# Technical and Economic Assessment for Installing Micro-CHP in Residential Homes

Ladan Darougaran, Hossein Shahinzadeh, Mahdi Mozaffari Legha, Houman Gadari

***Abstract*****—**Much has been written about the theoretical advantages and disadvantages of combined heat and power (CHP) systems at the household level (micro-CHP). However, little research has been carried out on the parameters affecting the potential of mass adoption of micro-CHP. An important step in arriving at reliable predictions is the study of the relevant variables that should be included in a model of household investment decision making. In this paper, the sensitivity of mass adoption to a broad range of variables, including technical parameter values, economic data and household characteristics, is being researched. Sensitive variables are the heat to power ratio and the total energetic efficiency of the micro-CHP units, the initial market price, the feed in remuneration scheme and the choice between fixed or variable electricity transport costs.

***Keywords*****—**micro-CHP, energy demands, Gas distribution network, domestic sector

## I. INTRODUCTION

DISTRIBUTED generation of electricity by means of micro combined heat and power systems (micro-CHP) arouses much interest from electric utilities, network operators, consumers, fitters and suppliers of heating systems, as well as the government. When micro-CHP systems turn out to become a real alternative for conventional heating systems in households, this can have a huge impact on the design and operation of electricity distribution networks, the fuel mix of the overall electricity production market and the different economic roles in the electricity value chain. However, a thorough quantitative basis to estimate the possible potential of micro-CHP adoption is still lacking. For these estimations, insight into the structure of the decision making by the actual decision-makers (households) is needed.The goal of this paper is to identify the key variables that determine the replacement of conventional domestic heating systems by micro-CHP. Micro-CHP is a novel heating technology that competes with other residential heating technologies such as condensing boilers, heat pumps, solar boilers and district heating networks.

The core of our approach is the modelling of the cost comparison between micro-CHP and conventional systems, for a variety of households. We do this by simulating domestic investment decision making in which households compare – ceteris paribus – the costs of three different options:

1) retaining their current conventional system;
2) replacement by a new conventional (but high efficiency and, depending on the age of their current system, sometimes higher efficiency) system;
3) replacement by a micro-CHP system.

By ‘conventional heating system’ a high-efficiency condensing boiler is meant. For the micro-CHP prime mover technology a Stirling engine is assumed, as this is the first technology to enter the market [1]. Both the conventional system and the micro-CHP are assumed to operate in conjunction with a hot water storage and they provide both space heating and domestic hot water.

This paper is limited to comparing investments in conventional systems or micro-CHP systems. Choosing from a broader set of heating technologies by households is not looked into. Therefore the simulation outcomes in terms of micro-CHP market penetration are not fully realistic. As said before, our objective is the determination of the relevant variables that drive the cost comparison. All variables included in this paper should be considered as hypotheses. By testing the sensitivity of the simulation outcomes (i.e. micro-CHP market penetration) to changes in the values of the variables, we distinguish between sensitive variables – that need to be included in simulation models aimed at detailed market predictions or policy analysis – and insensitive variables – those that hardly result in different outcomes and therefore add unnecessary complexity to the model. The result of this study is an overview of these variables, to assist the choice of variables to be included in models on micro-CHP market penetration.

We acknowledge that, besides economic viability (lowest cost), there are more factors that determine a household’s decision to invest in a micro-CHP system. To explain real world decisions about technology investment, additional aspects such as institutional context, actor cooperation, and intrinsic motivation and strategic attitudes should also be considered [2-4]. Still, economic barriers are amongst the most important impediments to micro-CHP uptake by individual consumers or energy companies [4]. This study thus aims to

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get in depth knowledge of the structure of the demand side of the market with regard to households that make decisions purely on the basis of rational economic analysis and intrinsic risk attitude. Integrating the results of this model into a bigger picture would require additional research into the other contributing factors and perspectives from other actors.

Because many variables will become uncertain in the medium term, we limit the period for which can be forecasted. Therefore, a reasonable but arbitrary cut at 10 years is used.

