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THE ROLE OF SYSTEM DYNAMICS MODELLING IN SUSTAINABILITY PLANNING

Márta SOMOGYVÁRI
University of Pécs, Faculty of Business and Economics, Hungary
somogyv@ktk.pte.hu

ABSTRACT

The energy market architecture has a great impact on present and future economics and society. The sustainability of our whole global civilization depends on the transition into the post-fossil epoch. System dynamic modelling provides strong and effective tools to evaluate and communicate the future strategic possibilities of whole industries and national and global markets. Two main subsidy politics exist to speed up the diffusion of renewable energy technologies: Feed-in-Tariffs and Green Certificate Markets. Three system dynamic models of the Hungarian renewable electricity sector were developed: baseline system, Feed-in-Tariff, and Green Certificates. These models reveal the dynamics and efficiency of the different subsidy-systems. The focus of the model is the investor, whose decisions depend on the risks and the costs of the technologies. It is possible to develop future scenarios in order to investigate the renewable energy-mix over the short- and long-term and to compare the overall costs. The lack of historical data prohibits the verification of these models, because in Hungary the Feed-in Tariff system will be altered every year and the Green Certificates were never introduced. The approach is nevertheless very useful as planning method. It makes it possible to estimate the impact of alternative politics on the development of whole systems; thus it can be the basic methodology in all kinds of sustainability planning on all levels.
Keywords: system dynamic modelling, sustainability planning, energy policy, renewable electricity system

INTRODUCTION

The energy market architecture has a great impact on present and future economics and society. The sustainability of our whole global civilization depends on the transition into the post-fossil epoch. Everybody knows this, everybody speaks about the necessity of the transition, but nobody is able to show the exact steps into this brave new world of renewable and sustainable energy system. We know, or we pretend to know what is coming, but we have no idea about the way, about the means and about the necessary measures. There is one factor, which is quite clear: the costs of fossil energy are rising and in the near future, not the costs, but the availability will be the real problem. The first question to the energy supplier countries will not be the price of oil or gas, but whether they are willing to provide the necessary amounts of fossil energy carriers or not.

Hungary is a small economy in ongoing crisis and there is always a question: who will finance the transition? Who will be able to invest into the Hungarian energy system? The key target set by the European Union is 20% of Europe's total energy consumption to come from renewable sources by 2020 (RED). Hungary was able to bargain this target and the country has to reach only 13%, but despite of this "success", it is impossible to see the long-term policy that could lead to the fulfillment of this obligation.

The state has a controlling function in every market economy; it has the possibility and the obligation to set the rules, to make legislations, to shape the market infrastructure, and to optimize the subsidy distribution in order to reach the most effective renewable energy system. How is it possible to shape an effective market architecture, if we have no or very limited experiences, if it is very complicated to copy the systems of other countries, if we do not have a strong evaluation strategy, if we have to boost innovative technologies with the money of the tax-payer, and if we would like to eliminate corruption and rent-seeking?

System dynamic modelling is able to answer these problems. The aim of this paper is to show the strength and limitations of system dynamic modelling in shaping future energy-market-architecture.

THE GENERAL ASSUMPTIONS OF SYSTEM DYNAMIC MODELLING

The driving forces of system dynamic modelling

System dynamic modelling is not a methodological approach, it is a philosophy. System dynamic models deal with social and/or natural systems, they use a non-experimental method in order to gain profound knowledge about the behavior and structure of systems. The main driving force in a system dynamic model is causality (*Forrester*, 1980).

This kind of modelling differs from the econometric models, where the correlative dependencies of the various variables are in focus, and from the cross-impact analysis, which is based on probability (*Legasto and Maciariello*, 1980). We are able to model very complex social systems only if we have an intuitive image of the relationships between the various elements and we do not stay on the surface, we will not be satisfied until we can identify their structural interdependencies. This is more than statistical correlation, because it is possible that the variables correlating statistically are not connected to each other. System dynamics sets the ambitious aim to reveal the causal connections between the system elements. The intuitive image of the system is called mental model, which has to be formalized in the way that it serves a given purpose. The goal of a particular formalized model defines the system boundaries, canalizes the choosing of exogenous and endogenous variables and determines the possibility of validation and the practical and/or theoretical applications of the information collected by running various computer simulations.

