Exploring lock-in in the energy system

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Abstract

The purpose of this paper is to identify and describe lock-in mechanisms in the energy system, i.e. the world’s generation and consumption of energy. The discussion is based on an extensive data collection, on interviews with energy experts, on conceptual modelling and on simulation modelling; the latter two are based on system dynamics. The main finding is that the energy system shows several traits of path dependent behaviour, despite public and political claims of a free flow of capital. The value of this paper lies in the clear articulation of a complex and fuzzy topic with the help of modelling and simulation. Implications for research comprise a further elaboration of simulation studies within the energy field.

1. A systemic perspective on the energy system

a) Introduction

If one considers the widely accepted free market economy theory and the fact that it is publicly assumed to solve the problems of the energy system, such as excessive CO2 production, air, water and land pollution, geo-political stress, rising food prices (in the case of biomass production), one is inclined to wonder if and when these problems will indeed decrease in their size and impact. In the light of this question we have started an exploratory study of the energy system with a particular interest for the presence of path dependence and lock-in traits. The results thus far as presented here come from extensive data collection, dialogues with energy experts, conceptual modelling (Causal Loop Diagram) and from simulation modelling (Stock & Flow Diagram).

b) The energy system: definition and demarcation

In this paper we use the term ‘energy system’ in a broad sense. It includes the following forms of energy sources: oil, coal, natural gas, nuclear and biomass, solar, wind, geothermal and hydro energy. It also encompasses the technologies that are involved in the generation and use of these forms of energy. The various forms of energy and their accompanying technologies have been clustered in two groups: a conventional energy-technology sub-system (which
includes oil, coal, natural gas, nuclear and biomass, and the accompanying technologies) and an alternative energy-technology sub-system (which includes solar, wind, geothermal, hydro energy and accompanying technologies). In addition to conventional and alternative energy-technology, the energy system contains a financial sub-system (which includes the banking system and the stock market). This definition of the energy system is non-exhaustive (for instance, we do not consider an environmental sub-system in this paper) and limited to such extent that it sufficiently enables us to discuss the presence of lock-in traits.

In this paper we explore the energy system and the presence and behaviour of mechanisms in it that can be related to the concept of lock-in. Such exploration is done with the help of causal loop diagrams and stock & flow diagrams, originating in systems dynamics theory. After a brief methodological remark, we start out with an extensive description of the energy system, based on a conceptual map of the system. Subsequently, we discuss the presence of the “systems archetype” Success-to-the-Successful in the energy system. And, finally, we translate the description of the energy system as well as convert the structure of Success-to-the-Successful, into a formal model. Evaluating the model through simulation experiments provides insights in the behaviour of the energy system for as far as lock-in is concerned. The paper closes with an outlook to future research and a summary of the key insights gained so far.

**c) Mapping and modelling using systems dynamics**

People have difficulties understanding and dealing with feedback processes, and yet feedback is an ubiquitous mechanism by which life is pervaded (Sterman, 2000; Vennix, 1996). When starting out on our exploration of the energy system, we assumed that the energy system would be full of feedback processes and therefore decided to employ systems dynamics as means to help us map our thoughts of what we thought the energy system looks like (cf. Forrester, 1961). Since we intend to set up a qualitative representation of the energy system in the first part of this study, we use a causal loop diagram (CLD) to further our understanding of the energy system. A causal loop diagram consists of a multiplicity of feedback loops. Feedback loops are loops of action and information; any couple of variables in such a loop of action and information is connected. They have an effect on each other’s behaviour and consecutively react to each other’s behaviour. The notion of the feedback loop is closely linked with the concepts of circular causality and interdependence (Richardson, 1991).
A causal loop diagram consists of variables and arrows. The arrows link the variables. The variable at the back end of an arrow has a causal effect on the variable at the front end of the arrow. The links have either positive or negative polarity, indicated by a ‘+’ or a ‘-’ sign. In case of a positive link polarity, the two variables have a positive causal relationship. In other words, if the variable at the back end of the arrow increases, the variable at the front end of the arrow increases as well. The same goes for a decreasing variable at the back end of the arrow: with a positive causal relationship the variable at the front end of the arrow decreases too. An arrow with a ‘-’ sign indicates a negative causal relationship. This means that if the variable at the back end of the arrow increases, the variable at the front end decreases. Likewise, if the variable at the back end increases, the variable at the front end increases.

In case two variables A and B are connected to each other through two arrows in the following way—one arrow from A to B and one arrow from B to A—a causal loop is formed. If the two arrows are positive or if both are negative, a positive feedback loop exists (minus times minus equals plus) between the two variables. A positive feedback loop is self-reinforcing and leads to exponential growth or decline. If the two arrows in the causal loop have opposite polarities (‘+’ and ‘-’) than a negative feedback loop is in place. A negative feedback loop is self-correcting and counteracts change; it is a balancing or stabilising loop. To cite Sterman: “all systems, no matter how complex, consist of networks of positive and negative feedbacks, and all dynamics arise from the interaction of these loops with one another” (Sterman, 2000, p. 13).

