System Dynamics Modeling and Simulation of Distributed Generation for the Analysis of a Future Energy Supply

Maik Hollmann
University of Paderborn
Faculty of Electrical Engineering, Computer Science and Mathematics
Department of Electrical Engineering and Information Technology
Sustainable Energy Concepts
Pohlweg 55, D-33098 Paderborn, Germany
Tel: +49 (5251) 60 2303
Fax: +49 (5251) 60 3235
Email: hollmann@nek.upb.de

Abstract

In this paper an application of the System Dynamics approach in the field of energy supply is presented. Decentralized energy supply is introduced as a new energy system with a high potential for meeting ecological requirements and sustainability targets. System Dynamics models of one power supply unit (PSU) and of the decentralized energy supply (New Energy System Model) are described. The electrical and thermal power flow and the power conversion processes represent the basis for the stock-and-flow diagrams. At any time and for every sub process of the overall system the precise power and energy state can become certain and comprehended for the user. With examples some results of simulation are represented. Investigations of technical and ecological potential of decentralized energy supply systems are the primary objective of the models. The models are also used for education purposes for the elucidation of energetic supply processes with different power station technologies.

Key Words

decentralized energy supply, distributed generation, energy system analysis, power system modeling, power system simulation, system dynamics

1 Introduction

Decentralized energy systems are playing a continually increasing role in the energy supply industry. This has initiated a structural change in energy supply, the ultimate outcome of which is still open. The shift of energy supply policy is producing effects which cannot be overlooked. For example in the development of regenerative energy sources, distributed combined heat and power plants and international energy trading are attaining a magnitude comparable with the industrial revolution and will remain a major technological and social challenge for a long time.

Many questions around the decentralized energy supply are still unanswered. Important investigation fields are among others:

- The potential of decentralized power units for power reserve for the regulation of schedule deviations
- The potential of decentralized power units for net system services for the voltage and frequency stabilization
- The resource scheduling in a distributed (virtual) power plant
- Influences on ecological parameters like the emission of greenhouse gas and other air pollutants
- Influences on economic parameters like the costs of delivering power from decentralized energy converters embedded in a distributed (virtual) power plant.

Special tools from the field of system theory and system dynamics are utilized for making these analyses. In former works especially the System Dynamics concept has proved to be advantageous for the energy supply field, because of its modeling philosophy and flexibility. In particular this is interesting for enterprises of the energy supply industry which occupy themselves with decentralized energy supply as a business model. By the way, the System Dynamics concept is also a contribution to the need of novel modeling techniques like qualitative and semi-quantitative models which are required from the German Advisory Council on Global Change regarding energy research from the year 2003.

2 Decentralized Energy Supply Structures

Decentralized energy supply is first of all understood to mean providing energy with small plants close to the consumers (Figure 1). The energy demand is not covered as in the past by a few centrally located major power plants (for example nuclear power plant or coal-fired power station), but instead by much smaller and correspondingly more numerous smaller energy conversion plants. The new energy converters are located where the energy is required, so that numerous small power plants are present in the vicinity of the consumers. This gives rise to a changing power plant structure as well as modified requirements imposed on grid operation, energy management and protection engineering. Centralized and decentralized energy supply is thereby not mutually exclusive at all. Both energy systems can co-exist with mutual complementation (integral energy supply).

Numerous plant technologies are available for providing electrical energy and thermal energy. The primary energy source is converted to the desired energy form in a sequence of cascaded conversion steps. In particular technologies with combined heat and power plants (CHP) and energy conversion plants utilizing regenerative energies as primary energy sources have an enormous development potential for decentralized energy supply structures. CHP plants with the smaller power ratings chiefly operate with internal combustion engines (Otto or Diesel), fuel cells (FC), micro gas turbines as well as the Stirling engine. The chief regenerative energy sources, which can be technically exploited either directly or after suitable conversion, are solar radiation (PV), biomass, wind energy (WEC), geothermal energy and water power. Solar energy and wind energy are strongly dependent on the weather conditions, which are decisive for the correspondingly fluctuating electrical power output.

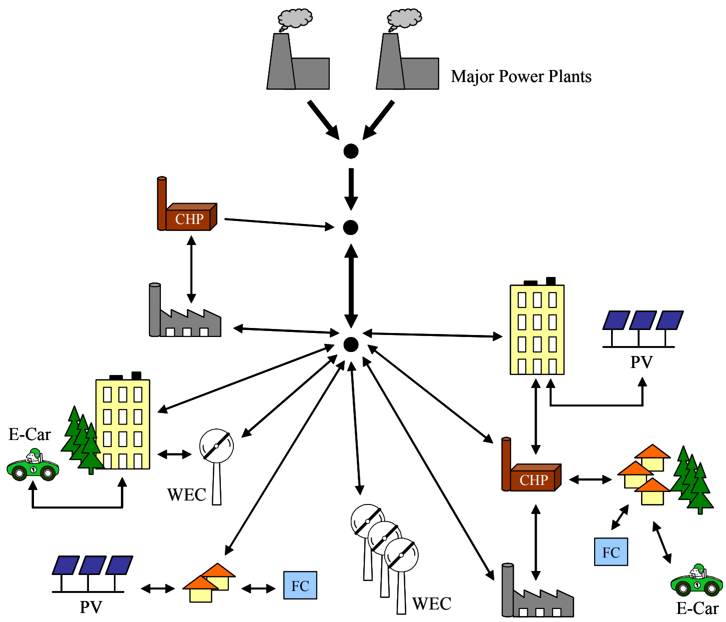

Figure 1: Decentralized Energy Supply

The technical and economic bundling of different decentralized power stations and loads (producers and consumers of electrical and thermal energy) is called virtual power plant (VPP). For this purpose a well-engineered communication infrastructure (IT) is necessary in connection with a centralized energy management system consisting of power plant management and demand side management.

Many questions are still unanswered at present regarding the technical, economic and social boundary conditions as well as the ecological effects of future utilization of the various plant technologies or a combination thereof in decentralized supply structures. For analyzing decentralized energy supply and to make the discussions regarding the future energy system more objective System Dynamics models are developed which can simulate the application of decentralized energy supply systems.

3 Modeling Concept

System Dynamics is a modeling concept for dynamic systems which has been developed by Jay W. Forrester at the Massachusetts Institute of Technology (MIT) in Cambridge. System Dynamics is a method which mutually links theories, procedures and philosophies which are necessary for analyzing the behavior of complex feedback systems encountered in various fields of economics, environmental science, corporate management, medicine or technology. It is based on cybernetic knowledge and utilizes, in addition to the approaches of System Thinking, a numeric simulation to determine the behavior of non-linear systems.

