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Model-based development of control strategies for domestic fuel cell cogeneration plants

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Abstract

This paper describes the development of control strategies for domestic fuel cell cogeneration plants, using the simulation environment ColSim [COLSIM-1]. The investigated facility is illustrated, including a fuel cell system fueled with natural gas and a stratified storage with an internal gas burner. The components of this facility are modeled in the used simulation environment ColSim as "plug-flow-types" [COLSIM-02]. Demonstrative of this, the object of a polymer electrolyte fuel cell stack is described. The model of the entire system is shown with the used vector graphic tool [XFIG].
Two criteria are defined optimizing the running costs or the primary energy balance. Based on these definitions control strategies are shown, including the use of a slider for variation. The efficiencies of the system are taken into account in several operating points. In addition the user behavior (electric and thermal energy demands) are considered and acknowledged by the control algorithm. Measured data of a "low energy consumption house", monitored by the German utility EnBW [EnBW-1], are used. In these investigations the user of the facility is premised as the owner. Dynamic tariff structures for natural gas and electricity offer the possibility to influence the operational point of the fuel cell system by the energy supply company.
Finally simulation results for the period of one year are illustrated for the defined criteria "ecologic optimized" and "economic optimized". The differences are quantified with the present values of efficiencies for domestic fuel cell power stations and for the electric grid.

Motivation

Domestic fuel cell heat/electricity cogeneration plants, fueled with natural gas, are presently promoted as one of the most efficient solutions to reduce the CO_2 emissions of private households. These small systems including a gas reformer, a fuel cell stack and an auxiliary burner are dimensioned to fulfill the heating and warm water demands of a building (by hundred percent in the winter season).
Energy supply companies recognize this way of cogeneration as an opportunity to open up the heat market. "Virtual power plants" as a result of these distributed power stations are seen as an important part in the future grid structure.
Depending on the energy load (heating/warm water and electricity demands), the dimensions of the installed storage unit and possible dynamic pricing concepts, different controller strategies are possible, optimizing the CO_2 emissions and/or the financial profits. Within the NEGEV R&D project (new energy concepts for buildings), coordinated by the Fraunhofer ISE, such energy management strategies are developed, evaluated and optimized. With this paper control strategies and their results will be presented. Therefore numerical simulations were carried out over a time interval of one year, using the measured data for a "low energy consumption house" monitored by the German utility EnBW [EnBW-1].

Schematic of the considered system

The facility includes a fuel cell power system, a stratified storage with an internal gas burner and optional a solar thermal system (figure 1). The nominal electric power of the fuel cell is dimensioned with 1 kW_{el}. This means a respective thermal power of about 2 kW_{th}. The volume of the stratified storage is specified with 750 l. To cover thermal peaks during winter, it is necessary to include a secondary thermal source. The presented system uses a gas burner, which is integrated in the stratified storage with a thermal power of 5 kW_{th} [SOLVIS]. The regarded load is a building sufficing the "low energy consumption" standard, which means an average heat load of under 75 kWh_{th} per year and square meter at Middle-European climate. The maximum thermal load of one day was measured to 80 kWh_{th}.

Simulation environment

The model-based development, evaluation and optimization of controller strategies is realized with the simulation environment ColSim [COLSIM-1]. Originally developed at the Fraunhofer ISE to calculate solar thermal systems, this simulation tool now offers recent models to simulate fuel cell cogeneration plants and

