Smart-Energy Operating-System (SE-OS) framework

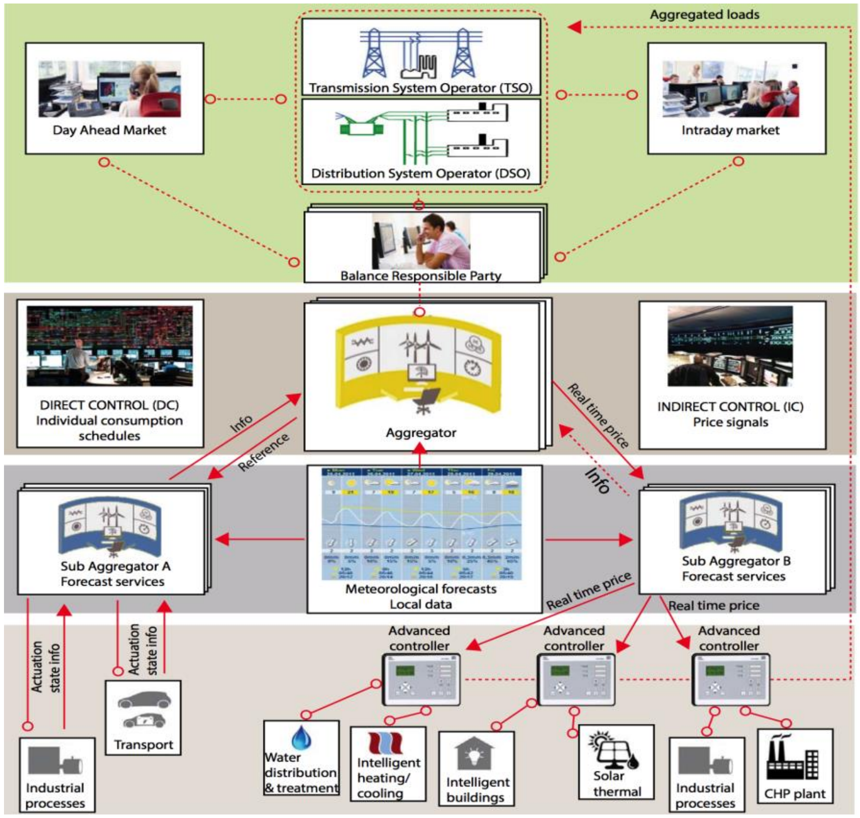

Figure 1: The Smart-Energy Operating-System (SE-OS) for digitalization of integrated energy systems.

Summary

The Smart-Energy Operating-System (SE-OS) is a framework for digitalization and implementation of smart energy solutions, including the use of heat pumps. Also connections to the energy related part of e.g. water and food processing systems are included. The SE-OS framework consists of both direct and indirect (mostly price-based) control of the electricity load, heat load, etc. in integrated energy systems. The system has embedded controllers for handling ancillary service problems in both electricity and heat grids. The entire setup of the SE-OS includes all levels of computing (cloud, fog, edge). The distributed setup of computing and data includes edge computing near the IoT devices. The SE-OS framework is used in the central data and cloud hub Center Denmark which is an European Digital Innovation Hub that is used for digital business models aimed at providing new data-driven services for the energy and water sectors (https://www.centerdenmark.com/en/)

A hierarchy of optimization and control problems

The SE-OS, as shown in Figure 1 (this version of the SE-OS has a focus on electricity), is built as a hierarchy of four nested stochastic optimization and control layers representing aggregated consumption on various spatial and temporal scales. Today, the framework is used in several European projects for optimized operation of heat pumps and IoT devices. Within e.g. the CITIES project (https://smart-cities-centre.org/), the SE-OS has been used to implement flexible and smart grid enabled solutions for heat pumps, wastewater treatment plants, super markets, HVAC systems, indoor comfort, etc. Please see the homepage for specific examples.

Multi-level control and markets

Ultimately the purpose of the future smart energy system is to establish a connection between the controllers related to IoT devices operating at local scales, and high-level markets, which obviously is operating at large scale. Essentially a spectrum of all relevant spatial aggregation levels (building, district, city, region, country, etc.) has to be considered. At the same time control or market solutions must ensure that the power system is balanced at all future temporal scales. Consequently, data-intelligent solutions for operating flexible electrical energy systems have to be implemented on all spatial and temporal scales.

