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by

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I. INTRODUCTION

The energy related industries are sectors where, compared to many other industries, extremely long time horizons are relevant for the strategic planning of the actors. On the one hand the investment costs are extremely high and most often irreversible, i.e. the power plants cannot be used for other purposes, on the other hand also the investment time of constructing new power plants and complementary activities as the construction of distribution networks is extremely long. Additionally, the influence of regulatory authorities as well as political actors is strong due to the specific industry history (i.e. energy is considered of decisive national importance) and the strong interrelation to other economic and social activities (e.g. environmental issues, transport etc.). Finally, technological development most often is extremely costly as well as uncertain, which makes joint efforts between public and private actors necessary. Having in mind these specific industry characteristics, the energy sectors

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seems to be of outstanding interest when it comes to the analysis of the long run and technological driven evolution of industries.

Although, meanwhile there exists a rather long tradition in economics to study the transformation of industries starting at the begin of the 20th century with Schumpeter, Kuznets and Clark, since the late 1950s this long-term view has been lost in the industrial economics literature. Responsible for this are basically two reasons:

On the one hand, industrial economics was mainly embedded in the dominating neoclassical framework and its so-called Structure-Conduct-Performance-Paradigm (e.g. Bain, 1956). Due to the specific assumptions necessary for an analysis within the neoclassical framework, a process perspective including qualitative change and development is neglected. Instead, only the quantitative dimension of potential equilibrium states and its comparative static are considered. On the sector level this means that the analysis is restricted to long run equilibria structures describing e.g. the number of firms in a particular industry without putting emphasis on those factors driving the emergence and maturation of industries. By restricting their analysis on the quantitative dimension, industrial economics implicitly confines itself to the analysis of a system characterized by a constant set of activities and proportional development basically neglecting innovation processes and technological development.

On the other hand, since the early 1980s the upcoming evolutionary strand within economics is responsible for a so-called *Schumpeterian Renaissance* (e.g. Giersch, 1984). Within the evolutionary economics approach it is argued, that only by relaxing the strong assumptions of neoclassical economics an understanding of long run transformation processes within economies and with this of the sources of economic growth and qualitative change can be developed. Basically, instead of homogenous and well informed actors optimising their profits, in evolutionary economics the analysis draws on heterogeneous populations of bounded rational actors which experimentally try to improve their situation or even only to survive. However, the respective tools allowing the consideration of these constitutive elements were not available from the beginning but first have to be developed.

In evolutionary economics analysis is heavily supported by the tremendous development of and easy access to computational power within the last 30 years which has led to the widespread use of numerical approaches in almost all scientific disciplines. Nevertheless, while for example the engineering sciences focused on the applied use of simulation techniques from the very beginning, in the social sciences most of the early examples of numerical approaches were purely theoretical.

There are two reasons for this. First, since the middle of the 20th century, starting with economics, equilibrium-oriented analytical techniques flourished and were developed to a highly sophisticated level. This led to the widely shared view that within the elegant and formal framework of linear analysis offered by neoclassical economics, the social sciences could reach a level of accuracy not previously thought to be possible.

Second, within the same period, new phenomena of structural change exerted a strong influence on the social and economic realms. Despite the mainstream neoclassical successes in shifting the social sciences to a more mathematical foundation, an increasing dissatisfaction with this approach emerged. For example, by the 1960s the benchmark of atomistic competition in neoclassical economics had already been replaced by the idea of monopolistic and oligopolistic structures under the heading of workable competition (e.g. Scherer/Ross, 1990). A similar development emphasising positive feedback effects and increasing returns to scale caused by innovation led to the attribute "new" in macroeconomic growth theory in the 1980s (Romer, 1990).

In addition to these stepwise renewals of mainstream methodology, an increasingly larger group is claiming that the general toolbox of economic theory, emphasising rational behaviour and equilibrium, is no longer suitable for the analysis of complex social and economic changes. In a speech at the International Conference on Complex Systems organised by the New England Complex Systems Institute in 2000, Kenneth Arrow stated that until the 1980s the "sea of truth" in economics lay in simplicity, whereas since then it has become recognised that "the sea of truth lies in complexity". Adequate tools have therefore to include the heterogeneous composition of agents (e.g. Saviotti, 1996), the possibility of multilevel feedback effects (e.g. Cantner/Pyka, 1998) and a realistic representation of dynamic processes in historical time (e.g. Arthur, 1988). These requirements are congruent with the possibilities offered by simulation approaches. Accordingly, it is not surprising that within economics the first numerical exercises were within evolutionary economics.

The first generation simulation models were highly stylised and did not focus on empirical phenomena. Instead, they were designed to analyse the logic of dynamic economic and social processes, exploring the possibilities of complex systems behaviour. However, since the end of the 1990s, more and more specific simulation models that aim at particular empirically observed phenomena have been developed focusing on the interaction of heterogeneous actors responsible for qualitative change and development processes. Modellers have had to wrestle with an unavoidable trade-off between the demands of a general theoretical approach and the descriptive accuracy required to model a particular phenomenon. A new class of simulation models has shown to be well adapted to this challenge, basically by shifting outwards this trade-off: So-called agent-based models are increasingly used for the modelling of socio-economic developments.

Agent based models in an evolutionary setting seems to be the adequate tool for the analysis of long term qualitative developments as we can observe them in the energy related industries. Our chapter deals with design of a conceptual framework for such a model. The next section is concerned with the importance of an analysis of qualitative development in general and it is shown that evolutionary economics is offering an adequate framework for this. Section 3 then focuses on agent-based-modelling as "the" tool allowing to incorporate endogenously caused development processes. Section 4 deals with particular phenomena of qualitative change in the energy related industries. In section 5 the constitutive elements of an agent-based model of qualitative change in the energy sector are introduced. Section 6 closes the chapter with some conclusions and an outlook on further research.