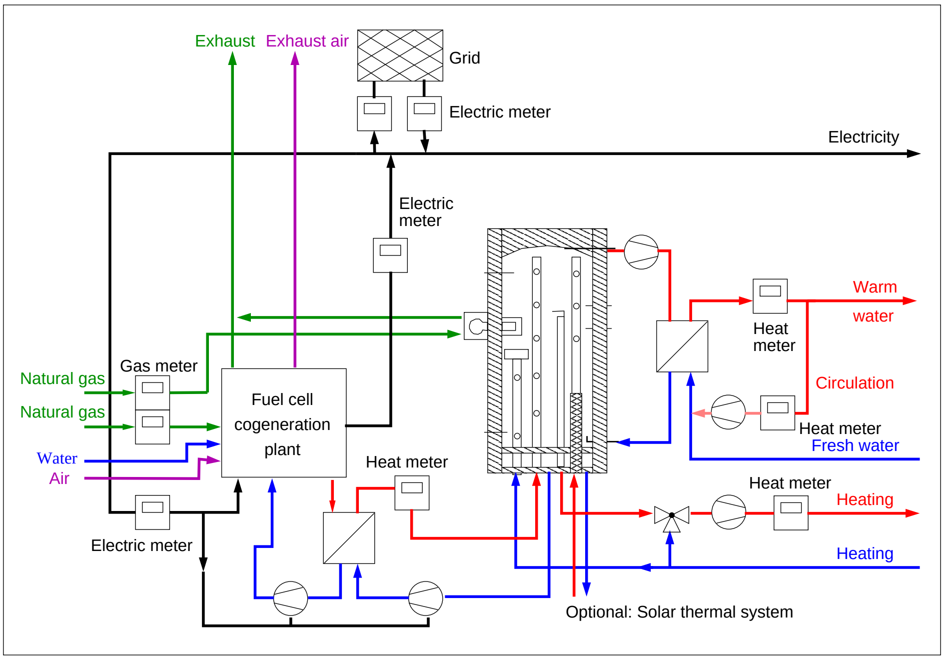


Figure 1: Schematic including a grid connected domestic fuel cell heat/electricity cogeneration plant, a stratified storage with an internal gas burner and optional a solar thermal system.

their control systems in the HVAC building environment. Therefore the library includes models for fuel cell stacks, reformers, power inverters, heat storage units, pumps, compressors, valves and controllers. Using so-called "plug-flow modeling" [COLSIM-02] and a modified Euler algorithm to solve the differential equations, time steps in the range of seconds are feasible. In spite of using small time steps (e.g. 5 sec), one year can be processed with a modern Linux PC in about one hour. This offers the possibility to develop controller algorithms (controllers for components and control strategies) inside the simulation environment. All models and control sequences are implemented in ANSI-C, whereby the developed algorithms can be ported onto the controller hardware. Furthermore, the modular concept of ColSim allows the energy evaluation of different system concepts. Interactions between single elements, for example the cooling circuit of the fuel cell stack and the storage unit, can be taken into account.

Fuel Cell model description

Each object of ColSim, which uses mass flow, is described with the previously mentioned plug-flow principle. The plug flow model uses finite mass elements $\triangle m = \dot{m} \cdot \triangle t$ and finite energy elements $\triangle Q = \dot{Q} \cdot \triangle t$ with a fixed time step, allowing the mass flow through closed and opened networks to be traced. This guarantees a fast calculation of the object chain [COLSIM-2]. The plug is initiated at a pump or ventilator object, then shifted through the branched network and is returned to the origin (pump or ventilator). This mechanism allows simple modeling of flow delay effects and mass balance at the second call of the pump/ventilator in one time step. The state equations are solved with the updated mass flow.
The following section describes the plug flow modeling with the fuel cell stack. Figure 2 shows the plug flow model with four nodes (gas anode, gas cathode, sum of the solid material of the stack and cooling fluid). The electric characteristics are taken into account with a combination of a mechanistic and an empirical model [AMPHLETT]. The mass flux in the singular cells, electro-osmotic effects and diffusion processes are implemented according to the model of [NGUYEN].
The mathematic description of this object results in four differential equations in the state space (1)-(4). The node "anode gas" and the node "cathode gas" symbolize the head space of all gas components in the solitary cells. The node "solid" includes all solid materials of the stack. The sum $\sum_{i=1}^{n}$ in these equations represents the gas components in the anode and in the cathode head space. The temperature dependent capacities C_{AG} and C_{Gc} of the anode and the cathode gas vectors are calculated with a non-linear equation system.
The left side of a state equation represents the change of the thermal energy of this node. This change of energy is calculated by the heat transfers to other nodes and to the ambient (e.g. $kA_{AG} \cdot (T_{solid} - T_{AG})$), by incoming mass flux (e.g. $\sum_{i=1}^{n} \dot{m}_{AG_{in_i}} \cdot c_{AG_i} \cdot T_{AG_{in}}$), by outgoing mass flux (e.g. $\sum_{i=1}^{n} \dot{m}_{AG_{out_i}} \cdot c_{AG_i} \cdot T_{AG}$), by mass transfers between nodes (e.g. between anode and cathode: $\dot{Q}_{mat\ flux}$) and by internal gains (e.g. thermal gains of electric losses: $\dot{Q}_{loss_{el}}$ and thermal gains of condensation: $\dot{Q}_{cond_{CG}}$).

