Why and How Scaling down TPO's ML into a Residential building

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Acronym

AS Alternative system
CC Combined cycle (gas and steam power plant)
CHP Combined heat and power (= cogeneration)
CCHP Combined cooling heat and power (= tri- or poly-generation)
DHW Domestic hot water
DW Dish Washer
ESWH Electric Storage Water Heater
GHG Greenhouse gases
ICE Internal combustion engine
LHV Lower heating value
MCHP Micro-combined heat and power
MFH Multi-family house
NPV Net present value
NRE Non-renewable energy
NRPE Non-renewable primary energy
OC Operating cost
PES Primary energy savings
RE Renewable energy
SPB Simple pay-back period
SFH Single-family house
SH Space heating
SC Space cooling
Th Thermal
TS Traditional system
Washing Machines (WM)

SCOPE

This document aims at describing reasons and technical approach to project the TPO approach into the residential buildings' market, where the final proposition of the product must be the management of energy demand, e.g. the energy needed to fulfill the user's requirements for space heating or cooling, for domestic hot water, for ventilation, and for electric lighting and appliances.
The basic assumption of this work is the use of micro-CHP (≤ 15 kWel) to supply heat and power to small scale end-users.
Attention has been paid to the problems derived by the transfer of Di-BOSS's TPO technology to small-scale applications: following paragraphs are a collection of different lessons learned throughout the Rudin CO, personal analysis and RSE and ENEA reports about this topic.

WHY

During the last decade, small-scale combined heat and power systems have become a viable alternative to conventional power supply and boiler-based heating system in many types of applications. In the domestic sector the use of combined generation on micro scale is currently relatively uncommon, but the market availability of gas-fuelled generating equipment, together with a significant number of current R&D projects, confirms the large potential for micro-CHP, which was until now limited to niche applications.
But the utilization and wide diffusion of MCHP is strongly related to the characteristics of final users (i.e. to the load profiles or electrical, thermal and cooling requirements that have to be matched by the MCHP output) as the Figure 1 shows sketching energy conversion processes and energy terms in a generic residential building/apartment.

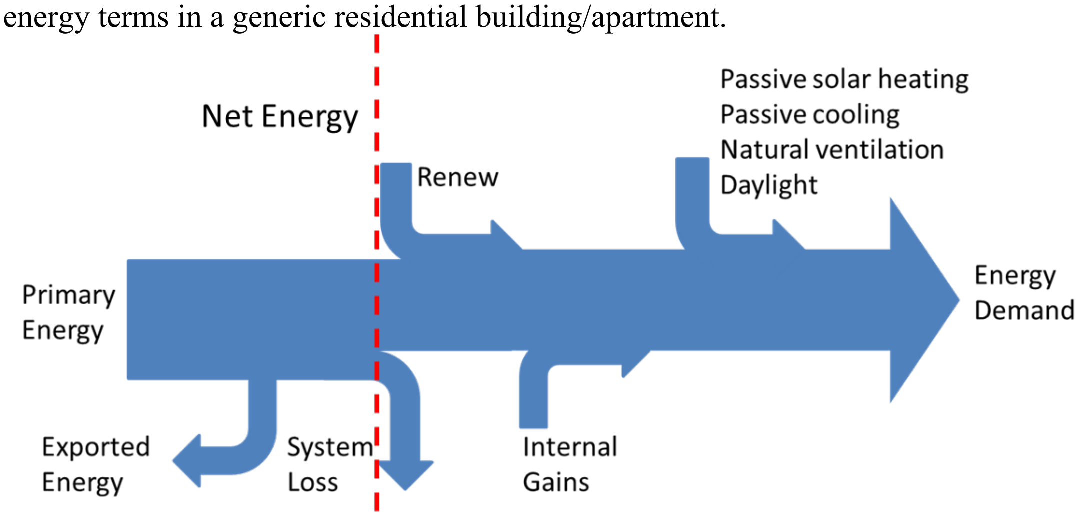

Figure 1 - Energy Flow in a residential building

Net energy is the part of the energy demand which is provided by the HVAC system (including RE systems) to cover the energy demand for space heating/cooling, domestic hot water and electricity respectively