## II. MODEL CONCEPTUALIZATION

In this section, the conceptual choices regarding the model are described. First, the operational mode of the micro-CHP system is dealt with, and the scope of the model is sharpened. Then, the different exogenous variables are identified. Also, the household characteristics that are entered into the calculation are described. After that, the calculations that have to be made for each household are outlined. This section concludes with some details of the chosen modelling method.

### A. *Micro-CHP Model*

The energy flows in a household equipped with a micro-CHP system are shown in Figure 1. The Stirling engine uses natural gas to generate both heat and electricity. For heat the household entirely depends on the micro-CHP system; electricity can also be obtained from the electricity distribution network. The Stirling engine of the micro-CHP system is assumed to produce heat and electricity in a fixed ratio over the output capacity. As sometimes not all the electricity produced will be used by the household at the same moment, surplus electricity is fed back into the electricity network. For this electricity the household can receive revenues in the form of a feed back tariff.

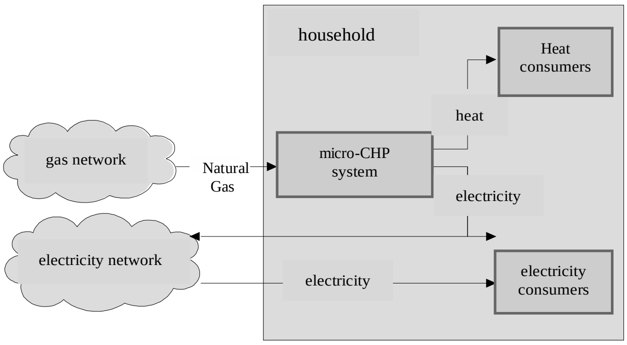
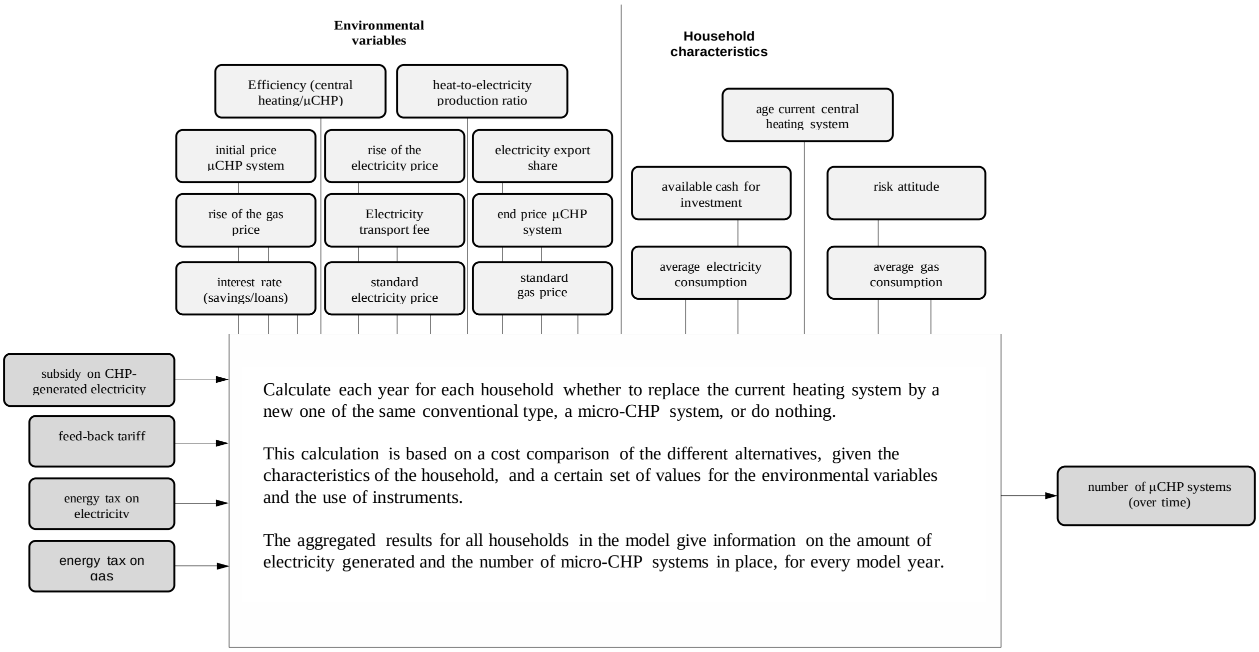


