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ENERGY SIMULATION IN DYNAMIC PRODUCTION NETWORKS (ESPRONET): SIMULATION FOR INDUSTRIAL SYMBIOSIS

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ABSTRACT

Industrial symbiosis provides several positive aspects regarding energy and material efficiency, but it is also a challenging concept due to additional dependencies in a production cluster. As a consequence the risks inherent to these partnerships are high and thus the concept is not widely used. The project ESProNet supports the analysis and assessment of industrial symbiosis in a given cluster via simulation and research of altered scenarios. This paper contains the first steps in the project including the ontology to breakdown the complex problem as well as the modeling approach for the components in a new library based on material and energy balances. A proof of concept with the simulation of an industrial symbiosis cluster containing a server providing waste heat to an office building shows a great potential with up to 20 % less energy input for heat.

1 INTRODUCTION

The increasing importance of energy research in an industrial environment arises from changes of the political, economic and technical conditions. The current focus is on the optimization at the factory or machine level (Haag 2013), which limits the chance of saving energy to a relatively small scale. The potential of an optimization in a heterogenic industrial cluster with several industries is much higher, because of the different individual needs. Especially the sectors industry and transport, which consume over 55 % of the energy (IEA 2016), are taken into account to decrease the energy consumption and CO_2 emission. Beyond that there are mid-term goals of encouraging the use of renewable energy sources and energy collaboration, which are one topic of the G20 Action Plan on the 2030 Agenda for Sustainable

Development (G20 2016). The advancement of decentralized energy supply and the interconnection of different industrial sectors are new tendencies in the support programs of the EU (European Commission 2016) and national funding bodies (Projektträger Jülich 2017).

The approach of the research project ESProNet (Energy Simulation in dynamic Production Networks) meets those requirements. The main goal of the project is the enhancement of the industrial symbiosis (InSys) concept, which "engages traditionally [!] separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and/or by-products" (Chertow 2000, 313). The most famous example for InSys is Kalundborg (Denmark), where different partners like a refinery, a coal power plant, gypsum processing, a pharmaceutical company and others collaborate (Symbiosis Institute 2017). Among others the 30 symbioses result in a decreased water use (3 mil. m³, 24 %), lower emissions (CO_2: 7 %, SO_2: 13 %) and savings of 310 m USD since the beginning, with an average amortization time of 5 years (Jacobsen 2006; Symbiosis Institute 2017). Though there are approaches towards virtual eco-industrial parks the focus of this work lies on regional industrial clusters.

Despite the economic and ecological advantages of this concept it is uncommon in most industrial clusters. China has around 6,600 industrial parks in general (Augestad 2007) – only 17 (0.26 %) of them are practicing InSys (Massard, Jacquat, and Zürcher 2014). The main reasons are additional dependencies between the partners and volatility of different industries. If the synchronization of processes is not economically or technically feasible or one of the partners has to interrupt production it has a direct impact on other processes / partners. With the development and deployment of less expensive energy storages the risk of production breakdowns is strongly decreased due to the temporally decoupled processes. Nevertheless a tool which demonstrates the impacts of altered production (e.g. shift model, technology, machines) and infrastructure (e.g. district heating, energy storages, cogeneration units) in a dynamic model supports decision making and general analysis. Within ESProNet a database will be created, which allows model building and simulation of InSys clusters. Thus the economic and ecological effects of the described symbioses assessable and encourage enterprises to pursue this concept.

There are a few tools which also try to simulate an InSys environment, but most of them are used by the developer and are not available for the public, for example SymbioGIS or Presteo (Julien-Saint-Amand and Moenner 2008; Grant et al. 2010). Others focus on special industries or recycling and use of waste in other processes like SymbioSys (Álvarez and Ruiz-Puente 2016). The tool Looplocal matches industry data and InSys raw data to identify regions with a high InSys potential. To prove the software the authors set up a case study, which shows a heatmap with InSys suitable regions in Sweden (Aid et al. 2015). Although the software provides a benefit in identifying possible clusters, the model is too vague to give advice for a special symbiosis project in a local cluster. For the development of a new InSys tool it is necessary to integrate material and waste flows as well as energy in all forms. The sources to set up the database are:

- Ecoinvent: A life cycle inventory database with very detailed process mapping (Moreno Ruiz et al. 2016),
- Enipedia: A wiki containing energy and industry information concerning InSys provided by the Delft University of Technology (TU Delft 2017) which is constantly updated and
- Industry partners (among others): The BMW plant in Leipzig (Germany), an industrial park in northern Saxony (Germany) containing around 120 enterprises and a steel mill (BGH Edelstahl Freital GmbH) near Dresden (Germany).