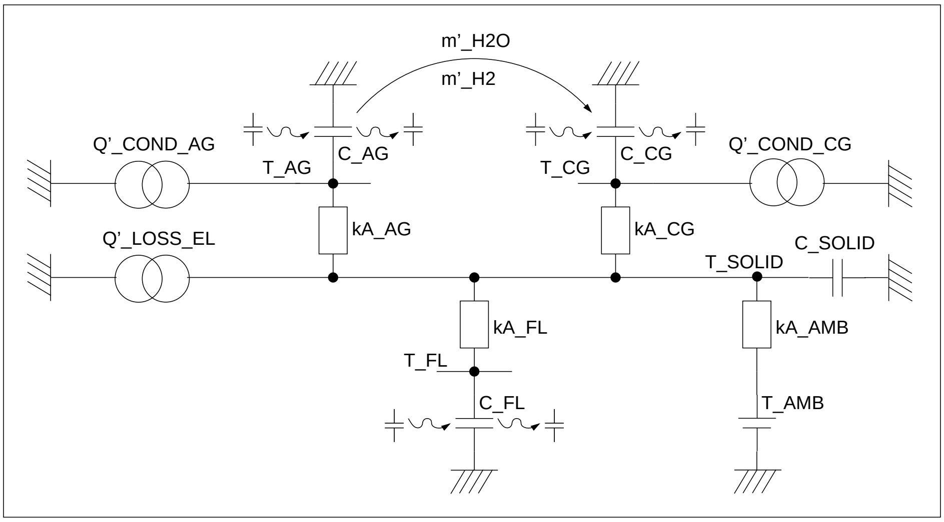


Figure 2: Plug flow model of the thermic behavior and the mass flux of a polymer electrolyte fuel cell stack.

- Anode gas head space (gas vector of the reformate)

$$\sum_{i=1}^{n} m_{AG_i} \cdot c_{AG_i} \cdot \frac{dT_{AG}}{dt} = \sum_{i=1}^{n} \dot{m}_{AG_{in_i}} \cdot c_{AG_i} \cdot T_{AG_{in}} + kA_{AG} \cdot (T_{solid} - T_{AG}) - \sum_{i=1}^{n} \dot{m}_{AG_{out_i}} \cdot c_{AG_i} \cdot T_{AG} - \dot{Q}_{mat\ flux} + \dot{Q}_{cond_{AG}} \tag{1}$$

- Cathode gas (gas vector air)

$$\sum_{i=1}^{n} m_{CG_i} \cdot c_{CG_i} \cdot \frac{dT_{CG}}{dt} = \sum_{i=1}^{n} \dot{m}_{CG_{in_i}} \cdot c_{CG_i} \cdot T_{CG_{in}} + kA_{CG} \cdot (T_{solid} - T_{CG}) - \sum_{i=1}^{n} \dot{m}_{CG_{out_i}} \cdot c_{CG_i} \cdot T_{CG} + \dot{Q}_{mat\ flux} + \dot{Q}_{cond_{CG}} \tag{2}$$

- Solid node of the fuel cell stack

$$\sum_{i=1}^{n} m_{solid_i} \cdot c_{solid_i} \cdot \frac{dT_{solid}}{dt} = \dot{Q}_{loss_{el}} - kA_{AG} \cdot (T_{solid} - T_{AG}) - kA_{CG} \cdot (T_{solid} - T_{CG}) - kA_{FL} \cdot (T_{solid} - T_{FL}) - kA_{AMB} \cdot (T_{solid} - T_{AMB}) \tag{3}$$

- Coolant (the fuel cell stack is cooled with DI-water)

$$m_{FL} \cdot c_{FL} \cdot \frac{dT_{FL}}{dt} = \dot{m}_{FL_{in}} \cdot c_{FL} \cdot T_{FL_{in}} + kA_{FL} \cdot (T_{solid} - T_{FL}) - \dot{m}_{FL_{out}} \cdot c_{FL} \cdot T_{FL} \tag{4}$$

While using the nomenclature of the state space description with the node temperatures as state variables, the four differential equations can be expressed as followed:

$$\underline{\dot{T}} = \underline{A} \cdot \underline{T} + \underline{B} \cdot (\underline{T}_{in}{}^{T}, \underline{\dot{Q}}_{in}^{T})^{T} \tag{5}$$

$$\underline{T_{out}} = \underline{C} \cdot T \tag{6}$$

The differential system is solved by a finite difference method. ColSim uses a spreaded modified Euler method to calculate system state during the running time of each object. System equations are solved inside the object calculation. There is also the possibility to use other integration methods, when plug mass flow and external heat flow for each time step are declared.

