Smart-Energy Operating-System

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Abstract

The methodologies and solutions suggested in this poster aim to describe the relations between different appliances, aggregators, and the markets at all scales as described by the Smart-Energy Operating-Systems (SE-OS). The SE-OS describes a systematic and flexible framework for implementing methods for controlling the power load in future integrated (power, heat, gas, ..) energy systems. Intelligent systems integration using data and ICT solutions are used to establish models and methods for real-time operation of the energy flexible systems. Here the SE-OS setup is briefly described and demonstrated using two concrete examples. In the first example direct control based on a market bidding setup using saturation curves is considered for a supermarket refrigeration systems, while the second example is indirect control using prices of a system with a heat pump.

Hierarchies in future flexible energy systems

The SE-OS setup consists of a hierarchi of nested optimization (or control) problems which ultimatively connect the appliances with the market as illustrated in Figure 1, where the different levels are displayed vertically with roman numbers (from I to IV) moving from the markets to the consumers. Direct control (DC) on the left where the power is altered directly by the aggregator, and indirect control (IC) on the right where the aggregator sends out a price signal to incentivise changes in the energy consumption. The optimization and controllers take advantage of various systems for forecasting.

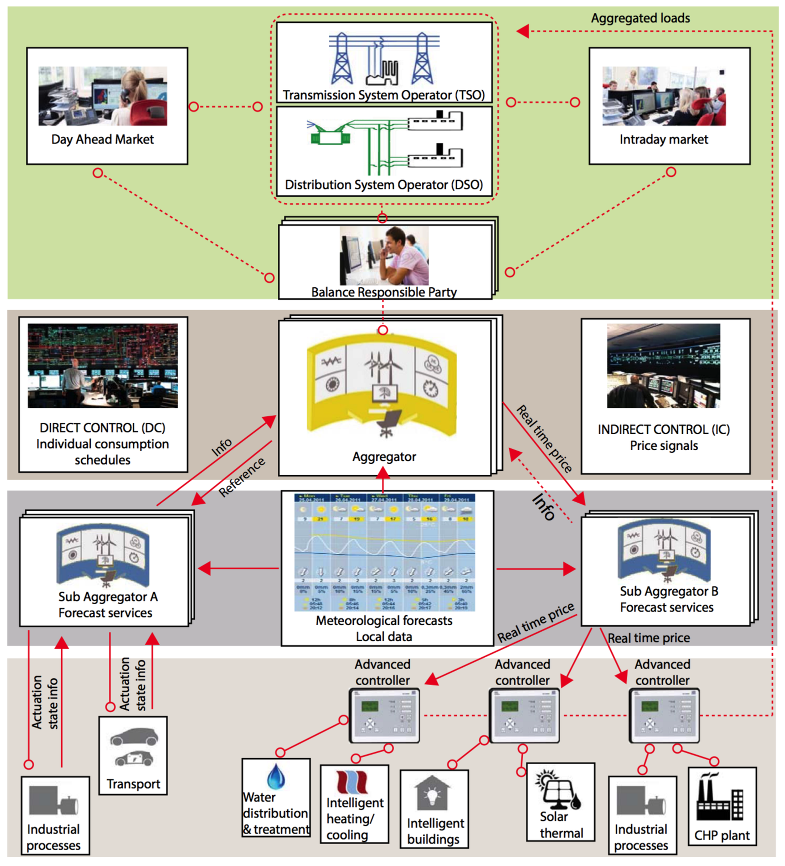
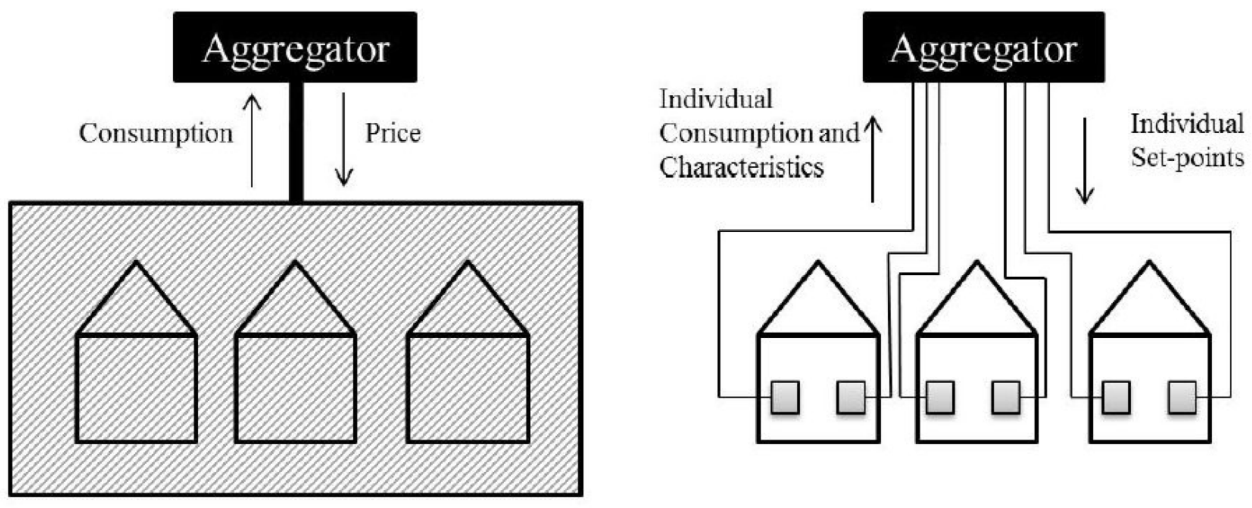