II. QUALITATIVE CHANGE IN AN EVOLUTIONARY ECONOMICS PERSPECTIVE

When concerned with the examination of change and development processes within industrialized economies economists usually focus their attention on the movement of certain variables they consider a good description of the basic effects of economic growth and development. In mainstream economics the phenomenon of economic development is e.g. empirically analysed on the macro-economic level as the improvement of total factor productivity in time which lowers prices and leads to the growth of incomes. Accordingly, most often the GDP per capita is used as an indicator describing economic development in a quantitative fashion. Although it is impressing to observe the growth of income in economies over a long time span (fig 1), this indicator, due to its quantitative nature only, does not give any idea about the structural and qualitative dimensions underlying economic development. This becomes even more obvious on the sectoral level where the analysis is most often restricted to long run equilibria structure describing e.g. the number of firms in a particular industry without putting emphasis on those factors driving the emergence and maturation of industries. By restricting their analysis on the quantitative dimension, the economic mainstream implicitly confines itself to the analysis of a system characterized by a constant set of activities basically neglecting innovation processes.

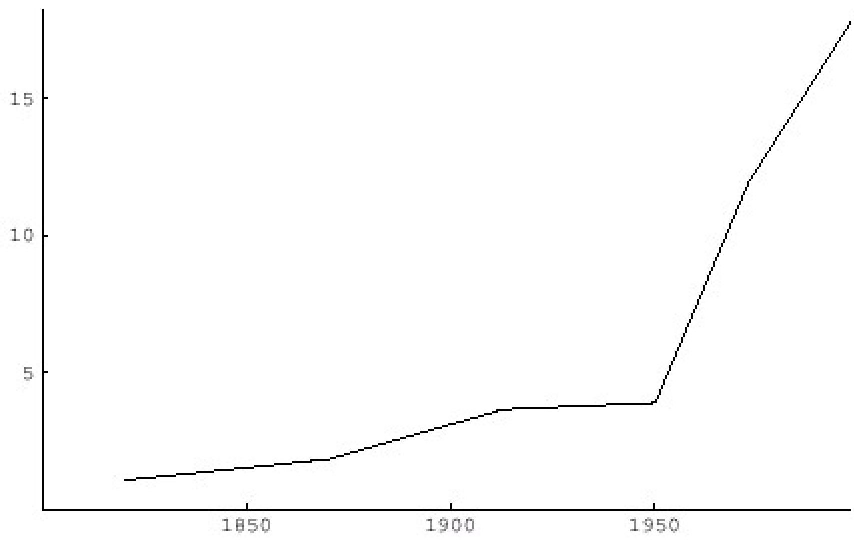

Fig. 1: Germany's GDP over the last 200 years

However, in less orthodox economic approaches it is argued, and it is indeed also one of Schumpeter's major contributions, that economic development does also include prominently qualitative changes not only as an outcome but also as an essential ingredient which justifies us to speak of transformation processes going on. Qualitative change manifests itself basically via innovation of different categories (e.g. social, legal, organizational) of which technological innovation very likely is among the most important ones. Qualitative change is the transformation of an economic system, characterized by a set of components and interactions into another system, with different components and different interrelationships (e.g. Saviotti, 1996). An analysis of qualitative change therefore necessarily has to include the actors, their activities and objects which are responsible for the ongoing economic development.