Delivered Energy is the primary energy represented separately for each energy carrier (fuel, electricity, heat/cold, incl. auxiliary energy), that is entering the individual building envelope (the system boundary) in order to be used by the heating, cooling, mechanical ventilation, hot water, lighting systems and appliances. This may be expressed in energy units or in units of the energy ware (kg, m^3, kWh, etc.). Locally generated solar and ambient energies are not considered as delivered energy, but are accounted for by a separate contribution to the net energy demand. However, delivered energy may include heat or electricity produced from renewable sources elsewhere, like electricity from a PV plant, or heat from a plant fired by sustainable grown wood, fuel from renewable energy sources (e.g. hydrogen or wood) is taken into account as renewable energy.

MCHP can provide considerable contribution in reducing building CO2 emissions in residential multi-family buildings for all Italian climate areas, even though the percentage of CO2 and Primary Energy reduction is higher in cold climates (climate zone E) than in warmer areas (climate zone B).
One reason for that concerning reduction potential could be the bad energetic quality of the reference building stock, representing the actual social building stock in Italy.
CHP gives more primary energy reduction in the social buildings with bad energy level than in the new buildings. This fact is due to difference (in terms of time shifting) of electric load demand compared to heating demand profiles.
That means also that in case of well retrofitted buildings an improvement of the building envelope performance may considerably reduce the potential for micro cogeneration applications (see Schneider commercial proposition). On the other hand, because in many cases building envelope retrofit is difficult to realize, the adoption of micro cogeneration technologies could be considered as a possible promising additional measure in order to achieve substantial primary energy and CO_2 emissions reduction.
The electricity costs with cogeneration plant are lower in colder areas, where the system works longer during heating period so it generates more electric energy, reducing delivered grid electricity and increasing exported electricity to the grid.
Unitary thermal costs for space heating and DHW with cogeneration system are almost equal in each climatic zone. This cost depends on thermal efficiency to convert primary energy (natural gas) to delivered thermal energy: thermal CGU part load performance, based on generated electric power, is almost constant throughout the working interval.
An efficient power supply system, such as a co-generator, is attractive in residential and light commercial markets because of the contribution of these sectors to the total energy consumption of developed countries. In Italy, commercial and residential sectors were responsible for 35.6% of the national energy consumption in 2005 (in 1999 these sectors contributed about 30% to the total value). In 1999 a potential energy savings of about 200,000 toe (ton of oil equivalent) per year, about 16% of the total national energy requirement, was estimated if 500,000 micro-CHP units were to replace the usual energy-supply equipment in Italy.
Furthermore, about 71 million European houses are supplied with natural gas. The European Commission recognizes the advantages of cogeneration and has made increased cogeneration capacity a key part of its CO2 reduction strategy, as recent topics of H2020 demonstrate.

Recent researches by RSE and ENEA confirm that:

- for domestic building applications, at least 8 dwellings are the minimum target size for application of the 6kW MCHP device (upfront cost around 15K€) in the south of Italy (worse location where to install). This choice is based a simple payback period of less than five years, which is deemed acceptable to domestic users. Researches also show an increase of in the number of dwellings leads reduces the SPB, and the SPB is not influenced by MCHP operating strategy in buildings with 8 or more dwellings.
- the operating strategy does influence energy savings; variable start-up provides additional savings of as much as 13%. When deployed in a building with 8 or more dwellings, the equivalent CO2 emissions reduction is not influenced by operating strategy and the related increase with the number of dwellings is negligible.

For domestic appliances, MCHP systems provide significant energetic, economic and environmental savings due to the great importance of thermal recovery in electric driven appliances: the need for high quality power supply, the congestion and vulnerability of the transmission and distribution lines are key motivators to the development of distributed generation and poly-generation energy conversion systems, moving from the traditional centralized scenario based on separate "production" to the incoming decentralized one.

