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MODELING OF ENERGY-SERVICES SUPPLY SYSTEMS

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Abstract – A general model framework is developed which describes regional and municipal energy systems in terms of data-flow networks. It provides a highly flexible tool for dynamic and stochastic minimization of primary energy demand, emissions of pollutants, and monetary cost. Included are conventional energy-supply techniques, rational use of energy via heat-exchanger networks, heat pumps and cogeneration, demand-side measures such as insulation of dwellings, and utilization of renewable energy sources.

1. INTRODUCTION

In energy economics, energy systems are usually defined as technical and economic systems meeting the energy demand. However, the energy demand is not a fixed quantity but is subject to various influences, e.g., prices, regulations, and consumer preferences. Thus, the definition of energy systems should provide a much broader, socioeconomic view and refer to the technical and economic side of energy supply as well as the socioeconomic phenomena occurring in a society, which uses energy to enhance its standard of living; furthermore the impact on the natural environment is important.[1] Such a definition includes many qualitative phenomena which are hard or even impossible to map into mathematical models. Therefore, it is necessary to reduce the scope of any modeling activities. This reduction should be done in an explicit, systematic way, which allows for a critical analysis of model results with respect to the assumptions and simplifications made.

It is important to realize that the use of energy is no end in itself but is always directed to satisfy human needs and desires. *Energy services* are the ends for which the energy system provides the means.

The model framework NEMESS (Network Model of Energy-Services Supply Systems) is aimed at supporting decision making during the development and realization of municipal and regional energy concepts. NEMESS may be used to minimize the **non-renewable primary energy**, the **emissions of various pollutants**, and the **monetary cost** of the respective energy systems or to identify suitable compromises between these objectives. In so doing, it determines (pareto-) optimal combinations of conventional energy-supply techniques with techniques that enhance the rational use of energy (including measures reducing the demand for useful energy such as insulation of dwellings) or allow for the use of renewable energy sources. It detects competition between the techniques listed and examines possibilities to avoid them by using energy storages. It may be used to quantify potentials for saving primary energy and reducing the emissions of pollutants as well as the related monetary cost.

We have described similar model frameworks, called *ecco* and *ecco-solar* before.[2] We decided to develop a new framework, because the structures of those models were not flexible enough to incorporate additional features such as arbitrary instead of fixed numbers of steps in energy-conversion chains. In addition, we realized that most of the modeling activities undertaken so far, including our own, were not general enough to include all options for providing energy services to make them comparable in a consistent manner. Past activities were generally focussed on either the supply side, the demand side, or special techniques such as renewable energies. We developed the new model framework as a flexible and open platform.

2. DEFINITIONS AND ASSUMPTIONS

2.1. Physical Definitions and Assumptions

It is evident that such mathematical models will focus on the technical and economic parts of the energy systems. During the design of earlier model frameworks, we used the notion energy-supply system to describe the technical part of the whole energy system.[2] To emphazise the fact that we model both supply and demand sides of the energy system, we define a new subset of the full energy system.

Definition 1 : An **energy-services supply system**, abbreviated ESSS, consists of the **equipment**, the **commodity flows**,[†] and the **information** necessary to meet a given demand for energy services within a well-defined spatial area. The term *information* comprises statistical data on natural phenomena like the ambient temperature or solar radiation as well as energy-demand patterns. It may also include information on socioeconomic phenomena as long as they can be mapped into mathematical functions such as objective functions or restrictions (e.g., emission standards). Other qualitative phenomena have to be considered externally during the design and interpretation of scenarios, i.e. model calculations with different sets of parameters.

Assumption 1 : The ESSS is spatially homogenous with respect to the weather (ambient temperature, solar radiation, velocity of wind), losses during transportation of electrical energy and fossil fuels to any point within the ESSS, prices of energy carriers (for the same group of users) and cost of technical equipment, and transportation of heat; there are no time lags between production and usage of heat. Thus, the characteristics listed do not depend on the location within the ESSS.

Definition 2 : **Processes** are subsystems of the ESSS which will not be divided further and which are connected by loss-free commodity flows. They are treated as black boxes which are characterized by entering and outgoing flows and by functions that relate these flows to each other. Any activity within the ESSS that involves physical irreversibilities and causes production of entropy has to be represented by a process. The processes are defined in Sec. 3. The separation of the full system into these subsystems is not unique and, therefore, a genuine task of the model users. The guideline is always to find boundaries at which the crossing commodity flows can be measured easily.

Assumption 2 : The spatial resolution of NEMESS is such, that any process (Def. 2) of interest may, in principle, be modeled separately. Groups of processes may be represented by a single process (spatial aggregation) if no important information is lost with respect to the goals of the modeling activity. Periodic and stochastic temporal fluctuations of all relevant internal and external observables must be known in the form of time series or probability distributions. They must reflect the important information on auto-correlations within a single time series and correlations between different time series.

Definition 3 : The total time span Θ, for which the optimization of the ESSS is desired, is divided into **intervals** of equal, appropriately chosen length τ, such that $\Theta = T \cdot \tau$. Quantities, which depend on the intervals explicitly, are indicated by superscript t.

According to assumption 2, NEMESS focusses on periodic and stochastic fluctuations of the energy demand and supply, which occur very fast compared to structural changes of the energy demand due to technical progress, economic growth, or changing behavior of consumers. To keep the resulting optimization problem managable, we have to restrict ourselves to one of the two time scales. Therefore, we neglect structural changes of the energy demand during optimization and restrict its mapping in the model to the definition of scenarios. Consequently, a time span of one year divided into intervals of one hour length is appropriate for many cases.

Assumption 3 : For each process, a maximum quantity of energy demanded can be derived from the demand of energy services. This maximum demand is assumed to be fixed with respect to the optimization procedure. It may be varied in the course of scenario definitions. It is important to note that the calculation of the maximum demand is not unique, but depends on the model user's

[†]Commodity flows are defined in a very general way in Def. 10. For the moment, the reader may equate commodity flows with flows of an arbitrary physical quantity such as energy or mass.

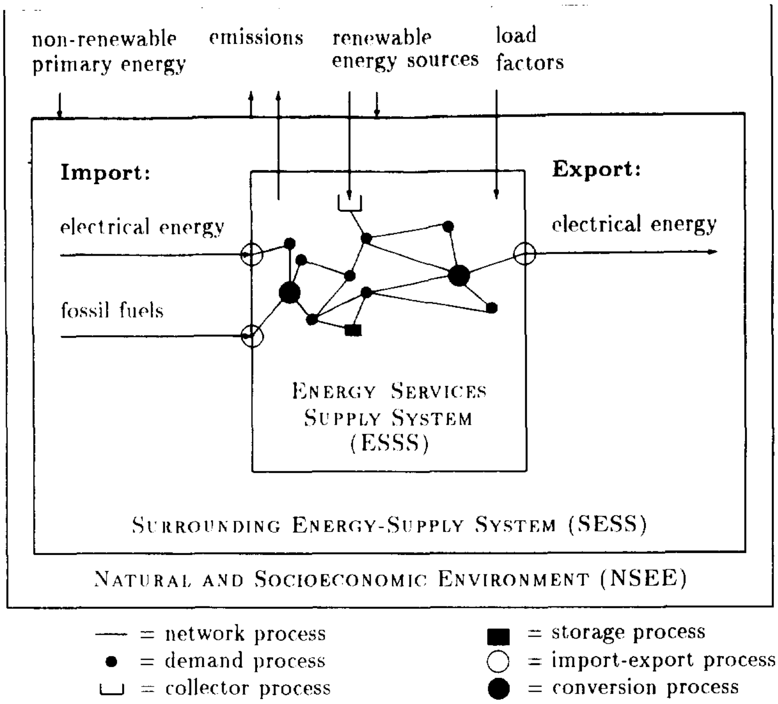

Fig. 1. Energy-services supply system (ESSS) embedded in the surrounding energy-supply system (SESS) and their common natural and socioeconomic environment (NSEE).

choice, which techniques of demand reduction are subject to optimization and which are covered by scenario definitions (see Sec. 3.7.).

In other words: The ESSS is assumed to be in a steady state with respect to historic time. It is dynamic with respect to periodical and stochastic phenomena which let the energy demand oscillate between zero and its fixed maximum.

Assumption 4 : The ESSS is embedded in the much larger *Surrounding Energy-Supply System*, abbreviated SESS, which has the following characteristics (see Fig. 1): The SESS provides the final energy (electrical energy and fuels) for the ESSS, which the latter cannot produce itself (energy import), and it takes back energy surplus created within the ESSS (energy export). Electrical energy may be imported and exported. Any fossil fuels needed in the ESSS have to be imported. Nuclear techniques may only be used as part of the SESS. The structure of and the activities within the ESSS have no influence on the intensive characteristics of the SESS. Thus, the average efficiency of electricity production in the SESS is not influenced by the amount of electricity needed for or produced by the ESSS. As in thermodynamics, the SESS may be viewed as the "reservoir" of the ESSS.

Assumption 5 : The ESSS and the SESS are both embedded in the *Natural and Socioeconomic Environment*, NSEE (Fig. 1), which has the following characteristics. The NSEE provides non-renewable primary energy such as coal or natural gas and renewable energy sources such as solar energy, wind energy, or biomass. The NSEE absorbs emissions of pollutants from the ESSS and the SESS. These emissions can be limited via model restrictions. In principle, any fuel- or equipment-related emissions can be considered. Among the most important emissions are CO_2, NO_x, SO_2, and CH_4. The NSEE provides the (possibly time-dependent) information necessary to quantify the energy demand. Especially, it provides the load factors which determine the fraction of the maximum energy demand actually needed within a certain time interval τ^t.