Traditionally power systems are operated by sending bids to a market. However, in order to balance the systems on all relevant horizons several markets are needed. Examples are day-ahead, intra-day, balancing and regulation markets. The bids are typically static consisting of a volume and duration. However, the Smart-Energy OS provides new and efficient methods for activating low-level flexibility. Given all the bids the so-called supply and demand curve for all the operated horizons can be found. Mathematically, these supply and demand curves are static and deterministic. Merit order dispatch is then used to find the optimal cost and volume. However, if the production is from wind or solar power, then the supply curve must be stochastic. In the future demand response will play an important role, and on the demand side the needed electricity depends on the history. If, for instance, a supermarket has reduced the electricity load for an hour, then the temperature constraints of the freezers etc. implies that the supermarket might have difficulties in reducing the electricity for the next few hours. Consequently, the demand flexibility has to be described dynamically. Mathematically, a so-called Flexibility Function is introduced, and this function is a core element of the SE-OS framework.

Summing up, new digitized markets need to be introduced, which are dynamic and stochastic, and instead of using a large number of markets for different purposes (frequency, voltage, congestion, etc.) and on different horizons, a concept based on the flexibility function and stochastic control theory is suggested. Zooming out in space and time, i.e. and consider the load in a very large area on a horizon of days, or maybe next day, then both the dynamics and stochasticity can be eliminated, and hence, a conventional market principles as illustrated in Figure 2 can be used. Zooming in on higher temporal and spatial resolutions (like for instance a house), the dynamics and stochasticity become important, and consequently the use of control-based methods for the flexibility is suggested.

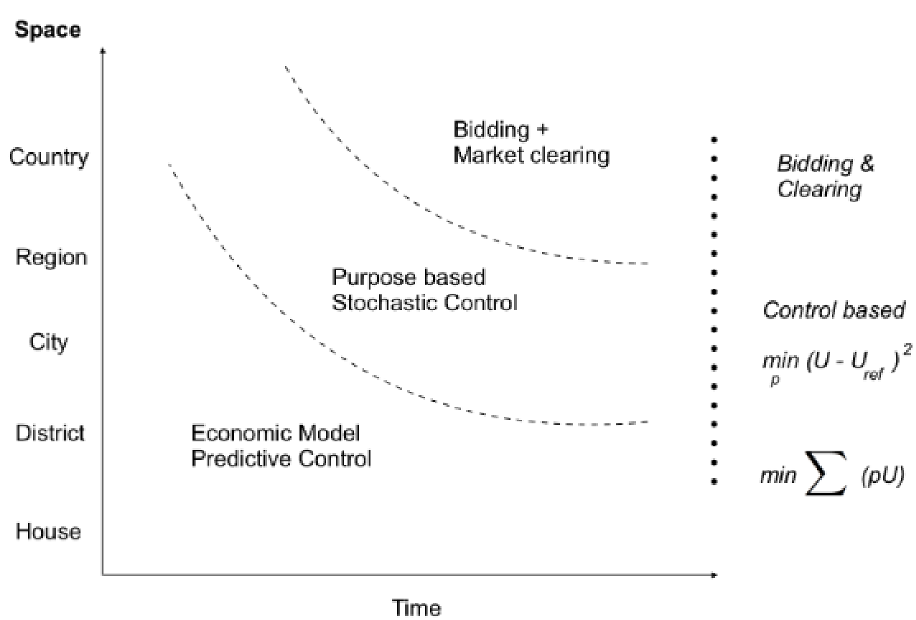

Figure 2: Hierarchical control and markets.

The total setup consists of a combination of all these options, and the best option depends on the zoom level. The conclusion is that a new future digitized refined market principles is needed, which operate as a hierarchy of conventional market-based bidding and clearing on the higher levels and control-based approaches on the lower level.

All these principles for forecasting, control, and optimization are included in the Smart-Energy Operating-System (SE-OS), which is used to develop, implement and test solutions (layers: data, models, optimization, control, communication) for operating flexible electrical energy systems at all scales.

Data-driven digital twins (grey-box models)

The models used for forecasting, control and optimization within the SE-OS framework are most often so-called data-driven digital twins or grey-box models. These models are optimized for real-time operations, and most importantly these models are optimized for assimilating information from available sensors into the model parameters.

