulation hard-linked with our macroeconomic simulation in order to allow feedbacks. Without a land use model of our own, we are reduced to using fixed results from IMAGE. Therefore, the appropriate cost-supply curves should be used along with corresponding assumptions made by the IMAGE team which are part of each IPCC scenario.

The cost calculations done by Rogner and Hoogwijk *et al.* provide values disaggregated for world regions. As a first approach, we have used these data to calibrate empirically

[8] Wind speeds follow a probability distribution of the Weibull type. For wind turbines of identical rated capacity, the integral of the product of this distribution with the turbine power curve as a function of wind speed determines the total amount of energy which is likely to be produced at each point of the grid. This, normalised by the rated capacity, determines the capacity factor, which generally ranges between 20 and 40 %. Wind data originates from the NASA (NOAA) and is publicly available, while wind turbine power curves can be obtained from individual manufacturers.

[9] This was done in order to avoid having to simulate food markets and competition with energy. Much uncertainty would be associated with food prices in such a system.

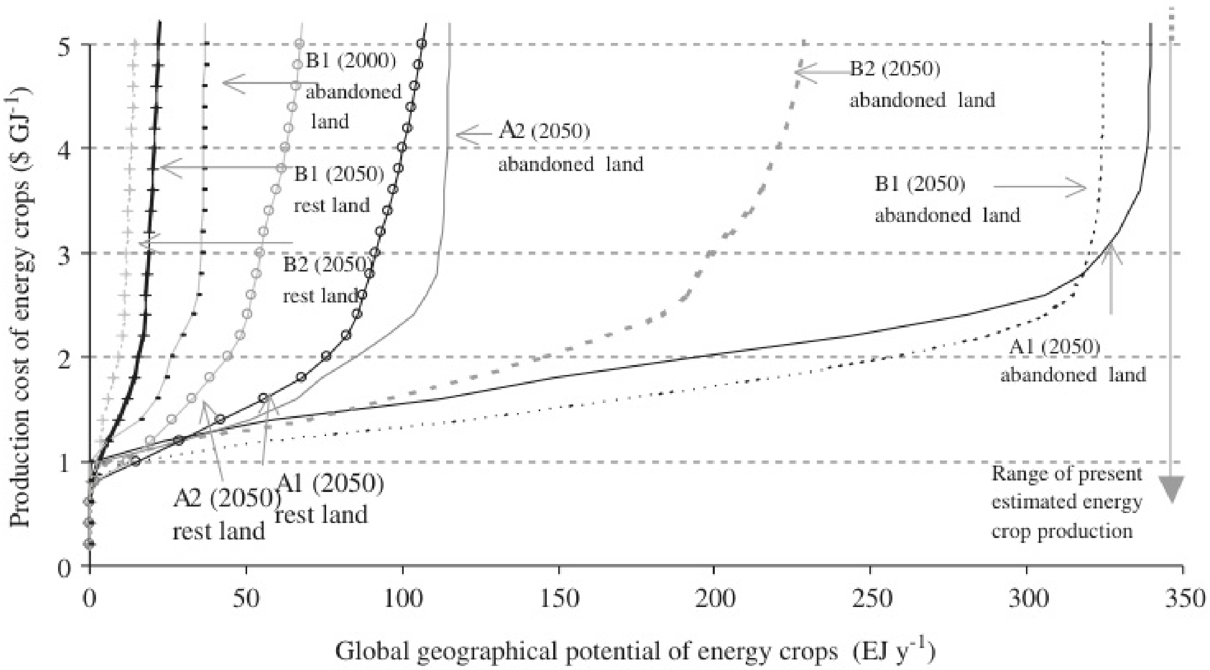

Figure 8: Global cost-supply calculated by Hoogwijk et al. (2009), for the four general IPCC scenarios A1, B1, A2 and B2, at various times in the future.

defined cost-supply functions, which we propose the analytical form below. Unfortunately, to our knowledge, cost-supply curves have not been calculated for the remaining types of energy systems. This is probably due to the fact that reliable cost values are difficult to obtain, as is the case for hydroelectric dams and geothermal plants, since each site involves detailed assessments by engineering firms. Approximate data is available, however, in a survey of global energy potentials provided in the World Energy Assessment (UNDP, 2000a,b) published by the United Nations Development Programme (UNDP). Values are provided for a number of world regions, which can be used to calibrate empirical functions. Finally, data for geothermal and biogas energy may be found in the works by Mock et al. (1997) and Themelis and Ulloa (2007).

For the initial version of the energy technology module produced as part of this work, we have devised a simple analytical function which may be fitted or parameterised using available data. We chose the following form for the histogram of energy units as a function of cost,

$$n(C) = \frac{AB}{C^2} e^{-\frac{B}{C-C_0}}, \tag{26}$$

which involves three independent parameters, A,B and C_0. This distribution has an associated cumulative distribution,

$$N(C) = A e^{-\frac{B}{C-C_0}}, \tag{27}$$

which can easily be inverted in order to obtain the cost-supply curve:

$$C(N) = \frac{B}{\ln\left(\frac{N}{A}\right)} + C_0. \tag{28}$$

The parameter A is the total technical energy potential at which the cost supply curve diverges. The parameter B scales the cost-supply curve, while C_0 corresponds to a cost offset. This function was chosen completely arbitrarily. It does, however, fit properly the cost-supply curves for wind power given by Hoogwijk et al. (2004). It gives a good first approximation for all cost-supply curves. However, it does not fit quite accurately the curves for solar or biomass energy. It does not represent perfectly the curves of Rogner for fossil fuels either, which indicates that a better methodology is required. In the ideal case, actual data should be used for all energy sources.

4.5 Evolution of capacity factors with resource use

Variable renewables, as described above, follow cost-supply curves through changes in their capacity factors as the best sites for energy production are gradually used up. For a number of sites already occupied by energy production capacity, newly built capacity is likely to possess lower capacity factors than all units previously built. The reduction in capacity factor results in higher investment cost per unit of energy, even though the investment factor per unit of capacity does not change. Thus, the value of the capacity factor for new units CF_i^{New} follow the inverse of a cost-supply curve. If the analytical form described in the previous section is used, eq. 28, it may be expressed as

$$CF_i^{New}(U_i) = \frac{1}{\frac{B}{\ln\left(\frac{U_i}{A}\right)} + C_0}.$$

The constant investment factor, when divided by this capacity factor, follows an ordinary cost-supply curve.

The change in capacity factor for new units results in all the units of a class of systems possessing different capacity factor values. In order to calculate the electricity generated by these, we are required to evaluate the average total capacity factor. If each new batch of units dU_i possesses the capacity factor $CF_i^{New}(U_i)$, the average capacity factor is

$$\begin{aligned} CF_i(U_i) &= \frac{1}{U_i}\int_0^{U_i(t)} CF_i^{New}(U_i) dU_i, \\ &= \frac{1}{U_i}\int_0^{U_i(t)} \left[\frac{B}{\ln\left(\frac{U_i}{A}\right)} + C_0\right]^{-1} dU_i, \end{aligned} \tag{29}$$

which does not have a simple analytical form, but can readily be included in the simulation as is.

4.6 Important aspects reproduced by the cost-supply framework

The cost-supply framework, as defined in this work, produces several very important effects which support the system as a whole and prevents it giving unreasonable results. The most obvious of these concerns hydroelectricity, shown for example, in figure 14 of the next section. As may be observed from the data in the WEA, the current world potential for hydroelectricity is not very large compared to other types of energy. However, from IEA's Projected Costs of Generating Electricity, the actual LCOE for hydroelectric dams which were recently built, especially those in China, are comparatively low. Thus, without information about the technical potential given by the cost-supply curve, the shares equation would naturally converge towards a world with a lot of hydroelectric dams. This result would be unreasonable, however, as there are not enough good sites for hydroelectric dams left around the world to meet global electricity demand. Thus, even though the current LCOE for hydroelectricity is low, it must increase steeply in the future as the last few good sites are developed. This is accurately represented by the current single region world model. It can be seen in figure 14 that hydroelectricity converges towards a constant capacity, and this occurs at the point where the LCOE reaches a value just above that of most competing technologies.

A second type of system that follows a similar behaviour is biogas. It appears reasonably cheap to construct that sort of capital at municipal waste sites. There is not, however, an enormous amount of methane produced by municipal waste compared to other biomass sources. These also converge towards a constant value when most of the biogas becomes used.