Definition 4 : All information refering exclusively to the natural environment and needed for optimization of the ESSS is contained in the **environmental-data vector $\mathbf{U}^t$**. For each time interval τ^t, this vector has components for the ambient temperature, the solar radiation, and other quantities which are necessary to calculate the energy demand and the offer of renewable energies.

Definition 5 : All **energy flows** relevant for description of the ESSS are measured at the system boundaries of the respective processes. They represent the amounts of energy that enter or leave the process per unit of time during the interval τ^t. Thus, energy flows have the unit of a power. Nevertheless, to indicate their nature as quantity per time, we use units like *kWh/h* for all flows in the model. Due to the applied optimization method, all energy flows are chosen to be positive. When necessary, their direction into or out of a process is indicated by indices *En* (Entry) or *Ex* (Exit), respectively.

The following energy flows during time interval τ^t are being considered for NEMESS :† **Electrical energy** $\dot{E}^t_{El}$, **fossil fuels** $\dot{E}^t_{Fuel}$ measured by their (lower) heating value, **thermal energy** (heat) $\dot{E}^t_H$, represented by the enthalpy H transported, and the **(non-renewable) primary energy** $\dot{E}^t_P$ which is used to create these flows of so-called final energy. For the sake of brevity, we define **a general energy flow** $\dot{E}^t_\alpha$ with $\alpha \in \{El, Fuel, H, P\}$. In reality, the transportation of heat is mostly done via mass flows (e.g., heated water) that carry the enthalpy. We are currently working on a model extension that will include characteristics of mass flows like pressure and temperature. However, this is not modeled here explicitly.

The non-renewable primary energy necessary to meet the demand for energy services can be seen as the energetic cost of the ESSS which is to be minimized. Since only refined fossil fuels and electrical energy cross the boundaries into the ESSS, a variable primary energy demand $\dot{E}_P^{Var,t}$ is assigned to each such energy flow. For fuels, it is calculated from the heating value of the fuel considering an average efficiency for extraction, refining, and transportation to the ESSS. For electrical energy it is derived from the average production efficiency within the SESS.

For mathematical reasons, the fixed amount of primary energy necessary to build, maintain, and demolish a piece of technical equipment is distributed over its life-time. Thus, for each process, the fixed primary energy demand per unit of time $\dot{E}_P^{Fix}$, measured in *kWh/h*, is calculated by dividing the total amount of primary energy "spent" in addition to the energy needed to operate the device by the life-span of the equipment and multiplying it by the length τ of the time intervals. Since $\dot{E}_P^{Fix}$ is constant for all intervals, there is no superscript t.

Definition 6 : We define a general flow of **emissions** $\dot{P}_\nu$ with $\nu \in \{CO_2, SO_2, NO_x, CH_4, \ldots\}$. The dots indicate the possible inclusion of other pollutants. The emissions are measured in mass units per unit of time, e.g., in *t/h* or *kg/h*. The different types of emissions form the components of the emission vector $\dot{\mathbf{P}}$. As for the energy flows in Def. 5, we distinguish variable emissions $\dot{P}_\nu^{Var,t}$ related to energy flows and fixed emissions $\dot{P}_\nu^{Fix}$ which account for building, maintaining, and demolishing the process equipment.

Definition 7 : The variable **monetary cost**, $\dot{M}^{Var,t}$, is the amount of money per unit of time that has to be paid for energy flows $\dot{E}^t_{Fuel}$ and $\dot{E}^t_{El}$ crossing the boundaries of the ESSS. On the one hand, it is determined by the prices of the energy flows. On the other hand, it may also include any other costs that are proportional to the energy flow, such as emission taxes, variable operation costs etc. It is measured in *DM/h* or any other currency per unit of time. The variable cost may be negative if money is earned by exporting electrical energy from the ESSS to the SESS. The fixed monetary cost, $\dot{M}^{Fix}$, accounts for the cost of building, maintaining, and demolishing the equipment of a process. It is calculated using the annuity method which distributes the total (discounted) fixed cost over the life-span of the equipment.

In short, to build, maintain, run, and demolish an ESSS, one needs primary energy, capital and labor, and one has to accept that pollutants are emitted into the natural environment. All of these quantities represent costs of the energy system in a general sense.

Definition 8 : To simplify notation and language and express the symmetry of the optimization problem, we define vectors of variable and fixed **generalized costs** (per unit of time) $\dot{\mathbf{C}}^{Var,t}$ and $\dot{\mathbf{C}}^{Fix}$. Their components are given by the primary energy demand $\dot{E}_P^{Var,t}$ and $\dot{E}_P^{Fix}$, the emission vectors $\dot{\mathbf{P}}^{Var,t}$ and $\dot{\mathbf{P}}^{Fix}$, and the monetary costs $\dot{M}^{Var,t}$ and $\dot{M}^{Fix}$, respectively:

$$\dot{\mathbf{C}}^{Var,t} \equiv (\dot{E}_P^{Var,t}, \dot{\mathbf{P}}^{Var,t}, \dot{M}^{Var,t})^\dagger , \tag{1}$$

$$\dot{\mathbf{C}}^{Fix} \equiv (\dot{E}_P^{Fix}, \dot{\mathbf{P}}^{Fix}, \dot{M}^{Fix})^\dagger . \tag{2}$$

The components of $\dot{\mathbf{C}}^{Var,t}$ and $\dot{\mathbf{C}}^{Fix}$ are also referred to as $\dot{C}^{\delta,Var,t}$ and $\dot{C}^{\delta,Fix}$ with $\delta \in \{\dot{E}_P, \dot{\mathbf{P}}, \dot{M}\}$, in the sense that, e.g., $\dot{C}^{\dot{E}_P,Var,t} \equiv \dot{E}_P^{Var,t}$. The total generalized cost for the interval τ^t is given by

$$\dot{\mathbf{C}}^t = \dot{\mathbf{C}}^{Var,t} + \dot{\mathbf{C}}^{Fix} . \tag{3}$$

†Renewable energy flows are not modeled explicitly, but taken into account via the energy flows of the types listed that are created from renewable sources (see Sec. 3.6.).

The average total generalized cost is

$$< \dot{C} >_T = \frac{1}{T} \sum_{t=1}^{T} \dot{C}^{Var,t} + \dot{C}^{Fix} . \tag{4}$$

The objective of NEMESS is to minimize the average total generalized costs, $< \dot{C} >_T$, of the ESSS. Obviously, the resulting mathematical problem involves vector optimization with conflicting objectives. It is often attempted to find a way in which the different objectives can be made cardinally comparable, mostly via assigning monetary values to all objectives. We have discussed the problematic of such an attempt at length elsewhere.[3]

Assumption 6 : Daly postulates as a fundamental principle of ecological economics that man-made and natural capital are complementary rather than substitutable (strong sustainability).[4] We relate the monetary cost of the ESSS to man-made capital and emissions as well as primary energy to natural capital. Based on Daly's claim, we then assume that the different costs of the ESSS are orthogonal to each other, meaning that one kind of cost cannot be expressed in terms of the other. For example, it is not possible, to calculate external costs of emissions accounting for the damage caused with sufficient precision for use within an optimization model.

2.2. Data-type Definitions and Assumptions

It is important in our model to comprehend the distinction between physical flows and knowledge about such flows. For example, if heat is transported from process A to B, it is often vital for modeling activities to know whether process A or B determines the size of the flow. If this is done by process B, the information on the flow size has to travel anti-parallel to the energy flow. As we will show, it is of advantage to base the whole model on the flows of knowledge, or, as we will call it, "data flows". To prepare this approach, we introduce a second set of terminology which characterizes the model components with respect to data management.

Definition 9 : Quantities, which are proportional to the size of the system, are called **extensive**. Quantities, which are independent of the system size, are called **intensive**.

Definition 10 : Generalized-cost flows, including primary-energy flows, and other energy flows are together referred to as **commodity flows** $\dot{F}$. The characteristic of a commodity flow is the existence of a conservation law. This is self-evident for energy and emission flows. It is reasonable to claim conservation for money flows related to the ESSS. It simply demands that all money has to be accounted for. Commodity flows are extensive. In contrast, **informational flows** (see Def. 1) can be divided arbitrarily often without loosing any of their contents.

Definition 11 : Intensive quantities, which describe properties of commodity flows like temperature or pressure, are called **flow attributes** or simply **attributes**.[5]

Definition 12 : Intensive quantities, which result from the division of two extensive quantities, are called **specific quantities**. For instance, process efficiencies are calculated by dividing the energy flow leaving by the energy flow entering a process.

Assumption 7 : Flow attributes are not considered within NEMESS . The only information about a flow that is handed from one process to another is its (extensive) size. Specific quantities have to be related to appropriate processes. For example, specific emissions of fuels are not related to the fuel flow but to the respective processes.

Definition 13 : **Process parameters** are intensive properties of a process (e.g., specific quantities like conversion efficiencies) which cannot be changed by the operation of the process itself and which are necessary for calculations involving only a single process (process-internal calculations). They are not explicitly time-dependent, but may result from calculations including time-dependent external influences and truely constant parameters (see Def. 17). Such calculations have to take place before the optimization is carried out. The efficiency of a heat pump that depends on the ambient temperature is an example of such a process parameter.