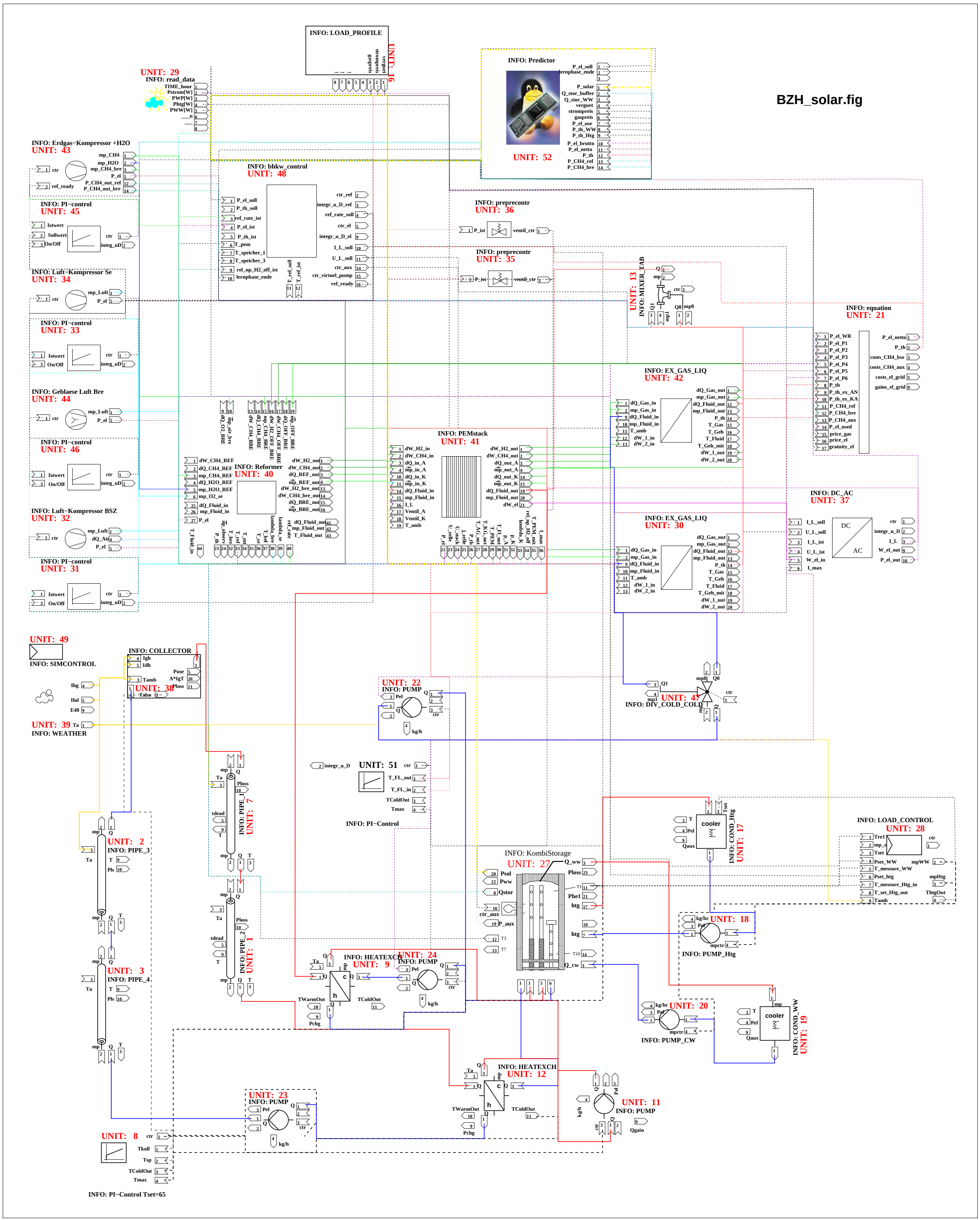


Figure 3: ColSim model of the investigated domestic fuel cell heat/electricity cogeneration plant, a stratified storage with an internal gas burner and optional a solar thermal system.