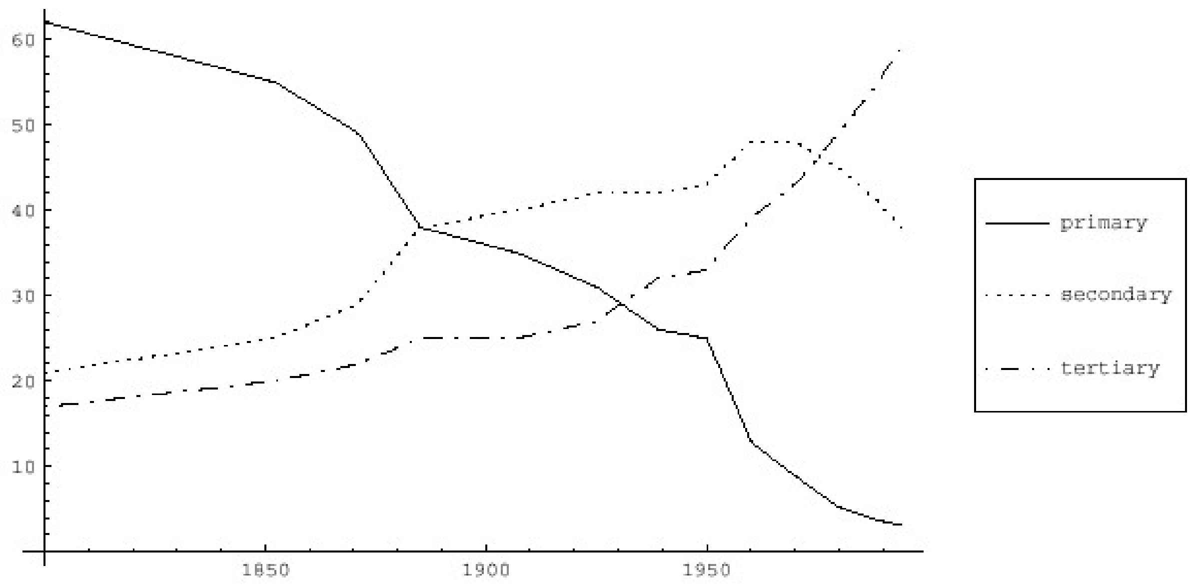

Fig. 2: Development of sectoral employment in Germany

An example for the significance of qualitative changes can be found in figure 2 which displays the development of employment shares of the primary, secondary and tertiary sectors in Germany for the same time interval as GDP per capita above. What strikes immediately is that everything else but a proportional growth of all sectors is taking place from 1800 to the 1990s. Instead severe and radical changes underlie the transformation of the economic system observed in figure 1. Of course there are many other variables e.g. the emergence of new industries, the increasing variety of different commodities available or the rate of introduction of new technologies which do also reflect the importance of the qualitative dimensions of economic development. By its very nature, the transformation of an economic system is a multi-facetted phenomenon. Accordingly, it is misleading to focus only on quantitative changes of the economy when analysing the driving factors of the transformation of economic systems over time. To better understand the mechanisms and dynamics behind the observed developments one has to explicitly include the qualitative dimensions. To achieve this, economic analysis has to consider besides the prevailing cost-orientation an important knowledge- and learning-orientation. The following paragraphs are concerned with the implications of this knowledge-orientation, which can also be considered as the heart of the matter of evolutionary economics.

Knowledge-based approach of evolutionary economics

It is beyond the scope of this contribution to discuss in detail the criticism brought forth by evolutionary economics with respect to assumptions underlying the mainstream economic reasoning. A major discussion can be found among others, in Dopfer (2001), Clark and Juma (1987) and Silverberg (1988). For our purposes it is sufficient to mention three major points, evolutionary economists claim to be of outstanding importance in the discussion of economic development processes and which are incompatible with traditional economic approaches. These points are also constitutive for that strand of literature within evolutionary economics which is concerned with industry evolution and technological progress namely the Neo-Schumpeterian approach. Here, instead of the incentive-orientation of neoclassical industrial economics a knowledge-orientation is underlying the investigation of industries and innovation processes in particular. First of all, the Neo-Schumpeterian theory wants to explain how innovations emerge and diffuse over time. A specific feature of these processes is uncertainty, which cannot be treated adequately by drawing on stochastically distributions referring to the concept of risk. Therefore, the assumption of perfect rationality, underlying traditional models cannot be maintained, instead the concepts of bounded and procedural rationality are invoked. Consequently, actors in Neo-Schumpeterian models are characterized by incomplete knowledge bases and capabilities. Closely connected, the second point concerns the important role heterogeneity and variety plays. Due to the assumption of perfect rationality, in traditional models homogeneous actors and technologies are analysed. Heterogeneity as a source of learning and novelty is by and large neglected, or treated as an only temporary deviation. Finally, the third point deals with the time dimension in which learning and the emergence of novelties take place. By their very nature, these processes are truly dynamic, meaning that they occur in historical time. The possibility of irreversibility, however, does not exist in the mainstream approaches, relying on linearity and equilibrium.

Thus, traditional economic theories, summarized under the heading of incentive-based approaches, with their focus on cost-based and rational decisions only, are excluding crucial aspects of actors' behaviours and interactions, which are influenced by a couple of factors lying by their very nature beyond the scope of these approaches. Although, of course cost-benefit calculations (with respect to innovation itself a problematic activity) play an important role, the actors’ behaviour is influenced additionally by several other factors as learning, individual and collective motivation, trust etc. It is the role of these factors the knowledge-based approach of evolutionary economics explicitly takes into account.

By switching from the incentive-based perspective to the knowledge-based perspective the Neo-Schumpeterian approaches have realized a decisive change in the analysis of the transformation of economic systems. In this light the introduction of novelties mutate from optimal cost-benefit considerations to collective experimental and problem solving processes (Eliasson, 1991). The knowledge-base of the actors is no longer perfect, instead a gap between the competences and difficulties which are to be mastered opens up (Heiner, 1983) (C-D gap). There are two reasons responsible for this C-D gap when it comes to innovation: on the one hand, technological uncertainty introduces errors and surprises. On the other hand, the very nature of knowledge avoids an unrestricted access. Knowledge in general, and new technological know-how in particular, are no longer considered as freely available, but as local (technology specific), tacit (firm specific), and complex (based on a variety of technology and scientific fields). To understand and use the respective know-how specific competences are necessary, which have to be built up in a cumulative process in the course of time. Following this, knowledge and the underlying learning processes are important sources for the observed heterogeneity among agents.

Challenges for analysing qualitative change

From the discussion above we can identify two major challenges for an analysis of qualitative change:

The first challenge is that a theoretical framework adequately displaying our notion of qualitative change has to incorporate concepts that comply with the notion of development of evolutionary economics in the sense Nelson (2001) discussed. Basically he refers to path-dependencies, dynamic returns and their interaction as constitutive ingredients for evolutionary processes in the socio-economic realm.

The second challenge is, that we generally have to focus on both, the micro- and meso-level of the economy as to our understanding the term qualitative change refers to a changing composition of components and interaction of and in the economic system. In doing so we can identify some stylised facts that are considered of crucial importance when qualitative change in an economy is considered. The most obvious ones are:

First, an increasing importance of knowledge generation and diffusion activities is observed at least in the sectors of the economy that are considered to be the most dynamic and innovative ones. This coins the notion of a transformation of the economy into a knowledge based economy. Second, this is accompanied by a continuously increasing specialisation and related to this an increasing variety of products and services coexisting simultaneously. Third, specialisation and differentiation goes hand in hand with an increasing importance of (market and non-market) interactions between the agents. Fourth, behind this increasing variety we observe innovation processes that at the same time improve efficiency of the production process and the quality of the products. Fifth, this innovation process is driven by competition selecting between different technological alternatives. Finally, the environmental constraints can be considered as filter- and focusing devices in this selection process either supporting or suppressing the diffusion of new technologies.

Once the relevance of these facts for the transformation of an economy is accepted the research has to account for those developments adequately.