Definition 14 : **Process variables** are extensive or intensive, explicitly time-dependent quantities which represent inputs or outputs of process-internal calculations (see Def. 13). There are two kinds of processes variables, which are defined below: process-state variables and data flows.

Definition 15 : **Process-state variables** are process variables which represent information on the state of a process at the beginning of a time interval τ^t. They have to be determined *before* the optimization for this time interval is carried out. A process-state variable will be used to represent the energy demand that has to be met during a time interval. Others may contain information on the history of a process that is relevant for its future development.[6] This is necessary to describe non-stationary phenomena such as the loading of a storage. For instance, the amount of energy in a storage tank, E^S, is a process-state variable.

In principle, the contribution of a process to the variable generalized cost of the ESSS is determined by the energy flows entering and leaving the process together with the process-state variables. In most cases, not all of these energy flows can be chosen arbitrarily, but they are related to each other via input-output relations. Unfortunately, there is no general rule identifying the independent and dependent flows. To find such rules for the individual processes, one has to consider the direction in which the information "flows" through a process and between different processes.

Definition 16 : Independent process variables are considered as flowing into the process and are, therefore, called **input-data flows**. Dependent, flow-related process variables are considered as flowing out of the process and are referred to as **output-data flows**. The output-data flow of one process will most probably be the input-data flow of another process. Thus, data flows are the informational links between processes.

Most data flows are associated with commodity flows entering and leaving a process, their directions being either parallel or anti-parallel to that of the respective commodity flows. Note that the numeric value of a commodity related data flow is given by the magnitude of the respective commodity flow. Since optimization does not distinguish flow directions, the optimization of commodity or data flows is equivalent.

Definition 17 : An **external influence** is an input-data flow containing information that is neither influenced by any flow or process nor by the decision makers and operators of the ESSS. The environmental-data vector $\mathbf{U}^t$, which contains, e.g., the ambient temperature, is an example of an external influence.

Definition 18 : Unequivocal mathematical functions that relate vectors of output-data flows $\mathbf{y}(t)$ to input-data flows $\mathbf{x}(t)$ and state variables $\mathbf{z}(t)$ are called **input-output relations**. Often, these relations can be expressed in the following, simple form:[7] $\mathbf{y}(t) = \mathbf{f}[\mathbf{z}(t), \mathbf{x}(t), t]$.

Definition 19 : Mathematical relations describing the temporal development $\dot{\mathbf{z}}(t)$ of state variables as functions of input data $\mathbf{x}(t)$ and state variables $\mathbf{z}(t)$ are called **state-transformation functions**: $\dot{\mathbf{z}}(t) = \mathbf{g}[\mathbf{z}(t), \mathbf{x}(t), t]$.

Definition 20 : When stating input-output relations, the following general ratios of energy flows are helpful ($\alpha, \beta \in \{El, H, Fuel\}$):

$$\lambda_\beta^\alpha = \frac{\partial \dot{E}_{\alpha,En}}{\partial \dot{E}_{\beta,Ex}}, \ \varepsilon_\beta^\alpha = \frac{\partial \dot{E}_{\alpha,Ex}}{\partial \dot{E}_{\beta,En}}, \ \kappa_\beta^\alpha = \frac{\partial \dot{E}_{\alpha,Ex}}{\partial \dot{E}_{\beta,Ex}}, \ \sigma_\beta^\alpha = \frac{\partial \dot{E}_{\alpha,En}}{\partial \dot{E}_{\beta,En}} \ . \tag{5}$$

Thus, λ_β^α represents the amount of energy form α entering a process and necessary to produce one unit of energy form β leaving the process. Conversely, ε_β^α is the specific efficiency of converting one energy form into another. Similarly, κ_β^α and σ_β^α stand for the coupled production and utilization of different energy flows, respectively.

Assumption 8 : NEMESS describes processes via their input-output relations. It is not necessary to know the internal functioning of the processes, which may be arbitrarily complex, in detail. As a consequence, an optimization of the processes themselves is not possible. NEMESS is designed to optimize the interaction of these processes.

Assumption 9 : The input-output relations considered within NEMESS have to be linear with respect to the extensive input data and the process-state variables. There may be, however, nonlinear dependencies on external influences. For instance, the efficiency of a heat pump may be an arbitrary function of the ambient temperature. To keep this assumption valid, the optimization intervals must be sufficiently short, so that the external influences remain constant during these periods of time.

3. DESCRIPTION OF PROCESSES

As a convention, roman indices represent numbers identifying and, if necessary, counting the members of sets having an arbitrary number of members. On the other hand, greek indices stand for alpha-numerical strings which identify the members of sets having a fixed number of members.

Definition 21 : The following sets of processes are defined within NEMESS : $\{d\}$ **demand processes**; $\{c\}$ **conversion processes**; $\{n\}$ **network processes**; $\{p\}$ **import-export processes**; $\{s\}$

Table 1. Notation for NEMESS .

Extensive quantities	
$\dot{F}^t$	general commodity flow
$\dot{E}_P^{Var,t}$, $\dot{E}_P^{Fix}$	variable and fixed primary energy flows
$\dot{E}_{El}^t$	electrical energy flow
$\dot{E}_{Fuel}^t$	fuel flow, viz. chemical energy flow
$\dot{E}_H^t$	net enthalpy flow, viz. heat flow
$\dot{E}_\alpha^t$	general energy flow, $\alpha \in \{El, Fuel, H, P\}$
$K_{\alpha,a}$	capacity of process a for energy flow of type α
$K_{\alpha,a}^{Max}$	upper limit for capacity $K_{\alpha,a}$
$\dot{\mathbf{P}}^{Var,t}$, $\dot{\mathbf{P}}^{Fix}$	variable and fixed emission vectors (per unit of time)
$\dot{P}_\nu^{Var,t}$, $\dot{P}_\nu^{Fix}$	components of the emission vectors, $\nu \in \{CO_2,\ NO_x,\ SO_2, \ldots\}$
$\dot{M}^{Var,t}$, $\dot{M}^{Fix}$	variable and fixed monetary costs
$\dot{\mathbf{C}}^{Fix}$	fixed generalized-cost vector, $\dot{\mathbf{C}}^{Fix} = (\dot{E}_P^{Fix}, \dot{\mathbf{P}}^{Fix}, \dot{M}^{Fix})^\dagger$
$\dot{\mathbf{C}}^{Var,t}$	variable generalized-cost vector, $\dot{\mathbf{C}}^{Var,t} = (\dot{E}_P^{Var,t}, \dot{\mathbf{P}}^{Var,t}, \dot{M}^{Var,t})^\dagger$
$<\dot{\mathbf{C}}>$	total generalized-cost vector, $<\dot{\mathbf{C}}> = \dot{\mathbf{C}}^{Fix} + \frac{1}{T}\sum_t \dot{\mathbf{C}}^{Var,t}$
$\dot{C}^\delta$	components of $\dot{\mathbf{C}}$-vectors; $\delta \in (\dot{E}_P, \dot{\mathbf{P}}, \dot{M})$
$\dot{C}^{\delta,Var,Max}$, $\dot{C}^{\delta,Fix,Max}$	upper limit of variable and fixed costs of type δ
$\dot{C}^{\delta,Max}$	upper limit of total cost of type δ
Intensive quantities	
λ_β^α	$\partial \dot{E}_{\alpha,En} / \partial \dot{E}_{\beta,Ex}$
ε_β^α	$\partial \dot{E}_{\alpha,Ex} / \partial \dot{E}_{\beta,En}$
κ_β^α	$\partial \dot{E}_{\alpha,Ex} / \partial \dot{E}_{\beta,Ex}$
σ_β^α	$\partial \dot{E}_{\alpha,En} / \partial \dot{E}_{\beta,En}$
$\varrho_s^{El+,S}$	specific electricity demand of storage s
$c_{\alpha,a}^{\delta,Var}$, $c_{\alpha,a}^{\delta,Fix}$	specific var. and fixed generalized costs of type δ and flow α of process a
External process influences	
$\mathbf{U}^t$	environmental-data vector
γ_d^t	load factor of demand process $d \in \{d\}$
Process-state variables	
$\dot{E}_{\alpha,d}^{D,t}$	energy of type α, $\alpha \in \{H,\ El\}$, demanded by demand process d
$\dot{E}_{H,l,d}^{W,t}$	waste heat flow (numbered l) available from demand process d
$\dot{E}_{\alpha,o}^{R,t}$	renewable energy of type α, $\alpha \in \{Fuel, H, El\}$, from collector process o
$\dot{E}_{\alpha,v}^{V,t}$	virtual energy of type α, $\alpha \in \{H,\ El\}$, from virtual-supply process v
$E_s^{S,t}$	energy content of storage s at the beginning of time interval t
$E_s^{S,Min}$, $E_s^{S,Max}$	minimum and maximum energy content of storage s
Superscripts and subscripts	
t	refers to time interval τ^t
H	refers to heat
H,k	refers to heat flow number k; (also: i, j, l instead of k)
$Fuel$, El	refer to fuel (chemical energy) and electrical energy, respectively
P, D, W	refer to primary energy, demanded energy, reusable waste heat, respectively
R, V, S, L	refer to renewable, virtual, stored, and lost energy, respectively
δ	refers to components of generalized-cost vector; $\delta \in (\dot{E}_P, \dot{\mathbf{P}}, \dot{M})$
α	refers to the energy-flow type, $\alpha \in \{Fuel, H, El, P\}$
Var, Fix	indicate variable and fixed quantities, respectively (with respect to time)
En, Ex	indicate entering and leaving energy flows, respectively