Italian context

To illustrate the key-point in MCHP utilization, consider its application in an Italian context where the building types considered is multi-family house, MFH (4-12 dwellings).
For average social multifamily houses, representative of Italian building stock (built between 1976 and 1985) MFH is a five floor building with 20 apartments and dimensions 30 l, 12 w, 17.5 h. Energy reference area of MFH is 2135 m2 and main axis orientation is NE-SW.

Italian building energy codes divide Italy in six different climatic zones, according to their degree days (DD) ranges: A, B, C, D, E and F. Each zone indicates a heating period to activate heater central plant for MFH, as following:

- Zone A: until 600 DD, heating period 1st Dec – 15th Mar, limit of daily heating: 6 hours
- Zone B: from 600 to 900 DD, heating period 1st Dec - 31st Mar, limit of daily heating: 8 hours
- Zone C: from 900 to 1400 DD, heating period 15th Nov-31st Mar, limit of daily heating: 10 hours
- Zone D: from 1400 to 2100 DD, heating period: 1st Nov - 15th Apr, limit of daily heating: 12 hours
- Zone E: from 2100 to 3000 DD, heating period: 15th Oct - 15th Apr, limit of daily heating: 14 hours
- Zone F: over 3000 DD, heating period: no limitation, daily heating hours: any limitation

Building distribution system for space heating and cooling ventilation system

Heat distribution is performed by water-based radiators while cooling is provided by an electric driven split system with air cooled condensing unit; it is noteworthy that in southern Italy split systems are used to in portions of the living spaces (i.e. bedroom, dining room) comprising 25%.
Space heating is required for only a third to half of the year. Even during the heating season the heating system is often operating for short periods of the day, and the electrical demand profile is not always well matched to that of heat. For example, a residence may require maximum thermal output during a cold winter night while electrical demand may be minimal; maximum electrical output may be required for residential cooling during hot summer day when there is little or no need for thermal energy.

To best match the MCHP's output to building loads, it must be considered the energy requirements of those domestic appliances that can use either electricity or hot water to meet their energy requirements (that is, water heaters, dish washers, and clothes washers).

In order to optimize the match between the micro-CHP and the thermal and electric users, the right attention must be paid on domestic electric storage water heaters, domestic washing machines, and finally on household dish washers, for two reasons:

a) They consume a significant part of household electricity. The energy efficiency of ESWH, WM and DW is analyzed by manufacturers, research groups, national and international energy authorities that are studying the technologies to reach the optimum balance between energy consumption and overall working performance;
b) They permit shifting the energy requirements from electricity to thermal energy: in fact the energy supplied to ESWH, WM and DW systems is mainly used to produce hot water, usually by means of electric resistance heaters. There are commercially-available equipment that are both thermally- and electrically-driven and therefore can be linked to alternative energy suppliers such as boilers and/or micro-CHP

Referring to topic (a), the total European Union electricity consumption by ESWH systems in 1997 was 87 TWh, and about 15% is due to household units. About 30% of the 142 million EU households use this equipment. The energy consumption of the estimated 120 million WMs installed in EU amount to about 38 TWh, which is approximately 2% of the total EU electricity consumption.
In Italy, ESWH, WM and DW systems are responsible for about 45% of the average annual household energy consumption. It is important to underline that about 70% of the total energy consumption of household appliances is covered by ESWH, WM and DW systems.
In the USA, WM and DW systems that meet the standards set in the National Energy Conservation Act consume about 30% of total annual energy consumption of typical domestic appliances.

Referring to topic (b), it can be noted that, for a ESWH, the energy supplied less the stand-by losses, is used to heat the water. Starting from cold water at 10 °C, in order to supply 100 liters of hot water at 60 °C, the average European citizen consumes 36 liters of hot water each day that is about 6 kWh of energy. However, during a whole 24-hour period, average stand-by losses range from 1 to 2.5 kWh, depending on insulation thickness, thermal conductivity of insulation material, geometry of the ESWH. In a WM typical wash cycle (at 60 °C) about 85% of the total energy requirement is used to heat water and only 15% to other electric devices. For a bio cycle of a DW, 55/65 °C, only 10% of the energy supplied is not used to hot water production.