Energy supply engineering, like no other technical discipline, has numerous common aspects with other fields of economics, ecology, sociology and politics. Especially the possibility of linking together modeling of these various sciences and diversified disciplines makes System Dynamics so interesting for solving important tasks in the field of future energy supply. Simulation models can be developed which are capable of calculating aspects of future energy supply systems. Processes can be analyzed with System Dynamics in structured and inter-disciplinary system orientated manner. Some properties of System Dynamics and the implementation in a simulation environment are introduced in the following of which we advantageously make use in the context of analyzing decentralized energy systems:

- Stock-and-Flow diagrams provide intuitive system modules.
- Processes taking place are directly discernible.
- All dependencies and relationships are directly visible and understandable.
- Feedback loops can be analyzed easily for understanding the system behaviour.
- All influencing factors are mapped via separate dynamic processes.
- Every process can be scaled and considered individually.
- Integration of qualitative processes and system elements is possible.
- Process groups can be formed and analyzed in context.
- Influencing processes can be considered dynamically in scenarios.
- All relationships can be considered and analyzed directly together.
- Further influencing processes can be integrated without any problems.
- Models from various disciplines can be mutually combined.

With the aid of System Dynamics models management processes can be sensibly complemented. Decision procedures in the field of strategic and operational business management can be fundamentally supported. Decision supporting information for value-increasing strategies and simulation of alternative scenarios can be proved in order to reflect the consequences of potential decisions in the form of key parameter values. Especially for the strategic and operational business management potential parameters for decentralized energy supply systems like power reserve, net system services, resource scheduling and emission of greenhouse gases and other air pollutants are essential. In particular this is important for enterprises of the energy supply industry which occupy themselves with decentralized energy supply as a business model.

Investigations of technical and ecological potential of decentralized energy supply systems are the primary objective of the models described in the next chapters. However, they are also used for education purposes for the elucidation of energetic supply processes with different power station technologies.

4 Model of a Decentralized Power Supply Unit

In the following a modeling of a cogeneration plant (CHP) with a heat accumulator (ACC) and peak load boiler (PLB) as well as selected simulation results is presented. The model consists of varying systems in different model sectors:

- Technical system of the power supply unit (PSU)
- Logic for resource scheduling
- Consumer system for the definition of power demand in dependence of the consumer type, the season and the weekday (definition of input parameters)
- Output system for result considerations

The technical system of the PSU and the logic system for resource scheduling are the core of the System Dynamics model. Figure 2 shows the power supply unit PSU with its input and output parameters.

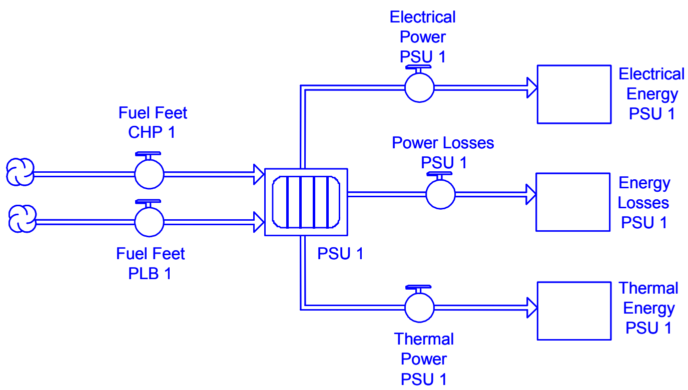

Figure 2: Input / output structure of the power supply unit PSU

In Figure 3 the technical subsystem of the power supply unit PSU is depicted. The modeling structure of the system consisting of a cogeneration plant (CHP) with a heat accumulator (ACC) and a peak load boiler (PLB) can be identified. The electrical and thermal power flow and the power conversion processes within the power supply unit are the basis for the stock-and-flow diagram. The physical system builds the fundament for the whole model. At any time and for every sub process of the overall system the precise power and energy state can become certain and comprehended.

The logic for resource scheduling is shown in Figure 4. With this logic the cogeneration plant, heat accumulator and peak load boiler are addressed and controlled for performing the supply requirements depending on a change of the current state of the system. Therefore in the logic system for the resource scheduling in connection with the technical subsystem of the power supply unit you can find the most important feedback processes. In Figure 5 an example of a counteracting (negative) loop is displayed. This feedback process describes the dependencies of the storage level of the heat accumulator. There are more feedback processes regarding the resource scheduling determined by the mutual interactions between CHP, PLB and heat accumulator.

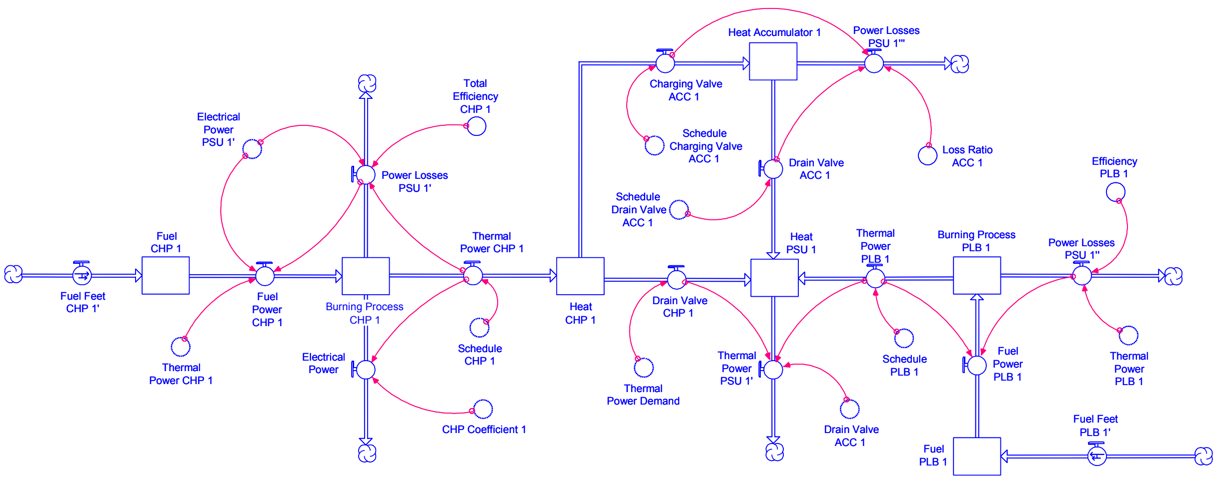

Figure 3: Technical subsystem of the power supply unit PSU: Cogeneration plant (CHP) with heat accumulator (ACC) and peak load boiler (PLB)