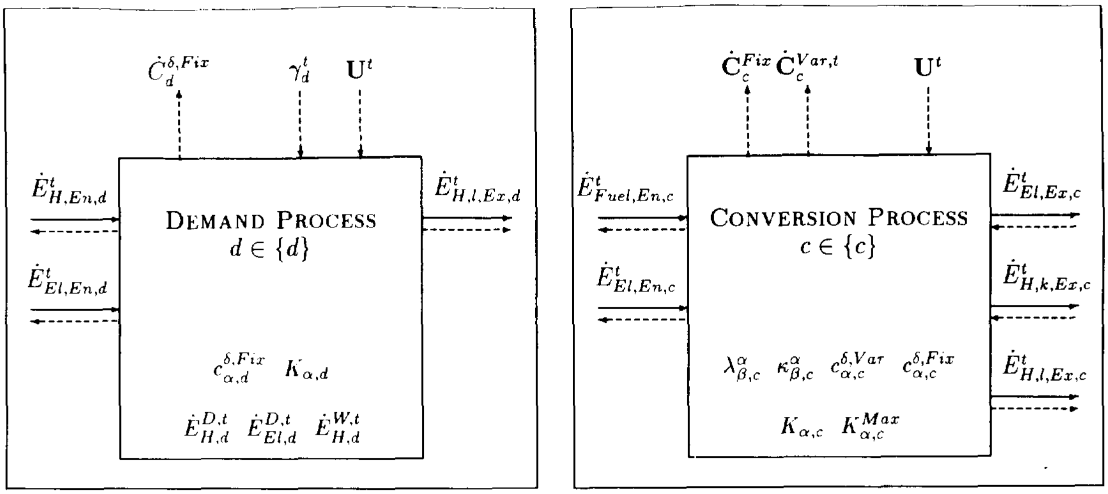

Fig. 2. Commodity- and data-flow diagram of demand and conversion processes. Solid arrows ($\longrightarrow$) represent commodity flows, dashed arrows ($- \rightarrow$) indicate data flows.

storage processes; $\{o\}$ **collector processes**; $\{v\}$ **virtual-supply processes**; $\{a\}$ **all processes**: $\{a\} = \{d\} \cup \{c\} \cup \{n\} \cup \{p\} \cup \{s\} \cup \{o\} \cup \{v\}$.

Definition 22 : The **capacity** $K_{\alpha,a}$ of an arbitrary process $a \in \{a\}$ is the maximum amount of the energy form α per unit of time that can enter or leave the process during any interval τ^t, i.e. the maximum value that $\dot{E}^t_{\alpha,a}$ may assume (Def. 5).

Assumption 10 : Capacities are optimization variables of NEMESS . They are derived from the respective energy flows via restrictions of the general form

$$\dot{E}^t_{\alpha,a} \leq K_{\alpha,a} \leq K^{Max}_{\alpha,a} \qquad \forall\, t\,. \tag{6}$$

During cost optimization, the capacities will automatically be chosen as small as possible while fulfilling Eq. (6), since additional capacity units will cause additional costs. Each capacity $K_{\alpha,a}$ may be limited by a $K^{Max}_{\alpha,a}$ which has to be chosen by the model user.

Definition 23 : The components $\dot{C}_a^{\delta,Fix}$ of the fixed generalized-cost vector of any process $a \in \{a\} \setminus \{s\}$ have to be associated with *one* of the capacities defined above. They are calculated as

$$\dot{C}_a^{\delta,Fix} = c^{\delta,Fix}_{\alpha,a}\, K_{\alpha,a} \qquad \alpha \in \{H, El, Fuel\},\ \forall\, \delta \in \{\dot{E}_P, \dot{\mathbf{P}}, \dot{M}\}\,, \tag{7}$$

where the $c^{\delta,Fix}_{\alpha,a}$ are the respective specific fixed cost factors. The selection of the energy flow, on which the capacity is based, is postponed to the model application to allow a maximum degree of freedom during modeling. For the fixed cost of storages refer to Eq. (30).

Definition 24 : The components $\dot{C}_a^{\delta,Var,t}$ of the variable generalized-cost vector of any process $a \in \{a\}$ have to be associated with *one* energy flow of the process. They are calculated as

$$\dot{C}_a^{\delta,Var,t} = c^{\delta,Var}_{\alpha,a}\, \dot{E}^t_{\alpha,a} \qquad \alpha \in \{H, El, Fuel\},\ \forall\, \delta \in \{\dot{E}_P, \dot{\mathbf{P}}, \dot{M}\}\,, \tag{8}$$

where the $c^{\delta,Var}_{\alpha,a}$ are the respective specific variable cost factors.

3.1. Demand processes

A demand process is the last link in the chain of energy conversions which starts with the extraction of primary energy and ends with the provision of an energy service. It translates the non-measurable energy service into measurable energy-demand data (i.e. enthalpy or electricity demand). The respective process boundary has to be defined by the measuring engineer according to the feasibility of obtaining reliable data. The closer to the energy service the points of measurement are located, the more technical degrees of freedom can be considered during optimization. The data gained are called *energy demand.* They cannot be classified by one of the standard concepts of energy economics like final or useful energy.

Commodity flows and data flows of the demand processes are shown in Fig. 2. The enthalpy demand $\dot{E}^{D,t}_{H,d}$ and the electricity demand $\dot{E}^{D,t}_{El,d}$ of a process $d \in \{d\}$ are process-state variables, which have to be determined before the optimization for the time interval τ^t is carried out. They are both functions of the environmental-data vector $\mathbf{U}^t$ and of external load factors γ^t_d, i.e.†

$$\dot{E}^{D,t}_{H,d} \equiv \dot{E}^{D,t}_{H,d}(\mathbf{U}^t, \gamma^t_d)\,, \qquad \forall\, d,\ \forall\, t\,, \tag{9}$$

$$\dot{E}^{D,t}_{El,d} \equiv \dot{E}^{D,t}_{El,d}(\mathbf{U}^t, \gamma^t_d)\,, \qquad \forall\, d,\ \forall\, t\,. \tag{10}$$

The two energy demands have to be met by the entering flows $\dot{E}^t_{H,En,d}$ and $\dot{E}^t_{El,En,d}$, respectively, viz.,

$$\dot{E}^t_{H,En,d} = \dot{E}^{D,t}_{H,d}\,, \qquad \forall\, d,\ \forall\, t\,, \tag{11}$$

$$\dot{E}^t_{El,En,d} = \dot{E}^{D,t}_{El,d}\,, \qquad \forall\, d,\ \forall\, t\,. \tag{12}$$

Information on these *entering* energy flows is *leaving* the demand process.

It is possible to define the entering energy flows directly as functions of $\mathbf{U}^t$ and γ^t_d rather than introducing the process-state variables. Nevertheless, to guarantee symmetry of all processes, no energy flows should be calculated externally, but they should all be determined during optimization, even if their magnitude is predetermined by some restriction. This constraint is important to ensure that all energy balances that will be introduced (Def. 25) will have the same format. Consequently, the number of exceptions that have to be considered is decreased.

Each demand process can produce several types of waste heat, *which are distinguished by the index* l. For each of these, a process-state variable $\dot{E}^{W,t}_{H,l,d}$ contains the available quantity, which depends on the vector of external influences and on the load factors, i.e.

$$\dot{E}^{W,t}_{H,l,d} \equiv \dot{E}^{W,t}_{H,l,d}(\mathbf{U}^t, \gamma^t_d)\,, \qquad d \in \{d\},\ \forall\, l,\ \forall\, t\,. \tag{13}$$

Thus, the amount of waste heat available during an optimization interval can and must be calculated beforehand. It may be utilized via leaving energy flows $\dot{E}^t_{H,l,Ex,d}$ which are restricted by

$$\dot{E}^t_{H,l,Ex,d} \leq \dot{E}^{W,t}_{H,l,d}\,. \tag{14}$$

For demand processes, Eq. (6) translates into

$$\dot{E}^t_{\alpha,d} \leq K_{\alpha,d} \qquad \forall\, \alpha \in \{(H,En),(El,En)\},\ \forall\, d,\ \forall\, t\,. \tag{15}$$

The capacity of a demand process is not really subject to optimization, since it is determined by the largest amount of energy demanded. However, Eq. (15) is useful to calculate the process capacity, which will then determine the fixed generalized costs of the demand process according to Eq. (7). Nevertheless, capacity restrictions according to Eq. (6) are not making sense, because they would make it impossible to meet the energy demand.

There are no variable generalized costs associated with demand processes $d \in \{d\}$.

3.2. Conversion processes

Conversion processes model the production of heat and electrical energy from chemical energy, i.e. fuels. They describe power plants, cogeneration units, boilers, and furnaces. The energy and data flows of conversion processes are shown in Fig. 2. There are two types of heat flows, which may leave a conversion process c and are distinguished by the directions of their respective data flows. The $\dot{E}^t_{H,k,Ex,c}$ refer to heat flows that are produced according to the main purpose of the device and are labeled by k. Therefore, the demand for such heat flows comes from outside the conversion process via entering data flows. We refer to these heat flows as *demanded heat*. On the other hand, the $\dot{E}^t_{H,l,Ex,c}$ are *waste-heat flows* that are unwanted but unavoidably produced during the operation of c and labeled by l.