2 MODELING AN INDUSTRIAL SYMBIOSIS CLUSTER

The first step in developing a tool for InSys studies is the requirements specification, where all features and necessary data is defined to set up an appropriate model of the problem domain. The object-oriented tool needs to support a graphical user interface, which simplifies the import, model building, simulation and visualization of results. Furthermore there is a new data library needed, which contains scalable components, like infrastructure (e.g. transmission) and industrial functions (e.g. heating or assembling). The scalability is one of the biggest challenges, because of non-linear industrial functions. In order to make the tool usable to a large group, we decide to use an established generic modeling and simulation environment. A generic environment and software allows for customization, extension and specification of concepts which can be introduced as an add-on. This contains the component library, methods and special visualization for the analysis of potentials in an InSys environment.

A suitable software is SimulationX® which is based on the Modelica standard. Since the software developer (ESI ITI GmbH) is part of the project, the add-on will be supportive for further versions of SimulationX®. The tool provides among others several component libraries like electronic, hydraulics and heat transfer, which are taken into consideration when developing the new library. Thus the compatibility of different components is granted and it is possible to describe a model on different abstraction levels. The most important library when developing the InSys add-on is Green City, which contains black box components in the targeted abstraction level and could be used as a basis (Figure 1).

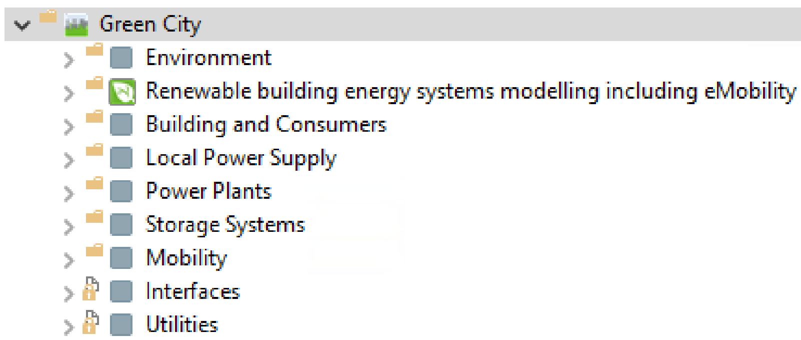


Figure 1: Component library Green City of SimulationX®.

Although Green City has a lot of components, the key features for modeling an InSys environment are missed and need to be developed: industrial functions. Applications of Green City focus on the modeling and simulation of quarters (Molitor et al. 2014). To structure the problem domain, develop a conceptual model of the tool and ensure the compatibility of different databases and results in the development process it is necessary to define a taxonomy or ontology.

2.1 Ontology

Ontologies enable the decomposition of a complex system by describing its structure based on concepts, their relationships and their properties and thus limiting the degree of complexity. In information science, an ontology is a formal, explicit specification of a shared conceptualization. This description is done by defining commonly used terms as concepts and their relationship to capture and share the domain knowledge within a community leading to a common structural and conceptual understanding of the domain (Borst 1997; Gruber 1993).

Since InSys is an interdisciplinary research field it engages engineers, ecologists, economists and social scientists each with different perspectives resulting in definitional issues of concepts. It is agreed in academic research that establishing a common language in the field of InSys is a challenge but necessary especially for application in information and communication technology (ICT) (Grant et al. 2010; Zhu, Davis, and Korevaar 2014). This issue will be addressed within the project by providing an InSys ontology in general and for the specific purpose of scenario simulation.

Being a knowledge-intensive discipline, InSys has to utilize multiple distributed data sources and formats for data collection, storage, maintenance and processing. Furthermore due to its dynamic nature (e.g. joining or exiting of network participants, changes in resource demand or supply because of shifts in the production technology of a facility) the knowledge base is continuously increasing. In this respect, data integration and interoperability is a prerequisite for developing a tool that can be used in the future.

So far computational and ICT tools in InSys are used for data storage and organization, often in form of Information Systems (Tochtermann et al. 2008; Isenmann and Chernykh 2009), Input-Output-Matching of waste (Brown, Gross, and Wiggs 1997; Grant et al. 2010; Trokanas, Cecelja, and Raafat 2014; Álvarez and Ruiz-Puente 2016) and agent-based simulation used to study behavior and interactions of InSys participants on an organizational level (Cao, Feng, and Wan 2009; Bichraoui, Guillaume, and Halog 2013; Couto Mantese and Capaldo Amaral 2017; Batten 2009). To the authors knowledge to date there is no InSys ontology for the purpose of modeling and simulation of dynamics in InSys processes with the specific focus on energy related aspects.