Below, as Appendix 1, we have included the causal loop diagram of the energy system as we have come to understand it. The CLD is the result of our discussions and dialogues with energy experts from various backgrounds such as physics, economics, sociology, engineering, as well as literature research. The CLD is not intended to be complete but reflects the mechanisms that we observed to be important for the discussion about the problems connected to the generation and use of energy. The diagram includes sub-systems other than the conventional energy-technology sub-system, the alternative energy-technology sub-system, and the financial sub-system (most notably an environmental and a societal sub-system). For the purposes of this paper, however, we concentrate on these three sub-systems and their relationships (which will later on also be investigated in the form of a formal feedback loops with more variables.

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1 The two variable case serves as an illustration; without loss of generality the explanation can be transferred to
simulation model). The comprehensive CLD in Appendix 1 serves as an indication of the complexity within the energy system and as a structuring device for the further discussion in this paper; we do not aim at discussing it in detail here.

d) A causal representation of the energy system and its sub-systems

The causal loop diagram is a result of our discussions and literature research to structure and improve our understanding of the dynamics of the energy system. We provide a concise description of the three individual sub-systems of the CLD we mentioned earlier. Many variables and arrows in the CLD are self-explanatory and are only shown in the diagram; we do not provide an explicit description of those in this paper. Note that the sub-systems are all interconnected and non-discrete. Therefore, the marking as ‘sub-systems’ has been made for analytical purposes only and is not intended to suggest any strict distinction between them: not only the operating mechanisms within the sub-systems influence the behaviour of the whole energy system; the connections between sub-systems, which determine how the sub-systems interrelate, are also critical in how the total energy system behaves. We describe the connections between the sub-systems that deserve extra attention because of their interesting function in the energy system as a whole.

The conventional energy-technology sub-system

At the lower right-hand corner of the CLD we have placed the conventional energy-technology sub-system. This sub-system contains oil, coal, natural gas, nuclear energy and biomass as energy input. Technologies contained in the conventional energy-technology sub-system are, e.g., technologies for coal gasification, cracking & refining and CO₂ sequestration. We have included these sources of energy and their accompanying technologies in the conventional energy-technology sub-system on the basis of (1) their environmental implications (be it air, land or water pollution, output of CO₂ or generation of nuclear waste), (2) the finiteness of their availability, (3) the geo-political stress that comes along with their extraction and trading, and (4) (specifically for biomass) their impact on availability of crop land and food prices.
To put things in time-perspective we refer to Figure 1, which is published by the International Energy Agency (IEA). Figure 1 shows that oil, coal, natural gas and nuclear are dominant in the world’s energy supply. According to the IEA, in 2007 oil (34.0%), coal (26.5%), natural gas (20.9%) and nuclear (5.9%) jointly accounted for 87.3% of the world’s total primary energy supply (TPES). In 1973 these accounted for 87.5% of the world’s TPES. In absolute terms, the world’s TPES rose from 6,115 million tonne of oil equivalent (“Mtoe”) in 1973 to 12,029 Mtoe in 2007. This indicates a more or less stable ‘market share’ for oil, coal, natural gas and nuclear energy of the world’s TPES in this period, but an increase of 96.3% of their absolute total supply.

In 2009 the IEA also published records on estimates of the budgets for research, development and demonstration projects of the various forms of energy. We have included Table 1 in Appendix 2 at the end of this document. It shows that RD&D investments made in conventional energy sources (excluding biomass as the IEA categorises it under alternative energy) in the IEA countries (e.g. China and India are not included) constituted 53.8% of all investments made in energy RD&D in 2000. In 2008 conventional energy’s share of RD&D was 50.9%.

In the same period, the damaging effects of the output of large amounts of CO₂, air, land and water pollution, production of nuclear waste, geopolitical stress and approaching shortages of energy reserves were observed and experienced in many parts of the world. Or, in terms of our CLD: the conventional energy-technology sub-system substantially “fed in” to the environment as well as society.

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2 Cf. IEA, Key World Energy Statistics 2009.

3 Here we do not list biomass since IEA includes biomass in ‘combustible alternatives and waste’ and does not differentiate in percentages in its World Energy Statistics 2009 between solid biomass & animal products, gas/liquids from biomass, industrial waste and municipal waste (which all have different effects on the availability of cropland and food prices), which are all part of ‘combustible alternatives and waste’.

4 At the time of writing this paper, the world’s largest accidental oil release has occurred. After the explosion of the Deep Water Horizon nearly 5 million barrels of oil have been released in sea (Cf. Roberson & Krauss, 2010). The co-owner of the oil rig British Petroleum has announced that it shall sell parts of its corporation to cover for the costs involved.
The alternative energy-technology sub-system
At the lower left-hand corner we have positioned the alternative energy-technology sub-system. It involves solar, wind, geothermal and hydro energy. The accompanying technologies incorporated in this sub-system are, e.g., concentrated solar technology and wind turbines. We have incorporated these into the alternative energy-technology sub-system on the basis of (1) the absence of air, land or water pollution and CO\textsubscript{2} emission as by-products, (2) the abundance of sun, wind, geothermal heat and water, (3) the lack of geo-political stress resulting from their production, and (4) the absence of influence on world food prices.