Micro- and meso-perspective

Obviously this aim can only be accomplished by abandoning an aggregate perspective but instead focusing on a micro- or meso-level population approach (Metcalfe, 2001). This allows for examining diverse agents, their interaction and the knowledge induced transformation of both. By doing this, modelling openly has to take into account the importance of micro-macro-micro feedback effects (e.g. Silverberg, 1988). In their decisions actors obviously consider macro (-economic) constraints, but they also exert a significant influence on the altering of these constraints (Dopfer, 2001). The interrelated inspection of the meso- and the micro-level reflects the idea that analysis on the aggregated meso-level relies on description whereas the analysis of the micro-level focuses on explanation of the phenomena found on the meso-level (Dopfer, 2001).

Knowledge

Considering this will lead to a revision of standard economic models as analysis here follows reality closely. Traditional ‘production functions’ include labour, capital, materials and energy. Knowledge and technology are only external influences on production. However, recent analytical approaches have been developed allowing the explicit consideration of knowledge as well as learning of actors as a mean of acquiring new knowledge. Improvements in the knowledge base are likely not only to increase the productive capacity of the other contributing factors of production and to lead to the introduction of new products, as a visible outcome of the transformation process, but also to alter the organizational processes of knowledge creation, namely the interrelationships between the actors. Thus, transformation relates to a result- and a process-dimension similar to the terminology elaborated in Herrmann Pillath (2001).

Consequently, it cannot be assumed that there exists a fixed set of activities and relationships in the social and economic sphere, especially when it comes to knowledge generation and learning. But this does by no means imply that no such set exists at all. It does exist, although, by its very nature it is evolving continuously. In this respect transformation does not only refer to the feedback processes, but it does also and with major relevance refer to the change of the set itself during the process. This is evolution, and evolution is the very reason for not using static equilibrium theories or dynamic models to analyse qualitative developments as they are based on the notion of reversibility. The notion of evolution demands that we resort to ideas of irreversibility and path-dependence.

III. THEORETICAL AND CONCEPTUAL CONSIDERATIONS

An exploration of settings fulfilling the above requirements very likely needs numerical techniques, which are regarded as a major tool in evolutionary economics (Kwasnicki, 1998, Aruka, 2001). Although simulation analysis comes in various flavours most of them reflect Boulding's call that we need to develop 'mathematics which is suitable to social systems, which the sort of 18th-century mathematics which we use is not' (Boulding, 1991). An increasingly growing literature today now is concerned with the application of so-called agent-based-models. This approach consists of a decentralized collection of agents acting autonomously in various contexts. The massively parallel and local interactions can give rise to path dependencies, dynamic returns and their interaction. In such an environment global phenomena such as the development and diffusion of technologies, the emergence of networks, herd-behaviour etc. which cause the transformation of the observed system can be modelled adequately. This modelling approach focuses on depicting the agents, their relationships and the processes governing the transformation. Very broadly, the application of an *agent based modelling approach* offers two major advantages with respect to the knowledge- and learning-orientation:

The first advantage of agent based modelling is the capability to show how collective phenomena came about and how the interaction of the autonomous and heterogeneous agents leads to the genesis of these phenomena. Furthermore agent based modelling aims at the isolation of critical behaviour in order to identify agents that more than others drive the collective result of the system. It also endeavours to single out points of time where the system exhibits qualitative rather than sheer quantitative change (Tesfatsion, 2001). In this light it becomes clear why agent based modelling conforms with the principles of evolutionary economics (Lane, 1993a, 1993b). It is "the" modelling approach to be pursued in evolutionary settings.

The second advantage of agent based modelling, which is complementary to the first one, is a more normative one. Agent based models are not only used to get a deeper understanding of the inherent forces that drive a system and influence the characteristics of a system. Agent based modellers use their models as computational laboratories to explore various institutional arrangements, various potential paths of development so as to assist and guide e.g. firms, policy makers etc. in their particular decision context.

Agent based modelling thus uses methods and insights from diverse disciplines such as evolutionary economics, cognitive science and computer science in its attempt to model the bottom-up emergence of phenomena and the top down influence of the collective phenomena on individual behaviour.

The recent developments in new techniques in particular the advent of powerful tools of computation such as evolutionary computation (for a summary of the use of evolutionary computation and genetic programming in particular see Ebersberger, 2002) opens up the opportunity for economists to model economic systems on a more realistic i.e. more complex basis (Tesfatsion,2001).

No entity, even though it may exist without the actors has no influence on the current state of the system or the development of the system. To illustrate this point, bits of information have nil influence on the system as long as they are not put into the appropriate context by a capable individual, influencing its activities. Any resource cannot change the system as long as it is not used for carrying out certain activities that change the nature and the structure of the system. Hence in the centre of the stage there is the actor and its activities.

IV. REASONS WHY TO STUDY THE ENERGY SYSTEM

The energy sector seems to be an example *par excellence* for our purposes outlined above due to a couple of reasons: The energy sector is relevant for the entire economy. In figure 3 we see the development of the world energy demand for the last 150 years continuously increasing over the whole time span with an increasing rate after world war II.