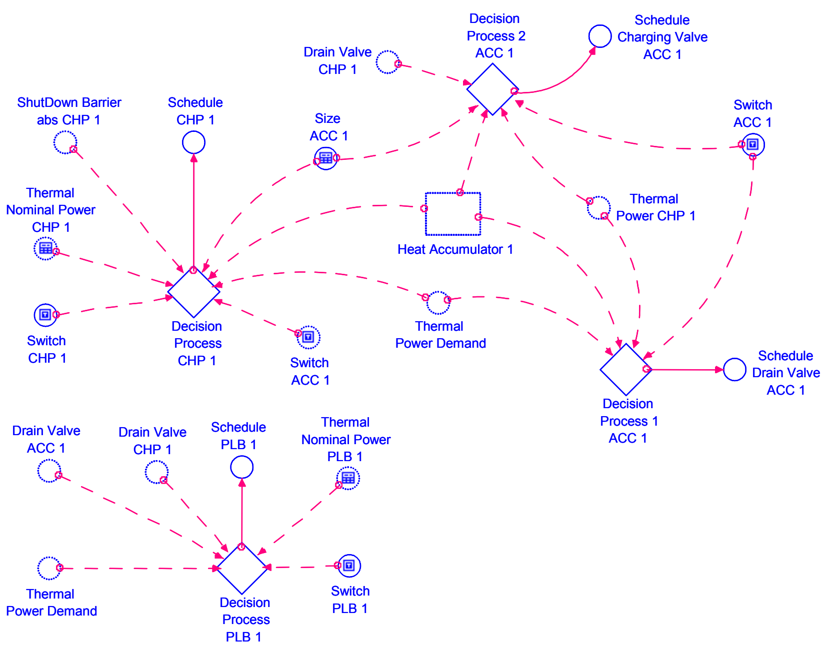

Figure 4: Logic system for resource scheduling of the power supply unit

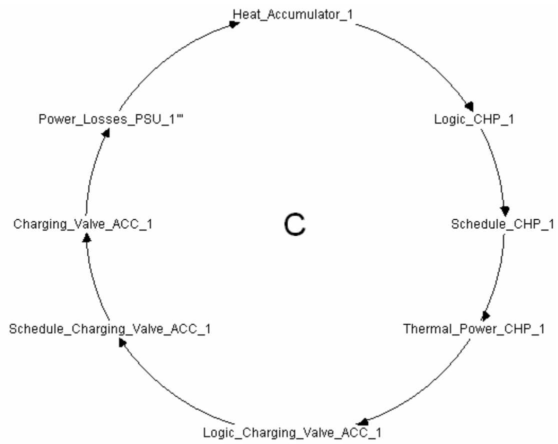

Figure 5: Example of a counteracting loop with the heat accumulator

The consumer system and output system are auxiliary systems. The consumer system (Figure 6) is for definition of electrical and thermal power demand in dependence of the consumer type (different load profiles), the season and the weekday. The model consists essentially of selection logic. Here the input parameters of the model are set. The output system (Figure 7) delivers valuable characteristic quantities for the characterization and assessment of the system.