In Figure 1, it is shown that solar, wind, geothermal (jointly 0.7%) and hydro energy (2.2%) in 2007 made up for 2.8% of the World’s TPES. In 1973, these combined represented 1.9% of the world’s TPES. If one compares these numbers with the numbers mentioned in the former section one can only conclude that in absolute numbers the growth in alternative energy supply is entirely outweighed by the growth in the conventional energy supply.

\[^5\] Source: Key World Energy Statistics IEA 2009.
Table 1 (cf. Appendix 2) shows that the budgets for research, development and demonstration projects for alternative energy-technology (including biomass since the IEA categorises it under alternative and also containing hydrogen) in the IEA countries (e.g. China and India are not included) added up to 8.9% of all investments made in energy RD&D in 2000. In 2008 alternative energy’s share of RD&D was 18.9%.

In its World Energy Outlook 2009 Fact Sheet the IEA records that as a consequence of the financial crisis, in late 2008 early 2009 the investments in alternative-based power generation dropped relatively more than in other kinds of energy generation capacity. Without governmental fiscal advantages it would have decreased by almost 30%.

The two energy-technology sub-systems: similar structures

In our discussions about the energy system our initial point of departure was the assumption that the conjunction of the two energy-technology sub-systems is at equilibrium—an equilibrium that shifts to the extent one of the two sub-systems performed better than the other—and that the conventional and alternative energy-technology industries are based on the same fundamentals, so that both energy-technology sub-systems have, mutatis mutandis\(^6\), an equal chance of being successful within the energy system. In terms of our CLD we therefore assumed the two energy-technology sub-systems operate predominantly under diminishing returns and both energy-technology sub-systems consist of the same internal causal relationship principles and predominantly similar variables, providing a fairly well-balanced energy-technology sub-system structure in the energy system. This assumption of equality of chances leads, for that matter, to an energy system in which—to phrase it in terms of economics—the most efficient technology (and accompanying energy form) dominates, in which bureaucratic companies with relatively expensive and in which low quality products

\(^6\) In fact our qualitative approach expressed through the CLD and the description of the energy system in this paper does not take into account, albeit with some exceptions, the varying numbers, amounts and quantities that are behind the mechanisms and structures of the two energy-technology sub-systems. The energy supply data (cf. Figure 1 of the IEA can be seen as a sound indicator in this perspective. Several internationally renowned energy research institutes, such as the International Institute for Applied Systems Analysis (“IIASA”) and the IEA, have done and are currently doing extensive research in the field of quantified information as to (financial) capital in the realm of conventional and alternative energy-technology (particularly IIASA’s global energy assessment is noteworthy in this perspective). The results of many of the existing reports on this subject matter vary significantly – the cause thereof lies in the different measurement methods applied as well as in the tremendous amount of numbers and complexity involved – but all indicate that the alternative energy sub-system is a mere fraction – number-wise – compared to its conventional peer. For simplicity purposes we refer to the reports of the above institutions for further information and quantified comparison.
lose ground in relation to their competitor’s market share. After we started our exploration of the energy system, however, it soon turned out that the energy-technology sub-systems and the energy system as a whole contain many powerful and dominant positive feedback loops, and thereby increasing returns. Below, we succinctly describe traits both sub-systems have in common.

The basic internal structures we found in both the alternative and the conventional energy-technology sub-system are incorporated in the CLD. We mention the most important (see the CLD for the more elaborate overview), and start with investments.

Bigger investments in energy-technology lead—via research and development—to improvement of technical quality of energy technology. Improved technical quality in turn triggers the increase of the efficiency and reliability. Bigger investments also lead to augmentation of energy and technology available (availability and supply of energy) such as bigger amounts of extracted oil and coal, larger refineries and more electricity provided by a larger capacity of wind turbines or solar cells. Increase of the availability and supply of energy lowers the price, which, in turn, provided the market-mechanism functions well, leads to higher demand. Higher demand (and therefore more turn-over) leads to more profits, and these can be reinvested in energy technology. Increased efficiency and reliability also leads to higher social acceptance of energy, which in turn leads to higher demand. In addition to this mechanism there is another important positive feedback mechanism operating. Investments are not only allocated for furtherance of the quality of technology but also to marketing, sales and advertising. These then in turn lead to better sales techniques, better product branding and higher familiarity of consumers with the technology. These in turn lead to higher sales volumes and, finally, to larger profits. Once these reinforcing feedback loops are in place and running in a growth mode, particularly in combination with stabilising loops keeping the prices high enough, they can be very successful and dominant in a given market.7

7 Even if we ignore the aforementioned energy-technology reports and their varying results, it is self-evident that in the event either of both energy-technology sub-systems – which are in this section assumed to be identical in structure (identical variables and arrows) – is based on positive numbers substantially bigger (e.g., more investments or more profits) than the other, given the fact that we are dealing with powerful increasing returns, the ‘bigger’ sub-system will have a structurally more advantageous position in the energy system than the other.
The financial sub-system

In the middle of the diagram we have situated the financial sub-system. During our discussions and the construction of the CLD, it turned out that the financial sub-system plays a central role in the operation of the total energy system. The financial sub-system is tightly connected with nearly all sub-systems in the energy system. These connections concern the arteries of many of the sub-systems: the availability of financial capital. The financial sub-system has an important function in the development of the energy system by means of its provision of financial capital to the conventional energy-technology sub-system and the alternative energy-technology sub-system. The way the financial sub-system distributes its financial capital to these sub-systems substantially influences their absolute and relative development.