Among others the project aims at developing an ontology intended to capture concepts relevant to Energy Management in InSys practice and to describe the relationships among each concept and their core elements. At the same time, the ontology shall be able to represent a singular organization as well as production environment to increase the potential of scalability (facility, plant, network) and replicability. This is ensured by deriving relevant terms from InSys case studies and the literature. Since ontologies are meant to be shared and reused it seems natural to be orientated by existing ontologies like the eSymbiosis ontology. The ontology does not meet the requirements of ESProNet, particularly requirements for simulation, but offers a top level ontology containing concepts like Resource, Attributes, Roles and Technology. These are adjusted and refined to consider the engineering and ecologist perspective.

The ESProNet ontology consists of eight main concepts as depicted in Figure 2. It additionally shows some exemplary relationships (hasInput, providedBy etc.) between those concepts.

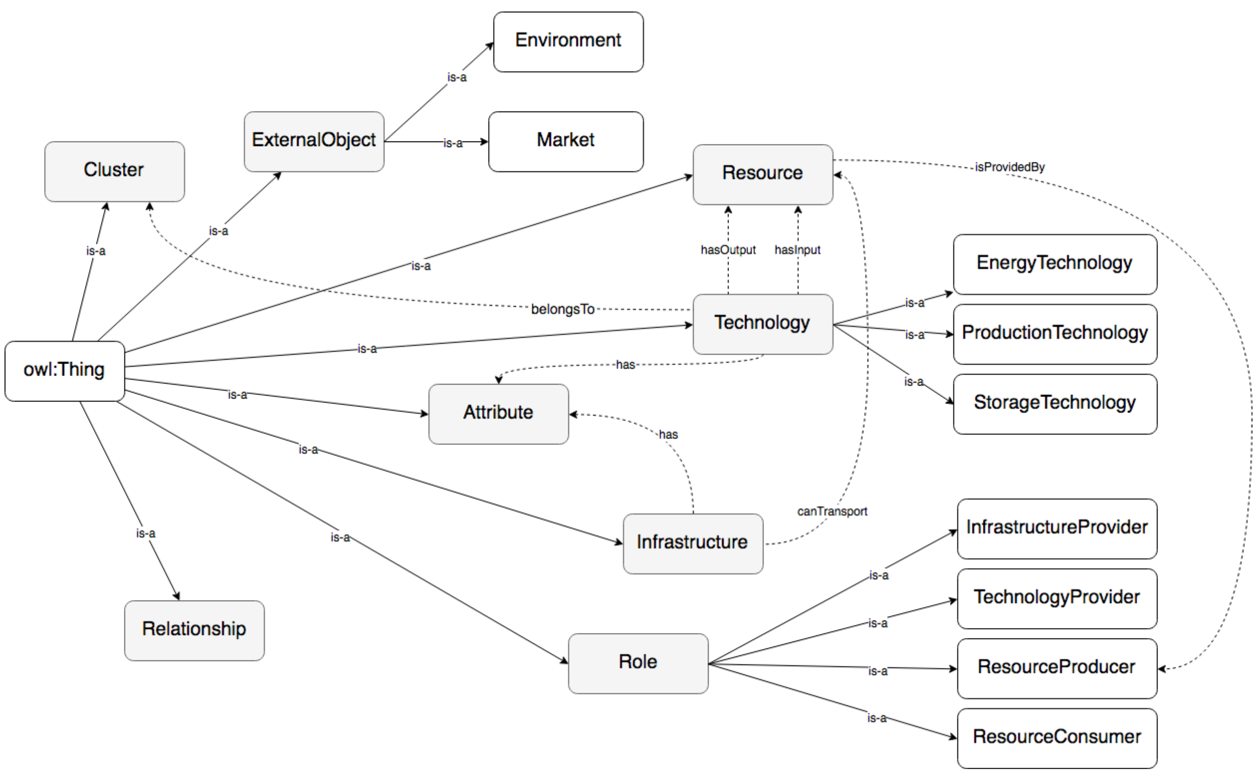


Figure 2: Excerpt of the ESProNet ontology in Ontology Web Language (OWL).