System dynamic models as communication tools

The computer simulations based on system dynamic models overwhelms us with a lot of data. In the focus of this kind of research is often not the connection between the real world and a simulation, but the model itself. The main interest in building system dynamic models will raise questions, such as:

- What are the driving forces of a real/hypothetical system?
- What will be the state of the world, if we introduce some measures?
- What should we do in order to reach a preferred state of the world?

The first question should be answered during converting the mental model into the computer simulation; the last question is about modifying the already developed model in order to test new assumptions.

The second question, which connects the purely theoretical curiosity with real social and political alternatives and practical problem-solving, defines the research of the internal behavior of the developed model. In the case that the model is able to generate the observed behavior of a particular system, than it is reasonable to test the effect of parameter-variation and/or variable-modifications on the model. This enables us to create links between the model and the real world. In this moment the model can be used as a communication tool in order to show the decision-makers the consequences of various measures. This is a kind of forecasting or testing the possible future outcomes of hypothetical actions.

THE SYSTEM DYNAMIC MODELLING PROCEDURE OF THE HUNGARIAN RENEWABLE ELECTRICITY MARKET

Fixing the problem

The design, implementation, monitoring and cautious, goal-oriented modification of the energy market architecture is a very complex task (*Sioshansi and Pfaffenberger*, 2006). A successful energy market functions well, if the society does not perceive its existence. Market reform failures, as the collapse of the Californian wholesale electricity market shows us that an energy market will be only in the case stable when the sector structure is the right one and the authorities let them run without too much interference (*Woo et al.*, 2003).

In the time of transition the governments must solve a complex task: they have to elaborate anew electricity market architecture in order to send correct signals for investment in the new, often innovative and sometimes very expensive non-fossil technologies.

The main issue here is to assess the right amount and kind of regulation, so that the electricity system remains technically and economically stable, the prices remain affordable and the energy-mix is compatible with long-term sustainability requirements.

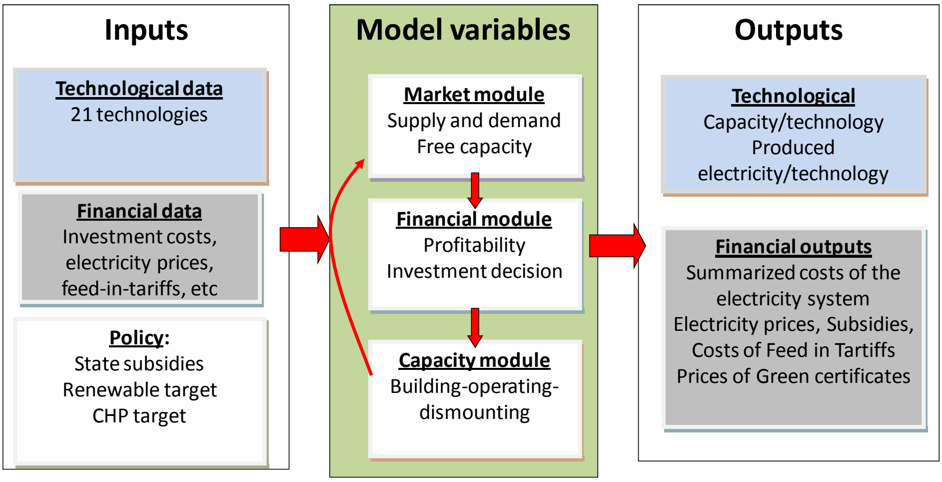
The system dynamic model of the Hungarian renewable electricity market developed by the Strategic Research Team of Pécs University is an investor focused model (*Somogyvári et al.*, 2010). The private investment in the electricity sector will shape the future technology-mix, and if we would like to force the transition into the non-fossil age, we have to examine the effects of the existing and alternative Hungarian regulations on the investor's decisions.