We describe the aspects of the financial sub-system which specifically turned out relevant for the energy system as a whole. We have left out structures that sustain the financial sub-system itself but do not strongly influence the energy system, such as banks making profits by lending money to consumers and reinvestment of these profits in the financial-sub-system itself in order to develop new financial consumer products. The financial sub-system includes the banking system that directly (through credits and loans) or indirectly (through, e.g., loans to hedge funds) provides the financial capital and it also comprises the stock market in which financial capital can move around freely all over the world.

In the financial sub-system of the CLD we furthermore observed a reinforcing investment-profit loop similar to the one that can be seen in the conventional energy-technology sub-system in which the conventional energy-technology sub-system perseveres in investing predominantly in conventional energy-technology (rather than in investing substantially in alternative energy-technology). It concerns investments by the financial sub-system in the conventional energy-technology sub-system leading to profits coming from the conventional energy-technology sub-system fed into the financial sub-system; these returns on investment lead to new investment in the conventional energy-technology sub-system.\(^8\) If these loops

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\(^8\) Note that these investors in the financial system are, inter alia, pension funds with large amounts of capital available; these pensions funds promote the pension interest of large amounts of employees. Thus, where many
have been running for a long enough period of time so that the sub-system that receives the profits has gotten used to these profits (which evidently does not—yet—apply to the alternative energy-technology sub-system), this history can render a (sub-)system, such as the financial sub-system or conventional energy-technology sub-system, incapable of breaking away from its historical path of investing in technologies where high and seemingly never-ending profits were always present (Perez, 2002). Moreover, the race for economic survival (i.e. investments must yield immediate and constant returns because otherwise, \textit{inter alia}, share prices will drop) aggravated by the incorrect ‘homo economicus’-assumption (i.e. cooperation is discouraged), combined with a facilitating financial-legal framework appears to exacerbate such path dependence pattern which prevents the vast majority of the decision makers of financial sub-system from investing in ‘risky ventures’, such as alternative energy-technology, that do not have the abovementioned historical track record of returns on investment. The fact that the allocation of financial capital is frequently subject to herd behaviour (Lux, 1995) and extrapolation of the recent past into the future (Rostow, 1993) establishes an extra obstacle to change to new and apparently highly uncertain investment options such as investments in alternative energy-technology. Within the financial sub-system, the risky ventures are dealt with by private (green) funds and venture capitalists. The amounts available through these funds are a fraction of the financial capital invested in and available for vested energy-technology industries.

\textbf{Investments by the financial sub-system and the industry}

The financial sub-system is, from its economic and risk avoiding nature, not inclined to heftily invest in industries which have no proven track record or which cannot provide a

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9 Perez provides an elegant historical account of financial institutions developing less trustworthy but highly profitable products that are to replace the diminishing returns of investments in once revolutionary technologies (and their energy inputs) reaching their ‘maturity phase’.

10 We argue that the current financial crisis is closely related to this trait of the financial system; the financial system continued to invest in industries with an proven but actual worn-out profit track record compared to the expectations of the financial system itself. As the industries went through a shake-out period, the financial system invented its own profits: securitization, pyramid games, etc. Cf. Perez (2002) for the periodicity in these developments.
constant and immediate level of profitability. Instead, the financial sub-system predominantly invests in industries that have a proven track-record and that provide a constant and immediate (short-term) level of profitability; this tendency leads the financial sub-system to invest substantially in the conventional energy-technology sub-system, and, as consequence, relatively little in the alternative energy-technology sub-system that predominantly requires long term investments and provides uncertain returns. Although a positive link exists between the profit generation in the financial sub-system and the availability of venture capital, the amounts available through these funds for the alternative energy-technology sub-system, is overwhelmed by the amounts of money available to and invested in the conventional energy system. A similar situation is applicable to investments made by the industrial parties in the energy market; their need to generate constant profits and security of energy supply at the same time—combined with the belief that such can only be done through proven technologies—leads them to predominantly invest in conventional technologies. In 2009, in a period often considered to be dominated by “sustainability hype”, the IIASA estimated the combined investments from the financial and conventional energy-technology sub-systems in conventional energy-technology in relation to and the investments made by the financial system in alternative energy-technology to have a 10:1 ratio. Another reflection of this unequal flow of investments is reflected by the overview of research, development and demonstration budgets in the total of IEA countries available for the various technologies in Table 1. In short, over the period 2000-2008 the RD&D budgets for fossil fuels grew faster than those for alternative energy sources. In 2008, alternative energy-technology (including hydrogen and fuel cells) received 18.8% of the total budget. The remaining 81.2% of the total budget went to fossil fuels and nuclear fission and fusion. Finally, in its World Energy Outlook 2009 Fact Sheet (energy investment) the IEA stated an amount of 26 trillion dollars (in year-2008 dollars) is needed to meet the projected energy demand through to 2030; in other words: attracting investment capital will in the coming decades be even more competitive than is has been before the financial crisis.