Resource classification is widely discussed and diverse in InSys literature. Commonly used terms in InSys literature are for example energy, material, resource, waste and by-product. An explicit distinction between these terms however is difficult as it depends on the context. Drawing on the generic definition of InSys from (Deutz 2014) and due to the goal of creating an generalist ontology terms such as "waste" or "by-product" are avoided. Furthermore whether a resource is used energetically or materially cannot always be exclusively defined (e.g. tapping fluid in a machine tool). Thus the ontology does not differentiate types of resources. Instantiation then allows the introduction of specific resources (e.g. steel, heat, electricity) for the system under consideration. The concept **Technology** contains conversion and storage technologies. Those are differentiated by their primary function. Production technology (e.g. hydraulic press) represents value-adding processing technology while energy technology (e.g. block-type thermal power station (BTTP)) ensures energy supply. Furthermore they are distinguished by the level of influence of other technologies. To keep up the performance of the tool, production technologies are defined by a specific behavior, which cannot be changed by other technologies. The energy technologies are influenced by the production technologies (e.g. a cogeneration unit which provides heat on call). Storage technology is used to store resources which later on are used for production (e.g. warehouse) or energy supply (e.g. battery storage power station). Unlike the eSymbiosis ontology (upper-level) where conversion, transportation and storage technologies are summarized in a singular concept and not further distinguished, the ESProNet ontology introduces subclasses. A separate class in the case of transportation technology as characteristics of each can differ vastly. **Infrastructure** represents modes of transportation for resources (e.g. district heating pipes).

The concept **Cluster** allows the definition of balancing groups and the assignment of ownership by combining different objects. A single facility for example consists of a set of technologies and infrastructure. The concept **Role** depicts whether or which Cluster is acting as a supplier, a provider or as both in a scenario. Defining system boundaries in form of balancing groups is essential to use energy and mass balances. Consequently it is necessary to introduce an **External Object**, the environment, to account for all resources, emissions etc. flowing in or out of the considered system. On the other hand environmental conditions have a great impact on technologies like photovoltaics or wind power plants. Furthermore looking closer at InSys it becomes clear that apart from the environment other objects not part of the InSys network are relevant. Resources can be bought from external markets (e.g. Energy Exchange EEX). InSys networks are characterized by the relationships between the participants, but interaction is not limited to those.

Introducing **Relationships** allows to assign attributes inherent to the specific relation. The price or cost of a resource, for example, is not determined by the resource itself or the seller alone, but by contractual agreements between two parties (Cluster-Cluster relationship). Similarly, emissions are not tied to resources themselves but to their technological processing (Resource-Technology relationship). The purchase of power from the Energy Exchange would hence be a Cluster-ExternalObject relationship.

At last **Attributes** provide information to describe the concepts of the ontology. These can be further distinguished according to their relevance for each perspective. For example the price/cost of a resource is an economically relevant attribute whereas the heating value is important from an engineering perspective and does not bother the economist. The knowledge base of InSys is thus formed by the ontology itself and the instances which are specific elements of the real world (Figure 3).

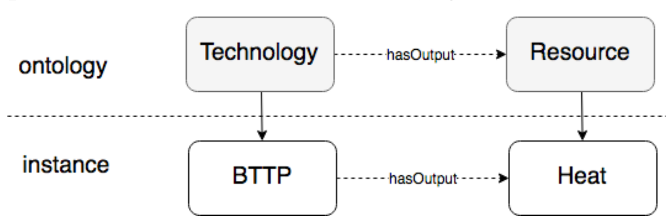


Figure 3: Instantiation example of the ontology.

Following the approach of graph modeling the presented concepts can be mapped to nodes (representing technologies, clusters etc.) and edges (representing infrastructure). Resources are transferred along the edges. The concepts are transferred into the library of the aforementioned software as components. Technology components will be described by diversified load profiles as presented in the next chapter.

2.2 Diversified Load Profiles

To give the single components a special behavior we use diversified load profiles, which include the input, output and the conversion of resources. Table 1 and Figure 4 show an example of a preheating furnace in a steel mill to clarify the component model and how the load profiles are used to calculate the output with given input and utilization. To simplify the example the electric energy used for the materials handling is neglected.

Table 1: Conversion with diversified load profiles.

Input	Conversion	Output
Gas • Quantity $q_G(t, u_f)$ [$^{m^3}/_h$] • Caloric Value $H_{i,G}$ [$^{kWh}/_{m^3}$] Steel • Quantity $q_{S,I}(u_f)$ [$^{t}/_{h}$] • Temperature $T_{S,I}$ [°C] • Specific heat capacity c_S [$^{kJ}/_{(kg \cdot K)}$] Environmental factors • Temperature $T_E(t)$ [°C] • Utilization $u_f(t)$ [%] • Simulation time t	Energy $\dot{Q} = q_G(t, u_f) \times H_{I,G} + q_{S,I}(u_f) \times c_S \left(T_{S,I} - T_E(t)\right) - q_{S,O} \times c_S \left(T_{S,O} - T_E(t)\right)$ Material $q_{S,L} = q_{S,I} - q_{S,O}$	Heat (loss) • Heat flow $\dot{Q}$[kWh] Steel • Quantity $q_{S,O}$ [$^{t}/_{h}$] • Temperature $T_{S,O}$ [°C] • Specific heat capacity c_S [$^{kJ}/_{(kg \cdot K)}$] Loss • Loss of material (burnup) $q_{S,L}$ [$^{t}/_{h}$]