	SFH
Space heating [kWh/(m2 a)]	77.3
DHW [kWh/(m2 a)]	35
Electricity [kWh/(m2 a)]	19.1
Electricity (including HVAC in hot season) [kWh/(m2 a)]	25.2
U-value exterior walls [W/m2K]	1.93

Figure 2 - Energy demands per m2 energy reference floor area

Moreover from the monitored data, as well as existing literature and Rudin experience, we can assume that domestic non-HVAC – it means the part of the energy demand that is provided by "natural" (passive) energy gains (passive solar, natural ventilation, natural ventilation cooling, internal gains, etc.) - electrical energy and thermal energy consumption is primarily dictated by the following factors:

- floor area of the dwelling;
- number of occupants;
- geographical location;
- occupancy patterns;
- seasonal and daily factors;
- ownership level of appliances.

In order to leverage the MCHP, WMs and DWs should be managed in hybrid operation mode (that is, powered by the electric network and with electric input in addition to hot water) rather than in the traditional one:

- For the DW, no restrictions were placed on the temperature level of input hot water and each appliance was linked to the hot water pipe instead of cold pipe to avoid water heating by electric resistance.
- For the WM, the water temperature must be controlled, and therefore appliances are available with two pipes for water inputs.

HOW

MCHP

The main components of the MCHP system layout are shown in Figure 3

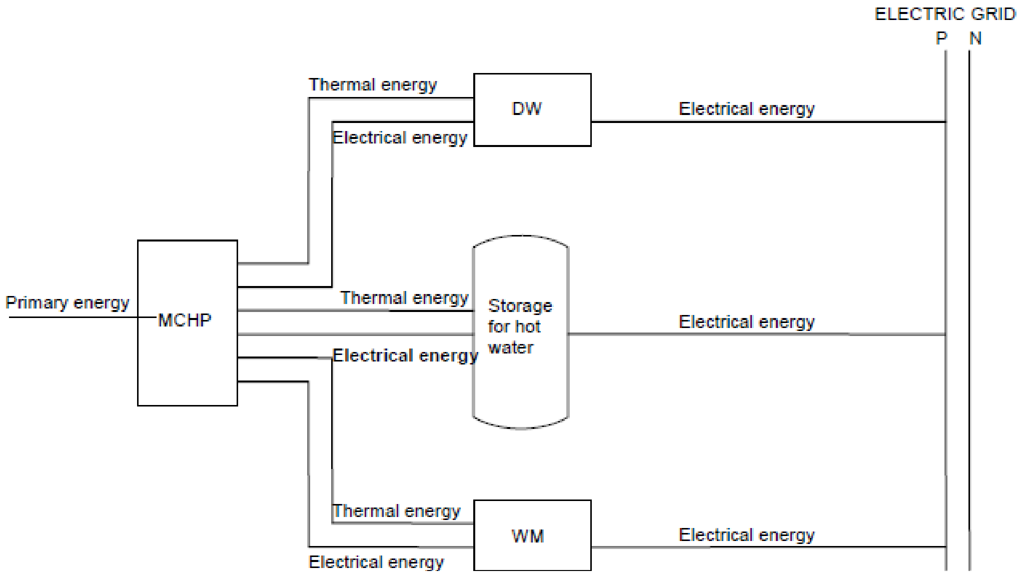

Figure 3 - MCHP schema

Typical CHP control strategy and methods

- Method: Build thermal load following
- Controlled Variables: Storages temperatures.
- Controlling parameters: ICE Modulation, On-Off auxiliary heaters.
- Building heat demand control:
    - PID controlled supply temperature to radiators
    - Rooms thermostats