The amount of fuel entering conversion process $c \in \{c\}$ is determined by the flows of heat and electrical energy, which are demanded from c:

$$\dot{E}^t_{Fuel,En,c} = \sum_k \lambda^{Fuel}_{H,k,c}(\mathbf{U}^t)\, \dot{E}^t_{H,k,Ex,c} + \lambda^{Fuel}_{El,c}(\mathbf{U}^t)\, \dot{E}^t_{El,Ex,c} \qquad \forall\, c,\ \forall\, t\,. \tag{16}$$

†Terms of the form $\forall\, x \in \{x\}$ are abbreviated as $\forall\, x$ when the meaning is unequivocal.

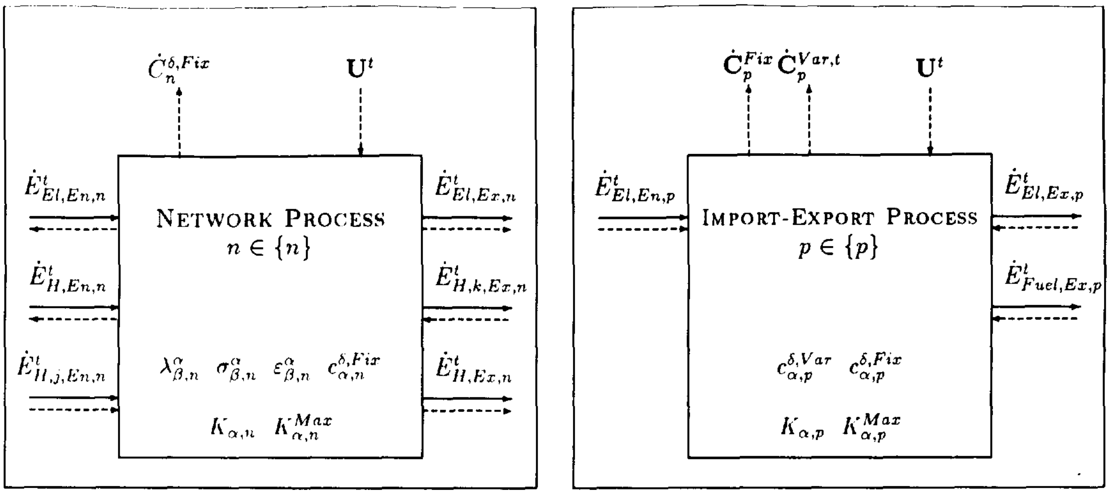

Fig. 3. Commodity- ($\longrightarrow$) and data-flow ($--\rightarrow$) diagram of network and import-export processes.

Eq. (16) allows to describe single-output units like power plants as well as furnaces and boilers by setting the specific fuel input for heat production, $\lambda^{Fuel}_{H,k,c}$, or electricity production, $\lambda^{Fuel}_{El,c}$, respectively, equal to zero. If both parameters are equal to zero, as it would be the case for an electrical induction oven, $\dot{E}^t_{Fuel,En,c}$ can be set equal to zero directly and the whole equation may be dropped from the optimization procedure.

For cogeneration of electricity and a single heat flow, the ratio of the produced electricity and heat has to be confined by additional *linear* constraints.

The electricity necessary to run process c is related to the leaving heat flows via

$$\dot{E}^t_{El,En,c} = \sum_k \lambda^{El}_{H,k,c}(\mathbf{U}^t)\, \dot{E}^t_{H,k,Ex,c} \qquad c \in \{c\},\ \forall\, t\,. \tag{17}$$

During the production of heat and/or electricity, several flows of reusable waste heat may be produced which are distinguished by index l and given by

$$\dot{E}^t_{H,l,Ex,c} \le \sum_k \kappa^{H,l}_{H,k,c}(\mathbf{U}^t)\, \dot{E}^t_{H,k,Ex,c} + \kappa^{H,l}_{El,c}(\mathbf{U}^t)\, \dot{E}^t_{El,Ex,c} \qquad c \in \{c\},\ \forall\, t\,. \tag{18}$$

The components of the variable generalized-cost vector of conversion processes c are proportional to the amount of fuel entering c:

$$\dot{C}_c^{\delta,Var,t} = c^{\delta,Var}_{Fuel,c}\, \dot{E}^t_{Fuel,En,c} \qquad \forall\, c,\ \forall\, t\,. \tag{19}$$

3.3. Network processes

Network processes are necessary to model the entropy-producing transportation of enthalpy (heat) between any two processes (Fig. 3), e.g., the transportation of heat from a central heating plant (conversion process) into a housing area (demand process) as well as the collection and distribution of waste heat.

Network processes may be demand-driven or supply-driven. In the first case, we have input-data flows of leaving energy $\dot{E}^t_{H,k,Ex,n}$, which determine the necessary output-data flow of entering energy $\dot{E}^t_{H,En,n}$ via†

$$\dot{E}^t_{H,En,n} = \sum_k \lambda^{H}_{H,k,n}(\mathbf{U}^t)\, \dot{E}^t_{H,k,Ex,n} \qquad n \in \{n\},\ \forall\, t\,. \tag{20}$$

†Allowing for more than one leaving energy flow is a simplification that may reduce considerably the number of network processes necessary to describe the ESSS. It is helpful if, for instance, one grid serves many demand processes. To state the reason for this, it is necessary to draw on notions and concepts that will be introduced in Sec. 4. for the first time: If only one leaving energy flow were allowed from the network process, it would have to be split at a balance point (Def. 25). But, each demand processes is proceeded by its own balance point. Since no two balance points may be connected directly, additional network processes would have to be introduced. On the other hand, allowing for multiple entering energy flows at the same time would cause severe problems when defining input-output relations. This concept does not reduce the generality of the model, since the most general network process with just one leaving and one entering energy flow can still be defined for model applications.

This combination has to be used if one wants to connect several demand processes with a single conversion process.

Supply-driven network processes are needed, for example, to transport waste heat from several sources into a storage. In this case, the output-data flow of leaving energy, $\dot{E}^t_{H,Ex,n}$, depends on the input-data flows of entering energy, $\dot{E}^t_{H,j,En,n}$:

$$\dot{E}^t_{H,Ex,n} = \sum_j \varepsilon^H_{H,j,n}(\mathbf{U}^t)\ \dot{E}^t_{H,j,En,n} \qquad n \in \{n\},\ \forall\, t\ . \tag{21}$$

Assumption 11 : To pump heat-carrying media through pipelines, *electrical* pumps are applied, exclusively.

Using Eq. (5), the amount of electrical energy necessary for the pumping of entering and leaving flows, and for steering purposes may be written as:

$$\begin{aligned} \dot{E}^t_{El,En,n} = \quad & \sigma^{El}_{H,n}(\mathbf{U}^t)\ \dot{E}^t_{H,En,n} + \sum_k \lambda^{El}_{H,k,n}(\mathbf{U}^t)\ \dot{E}^t_{H,k,Ex,n} \\ & + \sum_j \sigma^{El}_{H,j,n}(\mathbf{U}^t)\ \dot{E}^t_{H,j,En,n} + \lambda^{El}_{H,n}(\mathbf{U}^t)\ \dot{E}^t_{H,Ex,n} \qquad \forall\, n,\ \forall\, t\ . \end{aligned} \tag{22}$$

In addition, Eq. (22) may be used to model electrical heat pumps, which are in that case formally treated as network processes.

The production of electrical energy from waste heat may also be modeled via network processes. The amount of electrical energy that can be produced may be calculated as

$$\dot{E}^t_{El,Ex,n} = \sum_j \varepsilon^{El}_{H,j,n}(\mathbf{U}^t)\ \dot{E}^t_{H,j,En,n} \qquad n \in \{n\},\ \forall\, t\ . \tag{23}$$

There are no variable costs associated with network processes $n \in \{n\}$.

3.4. Import-export processes

Import-export processes model the connections between the ESSS and the SESS. They map not only pieces of equipment at the crossing point but represent all processes of the SESS that take part in delevering electrical energy and fuels to the ESSS. Nevertheless, they are treated as parts of the ESSS.

An import-export process can have one of the following functions: It may *import* either electrical energy or one type of fuel from the SESS and supply it to another process of the ESSS via leaving energy flows $\dot{E}^t_{\alpha,Ex,p}$ ($\alpha \in \{El, Fuel\}$) (see Fig. 3). Alternatively, it may absorb electrical energy from some process of the ESSS via the entering energy flow $\dot{E}^t_{El,En,p}$ and *export* it to the SESS. The SESS side of the import-export processes is not modeled explicitly.

The import of energy will, of course, cause (positive) generalized costs in the SESS which have to be associated with the ESSS. If, however, a surplus of electrical energy is produced within the ESSS and exported to the SESS, the electricity production of the latter is *decreased* and costs are avoided in the SESS. Thus, the import-export processes add possibly negative generalized costs occuring within the SESS to the total cost balance of the ESSS.

Since all energy flows represent input data of the import-export processes, there are no input-output relations between energy flows. The components of the generalized-cost vector can be calculated as

$$C^{\delta,Var,t}_p = c^{\delta,Var}_{\alpha,p}\ \dot{E}^t_{\alpha,p} \qquad \alpha \in \{(El,En),(El,Ex),(Fuel,Ex)\},\ \forall\, p,\ \forall\, t\ , \tag{24}$$

where $c^{\delta,Var}_{\alpha,p}$ is the specific cost of an energy flow of type α. The $c^{\delta,Var}_{El,En,p}$ are negative. Their absolute values should be marginally smaller than the cost of imported electrical energy exactly to avoid the effect that imported energy is re-exported.

The fixed costs of import-export processes represent the share of the equipment costs in the SESS that has to be assigned to the ESSS for utilization of equipment of the SESS.