System model of the investigated facility

The investigated system (figure 1) is represented with all necessary types inside the simulation environment ColSim. Figure 3 shows the system with the fuel cell stack, the reformer, pumps, ventilators, compressors, controllers and the load profiles of the monitored building. This method of simulation allows the observation of mass and energy transfers, of interactions between different types and the behavior of controllers in the same simulation. Furthermore the development, evaluation and optimization of controller algorithms is realizable before testing them in real systems. Due to the use of the ANSI-C standard, the implemented controller source codes can be ported directly to the controller hardware.

Control strategies

The operation management system has to consider all factors, influencing the characteristics of the facility. The significant factors are the user behavior (heating/warm water and electricity demands), the current weather, weather forecasts and dynamic pricing concepts for the delivery of gas and electricity as well as for feeding the grid with electricity of the fuel cell system. Beyond that internal values are also important for an optimized energy management. For example the temperature of the stratified storage terminates the running time of the fuel cell system [OTTI-01]. The current values of the electric efficiencies and the primary energy utilization ratios of the investigated cogeneration plants require system rejection when thermal energy can not be used or stored.

Therefore the energy management system has to consider and to acknowledge the efficiencies and the primary energy utilization ratios in the specific operation points. The power spectrum of the fuel cell power station is sub-classified to 700 W_{el}^{brutto} up to 1400 W_{el}^{brutto} in 100 W steps. The current efficiency values are observed for each operation point in this range. Therewith losses of power in dependance of parameters e.g. operation temperature or operation pressure can be detected. With this method the control system is also able to identify aging effects of the whole system and especially a possible degradation of the fuel cell stack. To smooth singular peaks a moving average is used.

With this described information a profile for one day is generated. According to the VDEW load profile [EnBW-2] the time range of one day is classified in five sections (night, morning, noon, afternoon, evening). The thermal and electric consumptions are recorded for each interval. A moving average is used for the several consumptions. With the fraction of the current value and the old moving average a trend is defined for the heating and the electric demands.

The warm water demand is considered with the maximum value. Due to reasons of comfort this amount of energy should be available instantly without using the additional gas burner.

If a solar thermal system is used, the forecast of the solar gains are also calculated with the current trend curve. Due to the networked control system of the facility it will be possible to obtain detailed weather forecasts of weather services via Internet.

At the end of each time interval a new operating route schedule for the next section will be selected. The electric power set value is chosen in order to optimize the costs/gains, or the primary energy demands depending on the user preferred criteria. These criteria are defined as followed, whereas dynamic rates for delivery and feeding are taken for granted:

- Ecological optimized (minimizing the primary energy demands):

$$W_{prim}(P_{el}) = \sum_{i=1}^{n} \int_{T_{int_B}}^{T_{int_E}} P_{i_{prim}}(P_{el}) \cdot dt \rightarrow min \tag{7}$$

- Economic optimized (minimizing the costs):

$$C_{sum}(P_{el}) = \sum_{i=1}^{n} \int_{T_{int_B}}^{T_{int_E}} (c_i(t) - g_i(t)) \cdot P_i(P_{el}) \cdot dt \rightarrow min \tag{8}$$

In both definitions $\sum_{i=1}^{n}$ represents the amount of the energy terms taken into account. The integrals are calculated for a time interval beginning with T_{int_B} and ending with T_{int_E}. The factors $c_i(t)$ and $g_i(t)$ are representing the time dependent costs for energy demands (electricity and natural gas) and the time dependent gains of grid feeding in $Cent/kWh$. With this paper these two parameters and the set value of the electric power of the fuel cell system are defined as constant for the time range of one interval. Therewith the two criteria can be expressed as followed:

- Ecological optimized (minimizing the primary energy demands):

$$W_{prim}(P_{el}) = P_{FC_{CH_4}} \cdot T_{int} + \frac{Q_{aux}}{\eta_{aux}} + \frac{W_{el_{supply}}}{\eta_{grid}} - \frac{W_{el_{feeding}}}{\eta_{grid}} \rightarrow min \tag{9}$$