It is clear from these examples that cost-supply curves not only make the model more realistic, but are actually crucial for system stability. As with the real economy, if there was an infinite supply of a particular type of energy which was very cheap to produce, the global market would naturally converge towards complete domination by that particular energy source. Similarly in the model, if one type of energy is not limited by a cost-supply curve featuring a total technical potential, and is additionally characterised by a very low cost, the system must converge towards using only this particular technology. Therefore, cost-supply curves must be given for every natural resource.

5 Results under various scenarios

5.1 A few simple basic assumptions

We intend in this section to explore the behaviour of the model presented in this work under various sets of assumptions. The model, in this form, is complete and consistent, since its underlying set of equations produce self-consistent quantities and it is able to give reasonable approximate projections for the global energy sector. Results presented in this section are however based on a single world region, and the reason motivating this choice is to use the simplest assumptions possible. The aim is to explore the properties of the set of equations when used simultaneously, rather than to actually explore scenarios of the global electricity sector, which is left for subsequent work and will involve local energy landscapes for the 20 world regions featured in E3MG. Therefore, in this version of the model, some interactions occur which would not exist within smaller areas. It makes the explicit assumption that every type of resource is available everywhere and that a perfectly efficient international power market exists with a single electricity price and a single world energy demand curve. Using local cost-supply curves and demand functions changes the results, where for instance, in a disaggregated model, it inevitably leads to different electricity prices and therefore energy trade between energy rich and poor areas. Given these considerations, the results are nevertheless reasonable and highlight some important properties that emerge from the combinations of technological learning-by-doing and the dynamic set of coupled logistic differential equations that is the shares equation. From this we can subsequently explore the subject of logistic technological transitions and what we call the energy technology ladder. We believe these effects to be fundamental to the mechanics of the decarbonisation of the energy sector, and that this system of equations can furthermore be applied to explore technological transitions in other sectors of the economy such as transport.

The model presented here features 24 different electricity production technologies. The first eight are those using exhaustible fuels: nuclear, oil fired power plants, conventional coal, coal with carbon capture and storage (CCS), integrated gasification combined cycle (IGCC) coal fired power plants, IGCC with CCS, combined cycle gas turbines (CCGT) and CCGT with CCS. ICGG plants possess slightly higher efficiencies than conventional coal, due to their use of the combined cycle turbine technology originating from CCGT. Gas technologies generally possess much higher efficiencies than all coal technologies. We furthermore assume that CCS removes 90% of the CO_2 from the gas flue of all thermal power plant. The next six categories are those using two different types of biomass: the first using solid forms of biomass, with simple thermal power plants, biomass with CCS, biomass IGCC (BIGCC), BIGCC with CCS, and the second using landfill gas from municipal waste, labelled biogas and biogas with CCS. Next are featured renewables: small and large hydro, where the first uses small scale installations on rivers, are more expensive but respond to local needs, while the second involves large basins to be flooded and produce very large amounts of electricity. Onshore and offshore wind use similar technologies, however offshore is much more expensive due to the requirement of underwater foundations. Solar photovoltaic (PV) technologies involve semiconductor devices, while concentrated solar thermal (CSP) uses parabolic mirrors and ordinary steam turbines. Geothermal energy uses water heated underground with simple steam turbines, while wave technologies may involve various methods. Finally, two more hybrid categories are featured, fuel cells which use natural gas with extremely high efficiency, and combined heat and power (CHP), which consists of a CCGT plant of which the waste heat is used for industrial applications, which in turn reduce their electricity consumption, increasing the effective efficiency to very high values.

For the current model version, the various components of the LCOE were taken from the Projected Costs of Generating Electricity 2010 recently published by the IEA (IEA, 2010a). Statistics were performed over the various costs in order to obtain median values and associated standard deviations, which are required by the shares equation.[10] Investment, fuel and OM costs were derived from this source. Carbon costs, however, were not calculated in this way, however, since the intention is to use the price of carbon exogenously. In this model, the carbon price follows a simple constant rate of growth.

The second set of assumptions concerns the cost-supply curves. There is one single curve per type of energy, that is, nuclear fuel, coal, gas, oil, biomass, biogas, solar energy sites, onshore wind sites, offshore wind sites, geothermal sites, large hydro sites, small hydro sites and wave sites. For some of these categories, several technologies compete, for example several types of thermal power plants use coal, but coal is a single source. Similarly, all solid biomass technologies compete for land, while biogas does not since it originates from municipal waste. In such cases, a single cost-supply curve is used and produces a cost as a function of the total energy or energy flow produced by these competing technologies together. Competition occurs between all carbon capture and storage (CCS) technologies and their non-CCS counterparts. It occurs between coal fired power plants, gas fired technologies, solid biomass, solar energy for space. No competition is assumed between onshore and offshore wind or small and large hydro, since these categories arise from the differing nature of the sites while the technologies are similar.

The possible existence of costs for carbon emissions stem from the assumption of a worldwide agreement on emissions which would involve an emissions trading scheme based on the European model. It may appear unlikely that such an agreement would be made in any near future. It is however very important to represent such a system in this model for two reasons. The first is that it already exists in Europe, and this model is intended to be used as multiple instances in 20 world regions, hence a model for carbon costs must be included for at least some of the regions. Secondly, it is hoped that models such as E3MG may contribute in helping the international community understand of the usefulness and implications of applying a worldwide carbon trading scheme.

Respective carbon costs are calculated from CO_2 emissions rates of the various emitting

[10] Note that some of the values involve statistics performed on very few values, for example oil and biogas power plants. In some cases, no data was available and estimates were used, for example for biomass IGCC. This is unavoidable since this type of information is not easy to obtain. However, it is necessary to have a complete set of data, hence estimates are required in the worst cases.

technologies, taken from the IPCC guidelines (IPCC, 2006). In this version of the model, the price of emission allowances is set exogenously. Thus any profile of cost as a function of time may be used, however we included simply a constant rate of increase per year of the price. Thus emitting categories must add to their LCOE a carbon term which equals their emissions rate times the price of carbon. Technologies using CCS see their emissions reduced by 90%, and thus pay 10% of the carbon cost of their non-CCS counterpart.

This system gives rise to an important issue. The process of biomass fuel production removes carbon from the atmosphere, and electricity production from biomass fuels is carbon neutral since it simply re-releases this carbon back into the air. However, biomass technologies equipped with CCS remove CO_2 from the atmosphere without putting it back, and therefore possess negative emission rates. In an emissions trading scheme, these systems use a negative number of allowances, or in other words, they *create* new allowances which they can sell to other parties, generating additional income. As our results show, when the price for carbon is high, these technologies may earn very large profits. These technologies usually dominate when the price of carbon is high. Furthermore, increases in biomass fuel costs through the cost-supply curve from large scale use may be compensated by these earnings, resulting with these industries using very large amounts of land. This is an important phenomenon which requires further detailed explorations.

The substitution matrix A_{ij} is, as described earlier, derived from lifetimes and construction times for various technologies. Exceptions to this rule must exist, however, since in specific cases the change from one category to another does not require a complete replacement of capital. The best example of this is in the addition of CCS technology to existing power plants. Some power plants are currently built with the option of adding CCS in the future kept open. Thus the substitution frequency between a technology and its CCS counterpart are set at values higher than the normal value, evaluated from the estimated time of adding CCS to an existing plant. A similar situation arises for technologies which are similar whether based on fossil or biomass fuels, such as BIGCC. Switching fuel may require adjustments to an existing power plant, but is likely to be less demanding than building a whole new plant, and must be represented using a higher switching frequency. These exceptions allow very rapid technological transitions between specific categories.

Finally, as mentioned in section 2.5, a learning spillover matrix is included. This stems from similarities between various categories, which are divided along lines based on our research interests rather than technical differences. Thus, if learning occurs in, for instance, IGCC technology, learning must also occur in the category IGCC with CCS. Since IGCC with CCS is kept as a separate category, its cumulative learning is kept separate as well, which is not consistent with the real world. The real world is obviously not divided into well defined categories, and thus these independent variables are not so clearly defined either. Therefore, mixing must be allowed between categories, controlled by the B_{ij} spillover learning matrix.

The remaining data values assumed are obtained from the IEA and consist in starting values for the shares of total capacity (IEA, 2010b). Learning rates were obtained from various sources (IEA, 2000; McDonald and Schrattenholzer, 2001). Lifetimes and construction times are consistent with those in the Projected Costs of Generating Electricity.