Shaping the model structure

The generic structure of the Hungarian renewable electricity market model is shown in *Figure 1*. This kind of model representation sketches the main functions and practical applications of any model regardless of the modelling philosophy or methodology.

Figure 1

The overall structure of the Hungarian renewable electricity market model



The input data includes the technological features of the most common 21 electricity generation technologies. In order to get a realistic view, we modelled the whole Hungarian electricity market: the renewable technologies, the CHP technologies and the fossil and nuclear capacities as well. The financial data are technology-specified data about investment costs, estimations about the future electricity prices and the Hungarian Feed-in Tariffs in 2010, when the time-line of the model starts.

The model variables on *Figure 1* portray the endogenous variables of the model. We find three modules there: the market model includes the market mechanism which steers the behavior of the actors, the financial module imitates the decisions of the investor and the capacity module keeps track of the capacity. The delay between the investment decision and the launching of the new capacity and the in time decreasing marginal costs of investment in new technology will be taken into consideration.

The outputs of the system depend on the interest of the researchers. In this case we are interested in the performance of the regulatory frameworks. The model calculates the capacity for each technology in each year on the 40 year timeline, the amount of the generated electricity and the overall costs of the electricity system, which include the investment costs, the costs of the electricity paid by the consumer plus the investment subsidies provided by the state.

Identifying the causal loops

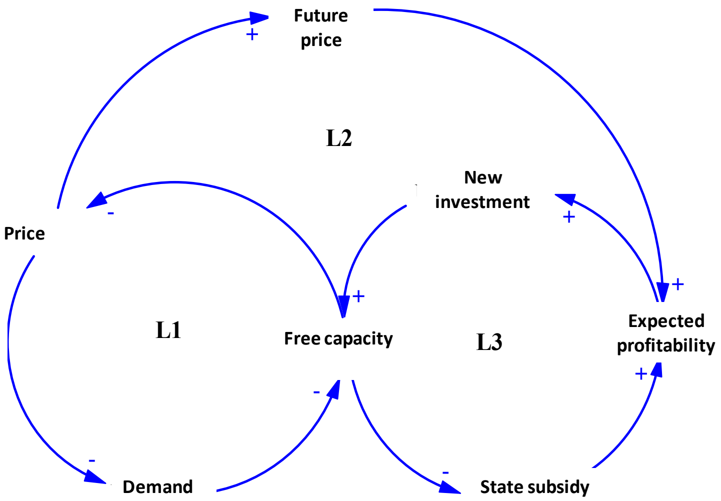
Electricity has unique features within the energy sector. The technical limitations of storing electricity, the necessity of keeping the same frequency in the whole grid and the minute by minute changing demand requires an accurate scheduling of electricity generation and a long-term capacity management. Moreover our whole society is dependent of electricity, so the security of supply is an important issue. Every intervention by the regulator, every attempt to introduce new technology has to guarantee the sufficient level of security in technical and economical sense (*Arriaga and Linares*, 2008).

Therefore the main driving force of our system is the free capacity. The demand and the supply is always balanced in the grid, otherwise the system collapses. In order to satisfy the peak demand the system should have always free capacity prescribed by the grid operator.

The causal links between the variables are depicted in *Figure 2*.

Figure 2

The basic causal loops of the Hungarian renewable electricity market model



The direction of the arrow shows the causal effect of one variable on another. The plus signalizes that if the value of the starting variable changes this will cause the change of the influenced variable in the same direction. The minus signalizes that the influence of one variable on the other will result the change in the opposite direction. The chain of the linked variables builds feedback loops. The feedback loop is the fundamental structure in a system-dynamic model.