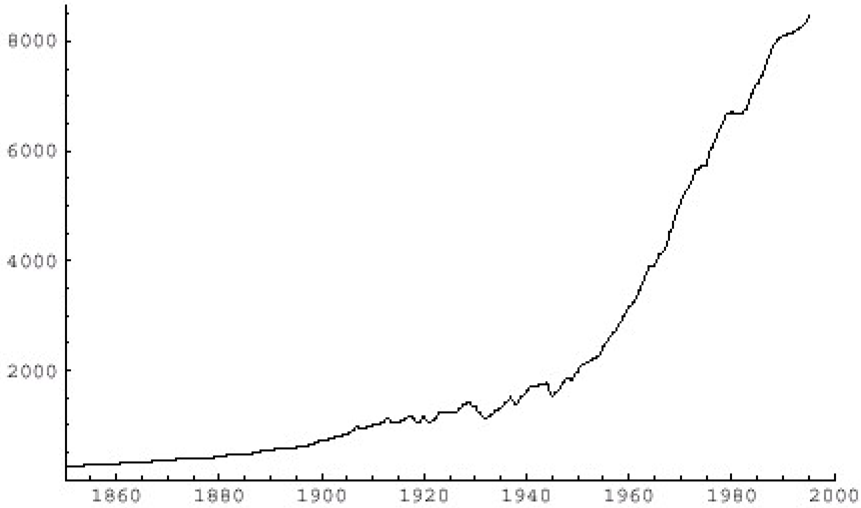

Fig. 3: Development of world energy demand within the last 200 years

Regarding the development of primary energy resources in figure 4, it becomes obvious that the importance of different energy sources diverges over time and that new energy sources enter the scene from time to time. We find the development of the shares of different energy sources over the same time interval. Whereas the importance of wood is decreasing in time and coal had reached its peak around the turn of the last century, natural gas entered the scene not before then. Nuclear energy technologies were not available before the 1960s.

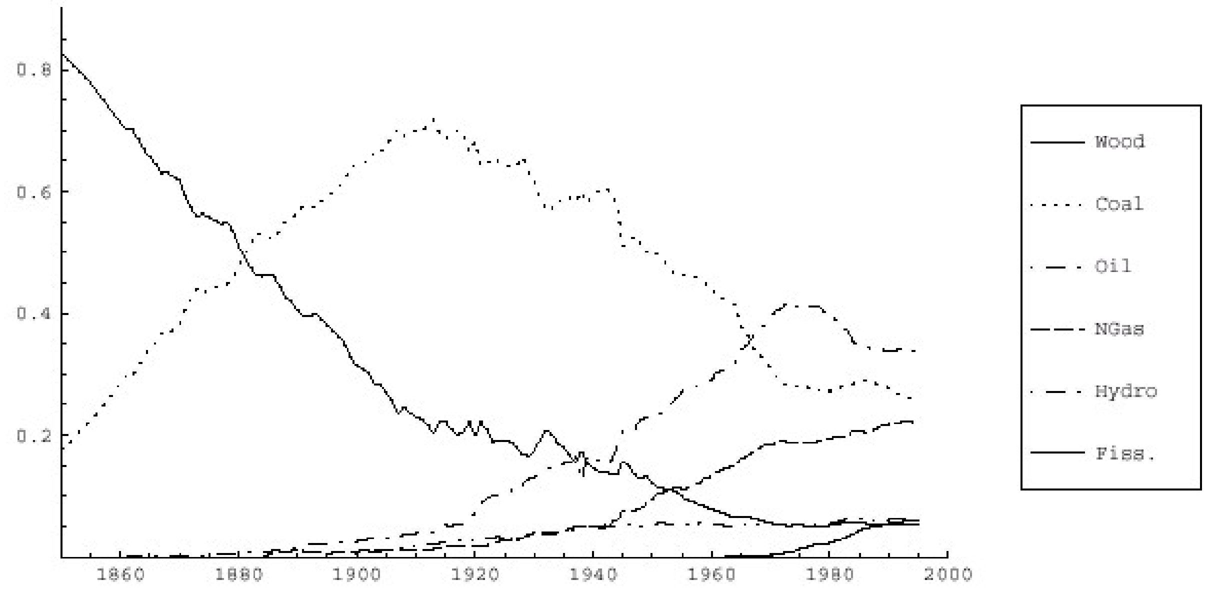

Fig. 4: Development of the shares of primary energy resources

Furthermore, compared to other sectors, qualitative change proceeds in relative long time periods. Accordingly, different mechanisms and effects are comparatively easier to separate as not too many overlapping developments are to be expected, which would make the discrimination of causes and effects more difficult. Related to this, not invention as the original idea creating is of particular importance, but the first commercial application i.e. innovation as well as the spreading of the new technologies i.e. diffusion. This means that in the analysis, when it comes to incremental innovation in the diffusion process, technological uncertainty is less severe. Most often the relevant technologies already exist as blue-prints and the transformation process basically deals with the application and improvement of these technologies.

In this respect, the political system exerts crucial influence on the transformation process asking for the applied population perspective including the interactions between economic and political actors. Finally, the transformation in the economic system very likely leads to qualitative changes in the energy demand, such as the most recent decoupling of economic growth and energy demand. Here, on the one hand, again political efforts as e.g. the Kyoto-protocol shape this development. On the other hand, however, it is very likely that within the bundle of goods and services in the demand function, the degree of knowledge-intensity increases and the degree of energy-intensity decreases parallel with the emergence of the knowledge-based economies. Whereas, as already mentioned above, the creation of knowledge is accompanied by positive external effects, due to thermodynamic principles the use of energy goes hand in hand with negative externalities. In this respect, an increasing knowledge intensity in production and demand is very likely to lead to a changing energy intensity of economic growth. Figure 5 illustrates the interesting decoupling of the world energy demand from the development of the GDP since the 1970s