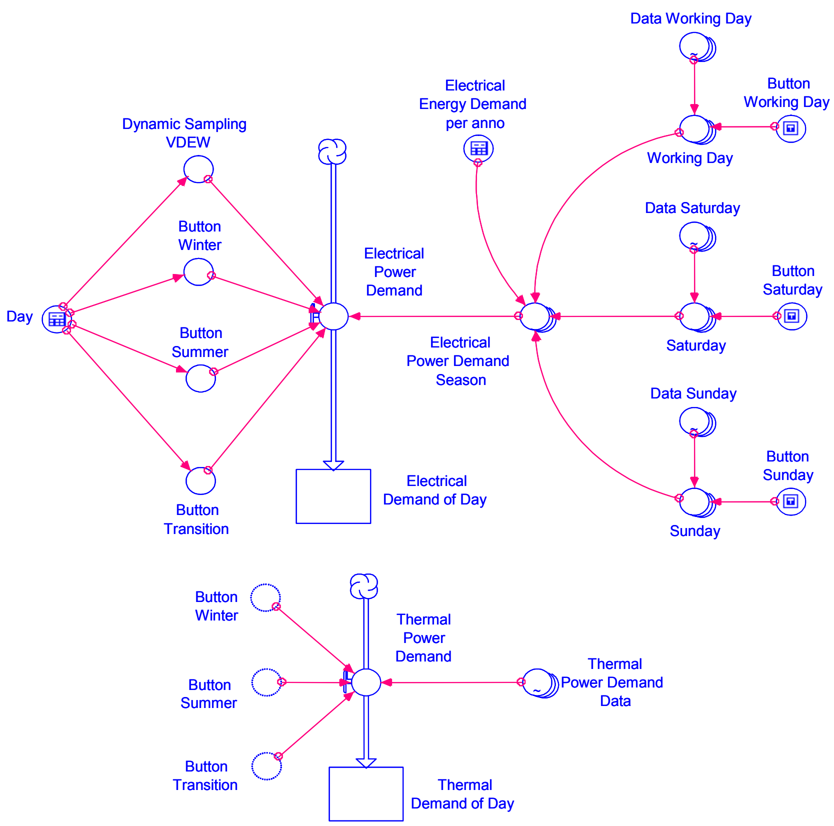

Figure 6: Consumer system for the definition of power demand

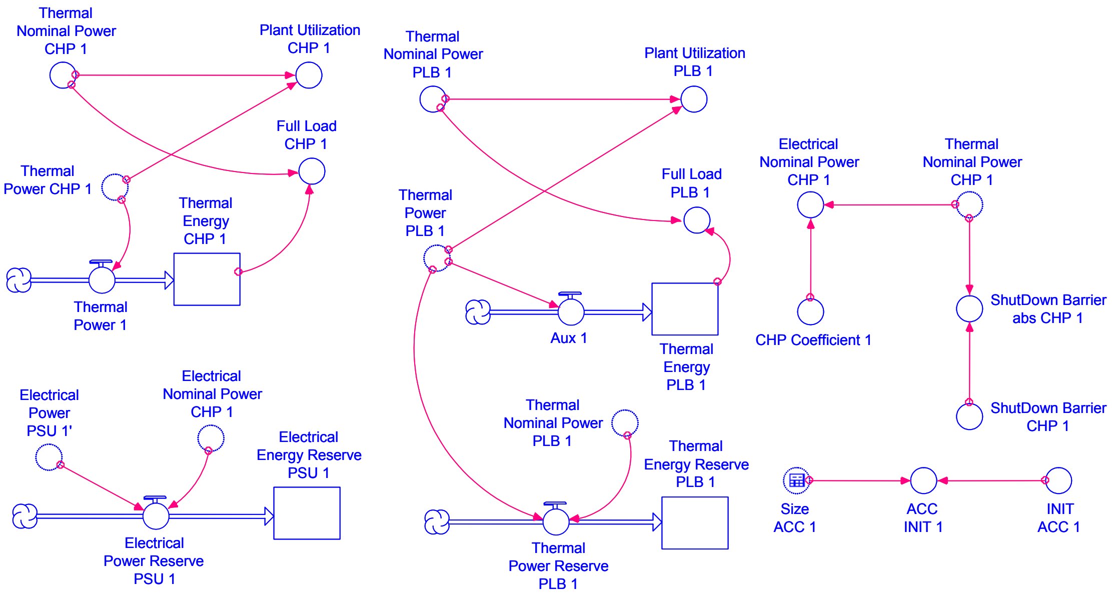

Figure 7: Output system for result considerations

The model is developed to investigate the application of a decentralized cogeneration plant for heat and power in different consumer structures. The user can simulate the operation of a cogeneration plant, a heat accumulator and a peak load boiler under different technical conditions. For this purpose it is possible to adjust in the simulation level (System Dynamics software ithink 9.0) various consumers, parameters of the technical devices and the desired output information, as shown in Figure 8. So the user can simulate the practice of a compact power supply unit - for example a fuel cell power plant in a residential building - for different days within a year. The description of the consumers (electrical and thermal) occurs via electrical standard load profiles and heat profiles. Seasonal variations in the load profiles can be considered.

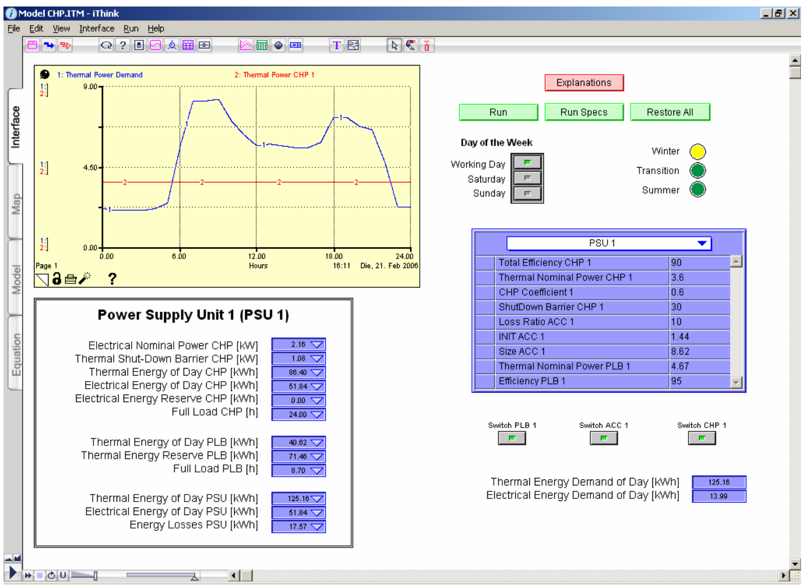

Figure 8: Simulation desk of the decentralized power supply unit model

After execution of the simulation it is possible to display and evaluate various parameters in graphical or numerical mode. For example, the utilization ratio and power reserve or the resource scheduling can be displayed. Figure 9 shows exemplarily the application of a power supply unit in a residential building for a typical working day in the winter. Clearly the time dependence of the parameters is to be recognized via the simulated day. In this case the CHP runs under full load between 5.30 a.m. and 10.45 p.m. To cover the thermal power demand the ACC and/or PLB must be turned on during this time, the electrical power reserve capacity equals zero. Only during the night it is possible to deliver electrical power reserve. The possible application of this reserve capacity remains to discuss.

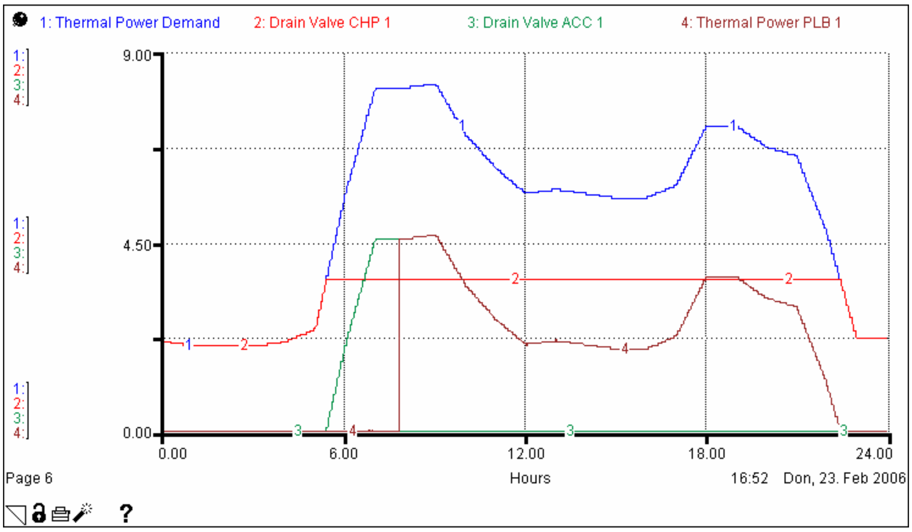

Figure 9: Application of a decentralized power supply unit in a dwelling house on a working day in winter, resource scheduling, resulting diagram (example)

Plant utilization ratio and electrical power reserve, as exemplarily displayed in Figure 10 for a working day in spring, are also important parameters for the judgment of the possible applications of the power supply unit. Ecological parameters like the emission of greenhouse gas and other air pollutants can be associated with that. Thus, the resource scheduling and the technical or ecological potential of decentralized power supply units for the use in decentralized energy supply structures and distributed power plants can be analyzed under certain conditions using selected parameters. Different scenarios can be compared.

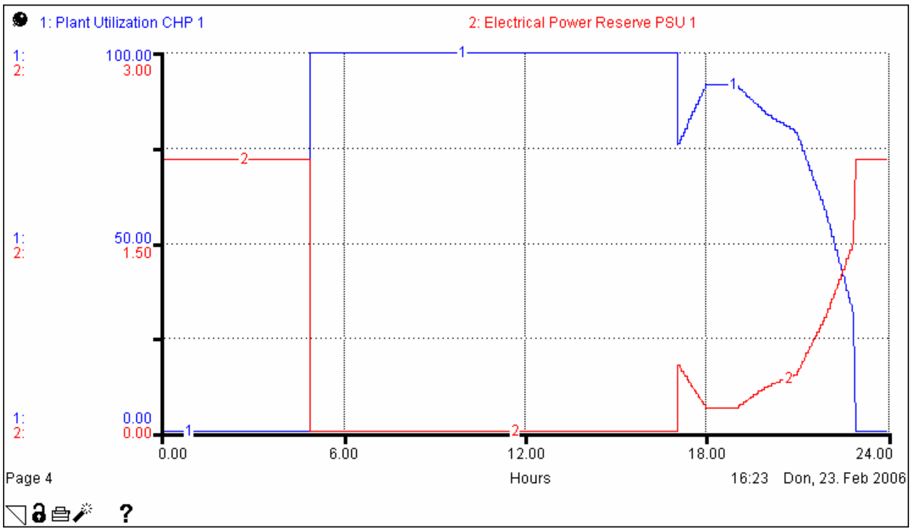

Figure 10: Application of the decentralized power supply unit in a dwelling house on a working day in spring, plant utilization ratio and electrical power reserve (example)