Above we discussed our observation of the many similarities between the core mechanisms of the two energy sub-systems; in the CLD both sub-systems’ structures consist of many of the

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11 This is expressed in the CLD by the red positive arrow coming from “investment in industries with proven track record that provide constant (immediate) level of profitability” feeding into “investments in conventional energy” and the red negative arrow coming from “investment in industries with proven track record that provide constant (immediate) level of profitability” feeding into “investments in alternative energy”. 

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same multiple positive feedback loops. In both energy sub-systems a positive feedback loop starts with investments in energy-technology by the financial system on the one hand and with reinvestment of profits by the pertinent energy-technology sub-system itself on the other hand. These investments then start a large number of positive feedback loops, for instance the investments are used for further development of the technology, efficiency of the production process, improvement of the workforce of the organisation, better marketing and sales activities. These, in turn, then finally lead to higher profits that can be reinvested in energy-technology and injected into the financial sub-system as dividend, thus attracting even more investments. Thus, the conventional and the alternative energy-technology sub-systems are, whilst operating under powerful increasing returns, competing for capital made available by the financial sub-system and the conventional energy sub-system (we deem the capital generated by the alternative energy-technology sub-system fractional in this perspective, and consider the amount of capital that is and can be made available to the energy-technology sub-systems finite). Investments of capital in conventional energy-technology thereby directly influence the availability of capital for the alternative energy-technology sub-system. The more the conventional energy-technology sub-system is successful, e.g. oil companies investing in technology for the production of tar sands, the more difficult it will be for alternative energy to be successful itself, e.g., Royal Dutch Shell ceasing investing in solar and wind energy because “they are not economic” (Webb, 2009). If the conventional energy-technology sub-system is thriving because, *inter alia*, it is capable of acquiring and generating large sums of investment capital, the alternative energy-technology sub-system is, as a consequence, not provided with that capital and hence less prone to be successful itself.

This behaviour, which concerns industries operating under increasing returns with a competition for certain resources, such as the battle for the investment capital of the holding company, banks and other financial organisations, can be likened to the systems dynamics archetype “Success-to-the-Successful”, as described by Senge (1990) and Braun (2002).

### 2. Success-to-the-Successful in the energy system

Above we described how a mechanism similar to the archetype Success-to-the-Successful appears to be operating between the two energy-technology sub-systems with investment capital (from the financial sub-system and the conventional energy-technology sub-system) as the resources for which the two energy sub-systems compete. One can observe the similarities between the basic structures of the energy sub-systems and financial sub-system as
represented in the CLD, on the one hand, and the archetype Success-to-the-Successful (cf. Figure 2) on the other. Let us elaborate more on the archetype.

The mechanism underlying the archetype Success-to-the-Successful is one of allocating resources to a party in reward of success to create even more success. At the same, the allocation of these (finite) resources is consequently not appropriated to another competing party, and such competitor is thus limited in its chances of success. It is self-evident that this mechanism with initially multiple equilibria (at the start any of the competing parties could get the resources allocated to them), path dependence (success propagates success and failure propagates failure) and lock-in (once a more or less consistent allocation to either A or B has occurred long enough, changing allocation to the other in this structure of behaviour is virtually impossible) can also be characterised by the linear and non-linear Polya process (Arthur, 1994) and may function as a powerful barrier to change. To cite Braun (2002, p. 12): “finding itself bogged down to this archetype can also lead to the erosion of innovation and change.”

**Figure 2. The archetype Success-to-the-Successful (after: Braun, 2002)**

When the archetype commences to operate, the allocation of resources to one sub-system, e.g., A, instead of allocation to another sub-system, e.g., B, rather than the other way around, is still a feeble equilibrium and can—with small changes, such as an invention or new regulation—relatively easily be disturbed so that the allocation switches to B instead of A. However, the longer this mechanism is operating with, e.g., A being successful and able to tap the resources competed for, the more difficult it will be, particularly when high up-front costs,
network effects, learning effects and self-reinforcing expectations are involved, not only for B, but any new market entrant with an interest for the same resources, to be successful. Whether a new entrant, e.g. a new technology, may be technologically or economically superior to the then dominant technology may not play a role in this division of market shares; historical choices and structures may cause the market to prefer other reasons than such superiority to invest in certain technologies. Nevertheless, as we discussed above, the lock-in to a certain division of market shares and its possibly damaging (cf. the problems of the energy system we discussed earlier) characteristics, however persistent, are not permanent. Somewhere in the whole system, or in the variables present in the Success-to-the-Successful mechanism itself, will always occur changes (such as stocks being depleted or new technological competitors entering the system that do not need to compete for the same resources) that finally break down the existing locked-in structure. Given the problems of the energy system, the question is when such change is to occur and whether we have the time to wait for such a change to occur, without actively intervening. After all, to phrase Keynes (1923): “in the end we are all dead”. And he continues: “economists set themselves too easy, too useless a task if in tempestuous seasons they only tell us that when the storm is long past the ocean is flat again”.