Figure 1: Hierarchies in the future energy system.

Direct vs Indirect Control - Level II

Figure 2 shows a conceptual comparison of the two forms of control of the power load. Indirect control has a reduced control, and communications burden, and the use of time varying prices is said to increase the social welfare. The load is controlled by broadcasting time varying prices, and the low-level control is a seperate controller which typically minizes the cost. Direct control allows for a more precise response, due to the ability to issue distinct power consumption directives to individual appliances, and is therefore often considered more appropriate for the provision of power system services closer to real time, when reliability is essential. However, direct control calls for some form of state estimation in order to ensure that the system are kept at resonable states (eg. temperatures). Some systems will allow for indirect control but not direct control; an example being wasterwater treatment plants.



(a) Indirect control (b) Direct control

Figure 2: Direct vs Indirect Control of Power Load.

Direct Control

Direct control involves the aggregator having a detailed knowledge of the system under control, through intensive monitoring, control and communication infrastructure. Under direct control, the aggregator will issue directives to individual flexible appliances to achieve the required power consumption level.

$$\min_{P} \sum_{t\in T}(P_t - P_t^{ref})^2 + \nabla P_t \gamma \quad (1a)$$

Subject to

$$x_{t+1} = Ax_t + BP_t + Ed_t \quad (1b)$$
$$y_t = Cx_t \quad (1c)$$
$$\nabla P_t = P_t - P_{t-1} \quad (1d)$$
$$T_{min} \le T_t \le T_{max} \quad (1e)$$
$$P_t \le P_{max} \quad (1f)$$
$$u_{min} \le u_k \le u_{max} \quad (1g)$$
$$\Delta u_{min} \le \Delta u_k \le \Delta u_{max} \quad (1h)$$
$$y_{min} \le y_k \le y_{max} \quad (1i)$$

Saturation Curves and Markets - Level III and IV (DC)

Participants on a market must submit offers, and each offer consist of a price, volume and a time period. In some cases the trading of a Demand Response (DR) implies a rebound effect. (Ref A) suggests to use saturation curves for describing the relationship between the flexible energy used or produced and the maximum duration for which it can be reliably maintained before reaching the saturation point. Consequently saturation curves can be used for characterizing the flexibility and for providing flexibility bids to the market.

A saturation curves can be obtained by estimating grey-box models for the considered system. Figure 4 reveals the estimated saturation curve for the case of a flexible refrigeration system which represents a system with a rebound effect. It can be seen that large magnitude changes to power consumption can only be reliably maintained for a short duration, whereas smaller adjustments are tolerable for significant periods.