5 New Energy System Model

The model of a decentralized power supply unit described above is a representative for a model of one specific energy converter. It is used as a subsystem in a super ordinate model. This comprehensive model is developed to simulate decentralized energy supply (distributed generation) as a new energy supply system for a big supply area (for example a small district) for different days within a year. Several consumer sub-networks (distinguished into homes net, commerce and services net, industry net and agriculture net) form the overall supply area net. Various energy converters like different cogeneration plant types (fuel cell, biomass, natural gas …), photovoltaic, solar thermal heating, geothermal heating, wind energy and accumulators for heat and electrical energy or a combination of the mentioned elements in the different sub-networks or the complete supply area net can be considered.

It is assumed, that the distribution grid of the supply area is connected with a classical transmission grid and that for the energy converters no entrance restrictions to the grid are existent. Stability questions are not the topic of the model.

The description of the consumers (electrical and thermal power demand) occurs via electrical standard load profiles and heat profiles. Different climatic and season-dependent conditions can be chosen. The feeding of wind energy can be adjusted for different wind circumstances. The irradiance - the amount of radiant flux impinging on a unit surface area - that serves for the model of the photovoltaic power plants as an input variable is dependent on the season. Different cloudiness can be adjusted. Also the logic for resource scheduling for all energy converters is implemented, as depicted in Figure 4 for a decentralized power supply unit (consisting of CHP, ACC and PLB).

The interconnection by different plants and consumers is modeled for a whole supply area consisting of different consumers and energy converters. For the description of the demand structure and generation structure of the supply area more refined information about the structure of the supply area are necessary, for example the amount of several types of energy converters or consumers. These information's are laid down in the generation model and demand model (Figure 11). The output variables of the simulation model form the basis for the evaluation of the technical, ecological and economical potential of decentralized energy supply.

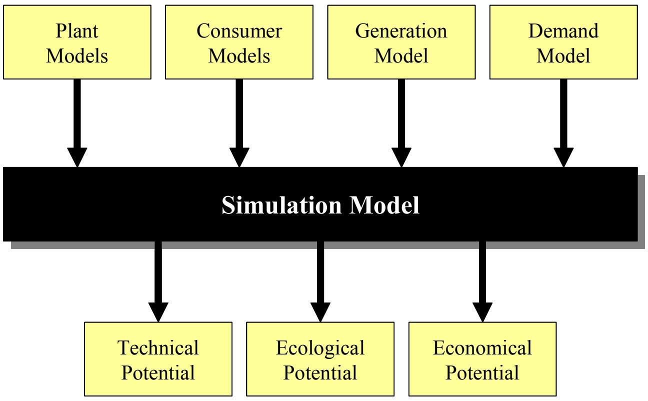

Figure 11: Input/Output structure of the New Energy System Model

In Figure 12 the concept in principle for the simulation model is displayed. This structure is valid for all individual consumer sub-networks as well as for the whole consumer net (whole supply area). This structure is the basis for the information flow and technical processes of the system. In Figure 13 the whole System Dynamics Model is depicted to receive an impression of the complexity of the system.

