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Geographically Parameterized Residential Sector Energy and Service Profile

Raluca Suciu*, Ivan Kantor, Hür Bütün, Luc Girardin, François Maréchal

École Polytechnique Fédérale de Lausanne, Rue de l'Industrie 17, Case Postale 440, CH-1951, Sion, Switzerland
raluca-ancuta.suciu@epfl.ch

The large share of energy consumption in the residential sector has necessitated better understanding and evaluation of the energy needs in this sector, with the objective of identifying possible pathways for improvement. A series of approaches have been used in the literature to evaluate the current situation and predict the future energy and service needs of residential centres. High-level approaches evaluate the impact of long-term changes in the residential sector on the energy consumption and focus on determination of the energy supply requirements. Other approaches use input data with a higher level of detail and are used to estimate the energy consumption of individual users as representatives of the residential stock. This work uses heat signature models and climate data to build a parametrized residential sector profile for different climatic zones. The energy and service profile constructed herein is well-suited for exploring the best technologies for supplying residential requirements, drawing from the domain of process integration. This work demonstrates the usefulness of the residential profile by applying process integration techniques within a mixed integer linear programming (MILP) formulation to evaluate optimal energy conversion technologies for two different district energy networks (DENs): the current network in place and a potential low-temperature refrigerant-based network. The results show that the refrigerant-based network, compared to the network in place, reduces energy consumption and operating cost by approximately 70 % and CO_2 emissions by up to 100 %, depending on the mix of electricity used.

1. Introduction

Energy consumption in the residential sector represents between 16-50 % of national totals, varying by country, and averages 30 % worldwide (Saidur et al., 2007). Given the high share of energy consumption in the residential sector and energy policies implemented worldwide in the past decades (e.g. Europe 20-20-20, a better understanding of the defining characteristics of residential energy consumption is clearly required.
Estimates of residential sector energy consumption are typically published by governments, which compile values from energy providers**;** however**,** these values may be inaccurate as they do not account for on-site generation. Methods which provide more detailed information are desirable, conducting house surveys (Department for Communities and Local Government, 2010) for example, but also have limitations such as data collection difficulties and cost. Billing data and surveys have been used to develop the residential sector consumption profiles, but they highly depend on the purpose of the model. High-level approaches to model residential sector energy consumption have been reviewed and other potential approaches have been discussed (Reinhart and Cerezo Davila, 2016).
High-level approaches do not distinguish energy consumption of individual users. The information used in these models usually includes macroeconomic indicators, house construction/demolition rates, or climatic conditions. Zhang (2004) developed such an approach to examine the residential unit energy consumption in China and compared it with the ones of Japan, Canada and the USA. High-level models use data which is widely available, and are relatively simple, but lack of detail regarding the individual user consumptions reduces the ability of the model to identify key areas where reductions in energy consumption can be achieved.
Other approaches use data from single users, single houses, or groups of houses and extrapolate the data to reach regional or national energy consumption totals. The usual parameters used in these models include building properties, climate properties, occupancy levels and equipment use. Fischer et al. (2016) presented a

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modelling approach based on the coupling of behavioural and energy balance models and stochastic modelling to generate realistic and consistent load profiles for end user demands and Girardin et al (2010) introduced a linear model to determine the thermal power requirements of a building based on the outdoor temperature and on the heating and cooling threshold temperatures. The primary drawback of these approaches is the large number of input parameters, which makes the models complex, and therefore hard to solve.

This work uses a method based on (Girardin et al., 2010) to build a residential sector energy profile, in view of assessing different service demands of urban areas in a variety of climatic zones. This paper provides data for a variety of energy services, such as heating, cooling, electricity for utilities, mobility and waste treatment for four different climate zones in Europe. The sector profile can be used in order to assess the demands of different settlements, needing as input just the number of capita, the climatic zone and the building distribution profile. The profile is also suited for finding the best energy technologies to supply the required services. This can be achieved using process integration techniques based on a mixed-integer linear programming (MILP) formulation (Marechal and Kalitventzeff, 2003). This approach encourages exploration of integration opportunities for new technologies and between residential services while also introducing interfaces with external providers such as industrial processes to provide district heating. The sector profile is validated using a typical European urban centre, the city of Geneva, and then its usage is illustrated using two different district heating and cooling (DHC) networks: the current network in place, and a prospective low-temperature, refrigerant-based network.

2. Materials and methods

2.1 European zones (EZ)

The sector profile data is provided for four different climate zones in Europe. The zones are obtained using the European heating and cooling indices, which are based on the number of heating/cooling degree days (HDD/CDD) (Nobatek, 2016). In this work, they are referred to as South (1&2), Central East (CEast, 3), Central West (CWest, 4), and North (5) (Figure 1).