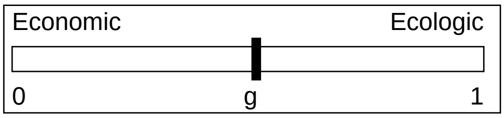
- Economic optimized (minimizing the costs):

$$C_{sum}(P_{el}) = C_{FC_{CH_4}} + C_{aux_{CH_4}} + C_{el_{supply}} - G_{el_{feeding}} \rightarrow min \tag{10}$$

The final electric power set value is calculated with the weighted results of the criteria optimization:

$$P_{el_{set}} = \frac{w_1 \cdot P_{el_{ecologic}} + w_2 \cdot P_{el_{economic}}}{w_1 + w_2} \tag{11}$$

With the definition of the weight factors $w_2 = 1 - w_1$ and $w = w_1$ the electric power set value can be expressed as shown in figure 4. The variation of the weight factor w can be interpreted as a slider, with which a user can influence the operational mode of the domestic fuel cell cogeneration plant.



$$P_{el_{set}} = w \cdot P_{el_{ecologic}} + (1-w) \cdot P_{el_{economic}} \ , \ w = 0..1$$

Figure 4: Slider for the set value of the electric power from the fuel cell system adjusting either an ecologic or an economic operational mode.

Simulation results

The presented system concept has to ensure the energy supply of a building [EnBW-1] obeying the "low energy consumption" standard defined by German law [ENEV]. Using the presented slider the weight to calculate the electric power set value of the fuel cell system can be switched between "ecologic optimized" and "economic optimized". In the following section simulation results of the two extrema are discussed. In this investigation the user is premised as the owner of the fuel cell system. As a result of the liberalization and due to the progressional decentralization of the energy markets dynamic tariff structures are possible also in low voltage sections (comparable to the electricity stock market in the high voltage level). The presented approach grants a higher price during peak load times than the guaranteed 5.11 Cent of the German cogeneration law [KWK]. The following section considers the results of the simulation cycles of the facility, including a fuel cell cogeneration plant and a stratified storage with an internal gas burner. Results with an additive solar thermal system are shown in [OTTI-02] and are also taken into account in this paper.
Figure 5a shows the values of the several energies for a time period of one year based on the "ecologic optimized" strategy. In figure 5b the dissenting results of the "economic optimized" energy management are shown.

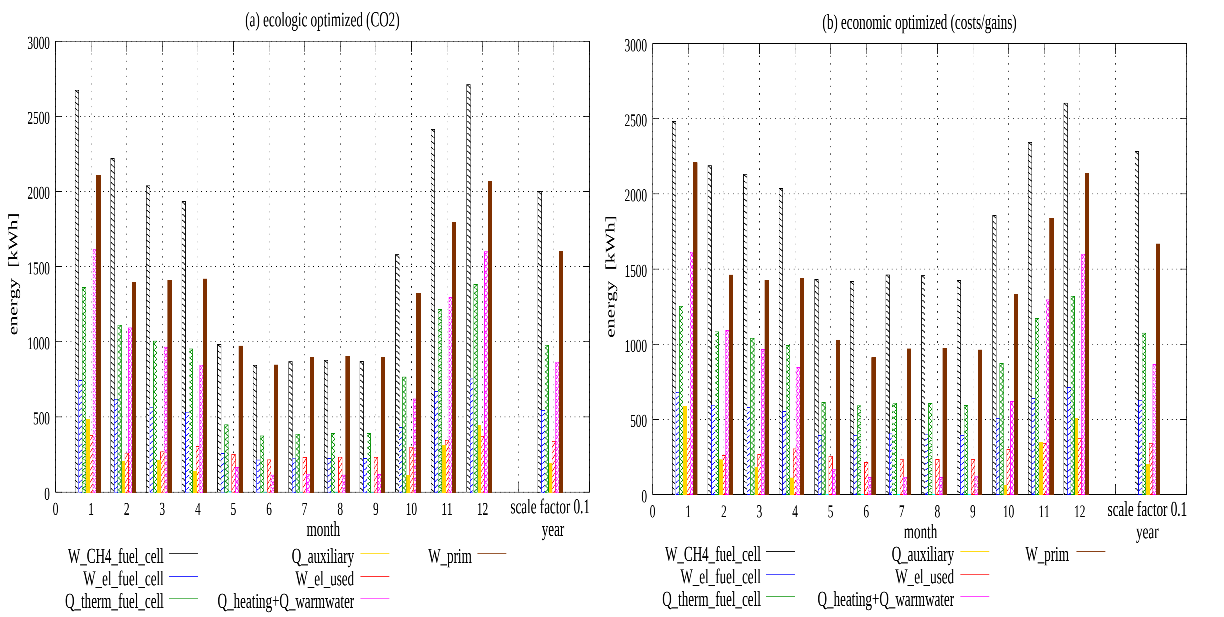


Figure 5: Monthly sums of the considered energies and the resulting energy sums of one year. In (a) the ecologic optimized and in (b) the economic optimized case is shown.