3.5. Storage processes

Storage processes model the storage of enthalpy (heat), electrical energy, or fuel. They include not only the storage itself, but all equipment necessary to fill and empty the storage. Each storage process

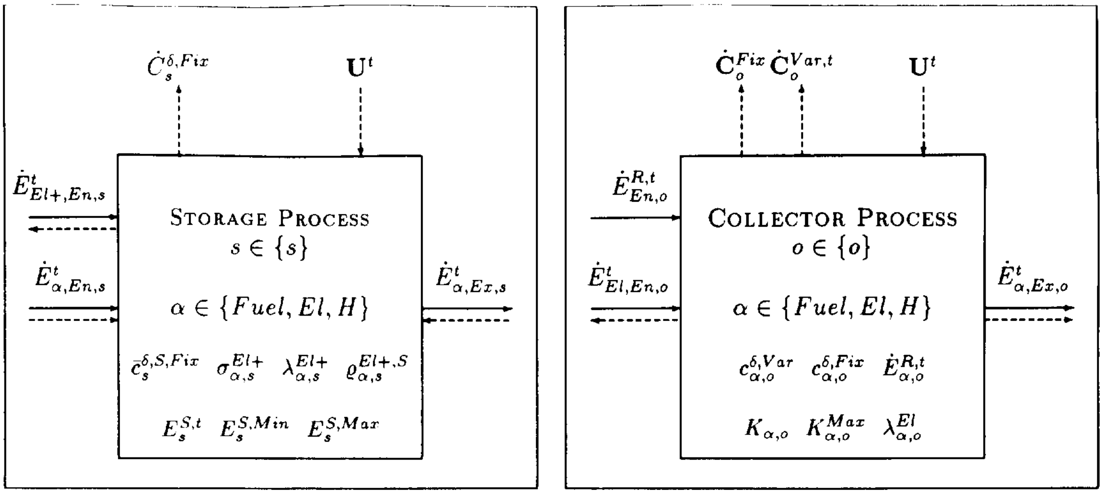

Fig. 4. Commodity- (⟶) and data-flow (– →) diagram of storage and collector processes.

can only store one energy form $\alpha \in \{Fuel, El, H\}$ and, in case of fuels, only one type of fuel. The storage of fuel is included to model the utilization of renewable fuels (biomass) that are produced and used within the ESSS. The export of biomass is not considered. The storage of electricity may not only be modeled in the physical sense, but can also be used to simulate dynamic load management at the demand side.[9]

The energy flows $\dot{E}^t_{\alpha,En,s}$ and $\dot{E}^t_{\alpha,Ex,s}$ ($\alpha \in \{Fuel, El, H\}$) entering and leaving the storage are shown in Fig. 4. The entering additional electrical energy $\dot{E}^t_{El+,En,s}$ is needed for the operation of the storage process. It has to be distinguished from the possible flow $\dot{E}^t_{El,En,s}$ of electricity that is stored due to different orientations of the related data flows (see Fig. 4). $\dot{E}^t_{El+,En,s}$ is proportional to the entering and leaving energy flows and to the energy contents of the storage:

$$\dot{E}^t_{El+,En,s} = \sigma^{El+}_{\alpha,s}(\mathbf{U}^t)\, \dot{E}^t_{\alpha,En,s} + \lambda^{El+}_{\alpha,s}(\mathbf{U}^t)\, \dot{E}^t_{\alpha,Ex,s} + \varrho_s^{El+,S}(\mathbf{U}^t)\, E_s^{S,t} \qquad \forall\, s,\ \forall\, t\,, \tag{25}$$

where $\varrho_s^{El+,S}$ is the specific electricity demand of the storage itself.

The amount of energy stored in storage s at the *beginning* of time interval τ^t, $E_s^{S,t}$, is a process-state variable, whose value has to be calculated before the optimization for the single time interval τ^t starts. For sufficiently small τ, it is determined by the differences equation

$$\frac{E_s^{S,t} - E_s^{S,t-1}}{\tau} = \dot{E}^{t-1}_{\alpha,En,s} - \dot{E}^{t-1}_{\alpha,Ex,s} - \dot{E}_s^{L,t-1}(\dot{E}^{t-1}_{\alpha,En,s}, \dot{E}^{t-1}_{\alpha,Ex,s}, E_s^{S,t-1}, \mathbf{U}^{t-1}) \quad \forall\, s,\ \forall\, t > 1\,, \tag{26}$$

with $\alpha \in \{H, El, Fuel\}$ and $\dot{E}_s^{L,t}$ representing the losses from the storage during interval τ^t as well as other effects that diminish the amount of energy added to or taken from the storage during τ^t. If $\dot{E}_s^{L,t}$ is a linear function of the energy flows listed and the stored energy, Eq. (26) is fairly easy to treat within a linear optimization procedure. This is, however, a simplification since the heat exchangers necessary to load and empty the storage do not expose linear behavior with respect to the temperature of the storage and the entering and leaving energy flows.

Assumption 12 : The size of the storage is not subject to optimization. Thus, a restriction of the form

$$E_s^{S,Min} \le E_s^{S,t} \le E_s^{S,Max} \qquad \forall\, s,\ \forall\, t \tag{27}$$

must hold, where $E_s^{S,Min}$ and $E_s^{S,Max}$ represent the minimum and the maximum amount of energy in the storage, respectively.

Consequently, the entering and leaving energy flows are restricted by

$$\dot{E}^t_{\alpha,En,s} \le (E_s^{S,Max} - E_s^{S,t}) \,/\, \tau \qquad \forall\, s,\ \forall\, t\,, \tag{28}$$

$$\dot{E}^t_{\alpha,Ex,s} \le (E_s^{S,t} - E_s^{S,Min}) \,/\, \tau \qquad \forall\, s,\ \forall\, t\,. \tag{29}$$

Due to Eq. (27), the fixed costs of the storage may not be determined by Eq. (7), but have to be *calculated* as

$$\dot{C}_s^{\delta,Fix} = \bar{c}_s^{\delta,Fix} \, E_s^{S,Max} \qquad \forall \, s, \, \forall \, t \, . \tag{30}$$

Since the size of the storage s cannot be optimized, its fixed cost is also not subject to optimization. The specific cost factors $\bar{c}_s^{\delta,Fix}$ have a different physical unit than the other cost factors, $c_{\alpha,a}^{\delta,Fix}$, since they are multiplied by energy rather than by power to obtain the total costs. There are no variable costs associated with storage processes.

3.6. Collector processes

Collector processes† $o \in \{o\}$ collect energy from renewable sources, which are – other than fossil and nuclear fuels – not available in arbitrary amounts for the ESSS within the time spans considered. They convert the collected energy into an usable form and offer it to other processes via an energy flow $\dot{E}^t_{\alpha,Ex,o}$ of type $\alpha \in \{Fuel, H, El\}$ (see Fig. 4). Collector processes may be used to map photovoltaics, wind mills, growing of biomass etc.

Physically, the renewable energy flow $\dot{E}^{R,t}_{En,o}$ enters the collector process. However, data on renewable energy sources are contained in the environmental data vector. Thus, there is no data flow associated with $\dot{E}^{R,t}_{En,o}$. Rather, the maximum amount of energy, which can be supplied from the renewable source $\dot{E}^{R,t}_{En,o}$, is a process-state variable that is determined by the environmental-data vector $\mathbf{U}^t$ and the maximum capacity of the collector process, i.e.

$$\dot{E}^{R,t}_{\alpha,o} \equiv \dot{E}^{R,t}_{\alpha,o}(\mathbf{U}^t, K^{Max}_{\alpha,o}) \qquad \alpha \in \{Fuel, H, El\}, \, \forall \, o, \, \forall \, t \, . \tag{31}$$

Consequently, the leaving energy flow $\dot{E}^t_{\alpha,Ex,o}$ is subject to the restriction

$$\dot{E}^t_{\alpha,Ex,o} \leq \dot{E}^{R,t}_{\alpha,o} \qquad \alpha \in \{Fuel, H, El\}, \, \forall \, o, \, \forall \, t \, . \tag{32}$$

It is important to keep in mind, that $\dot{E}^t_{\alpha,Ex,o}$ depends on the maximum capacity of the collector process. If, for example, $\dot{E}^t_{\alpha,Ex,o}$ is the total solar radition onto a roof of given size, $K^{Max}_{\alpha,o}$ would have to be the capacity of a photovoltaic device covering the whole roof area. Thus, for collector processes, the definition of a maximum capacity is mandatory. For some collector processes, the restriction given by Eq. (6), which does not take into account fluctuations of temperature and solar insolation, should be replaced by a stronger one similar to that of Eq. (37) discussed in the next section.

In this version of the model, collector processes can only account for renewable energy flows that do not depend on other processes. Solar collectors, for instance, cannot be modeled as collector processes, because their output depends on the temperature of the fluid, which also depends on the temperature within the storage. We are currently working on an extended version of the model which will include attributes of commodity flows and will, thus, be able to handle the inter-process information necessary to map solar collectors (see Sec. 6.). Within the current model version, solar collectors may provisionally be included into the storages as we suggested before when developing the model *ecco-solar*.[2]

The electrical energy $\dot{E}^t_{El,En,o}$, which is necessary to run a collector process, is proportional to the leaving energy flow:

$$\dot{E}^t_{El,En,o} = \lambda^{El}_{\alpha,o}(\mathbf{U}^t) \, \dot{E}^t_{\alpha,Ex,o} \qquad \alpha \in \{Fuel, H, El\}, \, \forall \, o, \, \forall \, t \, . \tag{33}$$

The variable cost of the collector processes is also proportional to the leaving energy flow and, therefore, given by

$$\dot{C}_o^{\delta,Var,t} = c^{\delta,Var}_{\alpha,o} \, \dot{E}^t_{\alpha,Ex,o} \qquad \alpha \in \{Fuel, H, El\}, \, \forall \, o, \, \forall \, t \, . \tag{34}$$

3.7. Virtual-supply processes

Virtual-supply processes model reductions of generalized costs that are due to a decreased energy demand rather than a more efficient supply. The insulation of dwellings and the installation of energy-saving light bulbs are examples of such demand-decreasing measures. However, to compare

†We use index o for collector processes, since the index c has been reserved for conversion processes.