As a summary, we enumerate here the various exogenous parameters which influence the results, in order of potential impact. The first is total demand $D(t)$, which may be chosen as any time dependent function. The current demand used is a handmade projection from 2008 up to 2100 based on an extrapolation of that given in the World Energy Outlook for the new policies scenario (IEA, 2010b). Next come the discount rate, the starting price of carbon and its rate of increase. Small changes in these parameters, for instance values between 5 and 10% for the discount rate and between 0 and 3% for the rate of increase of the price of carbon with starting value of 22\$/t CO_2, produce radically different energy landscapes. Thirdly, we have the demand profile parameters and those for energy storage, chosen arbitrarily as $dD/D = 15\%$, $E_s/D = 1\%$, $dU/U_{tot} = 30\%$ and $U_s/U_{tot} = 1\%$. These put more or less constraints onto the system, which generally results in more or less flexible type of generation technologies to be used, such as CCGT. No taxes or subsidies were used in these calculations other than the price of carbon, for simplicity. Since Solar and wind energy currently have higher costs than most other systems and are supported by governments through subsidies or feed-in tariffs, they do not appear in the calculations presented here.

5.2 Numerical results for various sets of assumptions

We first analyse the behaviour of the system using baseline parameters, which correspond to the 'business as usual' case with no mitigation effort, where no emissions trading scheme exist. The system is explored for two discount rates, 5%, shown in figure 9 (*top set*) and 10% (*bottom set*). These sets of graphs are organised with the shares S_i represented in the top left panel as coloured areas, the sum of which is unity, the corresponding electricity generation G_i and capacity U_i in the bottom panels left and right, respectively, and the LCOE in the top right panel. Shares are shown for all 24 categories, while electricity generation is shown for a smaller number of larger categories, which are simpler to interpret.

The first phenomenon to note is that large hydro quickly saturates in all cases to a constant just below 2 TW up to 2100. This is simply and only due to the small total technical potential for hydroelectricity, as given by the cost-supply curve. Upon closer analysis, we observe that the LCOE of large hydro rises as its capacity rises, until it is more expensive than most other technologies, where its capacity stops growing. It is the capacity which becomes constant, not the share or the associated electricity generation. The share is not constant since the total capacity keeps increasing to meet increasing demand, leaving the amount of hydro the same. Biogas is also seen to follow such a path, since its cost is low but its potential is very limited.

The second effect to observe is that for both discount rates, coal technologies dominate completely the electricity which is not produced by hydroelectric dams. Nuclear and oil power stations are gradually replaced by coal.

Given these results, carbon costs may be added in these two discount rate scenarios,

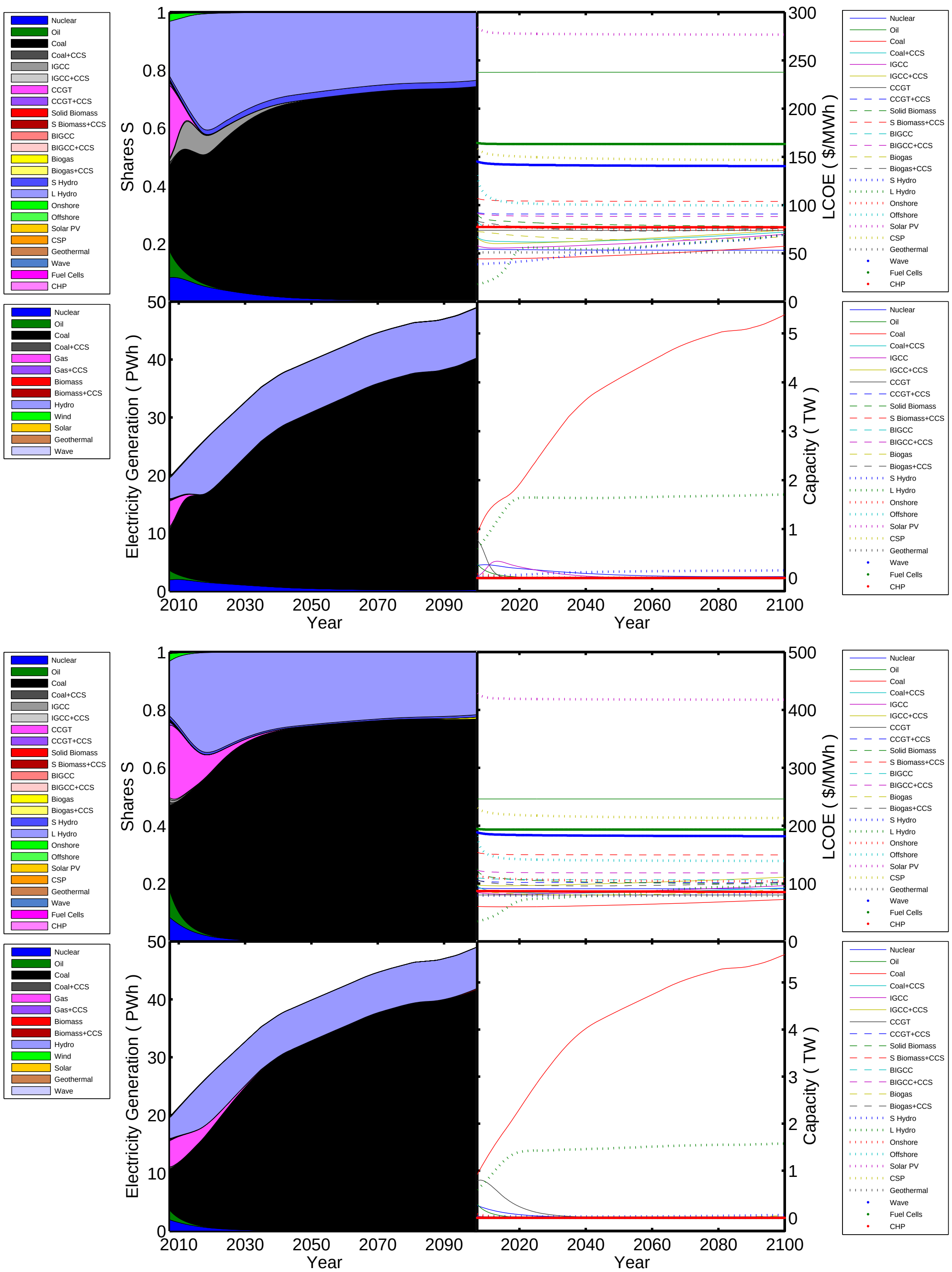

Figure 9: Baseline results where carbon is not priced, for discount rates of 5% (*top*) and 10%(*Bottom*).