ASC in the residential building

With the increasing application of distributed energy resources and newest information technologies in the electricity infrastructure, innovative possibilities to incorporate the demand side more actively in power system operation are enabled. As shown above, MCHP is a promising, controllable, residential distributed generation technology.
Micro-CHP is an energy efficient technology that simultaneously provides heat and electricity to households. In this paragraph I want to start discussing to what extent MCHP with intelligent, price-based control concepts (demand & response).
In Figure 4 we sketched a logical diagram where:

- The dark blue box contains the "brain" of the Residential Optimizer (RO). It includes two basic modules:
    - Demand&Response (D&R),
    - Regime Controller (RC)

  At each time step, an optimization problem is solved with the following components:
    - an objective function expressing which system behavior and actions are desired;
    - a prediction model describing the behavior of the system subject to actions;

  - possible constraints on the states, the inputs, and the outputs of the system (where the inputs and the outputs of the system correspond to the actions and the measurements of the controller, respectively);
  - possible known information about future disturbances;
  - a measurement of the state of the system at the beginning of the current control cycle.

  The objective of RO is to determine those actions that optimize the behavior of the system as specified in an objective function
- Utility is the entity having the accountability of delivering electricity or fuel to the residential
- Service providers are external stakeholders that publish data relating to commodities prices and weather
- Smart Appliances. They are appliances that can be controlled by RO; note that a dummy appliance can become "smartish" using a remote switchable plug
- Smart Meter
- MCHP, Micro-CHP: energy conversion unit with an electric capacity below 15 kW that simultaneously generates heat and power
- Energy Storage (thermal and/or electric)