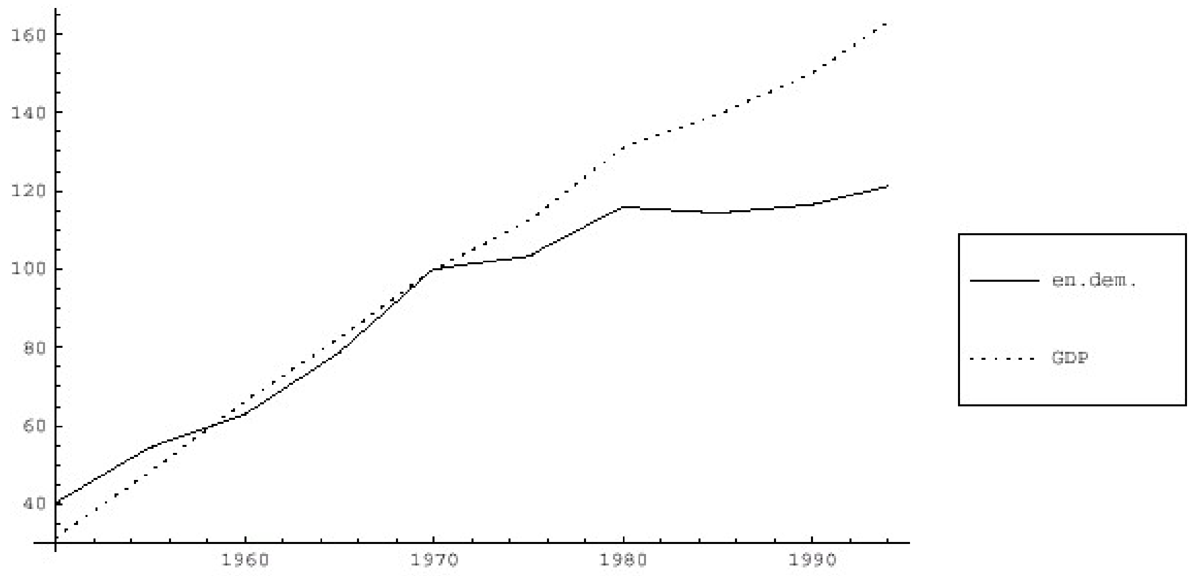

Fig. 5: Development of world's energy demand and GDP (index)

V. BUILDING BLOCKS OF THE MODEL

In accordance with the principles elaborated in the above section the techno-economic model of the energy system utilizes the agent based approach (Gilbert and Troitzsch, 1999, Tesfatsion, 2001). A conceptual framework for the analysis of long run qualitative change can be composed of the following building blocks. In particular we consider *actors*, *action*, *endowments*, *interaction* and *evaluation & decision processes* as the decisive building blocks for such a model.[1] The building blocks discussed here are not separate and unrelated entities. Rather are they the result of a systematisation process. They represent our conceptual view on

[1] Recently Mathews (2001) develops a conceptual framework for the analysis of an industrial market system, which is quite close to our building blocks. However the building blocks introduced here take account of the broader research program.

the issue developed to clarify the analytical concepts and to facilitate implementation of the simulation model in the second step. In the following sections we sketch the building blocks.

Actors

We consider actors being the major driving force in the evolution of the energy sector. As such, we regard them as the reason for the manifestation of qualitative change in the system. They are the crucial components of the system. The model requires a multi-agent approach, which assumes that agents populating the model can be divided into various categories according to their activities, resources, routines and relations.

On an aggregate level we have to distinguish different groups (populations) of actors that share common features, discriminating one population of actors from the others. However underneath the surface of the group we find a heterogeneous population of individual actors each being characterized by individual features.

Accordingly, a central issue is the general design of the actors. Actors are represented as code that has the standard attributes of intelligent agents (Wooldridge and Jennings, 1995):

- autonomy, which means that agents operate without other agents having direct control of their actions and internal states. This is a necessary condition for implementing inter- and most importantly intra-population heterogeneity.

- social ability, i.e. agents are able to interact with other agents not only in terms of competition but also in terms of cooperation. This includes the possibility to model agents that show various forms of interaction blended from competition and cooperation.

- reactivity, agents are able to perceive their environment and respond to it.

- finally, proactivity enables the agents to take the initiative. This means that they are not only adapting to changing circumstances, rather are they engaged in goal-directed behaviour.

The above points indicate that the actors in the simulation are able not only to adapt their behaviour to a given set of circumstances. In a Neo-Schumpeterian sense they are also able to learn from their own experience and to modify their behaviour creatively so as to change the circumstances themselves.

When modelling the features and characteristics of the artificial agents the above mentioned standard attributes have to be implemented. As the agents in our conceptual framework can be characterized by their *actions*, *endowments*, *interactions* and their *evaluation & decision processes*, these conceptual building blocks have to be designed such as to reflect the attributes.

Actions

The different actions performed by different actors enable us to classify certain groups of actors. Not only is it the actions that we use as a demarcation of different groups of actors - their endowment might be another criterion for differentiation - but actions is one of the most striking one and connected to the other features such as endowments, interactions, etc. that will be discussed below. At a first glance, we could distinguish between firms and households as the first group producing commodities and the latter group consuming them. However, we will discuss below that the grouping of households and firms cannot be sustained in the context of the energy system.

Energy-producing actors

Concerning the population of firms the actions of some firms might complement each other as most firms only account for a small fraction of the total production chain necessary for the energy sector's final energy production. The activities involved range from mining and refining of the resources to production and distribution of the final energy. On this grounds we differentiate the groups of actors according to their actions.

The actions carried out by the firms producing and distributing the final energy are constrained by the available and most of the time by the installed technology. Of course new technology can also be searched for by the individual firm, however this contributes only a minor part. The major part of the "new technology" can be regarded a given and the firms are able – given they acquire the respective competences and capabilities – to choose a specific technology. Their research and development activities are then basically concentrated on the improvement of the application of the different technologies.

Energy-consuming actors

Concerning the energy consumption we can distinguish two main populations of consumers following the activity energy is used for.

First, firms use energy as a factor of production. Energy enters the production function in the same way capital, labour and knowledge does. By combination of the factors firms produce commodities endowed with characteristics which give positive utility to the final users of the goods. In mainstream economics firms are usually seen as optimising the amount and kind of goods produced subject to some constraints.

