Summary

Smart Heat and Power: Utilizing the Flexibility of Micro Cogeneration

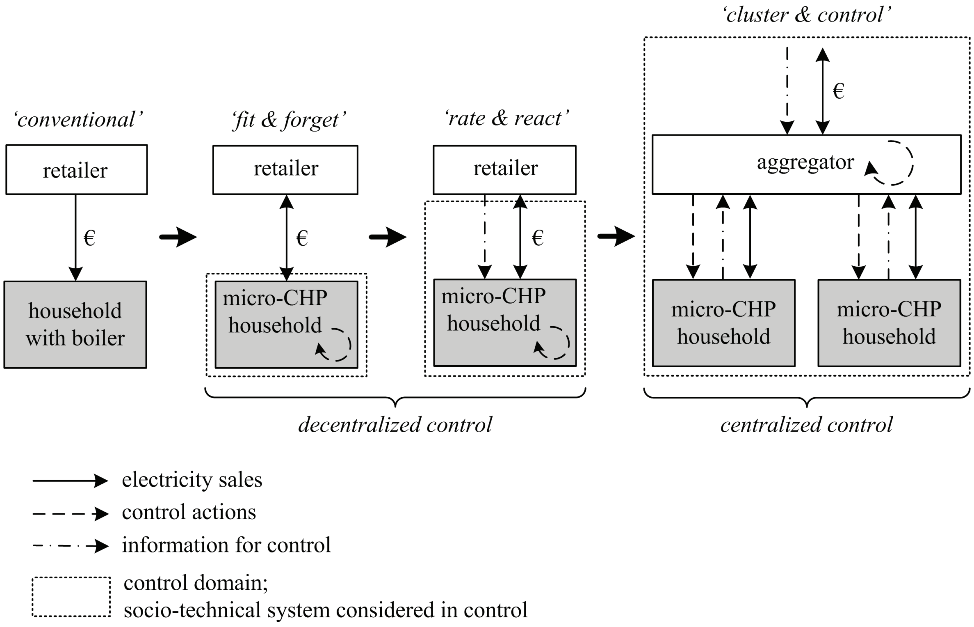
Problem description and research scope

Power generation is responsible for a large share of anthropogenic CO_2 emissions. Renewable energy sources and energy efficiency are therefore promoted worldwide. In a sustainable energy system, distributed electricity generation (DG) will play a prominent role. This thesis focuses on domestic energy use and on a new type of residential DG technology.

Specific potential for applying DG in households lies in utilizing heat and electricity from micro combined heat and power systems (micro-CHP). Micro-CHPs simultaneously generate heat and power and contribute to energy efficiency and CO_2 emission reductions. Micro-CHP systems are on the verge of becoming mass marketed as next generation domestic heating systems in countries with an extensive natural gas infrastructure, such as the Netherlands, the UK, Germany, Italy, Japan and parts of the United States and Canada. For these countries micro-CHP is considered an element in the transition towards a fully renewable energy system. The likely trajectory of the implementation of micro-CHP starts with Stirling engine and internal combustion engine systems, followed by systems based on fuel cell technology.

This thesis explores the potential cost savings from intelligent control schemes with micro-CHP systems. Micro-CHP is a special DG technology in the sense that its power output can be controlled (as opposed to stochastic generation such as wind power). To ensure smooth operation, micro-CHP systems will probably be operated in conjunction with heat storage systems. To fully utilize the controllability of micro-CHP and the additional flexibility provided by heat storage, *intelligent control* of micro-CHP systems is needed. Intelligent control relies on the use of advanced information and communication infrastructure and smart metering. These enable previously passive domestic consumers to become active participants in the electricity market and in the operation of the electricity system.

The main problem with micro-CHP systems is that in comparison with conventional gas-fired boilers the investment costs are still prohibitive. Besides variable energy cost savings and governmental policies that reward the positive externalities of micro-CHP application, intelligent control may also decrease variable costs and enhance the economic attractiveness of micro-CHP for investors. Potential investors are households, housing corporations, energy retail companies and other energy service companies. The research question this thesis answers is: *How and to what extent can intelligent control of micro-CHP systems increase*



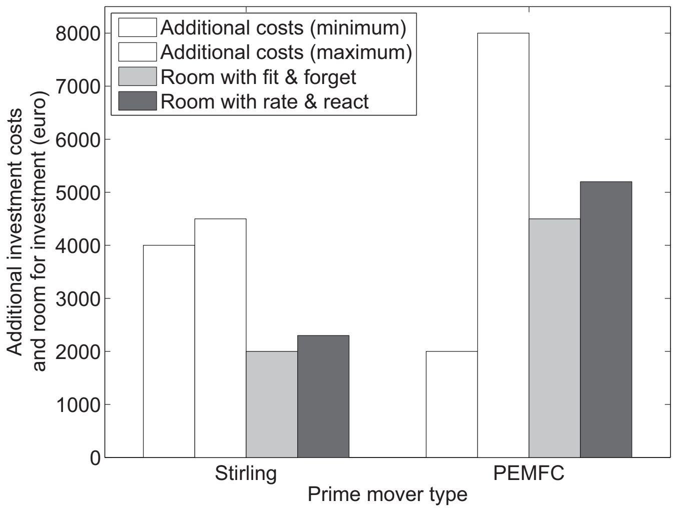
their economic feasibility? Economic feasibility is here defined as the difference between the cost savings with micro-CHP application obtained during an acceptable payback period of 10 years, and the additional investment costs of micro-CHP compared to gas-fired boiler.