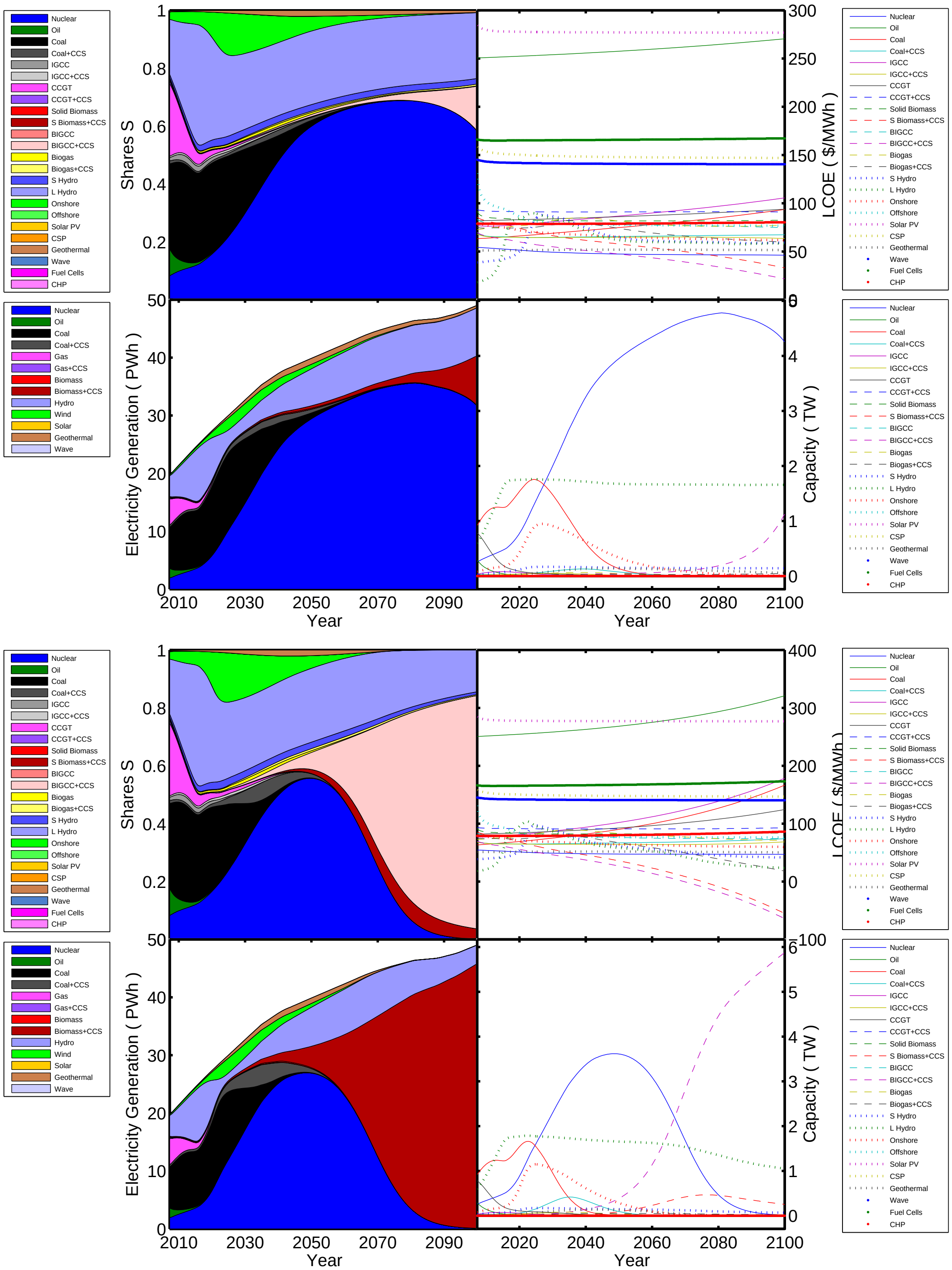

Figure 10: Carbon price increasing by 1%/y (*top*) and 2% per year (*bottom*) using a discount rate of 5%.

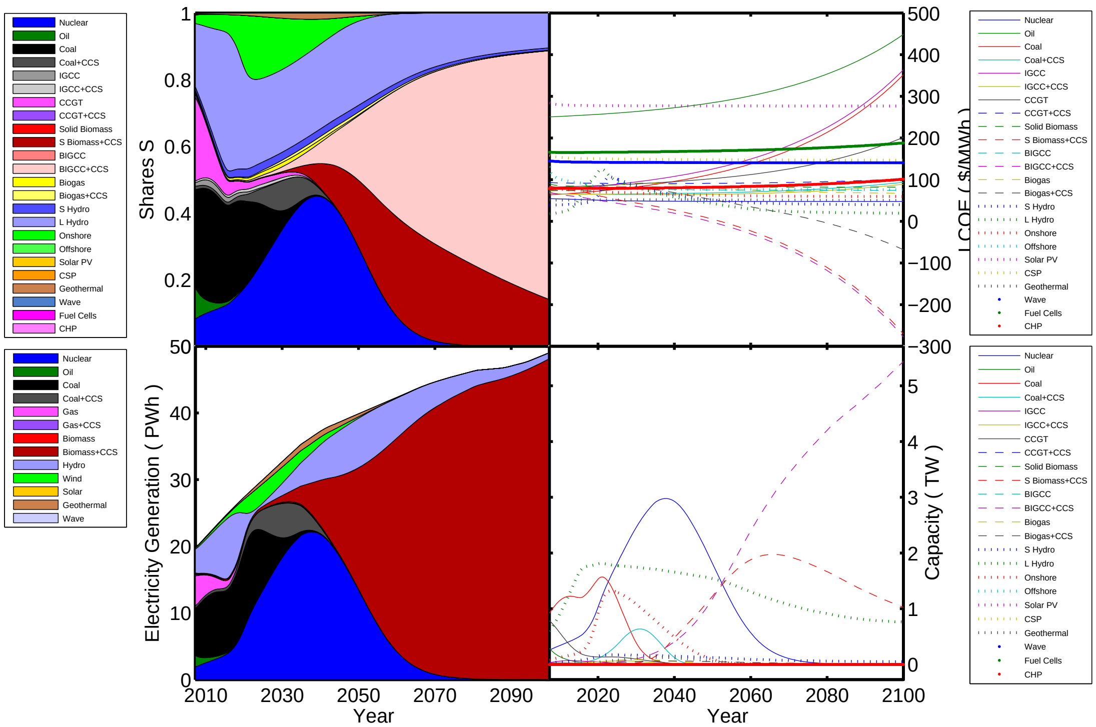

Figure 11: Carbon price increasing at a rate of 3%/y, and a discount rate of 5%.

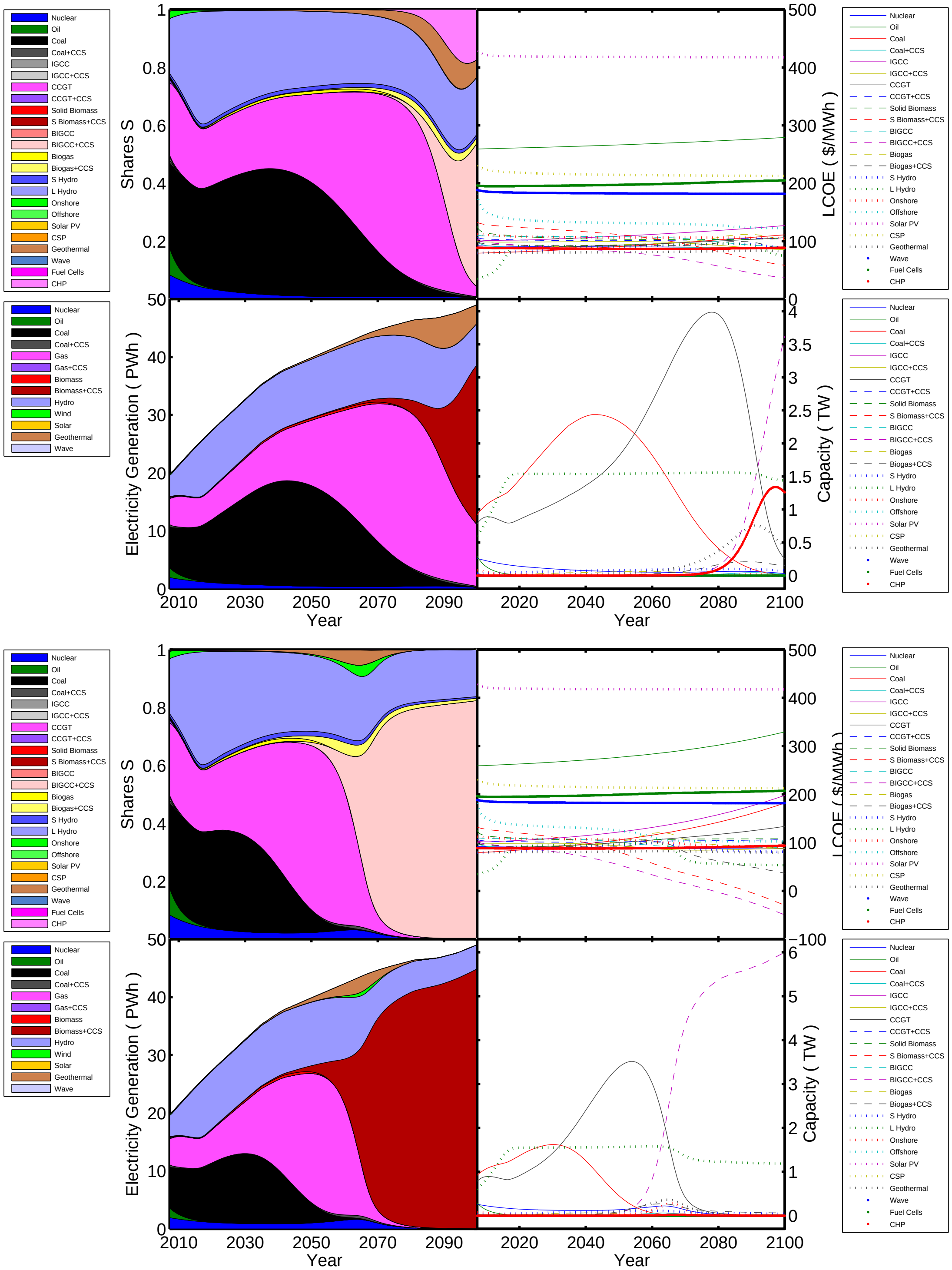

Figure 12: Carbon price increasing by 1%/y (*top*) and 2% per year (*bottom*) using a discount rate of 10%.