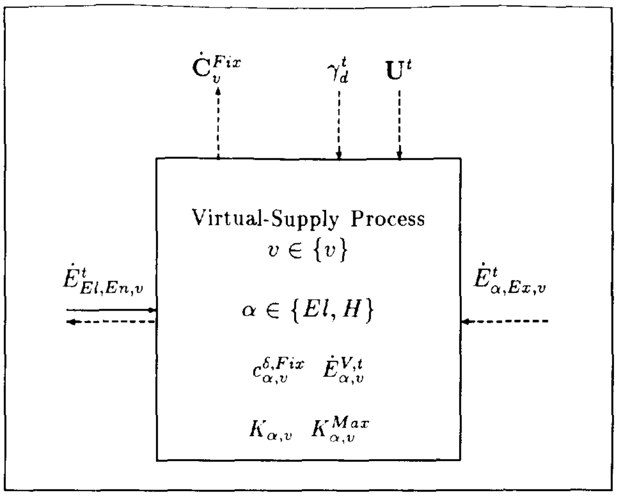

Fig. 5. Commodity- (⟶) and data-flow (– →) diagram of virtual-supply processes.

these measures with the efficient supply options and to make them accessible to optimization, they are modeled as (virtual) supply processes.

For each time interval, the process-state variable $\dot{E}^{V,t}_{\alpha,v}$ gives the maximum amount of enthalpy or electrical energy, which the virtual-supply process v may "supply" to another process of the ESSS via a (virtual) leaving energy flow $\dot{E}^t_{\alpha,Ex,v}$ ($\alpha \in \{H, El\}$). Since no energy is flowing in a physical sense, this flow is represented in Fig. 5 by a data flow, only. Similar to Eq. (32), we demand that

$$\dot{E}^t_{\alpha,Ex,v} \leq \dot{E}^{V,t}_{\alpha,v} \qquad \alpha \in \{H, El\},\ \forall\, v,\ \forall\, t\ . \tag{35}$$

Virtual-supply processes may possibly map a wide variety of demand-side measures. Therefore, different methods of calculating the process-state variable $\dot{E}^{V,t}_{\alpha,v}$ and the process capacity $K_{\alpha,v}$ will be necessary. In this paper, we restrict ourselves to describing one example.

Let $\dot{E}^{V,t}_{H,v}$ describe the amount of enthalpy that could be saved during time interval τ^t by insulating all dwellings of a city district, the latter being described by demand process d. Then, $\dot{E}^{V,t}_{H,v}$ will depend on the ambient temperature and on the current condition of the dwellings, which will together define a fraction of the energy demand, $\dot{E}^{D,t}_{H,d}$, that can be avoided by improved insulation:

$$\dot{E}^{V,t}_{H,v} \equiv \dot{E}^{V,t}_{H,v}(\mathbf{U}^t, \gamma^t_d) \sim \dot{E}^{D,t}_{H,d} \qquad \forall\, v,\ \forall\, t\ . \tag{36}$$

In Eq. (36), $\dot{E}^{V,t}_{H,v}$ depends on γ^t_d rather than $\dot{E}^{D,t}_{H,d}$, because no purely informational flow has been defined for the latter so far. However, $\dot{E}^{D,t}_{H,d}$ is given implicitly via Eq. (9). Since the process-state variable $\dot{E}^{V,t}_{H,v}$ depends on the load factors γ^t_d, each virtual-supply process of this kind has to be defined for an individual demand process d and may not be used otherwise.

The ratio of $\dot{E}^t_{H,Ex,v}$, determined by the optimization, and $\dot{E}^{V,t}_{H,v}$ represents the fraction of dwellings that should receive additional insulation based on time interval τ^t, rather than the quality of insulation for a single dwelling. The maximum of these ratios over time should determine the process capacity. Since this ratio has no physical unit, it has to be multiplied with some energy per unit of time. We suggest to use the maximum amount of energy that can be saved in any of the time intervals, i.e. $\max_{\{t\}} \dot{E}^{V,t}_{H,v}$. The actual capacity, which is subject to optimization, is then determined by

$$K_{H,Ex,v} \geq \frac{\max_{\{t\}} \dot{E}^{V,t}_{H,v}}{\dot{E}^{V,t}_{H,v}}\ \dot{E}^t_{H,Ex,v}\ . \tag{37}$$

Equation (37) ensures the selection of the largest ratio of $\dot{E}^t_{H,Ex,v}$ / $\dot{E}^{V,t}_{H,v}$ according to the principle discussed for Eq. (6). Since the ratio cannot be greater than one, $\max_{\{t\}} \dot{E}^{V,t}_{H,v}$ automatically determines the maximum capacity which corresponds to a situation where all dwellings are insulated.

Even though no 'real' energy is supplied, electrical energy may be needed to operate the virtual-supply process described, e.g., due to the fact that controlled ventilation is necessary after rigorous insulation of dwellings. It is assumed to be proportional to the capacity of the virtual-supply process:

$$\dot{E}^t_{El,En,v} = \lambda^{El}_{H,v}(\mathbf{U}^t)\ K_{H,Ex,v} \qquad \forall\, v,\ \forall\, t\ . \tag{38}$$

For a single dwelling, the electricity needed for ventilation is certainly not proportional to the amount of energy saved due to insulation. However, the heating demand of residential areas will mostly be aggregated. Then, the electrical energy for ventilation will be proportional to the number of dwellings insulated and, thus, to the capacity installed.

The fixed costs are determined by Eq. (7), where the specific fixed costs have to based on $\max_{\{t\}} \dot{E}^{V,t}_{H,v}$. Variable costs are not associated with virtual-supply processes.

Other virtual-supply processes may be designed with arbitrary relations as long as the fundamental principles defined in this paper are not violated. We are working on a type that will account for passive solar gains through windows or translucent insulation materials.

4. MODELING THE ESSS AS A DATA-FLOW NETWORK

Physically, the processes defined in Sec. 3. are interconnected by loss-free energy flows. However, the energy flow leaving one process need not nescessarily enter a single other process completely. Similarly, an energy flow entering a process need not stem from a single preceeding process. Therefore, it is necessary to introduce balances for the splitting and joining of commodity flows.

Definition 25 : A **balance point** is a point where a single commodity flow $\dot{F}$ (Def. 10) is split into several flows of the same commodity or where, vice versa, several flows are united into a single flow.

Due to the physical conservation laws, the sum of entering flows $\dot{F}^t_{En,k}$ must be equal to the sum of leaving flows $\dot{F}^t_{Ex,l}$:

$$\sum_k \dot{F}^t_{En,k} = \sum_l \dot{F}^t_{Ex,l} \qquad \forall\, t\ . \tag{39}$$

It should be noted that Eq. (39) is determined by the physical direction of the flows.

Assumption 13 : Between any two processes connected via a commodity flow, there must be a balance point. Between any two balance points, there must be a process.

The structure formed by processes, balances, and connecting commodity flows is described in terms of *graph theory* in the following.[10]

Definition 26 : A **graph** (N, L) is an ordered pair of sets, where N is a finite, nonempty set whose elements are termed **nodes**, and where L is a set of unordered pairs of nodes of N. Each element $(p, q) \in L$, where $p, q \in N$, is called a link and is said to join the nodes p and q.[10] The following graph properties are relevant for the modeling of ESSSs:

A graph is termed *weighted* if there exists a function $w : L \rightarrow \Re$ (where $\Re$ is the set of real numbers), which assigns a real number to each link of L. If the links have an orientation, the graph is called *directed graph* or *digraph*. In this case, node p is called *predecessor* of q and node q is called *successor* of p. Any node of a digraph, which has no links directed towards it, is called a **source**. Any node of a digraph, which has no links directed away from it, is said to be a **sink.** A **network** is a digraph which has a single source and a single sink. However, if more than one source or sink exist, it is always possible to introduce a single artificial source or sink which acts as a common predecessor of multiple sources or common successor of multiple sinks, respectively. By so doing, the previous sources and sinks loose this characteristic.

Assumption 14 : ESSSs are mapped as **networks** according to Def. 26 within NEMESS . Processes and commodity balances are the nodes of the network. Physically, the commodity flows, which run from processes to balances and from balances to processes, form the directed links of the graph. However, as we will show, considering a network of data flows instead of commdity flows brings about significant advantages.

Since there are two types of nodes, namely processes and balances, which strictly follow each other, the graph is called *bipartite*. The links bear weights which are given by the respective quantities transported per unit of time. The process nodes have structures which are defined by the input-output relations stated in Sec. 3.