Some of the input factors depend on the simulation time, whereby the utilization is most important for modeling. The component is given a utilization over a specific time (15 minutes), which is defined in a load profile. The time interval of 15 minutes is significant for the whole simulation since it is the smallest trading period on the spot market for electric energy. Starting from the utilization at a specific time the steel and gas input ($q_{S,I}(u_f)$; $q_G(t, u_f)$) can be defined. The relation is given by a diversified load profile shown in Figure 4 (next page).

The surface plot contains the utilization of the furnace and the output time of the material which is essential because of the two-shift model in the steel mill. The furnace is tempered in the night, where the temperature is ca. 600 K lower than the working temperature during shift times (from 06:00 to 22:00). Because of the heat up time in the morning starting around 03:30 and cooling time after 22:00 the plot shows diagonal bounds between the limits and the profile does not match at 00:00. To get a matching profile it is possible to calculate the overall gas consumption over the time and utilization. If the objective is a potential analysis, it is important to specify the output regarding exergy and anergy linked with the technological equipment of the machine or – more general – component/technology.

With that available information it is possible to calculate the heat and material flow of this furnace, which is necessary to extrapolate potentials in an InSys cluster. The characterization of a single component is not sufficient for this purpose, therefore the following chapter explains the interaction between them and the balancing concept in a cluster composed of four single components.

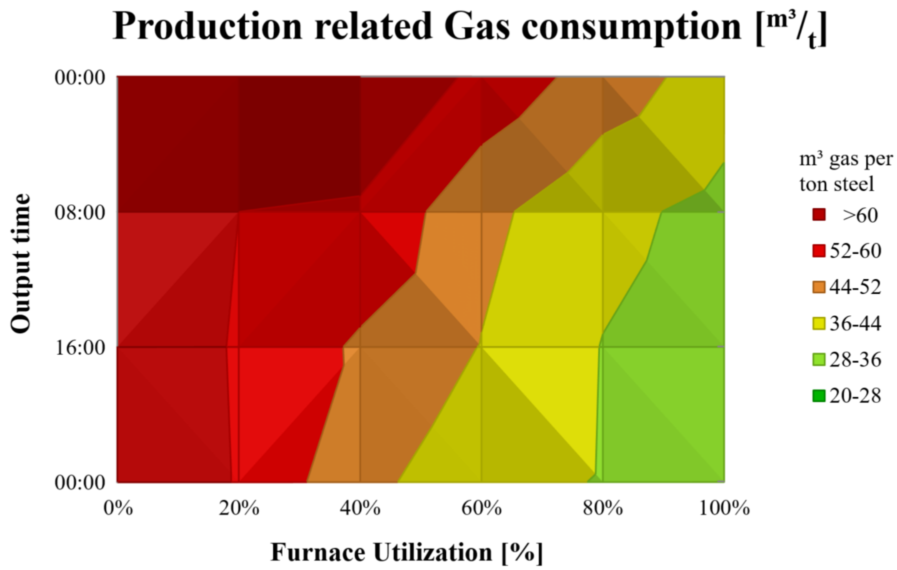
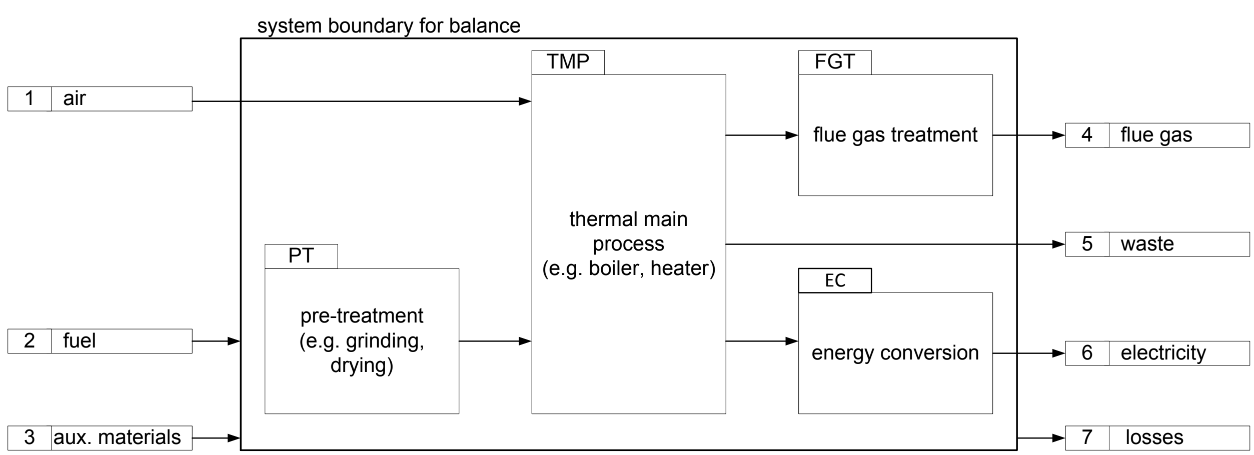