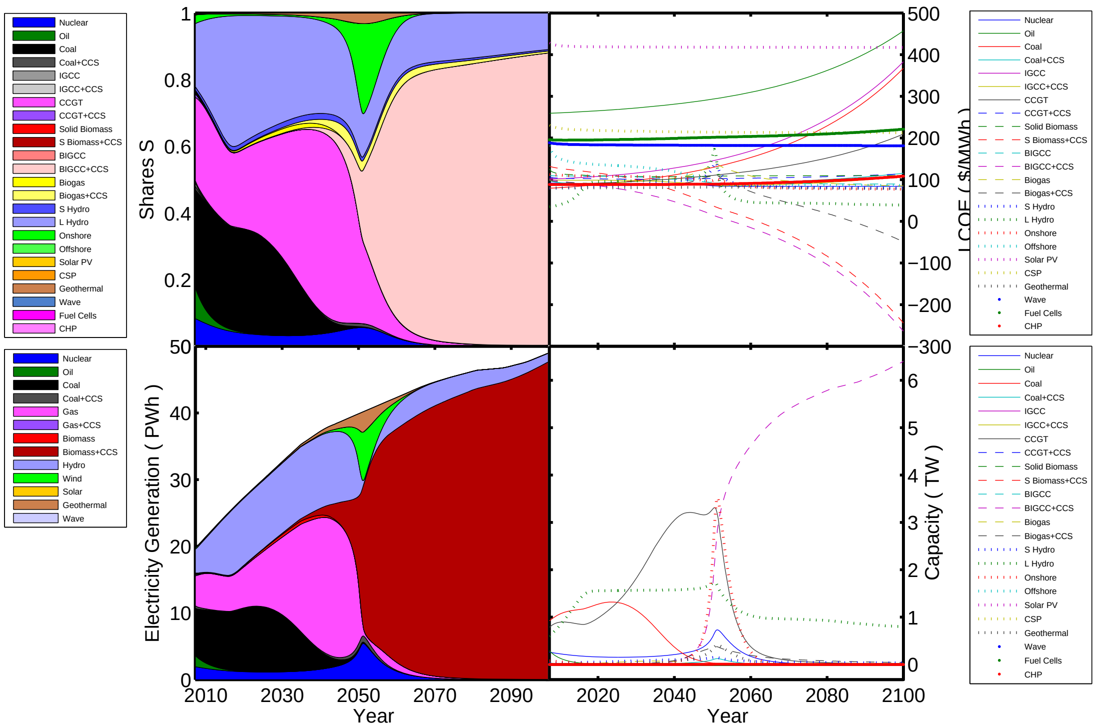

Figure 13: Carbon price increasing at a rate of 3%/y, and a discount rate of 10%.

and this generates very different results. Starting with $r = 5\%$, we use a starting price of carbon of about 22 \$/tCO_2, a value near the current price, along with three scenarios for its rate of increase, using 1, 2 and 3% per year, which results in 56, 142 and 360 \$/tCO_2 in year 2100. Three different energy landscapes are generated, all of which exhibit a particularly interesting phenomenon. We observe a gradual replacement of various types capacity as the cost of emitting CO_2 increases, each of which appears only temporarily. Heavy emitters are first replaced by light emitters, which are then replaced by zero or neutral emitters, which are in turn replaced by systems with negative emissions, and so on.

This can be clearly be seen in figures 10 (*top* and *bottom*) and 11, where the rate of increase of the price of carbon is, in order, 1,2 and 3%. In fig. 10 (*top*), one can see that from the baseline case, coal is replaced by nuclear. For 2% of increase, coal is quickly replaced by nuclear, which increases and then decreases, to be replaced by a new type of system, BIGCC with CCS. Note that BIGCC with CCS benefits from a negative carbon costs component of the LCOE which can become large.

In the case of 3% rate of increase, which produces a cost of more than 300\$/tCO_2 in 2100, even faster changes are observed, and may be interpreted as somewhat unrealistic. Coal is again rapidly replaced by nuclear, which is replaced again by BIGCC with CCS, with a short intermission of CCGT with CCS. Biogas with CCS is also strongly favoured, despite its limited potential. However, in 2100, almost everything, including nuclear, is replaced by BIGCC, which benefits from unrealistically large effective subsidies from the negative carbon costs. As stated earlier, such high negative carbon costs allows fuel costs to be very high without affecting the LCOE very much, and thus may lead the system to use up large amounts of land.

We turn our attention to a world with a discount rate of 10% and a carbon price increasing again by 1, 2 and 3% per year. The corresponding results are shown, in order, in fig. 12 and 13. For 1%, a similar result is obtained as with a discount rate of 5%, however nuclear is replaced by gas turbines. Thus coal is replaced by gas which is in turn replaced by BIGCC. This may be explained by the temporal distribution of costs in gas technologies compared to nuclear. The former defers large costs to the future since the initial investment costs are relatively low but the fuel costs are high. Therefore, it is favoured when a high discount rate is assumed, since it determines the preference of investors to hold money in the present rather than in the future. Gas replaces coal since its efficiency is much higher, and thus emits less CO_2 per unit of energy. Increasing the rate of the price of carbon here simply makes all this happen more quickly.

5.3 Results for all variables for one set of assumptions

We present in this section how all the variables of the simulation behave for one of the sets of assumptions presented in the previous section. The parameters used were a discount rate of 10% and a rate of increase of the price of carbon of 2%. This particular situation was chosen simply as an example, it does not have any more relevance than any other set of

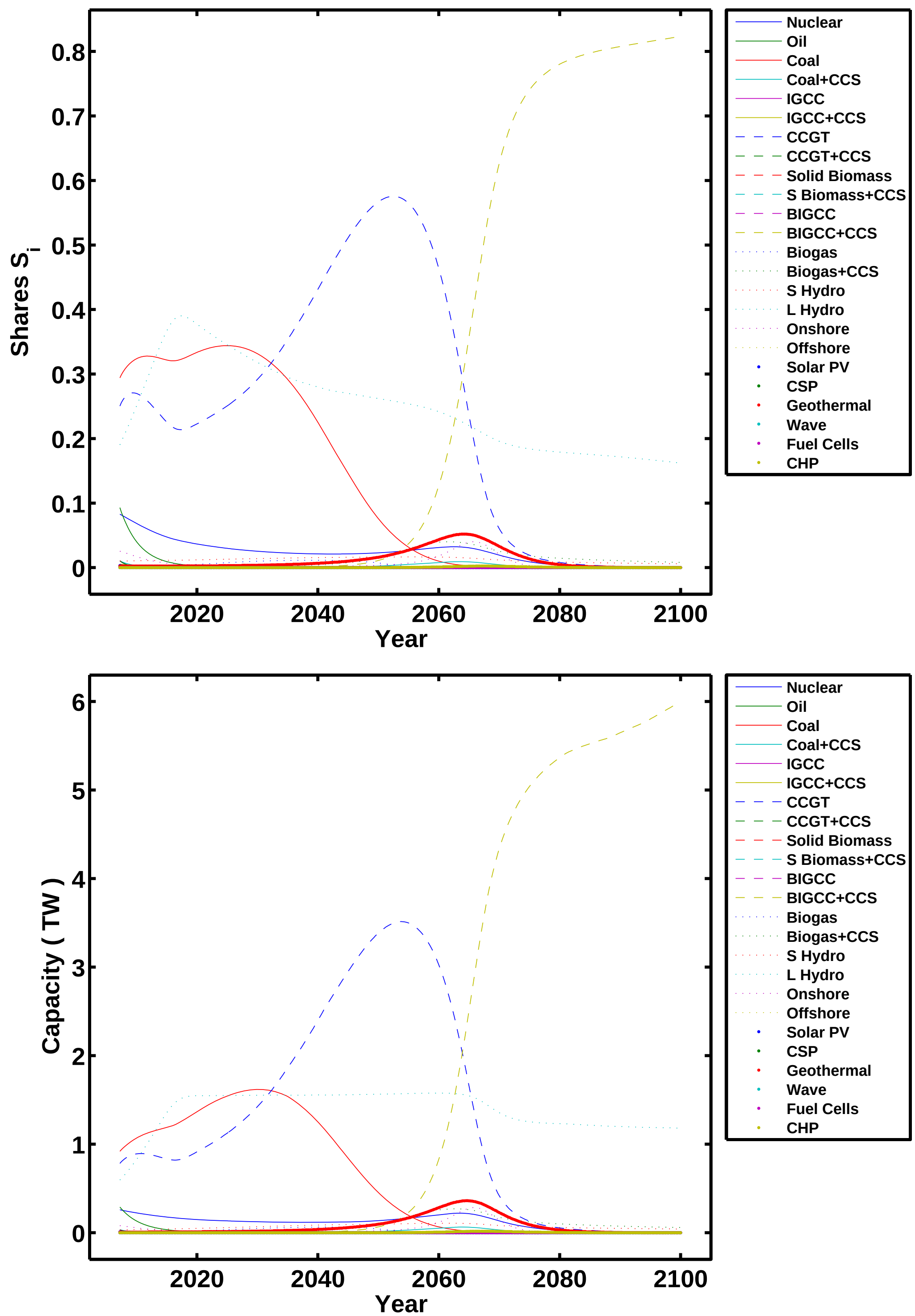

Figure 14: *Top* Shares of capacity. *Bottom* Generation capacities.