If the free capacity in the grid increases, than the price of electricity will decrease. Decreasing electricity prices will increase the demand. (The situation in reality is not as simple, because instantaneous electricity demand does not vary in response to changes in instantaneous electricity price demand curve of electricity (*Colella*, 2003). We can speak about price elasticity only in the long-time horizon.) The increasing demand reduces the free capacity. This is a balancing, a so called "goal-seeking" feedback loop which stabilizes the system. The decrease of free capacity endangers the supply security. The state has the obligation to guarantee the supply security in the short and in the long term as well, so it tries to boost the investments into the sector with the help of subsidies. The subsidies signalize the investors that the profitability of the investments will improve, this leads to decisions about new investments. The new investment will decrease the free capacity, which signalizes the state to cut the subsidies. This is although a balancing feedback-loop. The third feedback loop connects the price by the expected future price with the expected profitability and explains the connection from the increasing prices to the new investments in the form of a balancing feedback-loop. The overall causal map of the entire system is much more complicated but this simplified presentation reveals the logic and the main internal structure of the investor-focused model of the electricity market system.

In order to investigate the impact of the possible market architectures we developed three models: a basic model, a model of the Green Certificate and a model of the Feed-in-Tariff system.

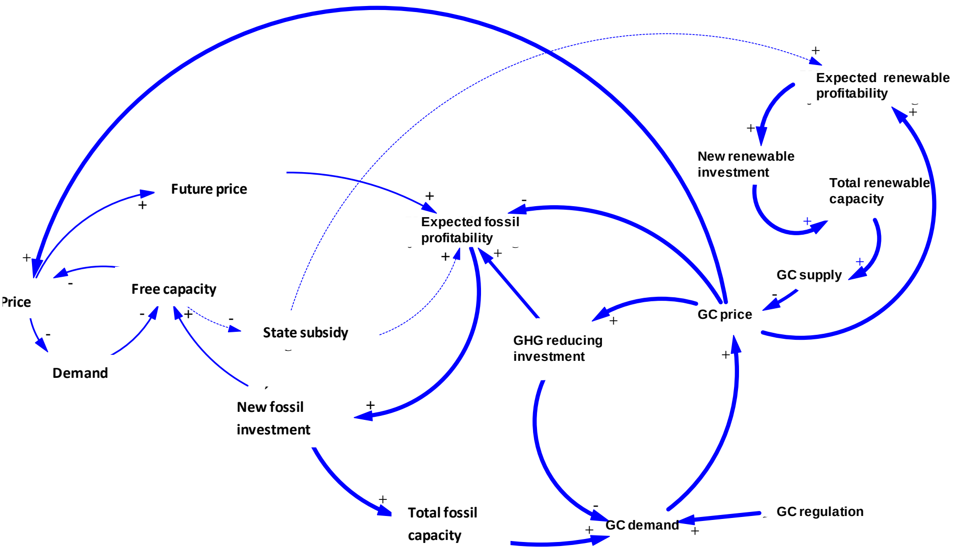
Modelling the Green Certificate and the Feed-in-Tariff system

The Feed-in-Tariff system alters the investment decisions of the potential investors by increasing the profitability and decreasing the risk associated with the new renewable technologies. The Feed-in-Tariffs give the regulator a possibility to express his preferences toward the non-fossil technologies. The tariffs will be set by the regulator which is the Hungarian Energy Authority (Magyar Energia Hivatal). Every investment will be evaluated and the actual tariff will be elaborated on the basis of the cost-structure of the particular project. This situation is a good opportunity for the investor to rent-seeking. The investor is interested in overstating the costs in order to get more subsidy and/or higher feed-in tariffs.

The Green Certificate system as shown in *Figure 3* creates an artificial market for Green Certificates.