Figure 4: Gas consumption of a preheating furnace related to material output time and utilization.

2.3 Balancing in an Industrial Symbiosis Cluster

One of the aims of the project is the investigation of an alternative, optimal multi-energy mix focusing on the specific energetic-physical transformation processes. It is not only focused on electrical energy but also on all relevant types of final energy demand: electrical, thermal, mechanical and chemical energy. In addition, the mix of primary energy sources in the form of gas, oil and other fossil fuels is taken into account. For this purpose, possible synergy effects are to be identified, which can be achieved by conversion, transmission and storage.

Therefore the assessment of processes (chain of components as mentioned in chapter 2.2) is based on balances, derived from the first law of thermodynamics, where the internal energy of a system remains constant apart from energy input and output. The procedure is shown by the example of a conventional power generation plant in Figure 5.



mass balance	material balance	energy balance
$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 = \dot{m}_4 + \dot{m}_5$	$\dot{m}_{i1} + \dot{m}_{i2} + \dot{m}_{i3} = \dot{m}_{i4} + \dot{m}_{i5}$ $i \in \{C, H, O, N, S \ldots\}$	$\dot{H}_1 + \dot{H}_2 + \dot{H}_3 = \dot{H}_4 + \dot{H}_5 + P_{el} + \dot{Q}_V$

Figure 5: Schematic representation of a balance sheet diagram (based on Beckmann et al. 2011).

At first the system boundaries are defined. This makes clear what type of cluster is to be assessed: a part of a plant, a group of technologies, a process chain or an entire plant. In this example the single technologies (PT, TMP, FGT and EC) are represented by components. All mass and energy input flows as well as output flows are applied to the system boundaries. Figure 5 shows a basic balance sheet diagram for the energy balance of an entire system with the major incoming and outgoing mass, material and energy flows. The results of the balancing can be summarized in key performance indicators, such as the efficiency or specific CO_2 emissions, and can be compared with other process chains. The results of such a balancing and the subsequent comparison show the direction for further technical developments.

This can be explained on a simple example in Figure 6. Two alternatives for satisfying the final energy demand for mobility (40 GJ) and heating (110 GJ) are shown. These values correspond to the fuel consumption of a car and heating of a single-family home.

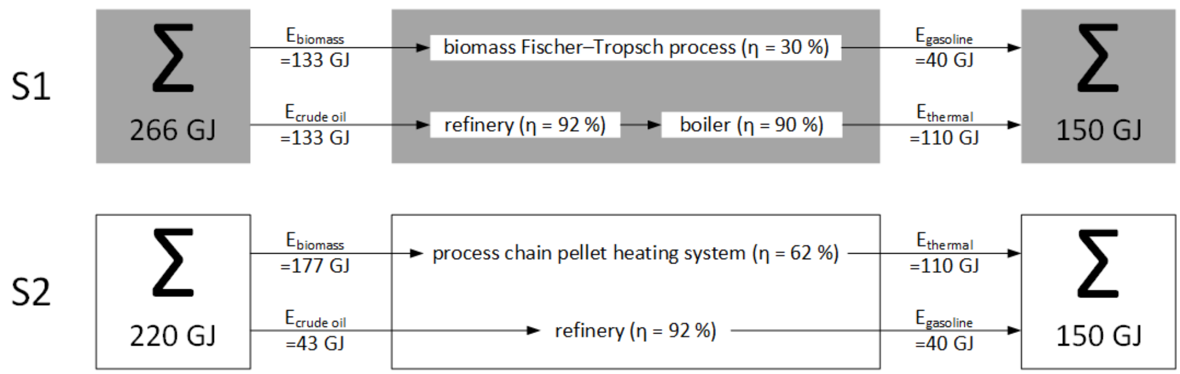


Figure 6: Example for an optimized primary energy input for a specific final energy demand (based on Beckmann, Rostkowski, and Scholz 2009).