Fig. 1 Heat and electricity flows of a micro-CHP system in a household

Besides the Stirling engine, the micro-CHP system also contains an auxiliary burner. This burner provides peak heat capacity when needed. The control mode adopted for the micro-CHP system will determine how the Stirling engine and the auxiliary burner will be operated. The total system is assumed to operate in a heatled way [5]. With hot water storage options, it can be assumed that the heat demand is fulfilled solely by the Stirling engine and that the auxiliary burner will not be used for heat supply [6].This means we take 1 kW electrical and 6.1 kW thermal power for the Stirling engine. We further set 14% electrical and 107% overall efficiency, based on the lower heating value of natural gas. This high overall efficiency equals the maximum present day value for space heating. With flue gas condensation an efficieny of 107% can thereby be reached. For domestic hot water supply the efficiency will be lower. As space heating represents a much larger share of total heat demand than domestic hot water, we assume 107% total efficiency. In this study we further assume that from the onset, different types of micro-CHP systems will be available, characterised by different power outputs and different consumer prices. Just as for conventional heating systems, the investment costs for micro-CHP systems is assumed to increase with higher thermal capacities of the Stirling engine. This is explained further on. In the model structure it is important to add a variable representing the electricity export share. This is the share of the electricity that is produced in house in a certain amount of time, but is not consumed by the house and is exported to the grid.Exported electricity might be remunerated by a feed back tariff, and different options exist on how high this tariff might be. The feed back tariff could be equal to the electricity import tariff, or, at the other extreme, no remuneration could be given. As a start for the model, the feed-back tariff is set equal to the consumer electricity price including taxes and transport fees (this situation is also referred to as ‘net metering’). Later on we investigate the sensitivity of the model for this assumption, which turns out to be quite high. However, as this concerns an instrumental variable, the sensitivity is more interesting than the – rather arbitrary – starting value. In determining the share of produced electricity that will be fed back into the electricity network, it is necessary to look at the heat and electricity demand profiles in the course of a day and the operational mode of the micro-CHP unit. In this research we work with a heat led control mode and assume an export share of 0.35, meaning that of the produced electricity 35% is being exported to the grid. With net metering, however, the export share is not relevant in the cost analysis, since the value of a unit of exported electricity is equal to that of a unit produced and consumed in house (i.e. avoided import) [7].

### B. *Variables*

In Figure 2, a system diagram shows instrumental variables, external (environmental) variables and criteria. The concept of ‘system’ should be viewed in a socio technical way, in that it encompasses technology, regulation, policy, actors and their relationships. Also, we added the characteristics of the households (model entities). All variables shown are outside the system border: they are exogenous to the model. Table 1 represents an overview of the values for the most important variables. The rest of the variables of Figure 2 are described below. The references for the values are also stated there.



Calculate each year for each household whether to replace the current heating system by a new one of the same conventional type, a micro-CHP system, or do nothing.

This calculation is based on a cost comparison of the different alternatives, given the characteristics of the household, and a certain set of values for the environmental variables and the use of instruments.

The aggregated results for all households in the model give information on the amount of electricity generated and the number of micro-CHP systems in place, for every model year.