At the same time, only if time has lapsed for such a period of time that the exponential growth modus of networks of loops has been able to grow to a critical mass that can resist substantial disturbances (like the current financial crisis), the alternative sub-system will be able to thrive in the energy system as a whole and compete with the conventional energy-technology sub-system in such a way that it can mitigate the problems arising from the use and generation of energy within the conventional energy-technology sub-system. In other words: should action be taken to fundamentally promote the interest of the alternative energy-technology sub-system, then such action should last until such critical mass has been created.

In addition to the competition for financial capital from the financial sub-system and the political sub-system (in the form of subsidies and loans), the conventional and the alternative energy-technology sub-systems are, whilst operating under increasing returns, also competing for the use and adoption of their respective forms of energy and accompanying technologies by customers. If a customer has bought and received the technology and pertaining energy he needed for a particular purpose such as the car and fuel for the car or the heating system for the house and natural gas, he does not require alternative technology with accompanying energy for that same need, which has been satisfied. If a certain energy-technology
combination has been chosen by a group of users to provide in their needs, other competing energy-technology combinations are thereby—for some time (as we assume the demand for energy-technology is at least for a certain period of time finite)—excluded from adoption by this group of users, these users’ needs have been fulfilled. In the event conventional energy-technology is adopted by consumers, the flow of money, pertaining profits and learning loops of both consumers and producers of energy-technologies increase, thereby diminishing the chances for the alternative energy-technologies of success, and vice versa. If one examines Figure 3 in this context it can be seen that from the point of view of the energy system and the Success-to-the-Successful archetype, out of these two competing energy-technology sub-systems the conventional energy-technology sub-system is currently by far the most successful in having its energy consumed and pertaining technology adopted.

![Graph showing evolution of world total final energy consumption from 1971 to 2007](image)

**Figure 3. World’s total final energy consumption from 1971 to 2007**

Finally, it is worthwhile mentioning the mechanism that governs the competition of individual beliefs and the social paradigm that follows from those beliefs. On the one hand the human brain has the tendency to snap to one reality as understanding of complex situations are involved, on the other hand, that same brain will, according to Hebb’s law, favour the line of thought that has been ‘executed’ before over a new line of thought. In other words: on an individual neuropsychological level of belief Success-to-the-Successful is operative as well. The more we have gotten convinced of a certain belief and the more the relevant part of our

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12 Source: Key World Energy Statistics IEA 2009.
brain have fired together, the more we appear to be convinced of such belief to the exclusion of another belief and the more these part of our brain have gotten wired together, as parallel competing beliefs are not what brains are designed for (cf. Scheffer & Westley, 2007). If the individual beliefs scale up to a level of a paradigm through social interaction and through individually and collectively passing the loop of conviction, action and confirmation, to form—to put it in Capra’s words (Capra, 1997, p. 6)—“the basis of the way the community organises itself”, the Success-to-the-Successful structure has established itself on a societal level as well.

3. A formal model of the energy system
In order to get a better understanding of the dynamic consequences of the relationships between the various elements and sub-systems of the energy system, we developed a formal simulation model following the system dynamics approach. System dynamics is a theory on the structure and the resulting dynamic behaviour of systems and a method to represent such structures as diagrams and mathematical equations (Größler, Thun, & Milling, 2008; cf. also for the method’s limitations). Developed by Forrester (1958, 1961), its original purpose was the analysis of industrial enterprises (and was therefore called “industrial dynamics”). However, in subsequent years system dynamics has been applied to many kinds of systems that change over time, in particular to socio-economic systems (for an overview, cf. Lane, 1999, 2007).

As a first step in developing a formal simulation model, we abstracted a simplified model of the CLD (as included in Appendix 3) and converted it into a stock & flow diagram. This stock & flow diagram focuses on the competition for (financial) capital from the financial sub-system by the two energy-technology sub-systems, and leaves out the other Success-to-the-Successful structures we mentioned in Chapter 2. Figure 4 shows a stock & flow diagram (Forrester, 1961; Lane, 2000) based on the conceptual understanding of issues represented in our comprehensive CLD discussed above and included in Appendix 1. The central chain (indicated by double arrows) represents the flow of capital from freely available (financial) capital into bound capital (in form of energy production facilities) in the two sectors, conventional and alternative energy-technology. Between these stocks (indicated by rectangles in the diagram), are flow variables (indicated by a valve symbol) that govern how

13 All CLD’s and S&F diagrams have been made using Vensim software.
capital flows from one stock to the other. These flows are controlled by information feedback loops that symbolize the decision-making process in allocation of the (financial) capital. The flows determine what amount of capital flows either way and how long, on average, capital remains productive. Their value is dependent on a discrepancy between desired and actual capital for energy production and on an inclination to invest in one of the two energy-technology sub-systems, conventional or alternative energy-technology. Together with the depreciation of capital, those two mechanisms form feedback loops (indicated by a circular arrow symbol).