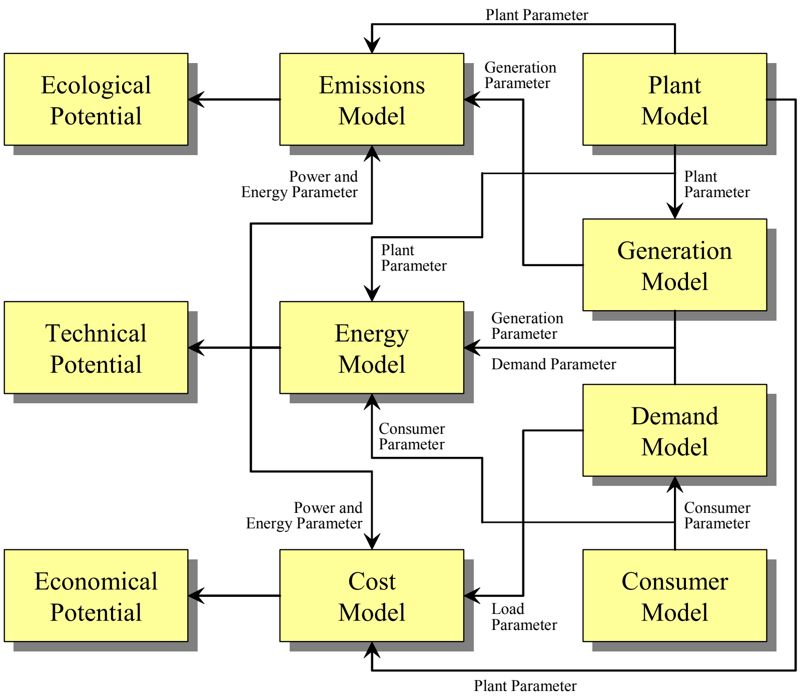

Figure 12: Structure of the simulation model

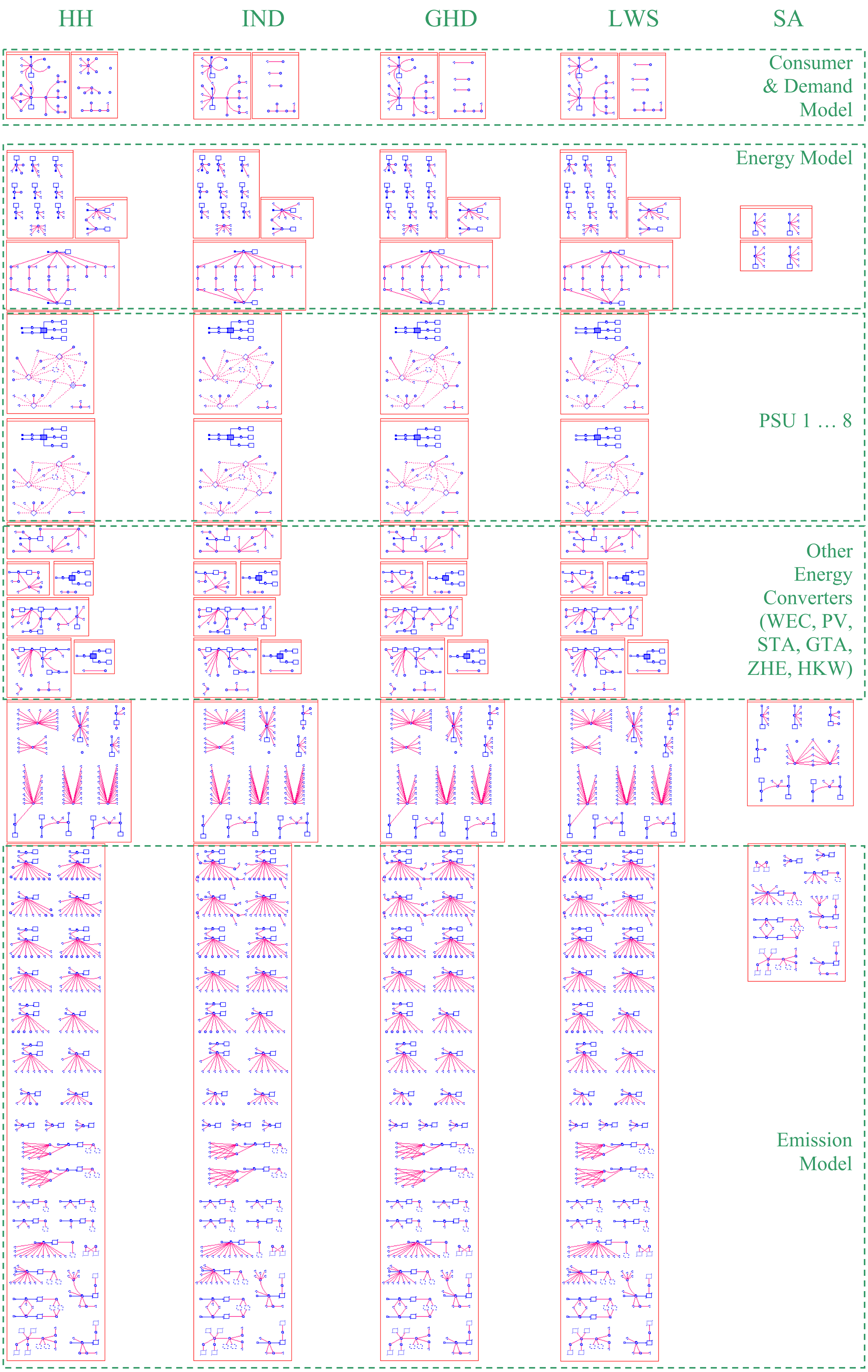

Figure 13: New Energy System Model

It is obvious, that an explicit introduction in different sections is not feasible within this paper. The section with the power supply units PSU 1 ... 8 described in the previous chapter can be recognized in the above area of the stock-and-flow diagram. Also the consumer nets, which are distinguished into 4 sub-networks (homes net HH, commerce and services net GHD, industry net IND and agriculture net LWS), can be seen in the first columns. The body for all sub-networks is similar. The fifth column represents the consolidation of the 4 sub-networks to a whole supply area net (SA). Each sub-network contains the definition of the consumers and the electrical and thermal power demand, the description of different power converters, the calculation of the resource scheduling and the calculation of the emissions of greenhouse gases and other air pollutants.

The electrical and thermal power flow and the power conversion processes are represented in the stock-and-flow diagram. The physical system builds the fundament for the whole model. At any time and for every sub process of the overall system the precise power and energy state can become certain and comprehended.

The feedback structure of the system is mainly based on the logic systems for the resource scheduling of the power supply units PSU. Anyway, these power supply units consisting of cogeneration plants with heat accumulators and peak load boilers are the most important energy converters in distributed generation structures, because these devices offer the degree of freedom concerning controllability of thermal and electrical power supply. With cogeneration plants the possibility of participation at the energy reserve market or the integration in an energy management system with power quality management in connection with a virtual power plant is offered.

The user of the new energy system model can simulate the operation of distributed generation for a defined supply area under different conditions. For this purpose it is possible to adjust in the simulation level various consumers, parameters of the technical devices and the desired output information. So the user can simulate the practice of decentralized power supply units for different days within a year. The description of the consumers (electrical and thermal) occurs via electrical standard load profiles and heat profiles. Seasonal variations in the load profiles can be considered.

In Figures 14 to 16 an extract of some input windows for parameter settings, the simulation desk and examples of some output windows (within the simulation level of the used System Dynamics software ithink 9.0) is depicted. Starting from a greeting window the user can navigate through the parameter setting process, simulation process and analysis via mouse click. It can be foreseen that the entire input and simulation level as the user interface is menu driven and very user-friendly. Furthermore help texts are offered at many places.

An important theme is the model validation. The model is based on the characteristics of real systems. For example, cogeneration plants are described with parameters which you can find in every datasheet of a CHP. The mathematical equations of the technical-physical systems are implemented in the model. The model and its subsystems are tested with plausibility considerations, comparisons with data from real systems, input / output characteristics, boundary value considerations and comparison to simulation results of other simulation tools.

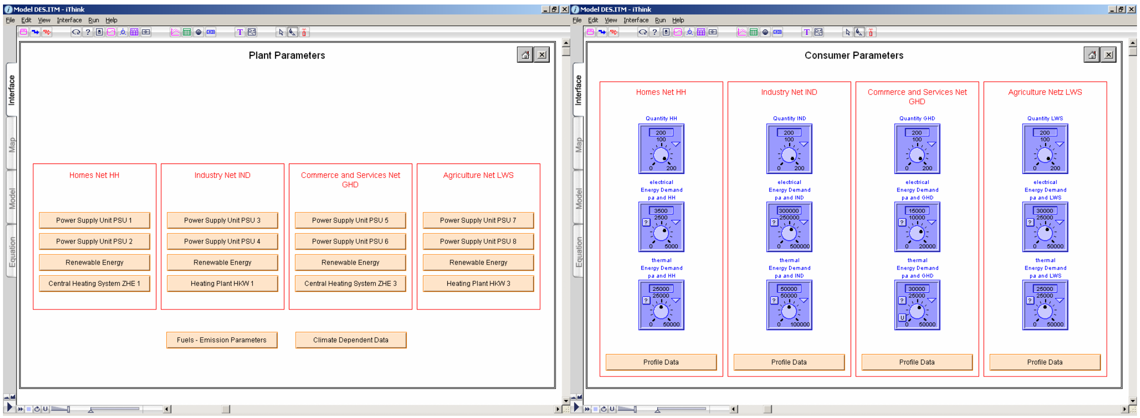

Figure 14: Input windows for parameter settings (extract)