Simulation results and main conclusions

In answering the research question, different control schemes were designed. These schemes are shown in the figure above. The system contains (clusters of) households that interact with their energy retailer. Conventional households obtain all their electricity from the grid and fulfill their heat demand with a high-efficiency, gas-fired boiler. Two micro-CHP technologies were researched: Stirling engines and proton exchange membrane fuel cells (PEMFC). Stirling systems are currently market ready and PEMFC systems are still mostly in the R&D stage. The main difference between these two technologies is their heat-to-power ratio, which is much lower for PEMFC systems. The main conclusions from simulations with models of the control schemes are the following:

Micro-CHP is currently economically infeasible, but future systems look attractive.
In the 'fit & forget' scheme, households buy gas and electricity from their energy retail company and sell electricity back to that retailer. This scheme serves as a base case with which the economic feasibility of more intelligent control schemes is compared. Heat-led control was found to be the best standard control strategy for micro-CHP systems.

Micro-CHP systems provide substantial energy cost savings compared to high-efficiency gas boilers. Less electricity is imported and a little more gas is used, resulting in an overall reduction in primary energy use of about 20 %. In a market where transport costs are billed per kWh of electricity sold, a feed-back tariff equal to the import price minus the transport



tariff is logical. With such a feed-back tariff, annual energy cost savings are around €250 for Stirling engines and around €500 for PEMFCs (both values for households with average heat and electricity demand). Considering the payback period of 10 years for the investment, these savings result in room for additional investment of about €2000 for Stirling engines and €4500 for PEMFCs. For Stirlings this is not enough as they are currently about €4000 more expensive than conventional boilers (see figure above). The PEMFC systems seem more economically attractive. This depends strongly on their eventual investment costs, however, which, after consulting the available price data, are very uncertain. The results do look promising for future generations of micro-CHPs, which are likely to be based on fuel cell technology.

Demand response moderately increases the room for investment in micro-CHP.
Micro-CHP systems can be applied more intelligently than in the 'fit & forget'scheme, without compromising the heating comfort for households. In the 'rate & react' scheme the retail company rates the electricity sold to and bought from households and intelligent controllers in households react to the tariffs when dispatching micro-CHP units. In that way the net-consumption of electricity responds to real-time prices.

Demand response was implemented in a model predictive control (MPC) strategy. MPC is a control strategy that incorporates future knowledge in control actions. With MPC applied to Stirling systems, the room for investment was increased with €30 to €300, which is still not enough to justify investment in Stirling technology. Cost savings with MPC strongly depend on the specific electricity pricing regime and are highest with the most heavily fluctuating real-time pricing scheme. With PEMFC systems, additional variable energy cost savings with MPC are much larger, resulting in an increased room for investment of up to €700. Depending on the eventual cost price of PEMFC systems, applying demand response to this technology can make it economically feasible.

Before contributing to improvements in economic feasibility of micro-CHP, cost savings with intelligence should cover investments in control systems and in-house domotics.

Especially when smart metering and options for data communication with households are already in place (which is plausible in the future), these investments will not be too high. Especially with PEMFCs, it is likely that the increased room for investment from demand response covers the investments in control systems and information and communication technology (ICT).

Intelligent control of Stirling micro-CHP does not make them economically feasible.
As a next step, the potential of *virtual power plants* (VPP) to enhance the economic feasibility of micro-CHP was analyzed. Placing intelligence at a higher system level and employing it to control clusters of households can provide economies of scale in the use of control and ICT: with intelligence at the aggregate level, simpler sensing and actuation devices can be used in households. Also, the energy demand of clusters of households can be predicted more accurately than the demand of individual households. In the 'cluster & control' scheme, micro-CHP systems are controlled in a VPP arrangement by an *aggregator*. An aggregator is defined here as an actor that *trades* with the aggregate power flows to/from households (i.e. retailer) *and/or operates* a VPP by controlling micro-CHPs (i.e. VPP operator). The aggregator can also invest in micro-CHPs and/or ICT systems.

Two VPP applications were analyzed. First, aggregate demand response schemes provided savings per household that are similar to the savings with domestic-level demand response. A second application was modeled in which a VPP provided balancing services to a wind farm. Wind power traders are inherently faced with imbalances due to the stochastic nature of wind power generation. VPPs with micro-CHP units can help traders to mitigate unwanted imbalance costs. Model simulations with a VPP of 200,000 1 kW_e Stirling systems reduced the imbalance volume of a 200 MW wind farm with 33 % and the associated costs with 20 %. An annual saving of about €1 million was achieved. Assuming that these savings are evenly divided between the VPP households, an annual saving of about €5 per household is arrived at. Such small savings will not improve the economic feasibility of individual Stirling micro-CHPs. So, looking at the results for Stirling engines in the 'rate & react' and 'cluster & control' schemes, it is concluded that intelligent control of Stirling micro-CHP does not make them economically feasible.

If investments are made based on 'fit & forget' application, aggregators have an economic incentive to set up VPPs aimed at demand response.
If Stirling micro-CHPs become cheaper in the future or if the technology receives government support, these systems can become economically feasible under 'fit & forget' application and large numbers can penetrate the market. As previously discussed, PEMFCs can also become economically feasible under 'fit & forget' application.

When households or aggregators already deem the investment in micro-CHP – when they operate in the standard 'fit & forget' way – economically feasible, the additional savings with demand response provide an incentive for aggregators to initiate VPPs. Net savings of about €50 per household per year provide an *aggregate economic incentive* to set up a VPP, because the total savings from all households together are considerable. The value of micro-CHP's inherent flexibility therefore lies in the clustered, intelligent application of this technology.

Michiel Houwing