This is illustrated by the red dashed line on Figure 3 which aims at illustrating that the used data-driven digital twins or grey-box models are simplified models of the considered system (building, wastewater treatment plant, heat pump, etc.). Please see the references for more information.

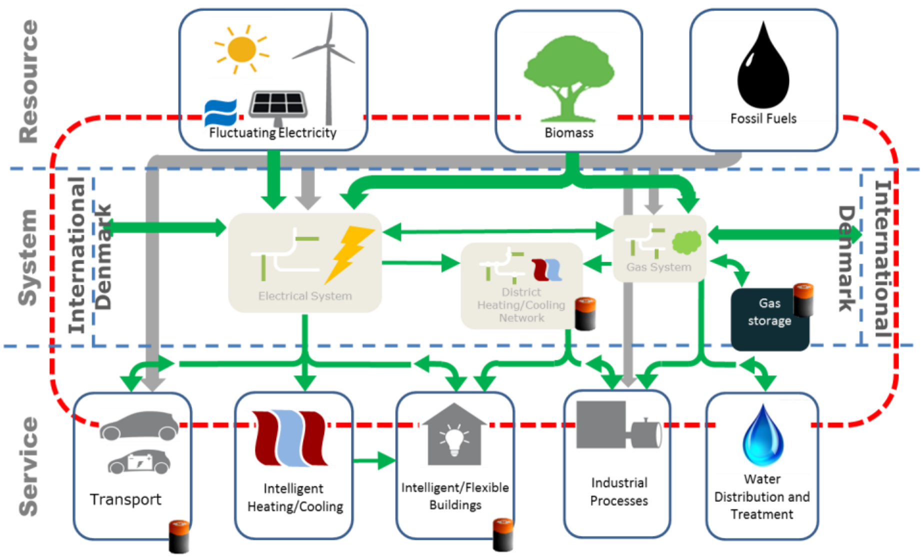

Figure 3: Grey-box models and data-driven Digital Twins.

Contact information

Henrik Madsen
Professor, Head of section, Department of Applied Mathematics and Computer Science,
Technical University of Denmark
hmad@dtu.dk
+45 2083 4304

References

R. Halvgaard, N. K. Poulsen, H. Madsen and J. B. Jørgensen, "Economic Model Predictive Control for building climate control in a Smart Grid," 2012 IEEE PES Innovative Smart Grid Technologies (ISGT), 2012, pp. 1-6, doi: 10.1109/ISGT.2012.6175631.

Corradi, O., Ochsenfeld, H. P., Madsen, H., & Pinson, P. (2013). Controlling Electricity Consumption by Forecasting its Response to Varying Prices. IEEE Transactions on Power Systems, 28(1), 421–430. https://doi.org/10.1109/TPWRS.2012.2197027

Madsen, H., Parvizi, J., Halvgaard, R. F., Sokoler, L. E., Jørgensen, J. B., Hansen, L. H., & Hilger, K. B. (2015). Control of Electricity Loads in Future Electric Energy Systems. Handbook of Clean Energy Systems.

Zemtsov, N., Hlava, J., Frantsuzova, G., Madsen, H., & Jørgensen, J. B. (2018). Economic nonlinear MPC for a population of thermostatically controlled loads. Computer Science - Research and Development, 33(1-2), 157–167. https://doi.org/10.1007/s00450-017-0354

Leerbeck, K., Bacher, P., Junker, R. G., Tveit, A., Corradi, O., & Madsen, H. (2020). Control of heat pumps with CO2 emission intensity forecasts. Energies, 13(11), 2851. https://doi.org/10.3390/en13112851

Thilker, C. A., Madsen, H., & Jørgensen, J. B. (2021). Advanced forecasting and disturbance modelling for model predictive control of smart energy systems. Applied Energy, 292, 116889. https://doi.org/10.1016/j.apenergy.2021.116889

Thilker, C. A., Bacher, P., Bergsteinsson, H. G., Junker, R. G., Cali, D., & Madsen, H. (2021). Non-linear grey-box modelling for heat dynamics of buildings. Energy and Buildings, 252, 111457. https://doi.org/10.1016/j.enbuild.2021.111457