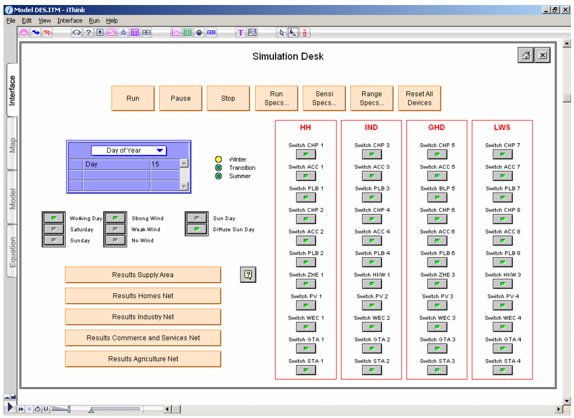

Figure 15: Simulation Desk

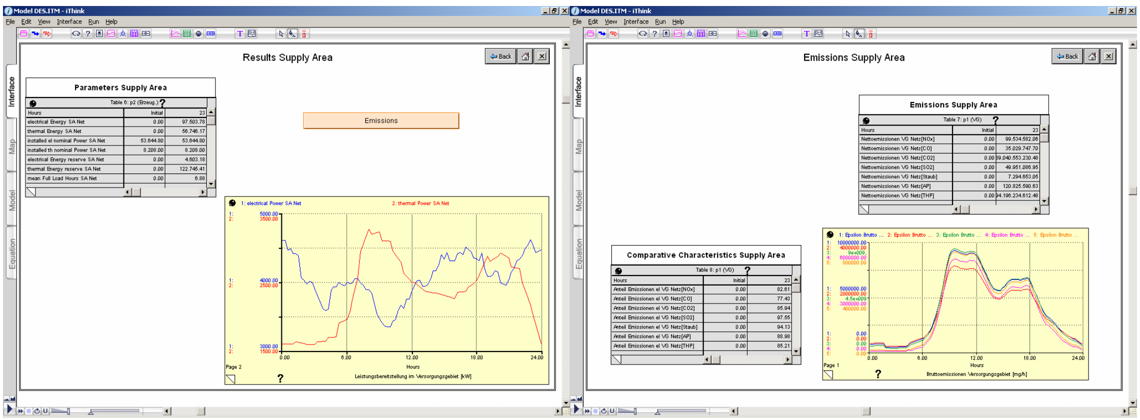

Figure 16: Output windows (extract)

The energy supply of a supply area with diverse decentralized power supply units can be simulated and examined considering different criteria. Potential investigations can be done for the following investigation fields:

- Utilization ratio of the energy converters
- Coverage of the electric and thermal power demands within a supply area with available decentralized energy converters
- Potential for power reserve for the regulation of schedule deviations, power and energy reserves
- Potential for net system services
- Resource scheduling in a distributed (virtual) power plant
- Emission of greenhouse gas (carbon dioxide) and other air pollutants like nitrogen oxide, carbon monoxide, sulfur dioxide and dust
- Emission saving in comparison with a reference system existing from the classical central energy supply
- Use of fuels and primary energy carrier
- System efficiency

Energy management systems like power management and demand control as well as decentralized energy management systems for distributed power plants can be discussed under certain conditions as well as economic aspects of a future energy system. In the following chapter an extract of some exemplarily simulation results are presented shortly.

6 Simulation Results

As an example Figure 17 shows some simulation results (balance of electrical and thermal power) for a representative supply area consisting of homes, industry, agriculture and commerce & services as well as a possible decentralized energy supply structure, like they are put into the practice in first pilot projects. For the elucidation of the applicability of the model this example simulation is done for a working day in winter with strong wind and diffuse irradiance.

The most optimal operating point in the field of the electrical energy supply is achieved in the case of a harmonious balance of power: generation equals consumption. In the Figures can be seen that this optimum at every time of the time scale is difficult to achieve. Between 6.30 a.m. and 09.30 p.m. there is a deficit cover of electrical power. During this time the deficit must be covered by the super ordinate electric power grid. In the case of the thermal power there is a deficit cover the whole day. That is due to not correctly dimensioned combined heat and power plants in the industry net. In comparison to the electrical power demand curve the serrated varying electrical power production of the decentralized power plants is noticeable. This results from swaying and fluctuating power producers (photovoltaic PV and wind energy converters WEC).

A precise evaluation of the diagrams and the conclusions regarding the use of different power plants in decentralized energy supply structures remains to discuss in dependence of the respective simulation aims.