In the economic optimized case 15 percent more electric energy is produced by the fuel cell cogeneration plant compared to the ecologic optimized strategy. This results in a higher demand of natural gas, needed by the fuel cell system (14 percent higher amount of primary energy). As visible in figure 5a and figure 5b, the main difference in the production of electricity and therewith in consumption of natural gas is given during the summer season.
The utilization ratio of the facility is defined with the electric energy production, the thermal needs of the

user and the primary energy demand of the fuel cell cogeneration plant and the additional gas burner:

$$\eta_{prim} = \frac{W_{el_{FC}} + Q_{htg} + Q_{ww}}{W_{prim_{FC}} + W_{prim_{aux}}} \tag{12}$$

The values of this utilization ratio for the ecologic optimized respective the economic optimized case are 64 percent and 59 percent, calculated with the current system parameters of a fuel cell cogeneration plant. This value is dependent on the quality of the thermal system (e.g. insulation of the storage, of the pipes and the pumps). Thus one risk lies in the possibility, that low thermal standards and therefore high thermal losses allow a higher electric energy production.

The primary energy balance of the economic mode lies only four percent above the value of the ecologic optimized strategy. The reason for this small difference can be explained with the current low efficiency of the electric grid. Each kWh of electricity fed into the grid is imputed with this average grid efficiency, signified in (9) by the term $\frac{W_{el\,feeding}}{\eta_{grid}}$. As a result of the use of modern power plants and of the increasing usage of renewable energy sources the average grid efficiency will improve in the future. For this reason the described primary energy credit will be reduced and the difference between the two energy management strategies will be extended.

If an additional solar thermal system is used [OTTI-02], the difference in the primary energy consumption is about six percent. As mentioned, the reason for this small difference lies in the low grid efficiency. With the use of a solar thermal system, the economic optimized operational mode reduces the solar gains at 29 percent [OTTI-02], because of the permanent high temperatures in the storage during the summer months. These high temperatures also influence the thermal efficiency of the fuel cell cogeneration plant and therefore the primary energy balance decreases.

In figure 6 the running costs of both operational modes are compared. It is visible, that an ecological optimized strategy implicates higher operating expenses than an economic optimized energy management. In this investigated system the ecological case generates 40 percent higher costs than the economic one, which allows the fuel cell cogeneration plant to run at nominal power during peak load times of the grid. Therewith the costs for the delivery of electricity are reduced and the gains for grid feeding during high gratuity times are maximized.

Compared to the results of a combination with a solar thermal system [OTTI-02], the running costs of both cases are on a lower level. The solar thermal gains are feeding the stratified storage and therewith the running time of the fuel cell system is limited during the non-heating period. Less electricity is produced, which means less gains from grid feeding.