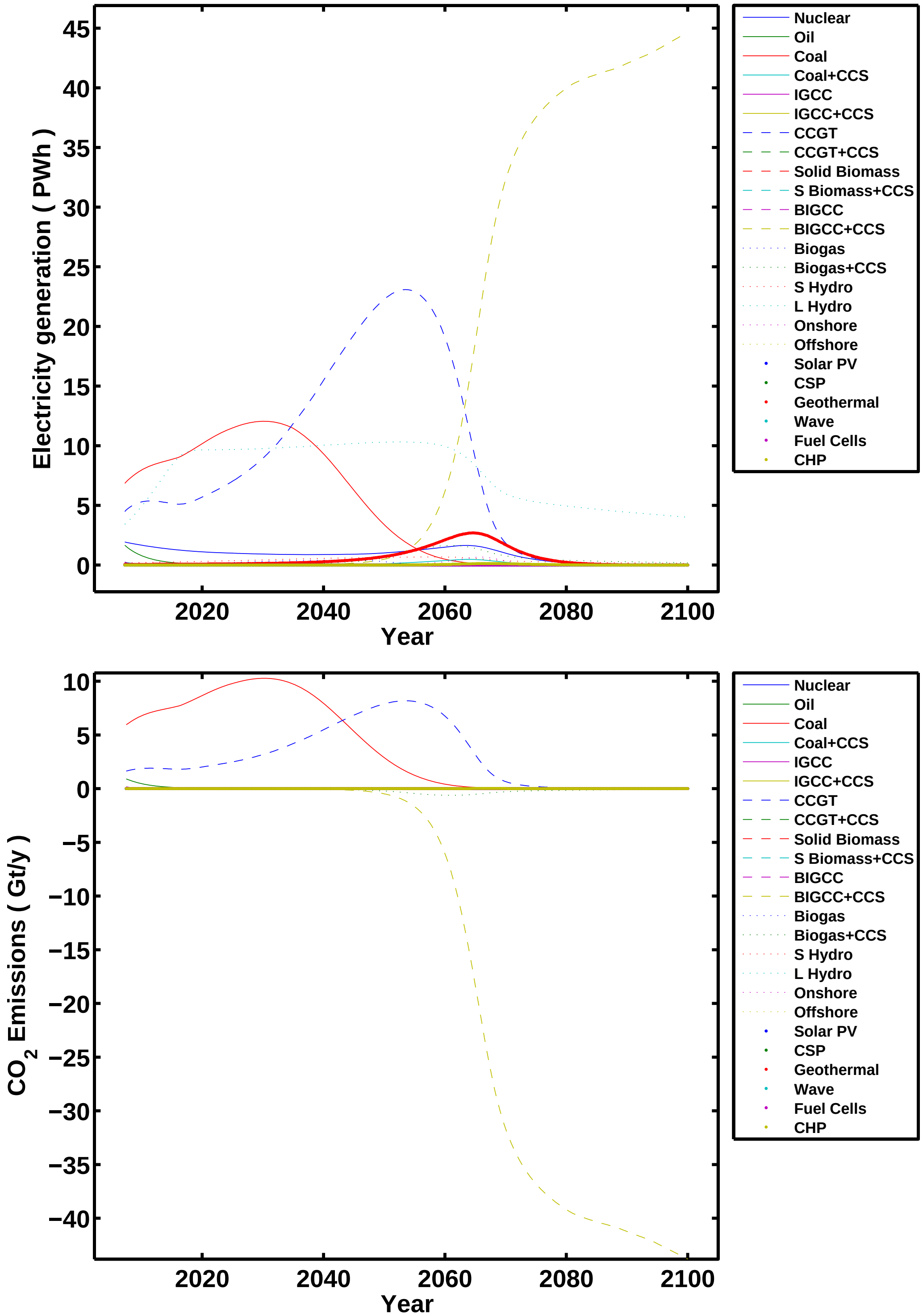

Figure 15: *Top* Electricity generation. *Bottom* CO_2 emissions.

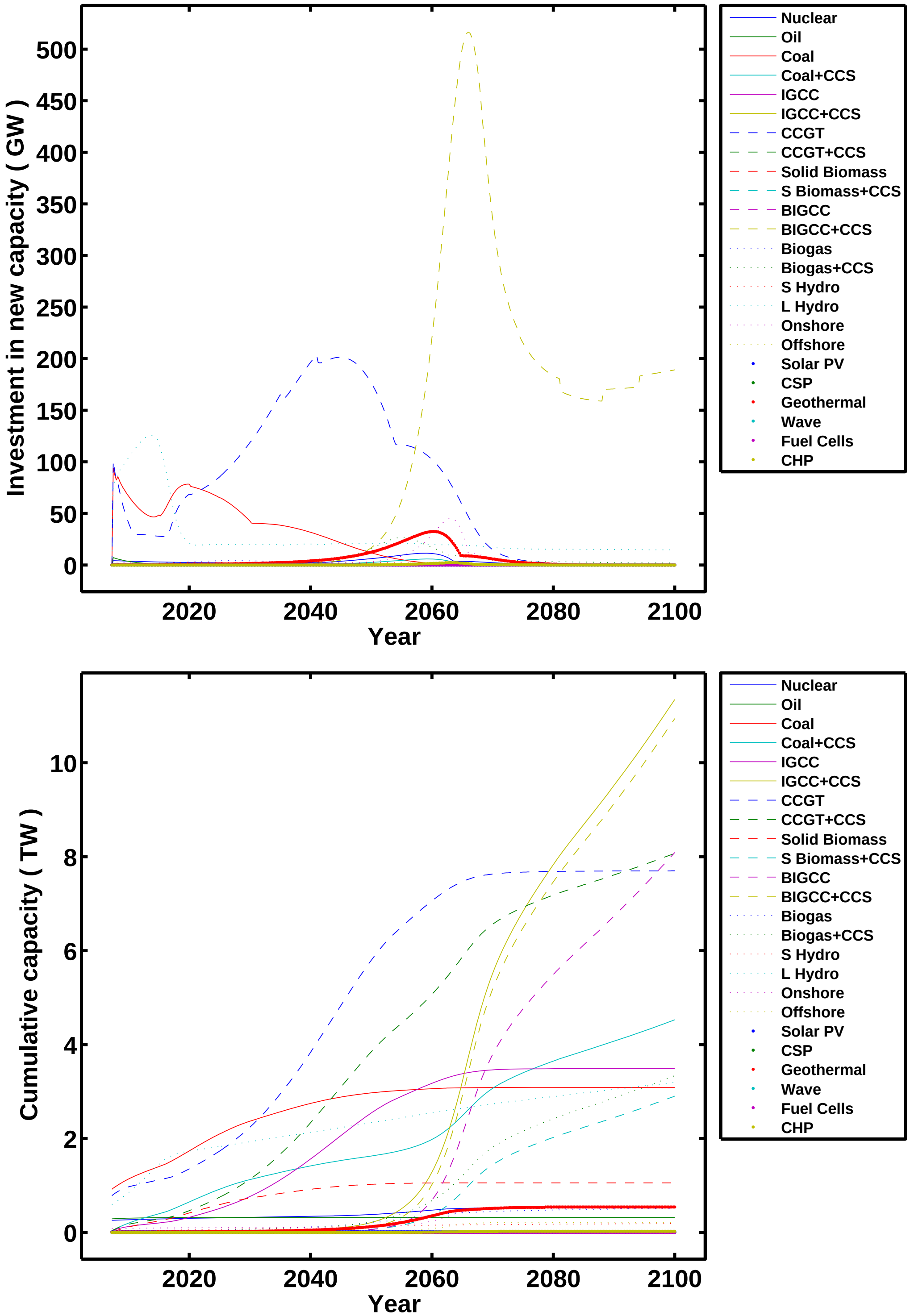

Figure 16: *Top* New capacity. *Bottom* Cumulative capacity.