Scenario 2 (Figure 6) shows that the amount of primary energy used can be reduced by more than 17 %, with the same output of usable final energy in an efficiency-optimized process. From here it can be directly deduced that in this example the chain using a biomass based Fischer–Tropsch process has to be further developed in order to be energetically on par with the conventional refining of crude oil. Of course, further technological and physical aspects such as energy density, flexibility or long-term storage capacity have to be considered. In the end, the multi-energy mix and the use of alternative input materials is taken into account when generating scenarios since the inclusion of new technologies for storage, transformation and transmission are an essential part of the study. On the basis of data obtained during the project, conclusions can be drawn on the optimized use of primary and secondary energy as well as residual materials.

3 SIMULATION AND PROOF OF CONCEPT

After descripting the InSys cluster modeling the simulation is used to identify potentials in a production network by evaluating different scenarios. In these shift models, infrastructure, partners etc. will be added / replaced / removed / changed to create a symbiosis and generate specific and general guidance for industrial parks and large plants. This evaluation is enabled by the extension / adoption of SimulationX®.

To specify the impact of InSys and the current functionality of SimulationX® a small cluster, containing an office building with heating and cooling load, a separate ice and heat storage, fed by a heat pump, as well as a short-term cold storage, will be altered. An additional server is brought to this system providing heat (~ 35° C air) via a heat exchanger to the heat storage feeding the office heating system (light module in Figure 7). The server is linked to the return flow of the office heating system, therefore the recuperation only works with a heat load in the office building. The office is a six story building with around 6,500 m² heated area and a yearly heat load of around 450 MWh. The server center has an annual electric energy consumption of 865 MWh. This seems very much, but Germany has around 50,000 server centers (from single server racks up to over 5000 m² computing centers) with a total energy consumption of approximately 12,000,000 MWh (Hintermann and Clausen 2014; Hintermann 2016). The volatile heat and cooling load of the office building is considered by using storages in contrast to the server building, that runs around the clock with a similar load. For further research components representing industrial functions will be added.