Fig. 2 System diagram

TABLE I
MODEL VARIABLES AND THEIR STANDARD VALUES

| Variable | Value | Unit |
|---|---|---|
| *Exogenous variables* | | |
| Total efficiency condensing boiler system | 107% | - |
| Total efficiency condensing micro-CHP | 107% | - |
| Heat to power ratio of micro-CHP | 6.64 | - |
| Gas price at start of the model | 0.42 | $/m$^3$ |
| Electricity price at start of the model | 0.10 | $/kWh |
| Rise of gas price | 7.1% | 1/year |
| Rise of electricity price | 6.3% | 1/year |
| Interest on own savings | 3.0% | 1/year |
| Interest on loans | 5.0% | 1/year |
| Electricity transport fee | 0.040 | $/kWh |
| Electricity export share | 0.35 | - |
| *Instrumental variables* | | |
| Energy tax on natural gas | 0.18 | $/m$^3$ |
| Energy tax on electricity | 0.084 | $/kWh |
| Subsidy on CHP generated electricity | 0 | $/kWh |
| Feed back tariff (standard: remuneration) | n/a | - |
| *Adoption barriers* | | |
| Early Adopter | -50 | $/year |
| Early Majority | 0 | $/year |
| Late Majority | 50 | $/year |
| Laggard | 100 | $/year |
| No adoption barriers when penetration reaches | 50 | % |
| *Market price micro-CHP system* | | |
| Initial market price | 6000 | $ |
| Final market price | 3500 | $ |
| *Other* | | |
| Lower Heating Value energy density natural gas | 31.65 | MJ/m$^3$ |
| Depreciation period conventional heating system and micro-CHP system | 15 | years |

## *C. Household Profiles*

For the model different household profiles were created. In these profiles, initial information is stored about electricity demand and gas demand for heating, the age of the current conventional heating system installed (used to determine the costs of early depreciation), the nominal thermal capacity of the current heating system, the availability of investment capital and the risk attitude of the household. This information is updated annually, when there is a ‘window of decision making’ in which the current heating system might be replaced. We choose to construct household profiles consisting of combinations of values of the described variables. The variables were assumed to be distributed uniformly but discretely between ranges as shown in Table 2. The parameter ranges are derived from statistical data. In total, 1500 unique profiles were entered into the model. To prevent unlikely combinations (for instance, a large gas demand and a small demand for electricity), we have matched several combinations in advance. The gas demand is coupled to the electricity demand and to the thermal capacity of the current heating system. That thermal capacity is again coupled to the investment costs of a conventional heating system and of a micro-CHP system. The set of coupled electricity and gas demands (with a conventional heating system) is shown in Table 3. The profiles are orthogonal with respect to the other variables, which means that no correlations exist. We assume that the electricity and heat demands remain constant over the modeled period [8-10].

TABLE II
PARAMETER RANGES CHARACTERIZING HOUSEHOLDS IN THE MODEL

| Parameter | Min value | Max value | Unit |
|---|---|---|---|
| *Coupled* | | | |
| Gas consumption | 1150 | 2060 | m$^3$/year |
| Electricity consumption | 1905 | 4470 | kWh/year |
| Thermal capacity of conventional system | 5 | 65 | kW |
| Price of conventional system | 2230 | 3637 | $ |
| Initial price of micro-CHP system | 4777 | 7789 | $ |
| *Uncoupled* | | | |
| Availability of investment capital (savings) | 3000 | 21667 | $ |
| Age of current heating system at start of simulation | 0 | 15 | Years |
| Correction for risk attitude | -50 | 100 | $/year |

TABLE III
DISTRIBUTION OF HOUSEHOLD PROFILES IN THE MODEL WITH REGARD TO ANNUAL ELECTRICITY AND GAS DEMAND (BEFORE MCHP)

| | **Gas demand before mCHP ($m^3$/year)** | | | | |
|---|---|---|---|---|---|
| **Electricity demand before mCHP (kWh/year)** | **1150** | **1450** | **1555** | **1760** | **2060** |
| **1905** | 15% | 5% | | | |
| **2385** | 5% | 10% | 5% | | |
| **3005** | | 5% | 10% | 5% | |
| **3655** | | | 5% | 10% | 5% |
| **4470** | | | | 5% | 15% |

### *D.Cost analysis*

The structure of the cost comparison and subsequent decision making on heating system replacement, annually executed by each of the 1500 households in the model, can be found in Figure 3, where a decision tree is presented. The elements of the cost comparison are shown in Table IV. For all three options, the sum of variable and fixed costs and income generated is calculated. We assume households will make a simple decision with regard to the overall yearly cost. Apart from a correction for risk perception, which will be discussed later on, they choose the alternative that has the lowest cost. We regard more advanced methods like net present value analysis, break even periods or internal rate of return, mostly used by corporate investment decisions, as non representative for a consumer investment situation [11].