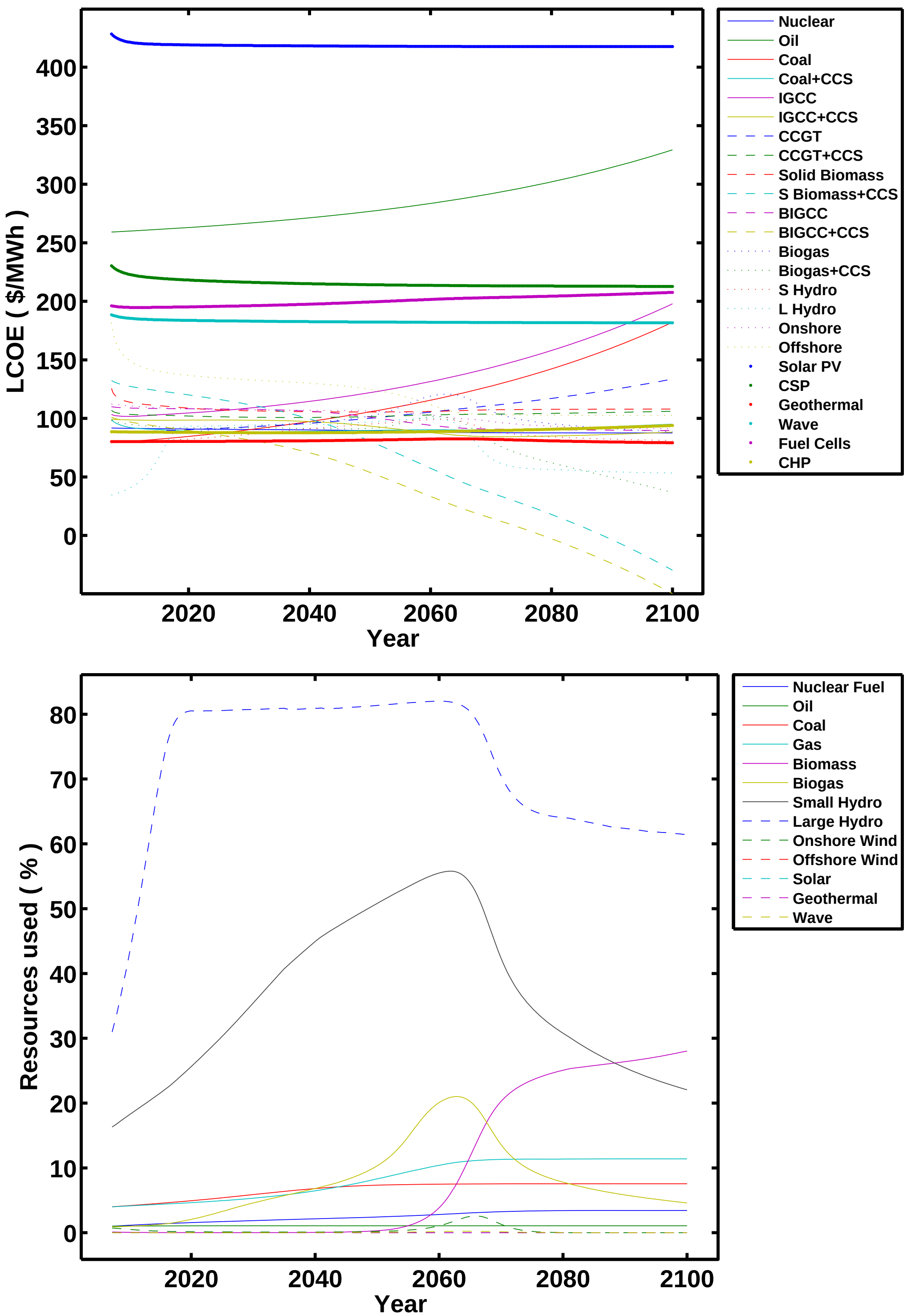

Figure 17: *Top* Levelised cost of electricity (LCOE). *Bottom* Resource use.

assumptions. It is a good example since it exhibits the gradual replacement of technology generated by the increase in the price of carbon.

Figures 14 to 17 display the behaviour of most of the important variables in the simulation. In order of appearance, they are the shares S_i, the capacities U_i, the electricity generation G_i, the CO_2 emissions E_i, the investment in new capacity, expressed in terms of capacity rather than money, I_i, the cumulative investment used in the learning process, expressed in terms of capacity W_i, the levelised cost of electricity $LCOE_i$ and the resource use in percent.

These variables appear in order of their determination at each time step of the simulation. The shares are first derived from the shares equation, using the LCOE calculated during the last time step. From S_i are calculated U_i using the demand D and average capacity factors $\overline{CF}$. The electricity generation G_i is obtained from U_i and CF_i. Therefore S_i, U_i and G_i possess similar but not identical behaviour. Using emission factors, CO_2 emissions are obtained from the electricity generation G_i. Investment I_i in new capacity is derived from positive changes in U_i plus the replacement for plants which are decommissioned. These are added cumulatively since the start of the simulation in order to obtain W_i. W_i is then used in order to rescale investment costs according to the learning power laws. Emission factors, capacity values, cumulative electricity generation and cumulative investment are used to calculate new values for the LCOE, which may become negative when large negative carbon costs arise from negative emissions. The fraction of resources used given here reflects the position of the simulation at each time in the cost-supply curves.

5.4 The price of carbon and technological transitions

Historically, technological transitions tend to follow the behaviour of a logistic curve, with a slow exponential growth at low market penetration, then increase linearly, before saturating exponentially at high penetration. This type of effect has been shown to apply to all sorts of systems for instance by Grubler et al. (1999), among which of course electricity production technologies. When change is driven by one particular variable, the gradual replacement of one technology by another follows a logistic curve characterised by natural time constants which stem from the nature of both systems, the new one and the one being replaced. This driver of change can be resource depletion, evolving relative fuel costs and conversion efficiencies or simply technological learning-by-doing, which enables new technologies to enter the market and possibly take over. If a driver of change is being continuously supplied to the system, it is possible to observe successive technological transitions. In our case of interest, this variable is the price of carbon.

This is depicted schematically in figure 18. In each scenario, electricity generation by technology is shown as solid lines. The sum of these yields the total electricity generation, which is equal to the demand, shown as a dashed line. The price of carbon is shown as a grey line. Each technology, with its respective rate of carbon emissions, pays a different carbon cost. At the starting point, the less CO_2 a technology emits, the more expensive it