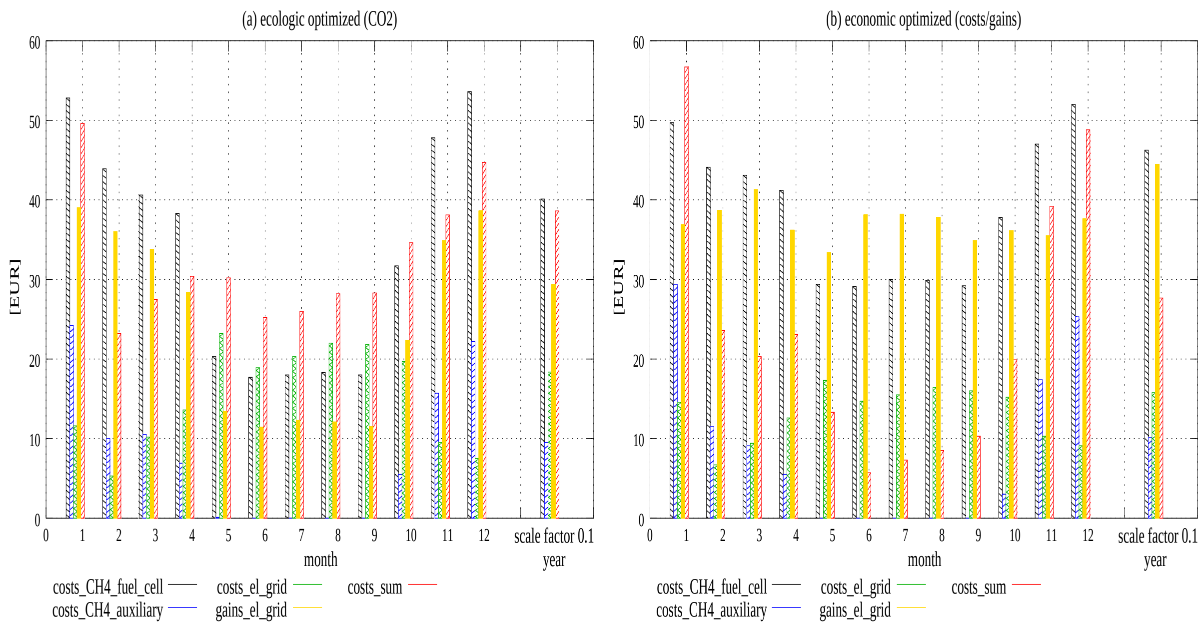


Figure 6: Monthly costs and gains and the resulting sums of the considered year. In (a) the ecologic optimized and in (b) the economic optimized case is shown.

Conclusions

In this paper the model-based development of control strategies for domestic fuel cell cogeneration plants is illustrated. To do so, the fuel cell system driven with natural gas has been modeled in the simulation environment ColSim [COLSIM-01]. The presented concept of an energy supply system for a "low energy

consumption house" based on a fuel cell cogeneration plant premised the user of the facility also as the owner. A possible "contracting"-operational mode has to be considered separately.
The results of the simulation cycles show the differences between a control strategy, which optimizes the primary energy balance, and a operational mode, which optimizes the running costs of the fuel cell system. The electric energy production with the present efficiencies of such a decentralized cogeneration plant is limited by the thermal load and the thermal storage. For this reason a risk in the use of these systems results in the fact, that low thermal insulation standards and therewith high thermal losses allow higher electric energy production. This can optimize the costs and gains of such a cogeneration plant during the non-heating period, depending on the granted fee. Such problems have to be be taken into account, when "virtual power plants" (decentralized energy production with a centralized control system) are planed with domestic fuel cell systems.
Beyond these aspects of integration of domestic fuel cell systems in the existent energy supply system, the following issues have to be considered. These fuel cell systems are driven with natural gas, which means still a fossil energy source emitting the greenhouse gas CO_2. For this reason, there is the question of how such cogeneration facilities can be combined with the use of renewable energy sources.
The main problem will be the integration of a solar thermal system in the concept of a cogeneration plant, which should reach a maximum in the running time over a year due to economic aspects. The production of electricity is limited by the thermal energy demands and storage possibilities. Moreover an additional thermal energy source, for example a solar thermal system, reduces the operating time of the domestic fuel cell power station. In [OTTI-02] these problems are discussed and quantified. In the economic optimized case the solar thermal gains are reduced by 29 percent, whereas the ecologic optimized strategy reduces the operating time of the fuel cell cogeneration plant to the heating period. This results in higher running costs, because less electric energy can be fed into the grid during peak load times.
In [ZSW-1] is mentioned, that the electric energy consumption of private households during the summer months is reduced to one third of the demand in the winter season. The results, illustrated in figure 5 and figure 6, show a lower electric energy production and therewith a lower demand of natural gas in the non-heating period, if the ecologic optimized strategy is chosen. As a result of these facts, the question is posed, whether a domestic fuel cell station should only replace the conventional heating system in the heating period. If systems are used in such a manner, the problem of profitability will occur. Without any political influence this idea is not realizable. One sensible political approach could be a seasonal staged gratuity for electricity produced by natural gas driven domestic fuel cell systems. This means a higher fee during the heating-period and only a low base price in the summer months. Then cogeneration plants and renewable energy sources could be combined in a building with the aim to reduce the fossil primary energy demands to a minimum in a economic passable manner.

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