Households consume energy not because of the direct utility gained from energy consumption but use energy as a factor of the household production. Energy has to be moderated by a process of factor combination to yield goods or services with characteristics that deliver utility to the household. Other factors of production such as capital and labour influence the efficiency of the energy use in the household. The goods and services produced in the household range from meals which need household appliances as capital goods, human labour and the ingredients and energy as factor inputs to mobility which needs cars as capital goods, human labour and gasoline as inputs. Hence, the households energy use can be modelled by a household production function.

Regulatory authorities

Referring to the conceptual framework of an industrial system (Mathews, 2001) it becomes obvious that for our purposes we have to broaden the view. We have to add actors other than firms to the description of the system. Policy actors shape the energy system in a decisive way by designing the overall framework within which the other actors operate. Consequently, our analysis cannot do without this particular group of actors responsible for the rules of the game. Furthermore, and particularly important when it comes to the analysis of long run transformation processes, policy actors also bridge the gap between basic and applied research. This means that most often those technological strands are developed to a commercial application which survive a politically guided selection process.

To summarize, we consider the following populations of actors: Agents responsible for the production and distribution of energy, commodity producing agents who use energy as a factor of production, as well as energy and commodity consuming agents, and policy making and regulating agents. By this, we acknowledge the role of the energy producing and consuming entities as well as the regulatory entities in shaping the energy sector. However, as already mentioned, the actors within one population do not exhibit homogenous behaviour, rather they are differentiated in terms of their carrying out of certain actions.

Routines

Each of the basic categories of actors is not modelled by a representative agent but by a population of heterogeneous agents. For any of those subpopulations rules and routines can be derived which govern the particular actions of the agents, the interaction and the interrelation of the agents within and among the sub-populations. Actions and routines are conceptually closely related. Take for example an electricity producing firm. The production of energy is the action of this particular firm. However, the way electricity is produced is governed by routines. Hence routines are realizations of actions and it is through routines that actors manipulate reality. It is not only the endowment with resources that shapes the nature of the actors it is their individual routines that make up a large part of the actors heterogeneity. Nelson and Winter (1982) relate routines to the satisficing behaviour and the bounded rationality of actors. Routinized behaviour causes some stickiness and some inertia of the system, that results in some stability of the system – stability, at least to a certain degree.

Households e.g. do not optimise their heating behaviour, they rather want to keep the room at a comfortable temperature, which might vary for several degrees centigrade. This behaviour translates into their energy demand, be it the immediate demand of natural gas or electricity or the amount of oil being kept on stock for the winter.

Large integrated energy suppliers e.g. maintain a simple rule based on the difference between wholesale or retail price of gas whether to stock gas, to resell it or to use it for electricity production.

Routines on the part of the commercial actors can be thought of being business processes and standard operating procedures. On the part of the households routines can be thought of habitualised or automated procedures and activities. Routines are repeated on a regular base as long as they lead to a sufficient result, then they are modified. Repetition of the routines results in a certain degree of stability of the system without requiring that the agents being fully rational and fully informed. In the context of the energy system it becomes obvious that the assumption of fully rational individuals can not reasonably be sustained. Who of the consumers e.g. knows precisely how a nuclear power plant works, what inputs are necessary to create which amount of electricity?

As indicated the actors manipulate reality through their routines. Hence routines are not only focused on internal procedures of the actors, but they also govern external relationships with actors of the same basic group and with actors of other groups. However routines of one group can only be replicated by actors of the same group. For simplicity we assume that routines cannot transcend the boundaries of the specific groups of actors.[2] Households may replicate successful routines of other households by imitation and learning, firms may imitate successful routines of competitors and collaborators often moderated and facilitated by business consulting companies.[3] The actors however are not constrained to pick the most suitable one from a given set of routines, as would be the case for purely reactive agents. Furthermore proactive agents can create routines themselves, try them and discard them if the routines do not meet the desired results. They can also continue using them once they are deemed to be successful. When creating new routines the actors do not have to design them from scratch most often agents adopt routines and modify them so as to customize them to their particular needs. Hence, building proactive agents for the simulation hinges on the implementation of routines, their modification and their updating.

Endowments

Access to material and immaterial resources, their availability together with the competences make up the endowment of the actors. They combine components of the endowment in production processes. Accordingly, the endowments are the crucial assets of agents in accomplishing their tasks be it production or consumption. Following Matthews (2001) what makes the difference of the evolutionary perspective compared to more conventional economic perspectives, is that resources are also the decisive factor which allow for

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[2] This assumption is in contrast to the idea of benchmarking in the business literature, where key features of "best" routines of units from other and unrelated sectors are the bases of improvement

[3] Here again the hierarchical composition of the model enables us to structure and stress the relevant features and to unify the building blocks and their relation so as to facilitate setting up an appropriate simulation model. The hierarchical composition in the context of routines refers to the micro-meso analysis laid out in the exposition above.

heterogeneity between the firms. This becomes even more important, as a specific resource endowment does not determine completely the output of a firm. The range of possible outputs, follows only from the actor's specific combination of its resources with its routines (see above).

All actors are characterized by different sets of endowments. This is true not only for the different populations of actors, but also for the actors within the single populations identified above. For example energy producing firms differ considerably with respect to their capital stocks which are not only of different age but also restricted to very specific technologies e.g. nuclear power stations or wind turbines. Furthermore, the access to primary energy resources on the one hand as well as to distribution networks on the other hand does make a decisive difference between single actors. Of course, also the commodity producing firms differ considerably in their energy dependence (e.g. steel companies vs. consulting companies) as well as on specific energy sources (e.g. oil vs. natural gas). In the same way, households cannot simply switch between alternative energy sources (e.g. natural gas vs. solar energy) but are dependent on distribution networks (e.g. gas pipelines), their specific income situation etc. Finally, different regulatory actors have rather specific possibilities to influence the energy markets which ranges from the fostering of certain technologies (technology policy) to the design of general contracts between the energy supply and demand side (regulation).