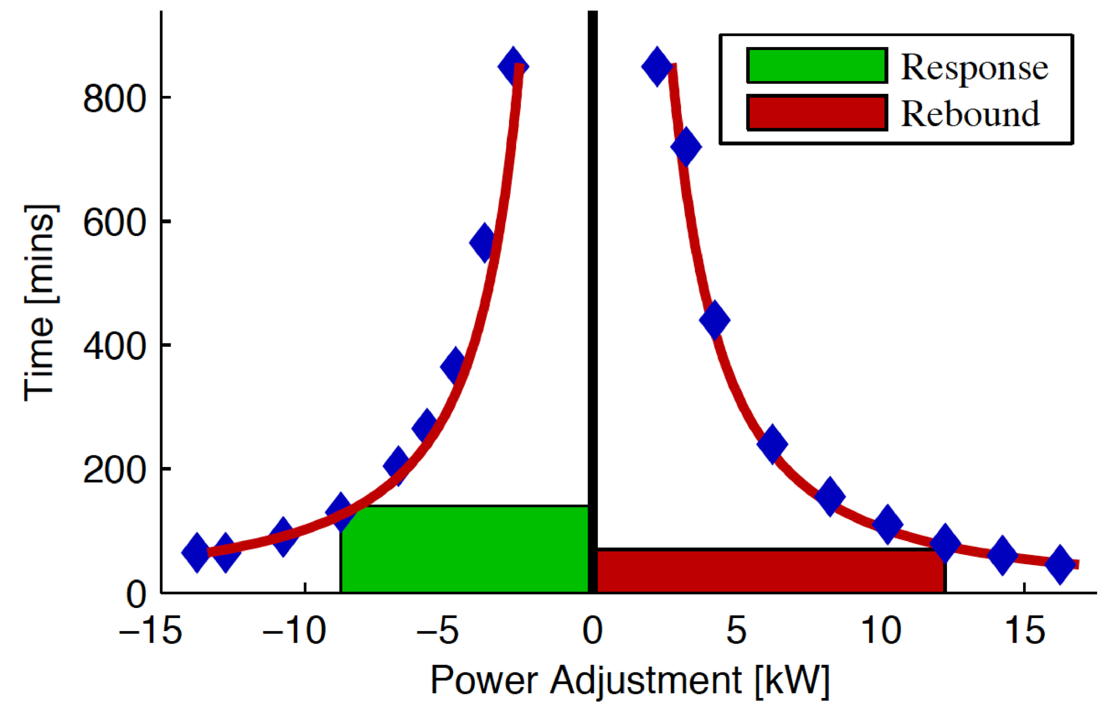


Figure 3: Relationship between adjustment in power consumption and the maximum allowable duration.

Dynamic price model and controller - Level III (IC)

Indirect control is a price based control framework, where the aggregator issues a price signal to the population of flexible appliances, expecting a particular response. Under this framework, the aggregator has limited information about the population of flexible devices under control and must estimate the price-demand relationship. This estimation can be done in real-time or can be based on historical data.

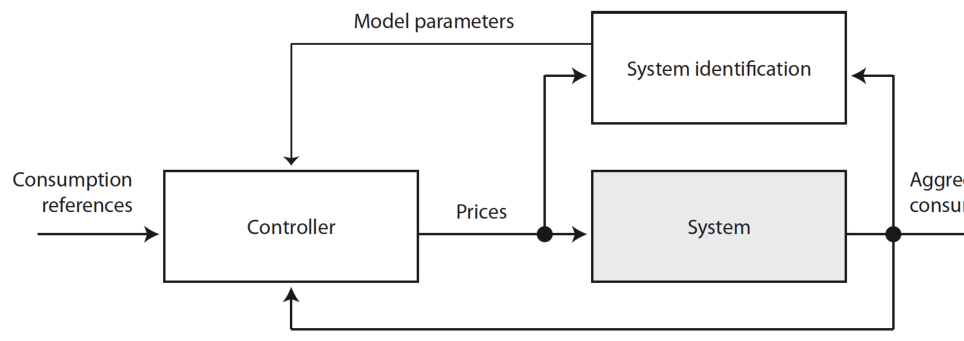


Figure 4: The controller emitting a price signal is able to influence an aggregate of price-responsive households (the system). On-line identification enables the controller to adapt to changes in the system (self-tuning).