Figure 3

The causal loops of the Green Certificate model



Every fossil electricity producer has to buy the emission permit, the Green Certificate (GC) which represents the right to emit or discharge a specific volume of the greenhouse gases (GHG). The renewable producers emit per definitionem no GHG and they can sell the permits. This will increase the investments into the renewable technologies or the investment into GHG reducing applications in the fossil power plants. The regulator has no possibility to influence the technology mix on project basis; he sets the framework by allocating the permits at the beginning to the producer and assigning the amount of the permits to each technology.

Developing the formal models

Feedback structures represented by causal loops provide an insight into the system behavior and represent a valuable tool to communicate mental models. The next step is to develop a computational model. The elements of the loops will be the essential components of the computational model, so the boundary of the model set by the problem definition predetermine the set of variables. The main problem is in this phase to determine which variable must be seen as endogenous or exogenous, how is possible to quantify the parameters and which functions describe the connections between the variables. The system dynamic approach to modelling is based mainly on difference-equation. The cause and effect view of the world will be demonstrated by flow-and-stock variables. The dynamics of the system-behavior originates from the cycles, stability, reduction and growths of the main stock variables (*Forrester*, 1980).

In our model the main stock variables represent the power plants in form of capacity. Every decision of an investor influences the future capacity of the whole grid. The investor makes a decision on a strict rational basis: the profitability and the risk of each technology will be weighed. While the profitability of each technology can be calculated, the quantification of risk is problematic. In the model we estimated the risk based on qualitative factors (diffusion, maturity, fallibility of the technology, volume of the investment, risk premium in project financing, etc.).

Setting the time-line for the simulation

The purpose of the model and the time-period of the system's cycles determine the time-line. We would like to examine the effect of the various frameworks on the whole grid, therefore it is not enough to take into consideration only the economical life-cycle of an investment, which is 20-25 year. We have to expand the time-line to the "technical" life-cycle, which is 40-60 year. So we have chosen a 40-year-long period, which seems to be too long if we look at the fast changing economics, technology and society of our century, but it is too short if we take into account that a newly installed PV panel will last 60 years and that is the lifetime of the new nuclear plants as well. The investors may have short or middle-time interests, and there might be fundamental structural changes, but history of the grid teaches us that the installed capacities are likely to function up to the end of their life-time (*Freese*, 2003).

Calibration and validation

The calibration of the model was completed with the data of benchmarking studies accepted by the Hungarian Energy Authority and with the Feed-in-Tariffs in 2010 in Hungary (*Pylon*, 2010). The current market framework in Hungary is the Feed-in-Tariff system, so the framework for the Green Certificate system was set in accordance with the 2020 targets of Hungary, determined in the Renewable Energy Directive of the European Union (*RED*, 2009) and in the Hungarian National Action Plan.

The validation of the models was not possible. This had some theoretical and some practical reasons. *Grubb et al.* (1993) explains that any model dealing with future situations makes use of estimates and assumptions which may or may not turn out to be valid under the changing circumstances, and will at the time of application inevitably be uncertain. The validation of a system dynamic model is always a controversial issue (*Starr*, 1980), because the system dynamic models often reveal the unusual behavior of a system and a validation with past statistical data does not guarantee that the model performs well in the future. The validation of our models was impossible because of the lack of data. The Hungarian Feed-in-Tariff system has been changed arbitrarily from year to year and the Green Certificate system was never introduced.

This is a serious methodological problem and therefore the whole modelling effort is open to criticism. The validation of a system dynamic model differs from the validation of an econometric model which is completed with statistical data. System dynamics deals with understanding the driving forces of the system, the validity of the model is given by the correct mapping of these driving forces into a formal model, the validation is the internal model structure per se (*Barlas*, 1994). If the model contains all the important variables and connections, and the structure of the model and the formulas (equations) match the available knowledge of the issue, we can speak about a "theoretical" validation. That was the case in our model. This does not exclude the demand for formal validation (*Barlas*, 1996), but in our case as mentioned above, this was impossible.