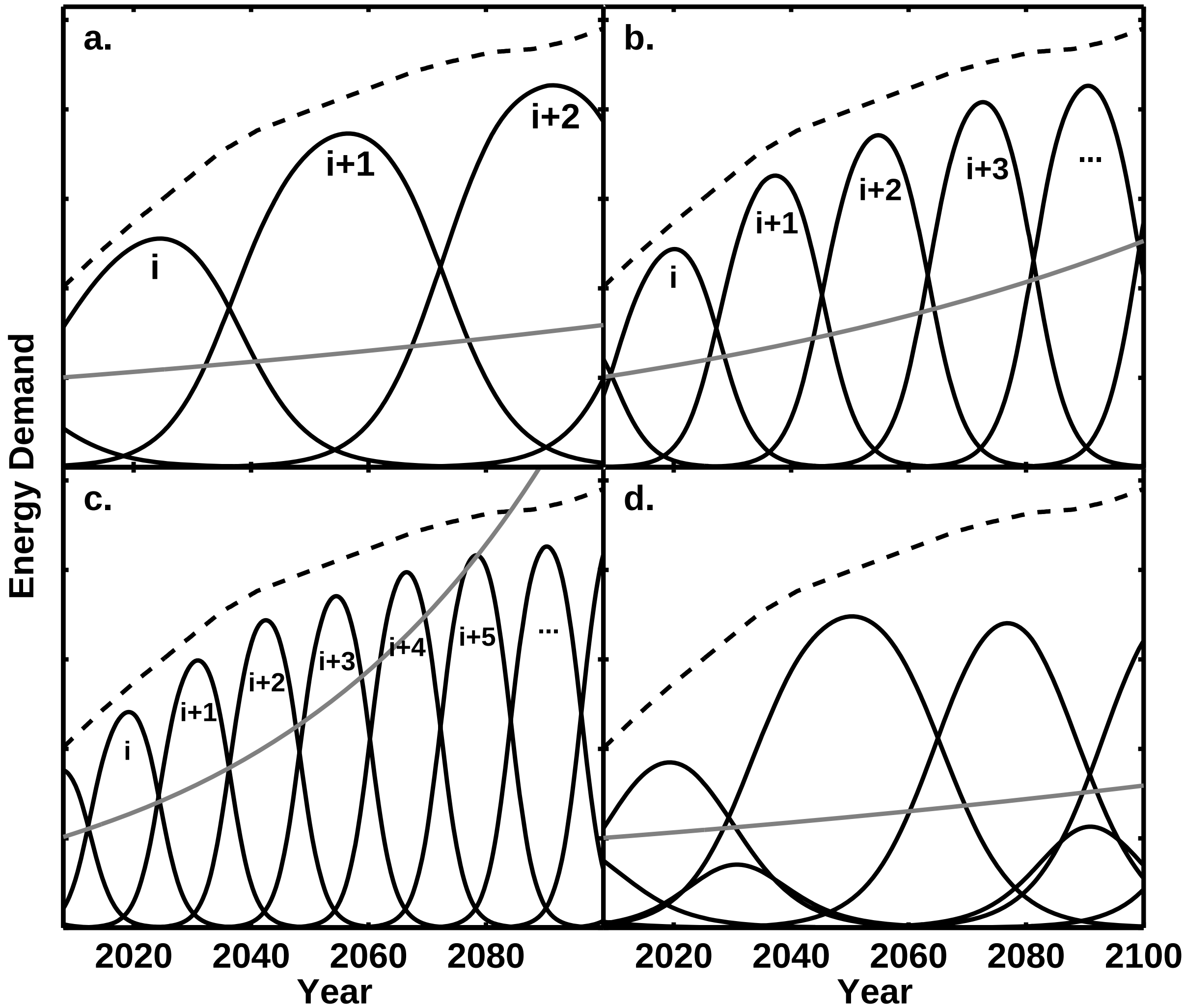

Figure 18: Sketch of the energy technology ladder concept, where energy technologies are gradually replaced as the price of carbon increases. The electricity generation by technology is shown as solid lines, the total energy demand is the dashed line, while the price of carbon is shown as a grey curve. Technology i is replaced by $i+1$, which in turn is replaced by $i+2$ and so on, where at each point in time the mix of technology possesses a marginal cost of abatement, the cost of an additional switching towards technologies with lower emissions, equal to the cost of carbon. *a*. Low rate of increase of the price of carbon. *b*. Medium rate of increase. *c*. High rate of increase. In this case many more intermediate technologies are used. *d*. A more realistic case: a heterogenous mix of technologies with scattered values for the rates of uptake and carbon emissions.

is. But also, technologies with lower emissions are new and their costs decrease faster than old ones through learning-by-doing. The technology with highest emissions is used first, when the price of carbon is low, which we denote i. As the price of carbon is raised, as seen in fig. 18a, i is replaced by newer technology $i+1$, which has lower emissions, which is in turn replaced by $i+2$, and so on. As the rate of change of the price of carbon increases (fig. 18b and c), the system becomes able to reach out to technologies with still lower CO_2 emissions, but also exhibits a larger number of transitory phases. Technologies higher along this ladder become economical to use later partly due to the price of carbon, partly due to learning-by-doing. In reality, however, technologies do not have evenly distributed emission coefficients or rates of uptake, which generates a situation more akin to that in fig. 18d. We call this effect going through the *energy technology ladder*, where each technology comes and goes as the price of carbon increases and exceeds its abatement potential.

The energy technology ladder is an effect which emerges from the equations underlying this model in a variety of sets of assumptions, whenever technological change is favoured. It is a general result that stems from the combination of technological learning as given by experience curves (eq. 13) and a shares equation based on a logistic set of differential equations (eq. 5), and leads to classic sigmoid (S-shaped) technological transitions. We stress that this property is not an equilibrium property, and that not all technological substitutions made economic by the price of carbon occur at any one time. This is due to the dynamic nature of the shares equation, which takes fundamental account of sector growth time constants. Therefore, by including the dynamics of growth, one cannot assume the equation of the price of carbon and the marginal cost of abatement, since an equilibrium is never reached.

Other sectors of the economy could be modeled in a similar way, and thus see logistic technological transitions and technology ladders. One of the sectors of interest is transport, in which the world may see similar types of technological transitions between petrol based vehicles and other types such electric cars or systems running on biofuels. As shown by Grubler et al. (1999) for transport networks and infrastructure, this sector is likely to follow the same logistic behaviour with its own set of time constants. Transitions could moreover be observed between kerosene and biofuel airplanes, traditional and nuclear ships, and so on, influenced again by specific policy instruments. Technological transitions in the transport sector are likely to have massive influence on the energy sector as a whole, and should thus be included in any energy model in order to be complete, since both systems are highly correlated to each other. For instance, while the decarbonisation of the global economy cannot be achieved without a transformation of the transport sector, a transition of the transport sector towards electricity based vehicles does not reduce GHG emissions if the power sector is not itself decarbonised. Moreover, biofuels compete directly with biomass for electricity production, while the additional load of electric vehicles to the power system requires an enormous expansion of electricity capacity generation. Thus both sectors require ideally to be modeled simultaneously.

6 Conclusion

We conclude this report by summarising the various concepts which have been introduced. These are divided into three aspects, which we hope have been appropriately described in the current text. We have introduced the concept of the logistic shares equation, which is based on probabilistic arguments regarding the likeliness of growth of various components of an energy market. This involves the current size of these components of the market and their rates of expansion based on plant construction times and lifetimes, and a comparison of their respective levelised cost of electricity. Given the number of switchings between the various options of the market, the system evolves in time as the levelised costs change.

The levelised costs evolve through three possible effects. The first is technological learning-by-doing, where costs decrease with cumulative deployment of a technology. The more a technology is deployed, the cheaper it becomes. The second effect is resource depletion, where costs increase with deployment according to cost-supply curves. The third effect is through the pricing of emissions of CO_2, which we assume occurs only through combustion of various fuels.

Without constraints, the shares equation represents equally each energy technology. However, real energy systems are highly complex and various energy sources are connected together in various ways. Energy markets are generally formally represented by the so-called merit order, where plants are used in order of cost of use, up to where the total demand is met, at every moment of the day. The plant with the highest cost normally determines the price of electricity. Such a representation is too complex for our purposes, and we have devised a simpler way of representing the matching of supply to a varying daily demand, represented by our technical constraints. These are formally given by two inequalities, from which are derived limits on the respective capacity of each type of systems.

We have introduced the concept of cost-supply curves to represent the availability, use and depletion of natural resources and the associated costs. For any type of resource, costs must increase with large scale development. This stems from the natural tendency of extracting energy at sources which have lower exploitation costs first, and then proceed in order of cost. The use of cost-supply curves for all types of energy systems enabled us to constrain the shares equation further in order to respect total technical potentials associated with these energy sources. Some of these are much more limited than others, even though they may currently have lower costs of production. These are thus likely to reach an economic limit where their cost increase until they lose their competitiveness with other energy sources, and remain to that limit thereafter. Therefore, cost-supply curves maintain the system within bounds of what is currently expected to be possible.

Finally, we provide a number of results given different sets of assumptions, regarding mainly the discount rate and the evolution in time of the price of carbon. These results differ markedly, however they follow roughly what is expected. We observe an interesting phenomenon, which we named the energy technology ladder, where, with an exponentially increasing cost of carbon, technologies are gradually replaced by others with lower CO_2

emissions, which are subsequently replaced themselves later by newer technologies with even lower emissions, and so on. The system progresses gradually in order through the use of the what is the most cost-effective solution at each step, however particular solutions change as the cost of carbon gradually increases. A whole range of systems is therefore expected to be seen temporarily before a final solution is found. This is an effect which has not been imposed in our system by assumption. Rather, it *emerges* from the complexity of the equations. We consider that many other sectors of the economy involving competing markets could in principle be modeled in a similar way, for instance in transport. This model covers only the electricity production sector, and therefore a complete model of the energy sector could include transport and heat production using a similar mathematical description.

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