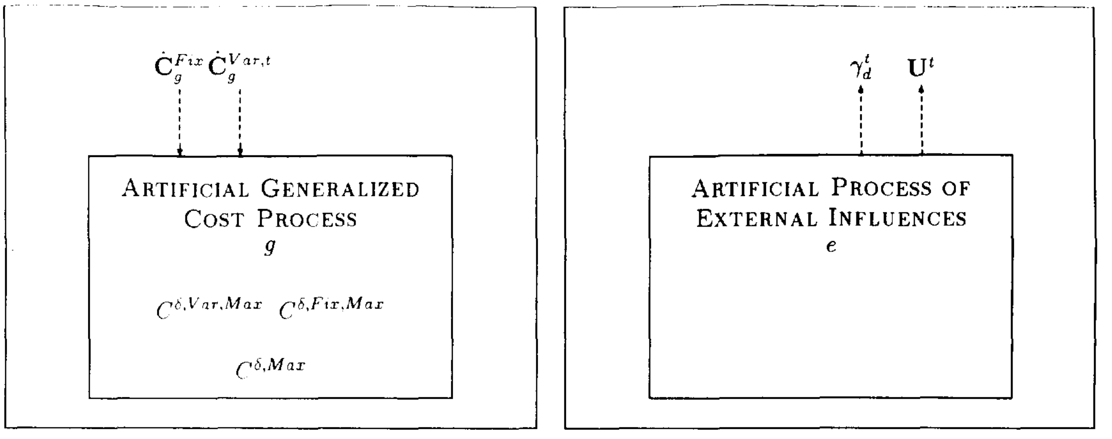

Fig. 6. Data-flow ($- \rightarrow$) diagram of the artificial generalized-cost process and the artificial process of external influences.

It is not straightforward to identify the sink and the source of the ESSS network. If one thinks in terms of energy (commodity) flows, the general flow direction is from energy sources to the places where energy services are demanded. Thus, the import-export, collector, and virtual-supply processes, which bring energy into the ESSS (or simulate this), should be the sources of the ESSS network. But, according to Figs. 3, 4, and 5, there are flows of electrical energy entering these "sources", which contradicts Def. 26. Since it is assumed that the energy demand is fixed with respect to the optimization, the general direction of data flow is opposite to the energy flow, i.e. starting at demand processes and ending at the energy sources. However, basing the identification of source and sink on data flows, will also lead to contradictions. The import-export process, for instance, is a sink of data flows related to electrical energy and fuels. Nevertheless, data flows concerning variable and fixed generalized costs leave this process. In addition, there is so far no node to which these data are transported. Thus, these respective links are "dangling", which again contradicts Def. 26. To resolve this problem, we introduce a new process:

Definition 27 : A process is called **artificial** if it is not associated with any hardware in the ESSS.

Each ESSS has a single **artificial generalized-cost process** g, into which all data containing information on variable and fixed generalized costs are flowing (see Fig. 6). It acts as the single sink of the data-flow network.

The data flows $\dot{C}_g^{\delta,Var,t}$ and $\dot{C}_g^{\delta,Fix}$ will be determined by balance points immediately preceeding process g, which means according to Eq. (39) that

$$\dot{C}_g^{\delta,Var,t} = \sum_a \dot{C}_a^{\delta,Var,t} \qquad \forall\, \delta;\ a \in \{a\},\ \forall\, t\ ; \tag{40}$$

$$\dot{C}_g^{\delta,Fix} = \sum_a \dot{C}_a^{\delta,Fix} \qquad \forall\, \delta;\ a \in \{a\}\ . \tag{41}$$

Equations (40) and (41) sum the generalized costs of all processes $a \in \{a\}$ for all cost types δ and transfer the result to single cost flows $\dot{C}_g^{\delta,Var,t}$ and $\dot{C}_g^{\delta,Fix}$, respectively. Introducing the generalized-cost process has an additional advantage. It allows us to introduce global restrictions on the generalized costs of the form

$$\frac{1}{T}\sum_{t=1}^{T} \dot{C}_g^{\delta,Var,t} \le \dot{C}^{\delta,Var,Max}\ , \qquad \forall\, \delta\ , \tag{42}$$

$$\dot{C}_g^{\delta,Fix} \le \dot{C}^{\delta,Fix,Max}\ , \qquad \forall\, \delta\ , \tag{43}$$

$$\frac{1}{T}\sum_{t=1}^{T} \dot{C}_g^{\delta,Var,t} + \dot{C}_g^{\delta,Fix} \le \dot{C}^{\delta,Max}\ , \qquad \forall\, \delta\ , \tag{44}$$

which are then associated with a single if artificial process rather than with the whole system. This will simplify the data model of the ESSS considerably.

In a commodity-flow oriented picture, the demand processes should be viewed as sinks. However, waste-heat flows are *leaving* the demand processes and are, thus, leading to contradictions. In the data-flow oriented description of the network, the demand processes could be sources. Nevertheless, there are several such sources and not a single one as demanded by Def. 26. To resolve this problem, we introduce yet another artificial process:

Definition 28 : Each ESSS has a single **artificial process of external influences**, out of which the environmental-data vector $\mathbf{U}^t$ flows towards all other processes and the load factors γ_d^t flow towards the respective demand processes $d \in \{d\}$ (see Fig. 6). It acts as the single source of the data-flow network.

Note that the generalized-cost process and the process of external influences model the interface between the ESSS and the NSEE, while the interface between the ESSS and the SESS is modeled by import-export processes. Altogether, the ESSS has been mapped into a true network according to the standards of graph theory.

We have now stated all necessary and some helpful constraints of the optimization problem. Nevertheless, model users may define additional constraints according to their needs as long as they keep them linear and follow the rules outlined so far. For example, some users might be willing to restrict the capacity or the fixed cost of a group of processes to enhance the flexibility of the ESSS.

5. THE OPTIMIZATION PROBLEM

The overall objective of modeling ESSSs is to minimize the generalized costs. Based on process descriptions in Sec. 3. and description of the network in Sec. 4., this may be expressed by the **vector-valued objective function**

$$\min \ < \dot{\mathbf{C}}_g >_T \ , \tag{45}$$

which is equivalent to

$$\min \ < \dot{C}_g^{\delta} >_T = \ \min \left(\frac{1}{T} \sum_{t=1}^{T} \dot{C}_g^{\delta, Var, t} + \dot{C}_g^{\delta, Fix} \right) \qquad \forall\, \delta \in \{\dot{E}_P, \dot{\mathbf{P}}, \dot{M}\} \ . \tag{46}$$

Equations (45) and (46) represent the key equations for optimization of the whole network. All other information necessary to perform the optimization is contained in the restrictions stated in Secs. 3. and 4. There are **temporal restrictions**, which have to be fulfilled within each interval t $(t = 1, \ldots, T)$. These are time-varying flow-size restrictions [e.g., Eq. (11)], input-output relations [e.g., Eq. (16)], and flow balances [e.g., Eq. (39)]. Next, we have **intertemporal restrictions**, which link the single time intervals in Eqs. (6) - (7) for capacity restrictions and fixed cost calculation for conversion, network, import-export, collector, and virtual-supply processes, Eq. (30) for the fixed cost of storages, and Eqs. (42) - (44) for global cost limits. Then, there are **process-state variables**, which have to be calculated before the optimization is started, according to Eqs. (9), (10) and (13) for demand processes, Eq. (31) for collector processes, and Eq. (36) for virtual-supply processes. Finally, we have the **state-transformation function** in Eq. (26) which adjusts the contents of the storages between two intervals thereby obeying Eq. (27).

The optimization variables of NEMESS are all the commodity-related data flows and the process capacities. As we have stated before, some of them are predetermined or completely dependent on other optimization variables. Thus, they could be used to simplify the optimization problem. Thereby, the model structure would become much more complicated causing additional effort for data modeling and programming of special cases. Since the expected gain in computer time during optimization is rather limited, we decided to make the model framework as general and as understandable as possible.

In principle, the optimization problem can be solved with standard methods of linear programming and vector optimization. In practice, however, the optimization matrix in linear programming will become far too large if all 8760 one-hour time intervals of one year are taken into account at the same time. The earlier models *ecco* and *ecco-solar* simplify the dynamics. *ecco* considers the temporal restrictions only and treats the time intervals as independent from each other. *ecco-solar* observes the temporal restrictions and the state-transformation functions for adjacent intervals.[2] For NEMESS , there are two possible ways to proceed. Either, one tries to decompose the optimization problem which yields connected optimization problems for the single time intervals that have to be solved in an iterative process (e.g., Dantzig-Wolfe Decomposition).[8] Or, one has to reduce drastically the number of time intervals considered, for instance by a factor of 100. This is usually done by introducing typical days, weeks, or months (see, for example, Ref. 9). However, we feel that this approach will possibly destroy important correlations between time series of demand and supply data. Therefore, we will try to use a structured approach to reducing the time intervals that is based on fuzzy clustering.

6. OUTLOOK

We are currently working on enhancements and applications of the model framework NEMESS , on which we will report later. First, we are currently gathering data for a model application to a German city. Second, we plan to introduce commodity-flow attributes such as temperature or pressure, which will allow making the input-output relations of one process dependent on the state of some other process. As we have discussed, this is very important for modeling the heat exchange in solar collectors and storages. Furthermore, we will account for uncertainties in model parameters and restrictions by using fuzzy-set theory. Emission restrictions, for instance, are not given by natural laws, but are the result of political compromises. Thus, they may well be varied within certain limits. Instead of probing such variations for all pollutants during sensitivity analysis, fuzzy-set theory allows to incorporate them in the main optimization process. Finally, we are trying to reduce the amount of data processed during optimization by clustering the input data, again with a fuzzy-set approach.

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