The lack and impossibility of validation determines the applicability of the results of our model. This is not a precise forecasting method, but an evaluation procedure in order to characterize the impact of the two market architecture on the technology mix and on the total costs. The assertions about the performance of the GC and FiT system are valid within the model boundaries, only if the decisions of the investors are fully rational. The driving forces of the models are the same in both cases, so the comparison is legitimized and can be transferred to the performance of the future renewable energy market systems in the real world.

Policy setting and scenarios

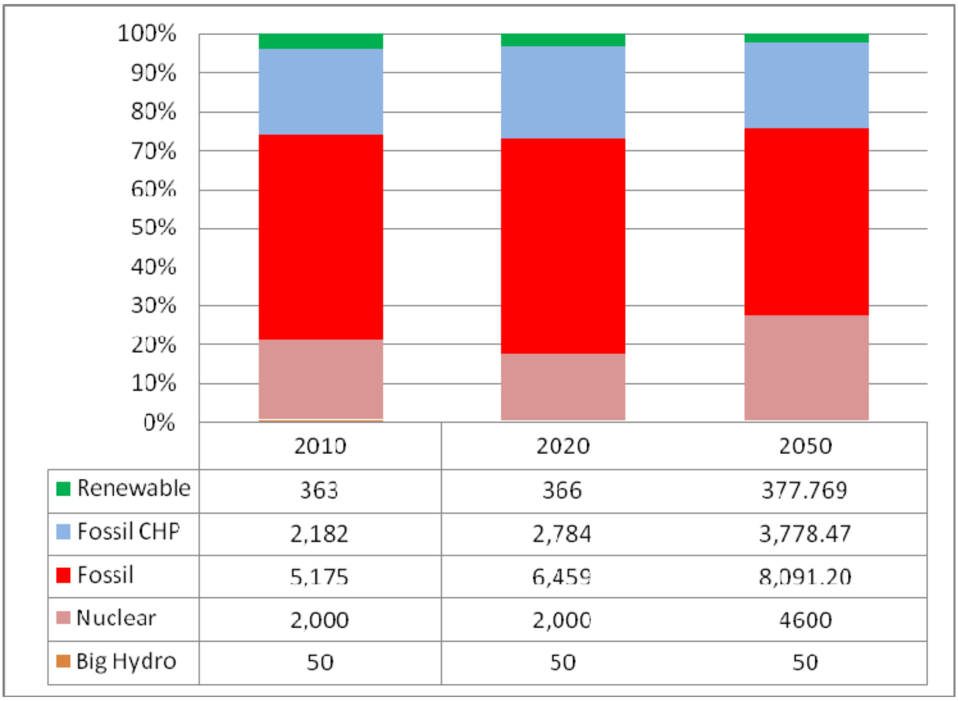
The relevance and impact of different policies can be compared in the simulation phase. The synergies among different policies are captured by the feedback-loops of the model, making possible the evaluation of particular policies or policy sets (i.e. subsidizing some technologies and/or lowering the risk by removing the various competitiveness barriers and/or increasing the Green Certificate obligation for the fossil producers, etc.).

In our model we examined the performance of the baseline, the FiT and the GC model in relationship with the total costs of the electricity system and the energy mix, and the effect of the state subsidy on reaching the 2020 target for renewable electricity generation, which was set as 15% of the total power production.

We were able to verify the necessity of the new market architecture in order to speed up the transition into the non-fossil era, because the basic model showed that the renewable technology would not grow otherwise as *Figure 4* shows.

Figure 4

The technology mix of the basic model in 2010, 2020 and 2050 (MW)



	2010	2020	2050
🟩 Renewable	363	366	377.769
🟦 Fossil CHP	2,182	2,784	3,778.47
🟥 Fossil	5,175	6,459	8,091.20
🟥 Nuclear	2,000	2,000	4600
🟧 Big Hydro	50	50	50

In order to compare the performance of both market systems we run a lot of simulations. We have found a lot of scenarios fulfilling the 15% target as shown in *Figure 5*.