TABLE IV
COST COMPARISON BETWEEN THREE POSSIBLE OPTIONS

| | **1. Maintain current heating system** | **2. Replace by new conventional heating system** | **3. Replace by micro-CHP system** |
|---|---|---|---|
| *Variable costs* | Gas consumption<br>Electricity consumption | Gas consumption<br>Electricity consumption | Gas consumption<br>Net electricity consumption (import export) |
| *Income* | - | - | Subsidy on CHPgenerated electricity |
| *Fixed costs* | Depreciation<br>Interest (financing) | Depreciation<br>Interest (financing) | Depreciation<br>Interest (financing) |
| *Fixed costs When prematurely replaced* | - | Early depreciation<br>Additional financing costs | Early depreciation<br>Additional financing costs |
| *Total* | *Total costs* | *Total costs* | *Total costs* |

As said before, we assume that electricity that is fed back into the network will be balanced with the imported electricity and further that this procedure is constant during the modelled period. Only the net amount of electricity imported counts for the electricity price, the transport fee and taxes. At the revenue side, a CHP related environmental subsidy may be received for electricity produced on site. We calculate capital costs, for both the current as well as the new systems under consideration, on the basis of the household liquidity, which determines whether the investment can be (partially) financed out of cash or whether it must be borrowed. Another cost category is only relevant when the current system is replaced before it is completely depreciated. This cost consists of the remaining depreciation and capital costs of the old system. We assume that households are not treated as business entities with regard to Value Added Taxes [12-13]. Furthermore, the maintenance costs for all types of installations is assumed to be equal, and installation costs are included in the overall unit price. Finally, we do not take the costs of the installation of intelligent meters to register residential electricity consumption, production and export into account.

## III. SIMULATION RESULTS

We ran a sensitivity analysis on all variables depicted in Table I, following a ceteris paribus approach. We changed the value of the variable with an arbitrary amount and looked at the change in the ultimate 'result' of the model: the degree of adoption of micro-CHP systems. Most variables are relatively insensitive, meaning that a change in their value does not lead to a disproportional change in the model outcomes. Several, however, do have a significant effect, as shown in the sensitivity analysis results in Table 5.

Note that the adoption rates have no absolute meaning. The relatively high adoption rates can be explained because the model only incorporates demand side characteristics and does not take the supply side of the market into account. Therefore, it is only about latent demand, not about real purchases of systems, since the systems are hardly available at this moment and will not be mass produced in the first years of the modelled period.

TABLE V
SENSITIVITY OF MODEL VARIABLES

| **Variable** | **Value** | **Unit** | **Absolute change in value** | **Leading To relative change in outcome (number of mCHP units)** |
|---|---|---|---|---|
| *Exogenous variables* | | | | |
| Total efficiency condensing boiler system | 107% | - | 10% | 12% |
| Total efficiency condensing micro-CHP | 107% | - | 10% | 80% |
| Heat to power ratio of micro-CHP | 6.64 | - | 10% | 127% |
| Gas price at start of the model | 0.42 | $/m$^3$ | 10% | 3% |
| Electricity price at start of the model | 0.10 | $/kWh | 10% | 12% |
| Rise of gas price | 7.1% | 1/year | 10% | 4% |
| Rise of electricity price | 6.3% | 1/year | 10% | 10% |
| Interest on own savings | 3.0% | 1/year | 50% | 32% |
| Interest on loans | 5.0% | 1/year | 50% | 7% |
| Electricity transport fee | 0.040 | $/kWh | 10% | 4% |
| *Instrumental variables* | | | | |
| Energy tax on natural gas | 0.18 | $/m$^3$ | 10% | 2% |
| Energy tax on electricity | 0.084 | $/kWh | 10% | 4% |
| Subsidy on CHP generated electricity | 0 | $/kWh | (change to 0.02) | 1% |
| Feed back tariff (standard: remuneration) | n/a | $/kWh | (change of model structure; new value: 0.10) | 34% |
| Change of transportation fee from variable to fixed | n/a | n/a | (change of model structure) | 21% |
| *Adoption barriers* | | | | |
| Early Adopter | -50 | $/year | 50% | 3% |
| Early Majority | 0 | $/year | 50% | 0% |