Concerning the standard attributes of agents its is obvious that autonomy of the agents can only be achieved with the notion of personal and individual endowment of certain factors. It is the idea of individual property rights on production factors or income that enables us to model actors acting on with their sets of endowments. There is no governing entity to rule the spending or the use of endowments as long as the agents obey the rules set up by the regulatory authority.

Interactions

Concerning the relevant interaction between the different actors in our model, we have to consider a rather broad set of relationships ranging from competitive to cooperative, from bilateral to multilateral as well as from decentralized to hierarchical relations. Furthermore, a technological as well as an economic realm has to be considered. For example not only technological competition (e.g. coal vs. nuclear power) shapes the qualitative development of the energy system but also the exploitation of complementary relationships between different demand needs (e.g. combined heat and power systems) or synergies between capital goods producers and energy suppliers. Also, economic competition can go hand in hand with cooperation between different actors, for example in market consolidating periods when networks of actors bundle their efforts (e.g. via mergers) and competition takes place no longer between different individual actors but between different networks (e.g. recent developments in the German electricity market). Cooperative relationships can also be found in user-producer relationships when e.g. transactions are characterized by long term contracts or technological specificities. Very prominently, network externalities shape the relationships in most of the energy markets, where the supply is pipeline-bounded. Additionally, hierarchical interaction is central for the regulatory authorities which on the one hand design the rules of transactions and on the other hand do play a moderating role between different actors or population of actors.

Evaluation and decision processes

The discussion up to this point reveals that we have to cope with a heterogeneous set of actors. Some actors produce energy, some consume it or use it for household production, some actors regulate, some actors maximize utility others satisfice.

The question here is, how to unify the decision process of such a diverse set of actors while preserving the possibility for heterogeneity.

If we resort to imaging the decision process as a competition of several possibilities and the selection of one of the possibilities we can use an evolutionary terminology to describe the process. Let us use the term fitness function[4] for the device that evaluates the possibilities and let us furthermore use the term selection for picking one or several of the possibilities. We model the prototype of the decision process in two stages.

First, a real world actor can only decide on the actions and routines he carries out on the bases of his perception of reality. The perception of reality by a real world actor is a mental representation of the world. Hence, by its very nature it is a model. A modelled actor contains models of the (modelled) reality. The actors' mental modelling of the current state of the

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[4] Again we use a notion also found in Mathews (2001). However we substantiate the idea and depict the decisions a two staged process.

reality however, is not a bijective mapping of the reality into the symbolic representation. Rather are there several models that are compatible with the observations available to the actor. In addition to the current state of the reality the actors condense possible future states of the reality into scenarios. To have a bases upon which the actor can decide, the most likely one has to be selected from the set of the competing mental models of reality. A fitness function e.g. representing the likelihood of each model does the job. A mental representation of this type can be modelled e.g. by genetic algorithms or genetic programming as can be seen in Dosi (1999) or Edmonds (1999).

Second, on the bases of his perception of the real world the actor decides on the actions to perform. As any situation can be handled by various actions and routines the actor has to choose which one to take. Here again we can think of a fitness function ruling the choice process. By focusing on certain features of the actions and routines and ignoring other characteristics the fitness functions in this stage implicitly include the aims of the actor.

The use of the metaphor fitness function requires the notion of selection as a subsequent step. The selection process performed after the fitness evaluation of the activities represents the type of behaviour the actor is assumed to perform.

The building blocks introduced above constitute the dynamics of a socio economic model which in a further step have to be connected with the technological realm in order to combine the socio-economic dynamics with real world phenomena. This makes sure that the realisticness of the model is taken care of.

Technology

To model the interaction of the agents the model needs a technological background, that is strongly determined by the characteristics of the already available or soon available technologies of energy transformation, transport and distribution. This background of the model consists of a flow model of the energy system that incorporates the energy resources and the technologies to transform and distribute the energy. As we model this by a directed graph we can easily track and manipulate the flow of energy from the resources to the end-user. Manipulation of the flow model is necessary as the introduction of a new technology such as fuel cells or photovoltaic changes the structure of the model and changes the background for the interaction of the agents. The agents however can change the structure and the content of the flow model according to their preferences, too. Again, here we have a component of the model that causes mutual interaction with other components.

VI. OUTLOOK

The agent-based model offers a possibility for investigating the socio-economic interrelationships in the energy system. Whereas the energy flow model incorporates the technological and environmental aspects of the energy system. Hence, each model has its particular and therefore restricted problem domain. We argued above that the energy system is characterized by strong socio-economic and techno-economic interdependencies. Those cannot be analysed in either the agent-based model or the energy-flow model in their stand-alone-version. The valuable insights on the mutual dependency of the socio-economic and the technological sphere can only be gained by a fusion of both models.

A fusion of both models will allow for the analysis of socio-economic and techno-economic characteristics of the system and will enable us to shed new light on various transition processes.

In particular we will apply the merged framework on two recent transitions in the German energy system. In the first endeavour we try to reconstruct the transition of the room-heating systems from oil to natural gas. The second transition to be modelled is the emergence and diffusion of technologies that exploit renewable energy sources and the effects of liberalisation and CO2-taxes on this.

Those two applications of the general framework will on the one hand be of particular interest to real-world agents such as energy suppliers and policy makers. On the other hand the application will serve as a tool to validate the methodological approach undertaken by this project.

An extension of our excavation in the energy system rises the question whether historical developments such as the large scale transition from wood to coal and from coal to oil can also be handled with the proposed methodological and instrumental framework.

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