For the sake of comparison we examined the capacity mix of these scenarios and we were able to find comparable capacity mixes with the same state subsidy policy in the Feed-in-Tariffs and in the Green Certificate electricity market architecture as shown in *Figure 6*.

Figure 5

Scenarios fulfilling the 15% target for renewable electricity production (MW)

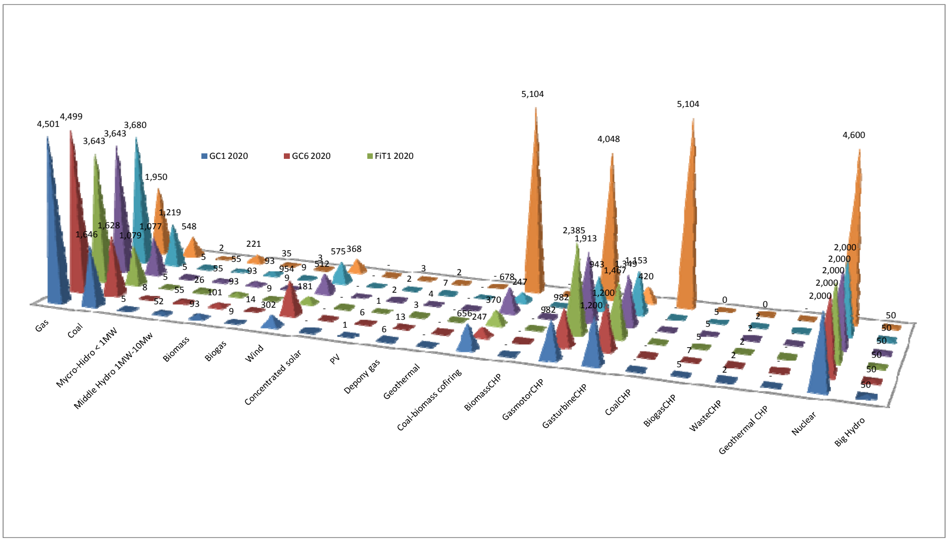
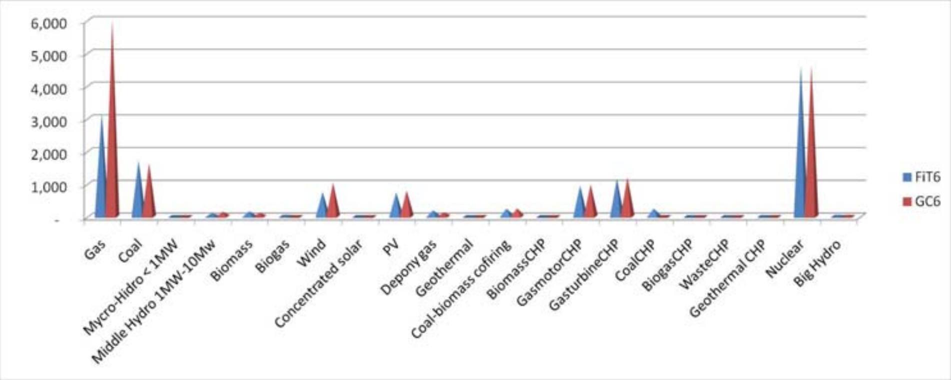


Figure 6

Scenarios with similar capacity mix under the same policy (MW)



The calculation of the total cost of the whole electricity system showed that the GC system in our model is faster and more cost-effective. The same technology mix with Feed-in-Tariff system was reached 12 year later and the cost of increasing the renewable capacity with 1 percentage per annum was 6 times more as in the GC model (*Table 1*).