| | | | | |
|---|---|---|---|---|
| Late Majority | 50 | $/year | 50% | 2% |
| Laggard | 100 | $/year | 50% | 1% |
| No adoption barriers when penetration reaches | 50 | % | 50% | 0% |
| *Market price micro-CHP system* | | | | |
| Initial market price | 6000 | $ | 10% | 20% |
| Final market price | 3500 | $ | 10% | 5% |
| *Other* | | | | |
| Lower Heating Value energy density natural gas | 31.65 | $MJ/m^3$ | n/a | n/a |
| Depreciation period conventional heating system and micro-CHP system | 15 | years | not tested, would require structural changes | n/a |

The total efficiency (heat and electricity) of the micro-CHP unit proves to have a strong impact on the penetration. Although the aim of micro-CHP developers is to deliver the same efficiency as a conventional high efficiency condensing boiler, the model shows that a slight deviation can have significant impact on the overall penetration. An even more important technical parameter is the heat to power ratio. A small upward change in the electric efficiency, at the expense of thermal efficiency, has a positive effect. Most current systems use the Stirling design, which places the electrical power share at a current technical limit of around 15% (14% was used in this model, based on [14], which hardly deviates from the specifications of Microgen [15].) It is expected that in the future the Stirling technology can possibly deliver 20 to 30% electrical efficiency. Other technologies, among which are fuel cells, can increase this value even further.

The electricity export share does not play any role when net metering is used for remunerating the exported electricity and when time invariant tariffs are used (i.e. the tariffs are constant over the day; no real time pricing).

The initial market price of the systems has quite a significant impact. The changes investigated, of 1000 $, represent the actual uncertainty, as different press statements about market introductions mention prices that differ around the same amount[15].

The existence of a fixed or variable scheme for transportation fees and the presence of net metering are key policy variables, the effect of which is much bigger than that of small changes in fees related to the amount of produced electricity.

## IV. CONCLUSION

The penetration level is particularly sensitive to changes in the technical parameters (system efficiency and heat to power ratio) and the initial market price. System efficiency and heat to power ratio can, to a certain extent, be influenced by manufacturers.

Net metering of electricity imports and exports is very supportive of micro-CHP development. Because this way of remunerating exported electricity can be captured in regulation, it is clear that the government could have an important role in stimulating the market, although the social legitimacy for this (i.e. opportunity costs) is beyond the scope of this study. A second beneficial factor is the variable transport fee for electricity. However, this is a more indirect instrument, since the consideration whether to switch to a fixed fee based on capacity will be impacted by many different perspectives as it is not only about micro-CHP.

The sensitivity of the above mentioned variables suggests that modellers should pay particular attention to these and should try to find reliable empirical data. The variables that are less sensitive can be dealt with in three ways. Some variables cannot be omitted from a model (such as the gas price), but their low sensitivity suggests that there is a certain tolerance for error in empirical data. Considering that it is often hard to get reliable data, this knowledge may be very helpful in deciding about data collection priorities. Other variables (such as risk adoption barriers and probably interest rates as well) may be omitted since they hardly effected the results of our model. This leads to a structural simplification of the model.

A noteworthy characteristic of our developed model is that it mostly consists of discrete structures. The simulated households make decisions based on absolute thresholds, whereas in reality the outcome of decisions will be better described by a statistical function around this ‘absolute’ mean. Normally, this does not cause problems when the law of large numbers comes in. However, with the limited sample size (1500 artificial household profiles) it may be that the hard thresholds have introduced some error.

A second caution we need to give is that the sensitivity to household characteristics is not tested. They would require fundamental changes to the model, which are outside the scope of this study. Nevertheless, in every model construction these characteristics play a role and their relevance and sensitivity need to be researched as well.

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