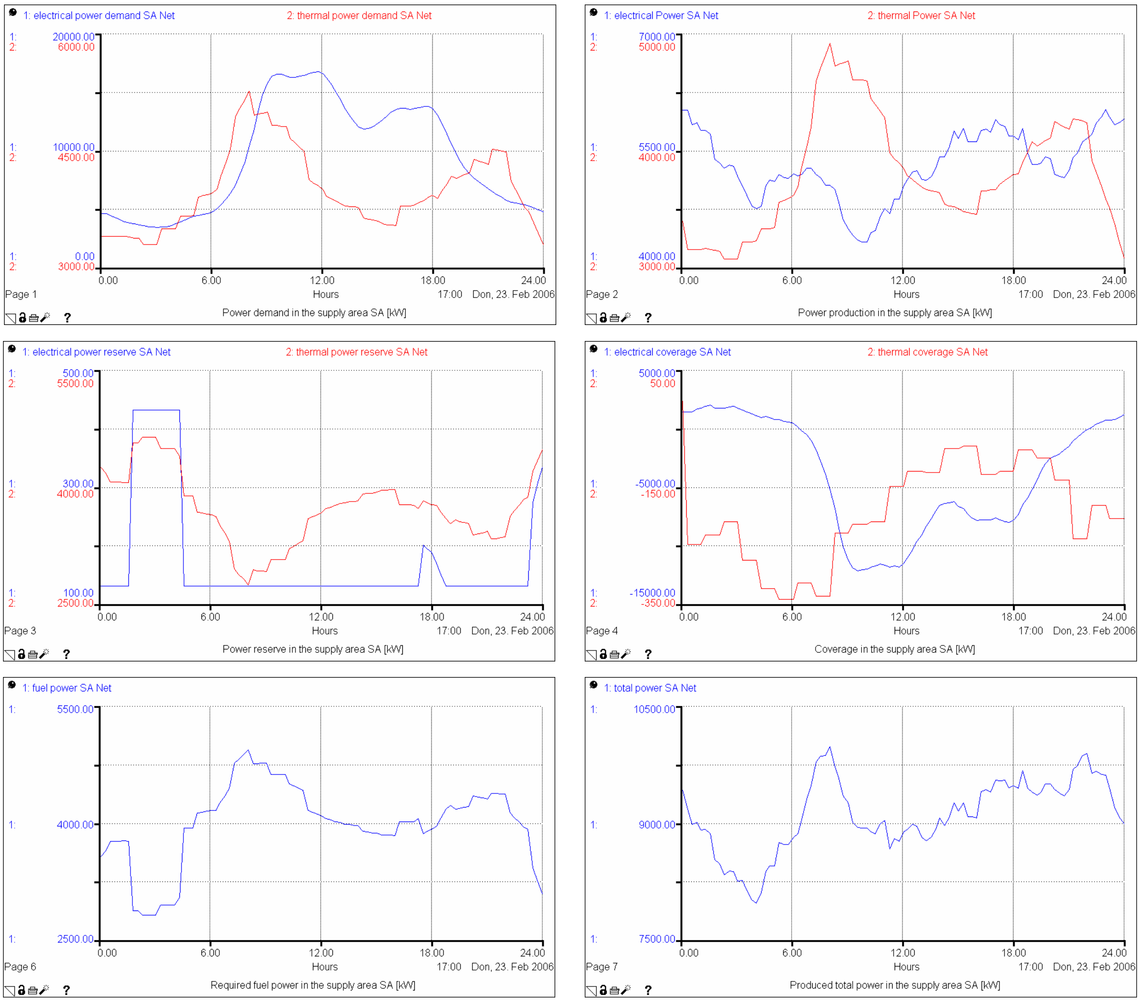

Figure 17: Balance of electrical and thermal power, simulation results, time series

Figure 18 illustrates the net emissions rate of diverse greenhouse gases and other air pollutants (dinitrogen monoxide NO_x, carbon mono oxide CO, carbon dioxide CO_2, sulphur dioxide SO_2, and dust) for the example described above. The temporarily negative values result from the net consideration. That means, that through the injection of surplus electrical power into the super ordinate grid the power from major power plants can be saved, and emissions can be saved as well. The total emissions of the decentralized power plants are credited with the saved emissions of the major power plants (substitution principle).

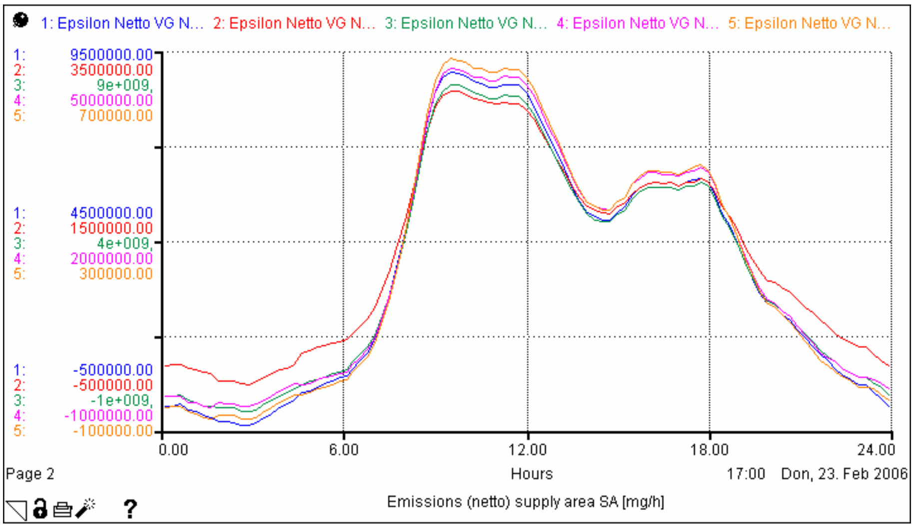

Figure 18: Net emissions of diverse greenhouse gases and other air pollutants (extract)

In comparison with that Figure 19 shows the gross emissions rate, so the total emissions which are caused by the decentralized power stations. These considerations are important for the evaluation of the ecological potential of distributed generation. Faced with the current discussions about saving of greenhouse gases (for example through the introduction of the emission trading in the energy supply industry) precise analyses of the emissions gain importance increasingly.

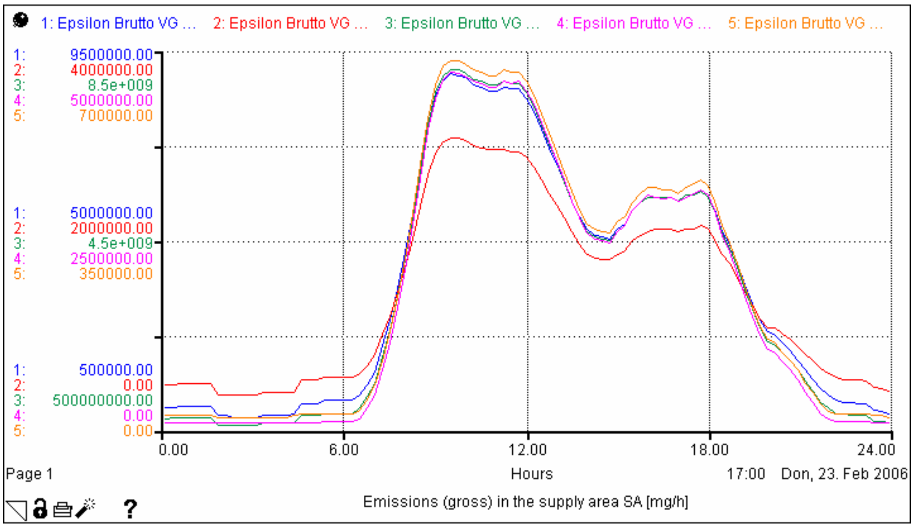

Figure 19: Gross emissions of diverse greenhouse gases and other air pollutants (extract)

A precise evaluation of the emission diagrams and the conclusions regarding the ecological potential of different decentralized energy supply structures and the potential of optimization the emission reductions with distributed generation systems remains to discuss in dependence of the respective simulation aims.

The shown simulation results are valid only for an example scenario. In practice the model is used for system studies at real supply projects or academic supply scenarios.

7 Conclusions

In this paper an application of the System Dynamics approach in the field of energy supply is presented. The advantages of System Dynamics regarding analyzing future energy systems are pointed out. For this purpose decentralized energy supply is introduced first as a new energy system with a high potential for meeting ecological requirements and sustainability targets.

The described models of one power supply unit (PSU) and of the decentralized energy supply (New Energy System Model) show exemplarily the huge application of the System Dynamics approach and underline the humongous potential of this modeling approach for the energy supply industry.

The electrical and thermal power flow and the power conversion processes are represented in the stock-and-flow diagrams. The physical systems build the fundament for the models. At any time and for every sub process of the overall system the precise power and energy state can become certain and comprehended for the user. The entire input and simulation level as the user interface is menu driven and very user-friendly.

Investigations of technical and ecological potential of decentralized energy supply systems are the primary objective of the models. The models are also used for education purposes for the elucidation of energetic supply processes with different power station technologies.

Especially in comparison with other simulation tools the advantage of this System Dynamics modeling lies in the flexibility of his application. The possibility to define time series with different increments as input parameter or the easy enlargement with further processes are in this case only modeling-technical advantages.

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