$$\min_{p} \sum_{k\in K}(L - L_{ref})^2 + \lambda||\Delta p_k||_2^2 \quad (2a)$$

Subject to

$$\hat{x}_{k+1} = A_{aggr}\hat{x}_k + B_{aggr}p_k + E_{aggr}\hat{d}_k \quad (2b)$$
$$L = C_{aggr}\hat{x}_k \quad \text{(Aggregated loads)} \quad (2c)$$
$$-1 \le p_k \le 1 \quad (2d)$$
$$\Delta p_k^{min} \le \Delta p_k \le \Delta p_k^{max} \quad (2e)$$

Economic Model Predictive Control - Level IV (IC)

The Predictive controller uses 24 hours ahead forecasts of the spot price, house combined heat-load and tap water consumptions and, solar thermal power production. The proposed method aims at minimizing the heat pump operational costs.

The Economic MPC problem, with the constraints and the model, can be summarized into the following formal formulation:

$$\min_{\{u_k\}_{k=0}^{N-1}} \phi = \Sigma_{k=0}^{N-1} p' u_k \quad (3a)$$

Subject to

$$x_{k+1} = Ax_k + Bu_k + Ed_k \quad (3b)$$
$$y_k = Cx_k \quad (3c)$$
$$u_{min} \le u_k \le u_{max} \quad (3d)$$
$$\Delta u_{min} \le \Delta u_k \le \Delta u_{max} \quad (3e)$$
$$y_{min} \le y_k \le y_{max} \quad (3f)$$

The top part of Figure 5 illustrates the average water temp y in red and the requested house load, d, in blue. The bottom figure illustrates the price trajectory, p, in green and the control signals, u, in red.

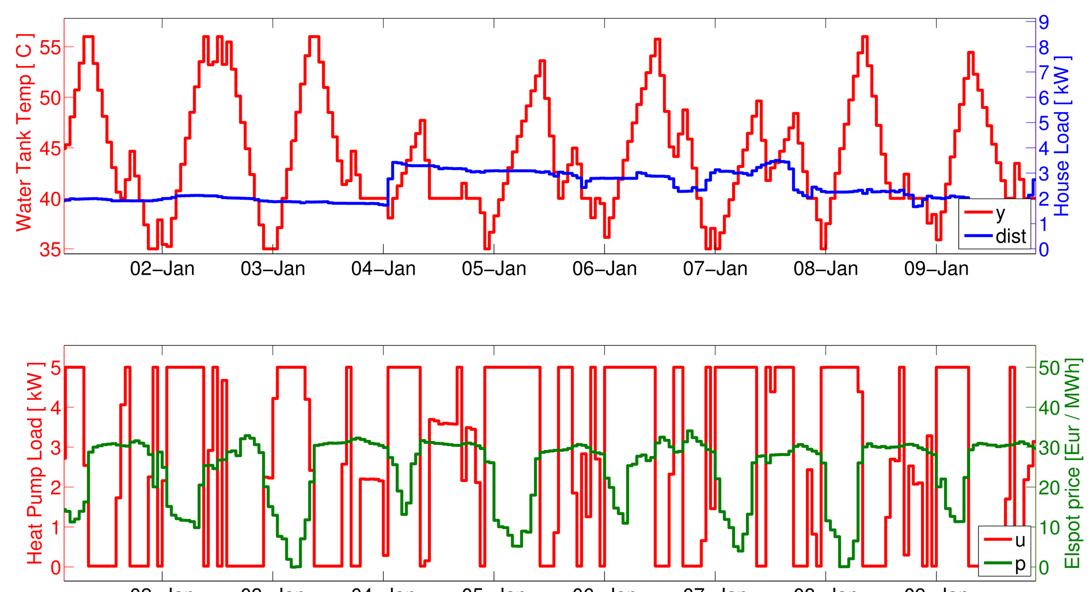


Figure 5: Controller performances

The economic savings over two years of tests are analyzed. Two different EMPC strategies are compared in order to estimate the economic savings achieved: flat tariff (FT) against dynamic tariffs (DT). The former is calculated simulating the reaction of the EMPC controller to a flat price signal. The latter is implemented in the test house. The economic savings for the DT in 2013 are 11% while in 2014 are 16%, against the FT that reached 3% in 2013 and 8% in 2014.

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