Table 1

Financial performance of the two comparable scenarios in the FiT and CG model

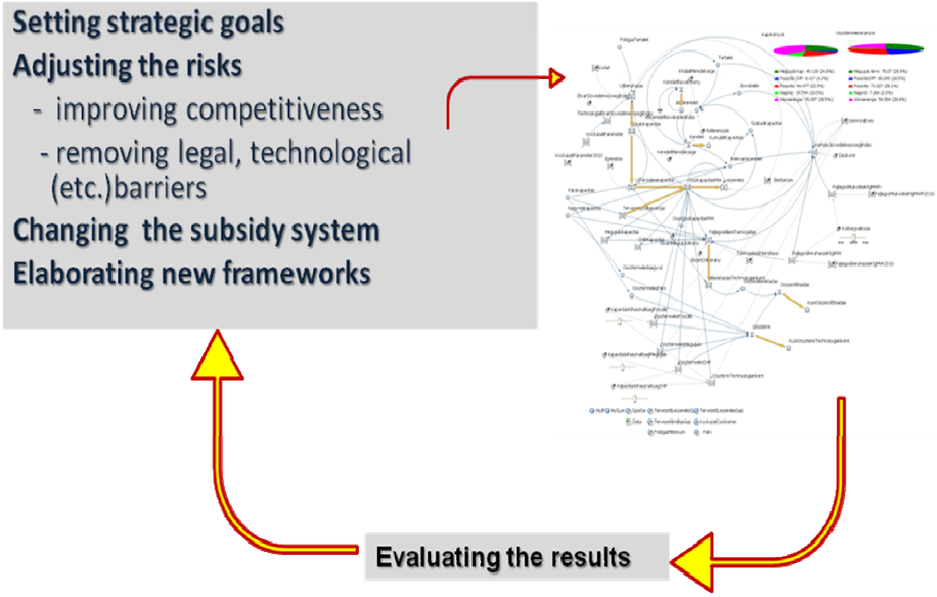
	Renewable capacity %	CHP capacity %	Renewable generation %	Renewable generation GWh	Total electricity generation GWh	Total accumulated power cost MFt	Total accumulated state subsidy Million HUF	Accumulated power costs Million HUF	Total accumulated investment costs without the nuclear plant million HUF	Total annual cost of increasing the renewable power production with 1 percentage point
GC6										
2010	4	22	4	1 576	36 816	474 357	0	474 357		
2020	12	19	18	5 359	41 981	4 254 310	954 316	3 299 994		343 690
2043	15	13	13	10 463	72 442	24 382 156	12 649 939	11 732 217	1 839 235	
FiT6										
2010	4	22	4	1 576	36 816	474 357	0	474 357		
2020	8	21	7	2 688	37 591	4 086 643	672 969	3 413 675		
2050	14	17	16	10 094	65 358	27 185 206	11 568 991	15 616 215	3 942 878	2 265 434

THE ROLE OF SYSTEM DYNAMIC MODELLING IN SUSTAINABILITY PLANNING

The presentation of the modelling procedure shows that system dynamic modelling is an interesting alternative to the stochastic-econometric models in energy-economics. Moreover, the advantages of such models are revealed in the context of sustainability planning. We do not have really sustainable energy system and energy-market architecture based on renewable energy, so we have to create it. The pure statistical and/or probabilistic approach will always fight in this situation with the problem of missing parameters, non-quantifiable variables, with the unusual behavior of dynamic processes, with the impossibility of forecasting the future structural changes on the basis of historical sets of data. System dynamics makes possible to develop new paradigm, to create new models and to test them. The simulations carried out by computers allows us to test the combinations of alternative policies and this can lead to the redefining the model boundaries. In the case of our model this may lead to an iterative process showed by *Figure 7*.

Figure 7

System dynamic model as planning and testing tool



The strategy of the transition can be tested step by step. The simulations with the current models are able to handle the availability and the evolution of power generation technologies, the effect of parameter variation (changing the Feed-in-Tariffs, or the Green Certificate allocations, risk adjustment, etc.) on the behaviour of the model. The model can be extended with a life-cycle-assessment module in order to measure the environmental impact of the particular technology-mix and it can be integrated into an overall Hungarian or European energy market model.

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