Figure 4. (Slightly simplified) stock/flow diagram of simulation model

The next step in modelling is the formulation of quantitative relationships between the model variables, in form of equations and parameters. In our model it is assumed that the allocation towards one of the energy-technology sub-systems depends on an inclination towards or preference for this sub-system, which is based on the investments that already occurred.\(^\text{14}\) In other words, more capital is invested where already much capital has been invested. The argumentation here is that capital invested has delivered profits in the past which makes it

\[^{14}\text{This could also be understood as an investment based on the sunk costs bias. In an economic understanding of sunk costs, they should not be considered for decisions since they have already been written off. However, if we apply a behavioural understanding of the sunk costs bias, this bias makes decision-makers invest more when they already have substantially invested in a certain technology (which has, in addition, led to reasonable profits in the past).}\]
reasonable to invest further in this sub-system’s energy-technology. An additional assumption in the model is that demand for energy is an exogenous parameter, i.e. its value is not influenced by model behaviour. All other values of variables are endogenously generated by the dynamics of the model. A model listing of the total model can be found in Appendix 4.

4. Validation of simulation and subsequent research

So far, the formal simulation model has been used to produce a variety of validation runs. We report on these here and deduce avenues for further research. In all of the following simulation runs, illustrative numerical values have been used that do not necessarily represent realistic numbers from the energy system. For all simulation runs we depict the development of capital (i.e. facilities to produce and distribute energy) in the conventional and the alternative energy-technology sub-systems.

Figures 5 and 6 show model behaviour in case of quasi infinite financial resources available. Also, in both figures, two simulation outcomes are depicted: the behaviour of the whole system when the two energy-technology sub-systems are initially equal (in terms of the capital that they encompass when the simulation starts) and the behaviour of the system when the conventional sub-system had an initial advantage over the alternative sub-system. Figure 5 shows capital in the two energy-technology sub-systems when demand and supply for energy-technology are in balance; Figure 6 shows capital in the two energy-technology sub-systems when demand exceeds the available capacity and there is a need for additional investment in capacity (in terms of capital used in either of the two energy-technology sub-systems).

As one can see from Figure 5, the system is in perfect equilibrium then: supply and demand are in balance; financial resources—which are necessary to account for depreciation of capital—is unlimited. Depending on the initial condition, the two sectors are either perfectly the same (when they started at the same level) or maintain their initial difference.
The situation changes slightly in Figure 6. Here, capacity needs to be built up in order to reach an equilibrium, which is done in the first 20 periods of the simulation. Due to the infinitude of the financial resources this poses no problem and the subsequent behavior equals the situation described in Figure 5.

Figure 7 shows the outcomes of two simulations when financial resources are limited and capacity needs to be increased. Now, the adaption process of energy capital to the demand for energy happens as long as financial resources are available. After period 25, all capital stocks
begin to shrink since there is not enough capital available to account for the depreciation in the capacity.

![Graph](image)

**Figure 7. Simulation output - finite resources, demand exceeds capacity**

The next simulation output reported here is depicted in Figure 8. The situation tested in this simulation experiment comprised infinite financial resources, demand that exceeds capacity and an initial advantage of the conventional energy-technology sub-system. Unlike in all other simulations before, additional investments are now allocated 50% to the conventional energy-technology sub-system and 50% to the alternative energy-technology sub-system, i.e. not depending on (the success stemming from) earlier investments anymore; there is an equal chance for investments being made in the conventional and in the alternative energy-technology sub-system. In systemic terms, the feedback between the capital already accumulated in a sector and further investments in that sector are cut. One can see that the capital stocks of both sectors approach each other over the course of the simulation.
Finally, Figure 9 shows a simulation run that mimics the classical “Success-to-the-Successful” archetype as discussed above and is to a certain degree the opposite of what has been studied in Figure 8. As in that simulation, financial resources are not limited and there is a lack of capacity compared to the demand for energy-technology; the conventional energy-technology sub-system has an initial advantage over the alternative energy-technology sub-system. Unlike before, however, the necessary investments in new production capital are not proportional to already accumulated capital (as in runs shown in Figures 5 to 7) nor is there an equal distribution of investments (as in the run from Figure 8). Rather, there is an “increasing returns” investment policy implemented here that allocates over-proportional additional investments in that sector that has an advantage already (thus, the conventionalenergy-technology sub-system). As one can see, now the conventional energy-technology sub-system dominates more and more, while the sustainable energy sector becomes increasingly irrelevant.
The simulation results in Figures 5 to 9 are of use to pursue further exploration of and discussion about the presence of Success-to-the-Successful structures in the energy system. We thus do not present the simulation results in Figures 5 to 9 as ground-breaking in themselves. Rather, we portray and understand them as giving confidence in the validity of the model, so that it can be used with justification for more intricate and interesting analyses of the behaviour of the energy system and the particular role of structures like Success-to-the-Successful. For example, we will further pursue the use of the simulation model to investigate:

- How initial advantages in one sub-system can be maintained under various environmental conditions;
- How initial disadvantages in one sub-system can be turned into an advantage in the long run;
- Where are sensitive points for overall performance of the whole system and how overall performance can be secured;
- What externalities come with different situations, for instance represented by the pollution generated;
- Why and how a system can be in lock-in, even though it is supposed to be open;
- What are conceivable decision rules of investors based on which the model is able to replicate historical behavior.