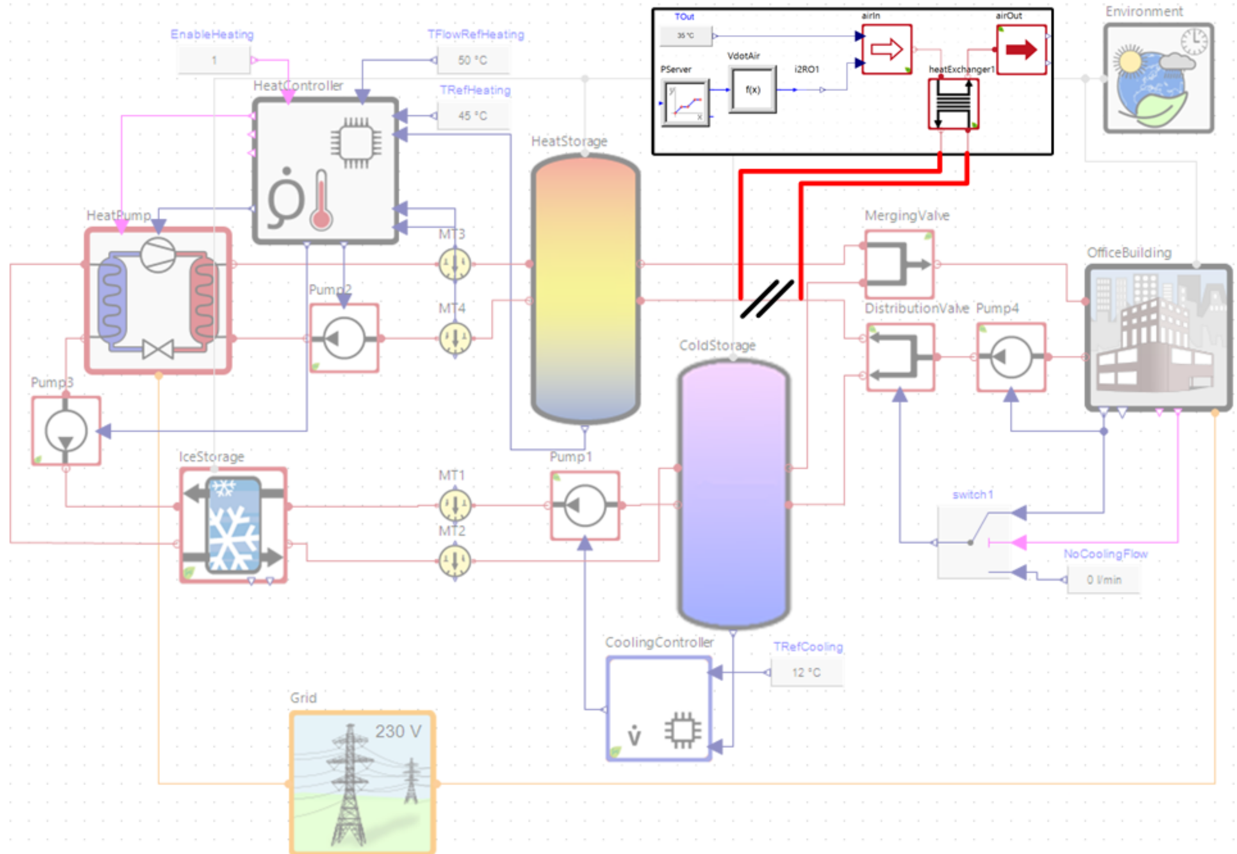


Figure 7: Extension of a conventional to an InSys cluster.

The whole cluster is connected to the regional distribution grid. Used technologies are state-of-the-art and could be replaced by others that are currently in research. Storages as well as buildings are influenced by weather data, which shows the different demand of heat and cold over the year.

With integration of the server the base load to keep the heat storage on a level of around 28° C is fully provided by the waste heat of the server, which leads to following positive aspects:

- Lower usage of the heat pump, which can be smaller for the system (similar to investment),
- Local server utilization improves responding times compared to servers located in esp. Scandinavia because of the great cooling load (Cloud&Heat 2017) and
- Decreased energy consumption – 42.7 MWh less electricity input for the heat pump per year (~ 19.5 %) and 31.8 % (142.9 MWh) of the heat load is covered by the waste heat of the server.

This proof of concept shows clearly two main issues the project ESProNet investigates – first: The simulation determines the benefit of InSys even with non-industrial partners. And second: SimulationX®

is suitable and adaptable for such a simulation. Therefore it is necessary to include industrial components, that are currently not described in the right level of abstraction and expand the focus of ESProNet on residential facilities that would lead to an urban symbiosis (Massard, Jacquat, and Zürcher 2014).

4 CONCLUSION AND FURTHER RESEARCH

The pursuit of the InSys concept, which addresses the collaboration between enterprises to enhance resource exchange, has ecological and economic advantages. Especially the decreased material input, whether it is used for energy generation or in a production process, leads to less environmental pollution and short amortization times of investment (Jacobsen 2006; Symbiosis Institute 2017). On the other hand the additional dependencies of processes and other enterprises result in a minor spread of the concept in industrial clusters. New technologies (energy storages and high-flexible decentralized power plants) help to decouple these processes and dealing with the higher volatility of energy generation.

The main goal of the ESProNet project is to spread the concept InSys by modeling and simulation of such clusters to show the economic and ecological effect. Especially the impacts on such a production network will be analyzed, where among others following questions can be answered:

- When does the symbioses work? How can the benefit of using InSys in a specific industrial cluster (e.g. industrial park or factories) be quantified?
- What is the impact when a partner leaves the symbiosis or reduces its production rate? Is the symbiosis still beneficial? What are actions to keep the symbiosis alive (robustness analysis)?
- What infrastructure does a cluster need to engage a symbiosis? What are the requirements for infrastructure regarding capacity, scale or safety?

SimulationX® with the Green City add-on will be enhanced to simulate InSys clusters. Since there is no ontology for InSys, the first step was setting one up which contains the dependencies between different modules and helps to breakdown the complex problem for the future development of the necessary library. The new ontology is used to derive a class diagram, which is important due to the integration of new components in an existing software. The key classes are resources, infrastructure and technology, based on the graph theory, where technologies (nodes) exchange resources over infrastructure (edges). To set up the library, containing industrial functions and energy modules, several industry partners take part in the project. Also the discrete material flow of products, by-products and raw-materials (resources in general) needs to be clarified, since SimulationX® is primarily used for mechanical and heat engineering.

The first attempt in simulating an InSys cluster showed the great potential optimizing several different industries compared to an individual optimization (global vs. local optimum). The energy savings in a cluster with an office and a server building is approximately 31.8 % over the year, when using the waste heat. Nevertheless the main part of the research is to set up the library with industrial technologies to enable an InSys simulation and provide guidance for regional industrial clusters. This contributes to answering the questions above and helps to design future energy supply and industrial clusters.

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