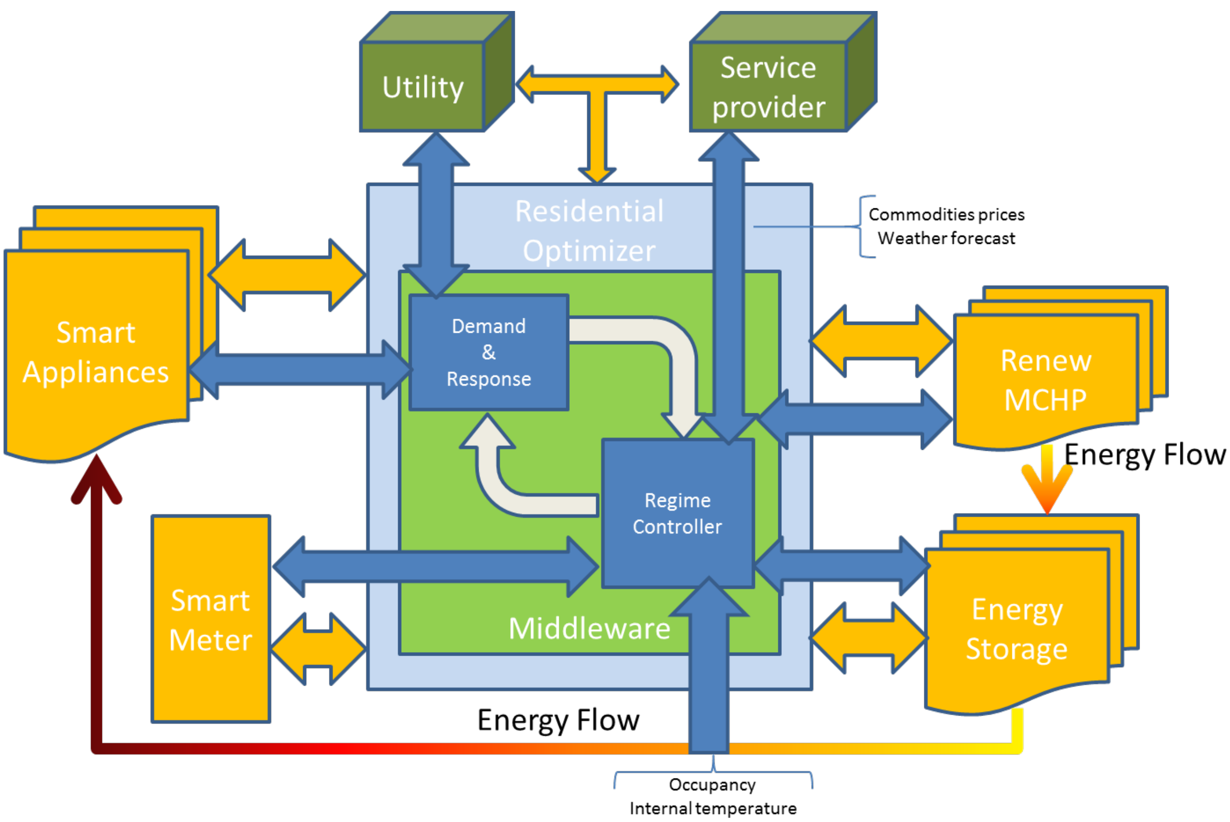

Figure 4 - Residential Case: a logical schema

We introduce two different operating modes:

a) Regime. It is the normal operating condition and RO has the objective for provisioning of intra-day balancing services, provisioning of black start services and improving power quality
b) Curtailment. It is a temporary mode, whose conditions are defined with the Utility in signing the contract for energy supply. RO must have the ability of domestic net-consumption of electricity to respond to real-time prices (net-consumption = consumption - production - storage)

Curtailment

It happens when the utility asked for a load curtailment. It can be achieved in two ways:

- Load shedding. Some loads with lower priority are shut down
- Load shifting. Loads' activity is rescheduled for satisfying utility's request.

We split loads in three different classes:

- HVAC. All electric loads used for assuring comfort, they are scheduled by the RC to control the indoor temperature for comfort. The RC collects sensor measurements, obtains model parameters, and schedules appliances using the logic presented below.
- Deferrable and Interruptible Loads (D&I_L) like PHEV. The specific example can be the charging of PHEV for which the earliest starting and the latest completion times are specified; the actual charging time and the amount of charging are part of the optimization. We assume that the charging can be suspended temporarily and resumed at a later time. The strategy of charging affects the customer comfort level indirectly through the peak power constraints and available budget. PHEV is required to be charged to a certain level by the deadline, which stands for a higher priority over the comfort level.
- Deferrable and NON Interruptible Loads (D&NI_L), like dryer or washing machine

To each class a specific policy is associated $\rho^{\pi} = [\rho^{\pi}_{HVAC}, \rho^{\pi}_{D\&I\_L}, \rho^{\pi}_{D\&NI\_L}]$

The objective function is the maintaining of the comfort during the curtailment period, the state variable is the interior space temperature like in $dx = \alpha x dt + Rp_{HVAC} dt + \sigma d\nu$; where x is the temperature, α is the average thermal capacity of the building, R takes into account the energy storage availability is known at the beginning of the D&R time window, ρ_{HVAC} is a policy of ASC, and the wiener process covers:

- the uncertainty for people counting
- doors/windows open/close
- anthropic effects like cooking

α and R are evaluated through the analysis of historical data and used to build the model for the ASC. The policy evaluation is expressed in terms of Dis-comfort $E[\sum_t \left\| x(t) - T_{default} \right\|^2]$ and the constraints that define the domain of the policies (as second reward function) is

$$C(\pi) = \sum_t price(t) * elapsed\_time * p^{\pi}(t) < MonthlyExpectedBill$$

Regime

The control objective is to minimize the variable costs of domestic energy use. For this reason:

- the policies concern with the operability of renewable sources, MCHP and Energy Storage;
- their evaluation is based on monthly cumulative energy bill;
- the second reward function is $C(\pi) < 1 - \min valueOfEnergyStorage$
- the model can be constructed based on measurements from the aggregation of individual component loads

TO TEST

To test small co-generators in actual operating conditions, a test facility must be built with some residential appliances, such as a dishwasher, washing machine, and water heaters that are used both in their traditional configuration (electric driven) and in more efficient configurations (thermal and electric power driven) with electric resistances and internal coil heat exchanger for thermal recovery of the MCHP hot water.
Trento looks like a good candidate for supporting a test bed on MCHP integration
BBDR (H2020 program) looks like a good candidate for supporting a test bed on D&R.