The system dynamics model allows us to approach quantitative as well as qualitative answers to these questions.
5. Summary
The authors, in co-operation with international energy experts, conducted desktop research and several multi-disciplinary dialogues and discussions about the energy system. These exploratory discussions had the purpose to acquire a better understanding of the mechanisms driving the energy system and the (apparent persistence of) problems caused by the generation and use of energy. On the basis of these discussions, our individual knowledge and additional literature research, a causal loop diagram of the energy system was developed. The causal loop diagram displays powerful reinforcing feedback loops in all of its sub-systems. In the context of the aforementioned problems essential reinforcing feedback loops were found most prominently in the financial sub-system and the conventional energy-technology sub-system. A comparison of the conventional and the alternative energy-technology sub-systems revealed, inter alia, the structural and fundamental investment mechanisms that can be likened to the systems dynamics archetype Success-to-the-Successful from the financial sub-system and the conventional energy-technology sub-system in conventional energy-technology, and the relative absence thereof vis-à-vis alternative energy-technology.

After formalizing the archetypal structures into a simulation model, additional analyses are possible. By now we have only reported on rather basic simulation experiments. However, in the previous section it was highlighted how the simulation model can be used to shed light on highly difficult matters like the quantitative relationships between successful and not successful energy sub-systems and principal policies to shift dominance from one sub-system to another.

References


Appendix 1
Causal Loop Diagram (comprehensive)
## Appendix 2

Table 1. RD&D Budgets - IEA 2010.

<table>
<thead>
<tr>
<th>COUNTRY</th>
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<th>FLOW</th>
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Appendix 3
Causal Loop Diagram (simple)
Appendix 4

Model listing (equations in alphabetical order; illustrative parameter values)

absorption of pollution = Pollution / ABSORPTION TIME; Units: pollUnit/Year

ABSORPTION TIME = 100; Units: Year

Available Capital = INTEG (capital inflow - investing in conventional energy - investing in alternative energy, INI AC); Units: Euro

BUILDING TIME CONVENTIONAL = 5; Units: Year

BUILDING TIME ALTERNATIVE = 5; Units: Year

CAPITAL BECOMING AVAILABLE = 100; Units: Euro/Year

Capital Conventional Energy Technology = INTEG (investing in conventional energy - depreciation conventional, INI CCET); Units: Euro

capital inflow = CAPITAL BECOMING AVAILABLE; Units: Euro/Year

Capital Alternative Energy Technology = INTEG (investing in alternative energy - depreciation alternative, INI CSET); Units: Euro

COEFFICIENT CAP-POL = 1; Units: pollUnit/Year/Euro

COEFFICIENT DEM-CAP = 1; Units: Euro/GWh

DEMAND = 1000; Units: GWh

depreciation conventional = Capital Conventional Energy Technology / DEPRECIATION TIME CONVENTIONAL; Units: Euro/Year

depreciation alternative = Capital Alternative Energy Technology / DEPRECIATION TIME ALTERNATIVE; Units: Euro/Year

DEPRECIATION TIME CONVENTIONAL = 30; Units: Year

DEPRECIATION TIME ALTERNATIVE = 30; Units: Year

desired capital energy technology = COEFFICIENT DEM-CAP * DEMAND; Units: Euro

effective capital conventional = Capital Conventional Energy Technology - (BUILDING TIME CONVENTIONAL * depreciation conventional); Units: Euro

effective capital alternative = Capital Alternative Energy Technology - (BUILDING TIME ALTERNATIVE * depreciation alternative); Units: Euro

FINAL TIME = 100; Units: Year

inclination to invest conventional = sunk cost conventional / (sunk cost conventional + sunk cost alternative); Units: Dmnl

INI AC = 1000; Units: Euro

INI CCET = 900; Units: Euro

INI CAET = 100; Units: Euro

INI P = 0; Units: pollUnit

INITIAL TIME = 0; Units: Year

investing in conventional energy = min (inclination to invest conventional * lack of actual capital energy-technology, Available Capital) / BUILDING TIME CONVENTIONAL; Units: Euro/Year
investing in alternative energy=min((1-inclination to invest conventional)*lack of actual capital energy-technology, Available Capital)/BUILDING TIME ALTERNATIVE; Units: Euro/Year

lack of actual capital energy-technology=max(0, desired capital energy-technology-(effective capital conventional+effective capital alternative)); Units: Euro

Pollution= INTEG (production of pollution-absorption of pollution, INI P); Units: pollUnit

production of pollution=Capital Conventional Energy-Technology*COEFFICIENT CAP-POL; Units: pollUnit/Year

sunk cost conventional=Capital Conventional Energy-Technology; Units: Euro
sunk cost alternative=Capital Alternative Energy-Technology; Units: Euro