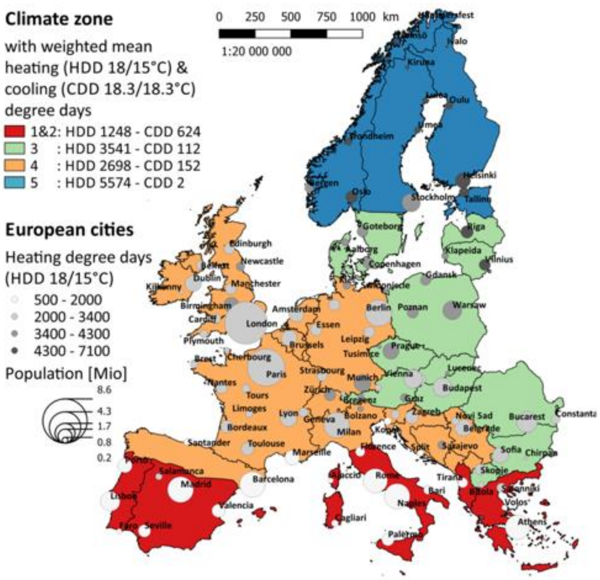


Figure 1: European climate zones

2.2 Service energy demand

A series of service energy demands are included in the current sector profile, namely: space heating (SH), domestic hot water (DHW), refrigeration (REF), air cooling (AC), electricity (for utilities) (El), mobility (Mob), and waste treatment (WT). A heating signature model of a typical urban centre is used to evaluate the specific space heating and air conditioning demands ($q_{SH/AC,EZ}$ [kWh/m^2]) (Girardin et al., 2010). The model relies on input data for external temperature (T_{amb}) and two linear regression coefficients (k_1 and k_2):

$$q_{SH/AC,EZ} = k_{1,SH/AC} \cdot T_{amb,EZ} + k_{2,SH/AC} \quad (1)$$

With $k_{1,SH/AC} = \frac{q_{SH/AC,typical\ city}}{HDD/CDD_{typical\ city}}$ and $k_{2,SH/AC} = -k_{1,SH/AC} \cdot T_{base,SH/AC}$, where $T_{base,SH/AC}$ represents the threshold heating/cooling temperature. The different parameters are given in Table 1 for the typical urban centre used (Geneva) and the building distribution considered.

Table 1: Typical city parameters

Building type	*Share* *[%]*	q_{SH} [kWh/m²]	q_{AC} [kWh/m²]	HDD	CDD	$T_{base,heating}$ [°C]	$T_{base,cooling}$ [°C]
Residential existing (RE)	50.3	93.970	0.000	2,104	226	15.5	18
Residential new (RN)	2.2	42.521	0.000	2,104	226	15.5	18
Residential renovated (RR)	1.9	51.418	0.000	2,104	226	15.5	18
Service existing (SE)	41.0	78.906	20.095	2,104	226	14.2	18
Service new (SN)	3.1	35.023	76.857	2,104	226	14.2	18
Service renovated (SR)	1.5	41.504	87.850	2,104	226	14.2	18

To construct the demand profile for domestic hot water for each time step t, the specific demand of the European zones ($q_{DHW,EZ}$ [kWh/m^2]) (ODYSEE-MURE Database, 2017) and real consumption profile of a typical urban centre ($Q_{DHW,typical\ city}(t)$ [kW]) were used as shown by Eq(2).

$$q_{DHW,EZ}(t) = q_{DHW,EZ} \cdot \frac{Q_{DHW,typical\ city}(t)}{\sum_{t=1}^{N} Q_{DHW,typical\ city}(t)} \tag{2}$$

A constant consumption profile throughout the year is assumed for refrigeration and electricity, and the specific demands ($q_{REF/El.Utilites,EZ}$ [kWh/m^2]) are considered according to (ODYSEE-MURE Database, 2017). The demands per capita ($q_{EZ,cap}$ [kW/cap]) are computed using specific demands (q_{EZ} [kWh/m^2]), total floor area (A=16,174,767 m^2), ratio of the different building types $\left(r_{building\ type}\right)$ and population (N_{cap}=201,164) of a typical urban centre and the number of operating hours (N_{hours}):

$$q_{EZ,cap} = \frac{q_{EZ} \cdot A \cdot r_{building\ type} \cdot N_{hours}}{N_{cap}} \tag{3}$$

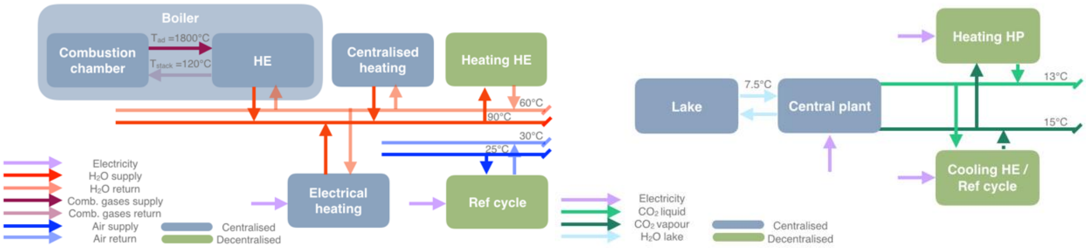
An average distance (d_{EZ} [km/ (cap y)]) (ODYSEE-MURE Database, 2017) is used to assess the energy requirement for mobility. The waste production ($m_{waste,EZ}$ [kg/ (cap y)]) (Hoornweg and Bhada-Tata, 2012) is also provided.

The different service demand profiles are described for three different building refurbishment stages: existing, new, and renovated; and two different building types: residential and service. A typical urban centre building distribution is used. The annual averages of the demands per capita for the different building types, services, and European zones can be found in Table 2.

2.3 Case study and scenarios

The sector profile is validated using a typical European urban centre, namely the city of Geneva (N_{cap}= 201,164), using a monthly resolution. The utilisation of the sector profile is exemplified using both the existing water/air-based district energy network and a potential low-temperature, refrigerant-based district heating and cooling network. The first scenario assesses the current system using water and air as the main heat transfer fluids. In this case, two independent loops are used: a water loop for heating at 90 °C and an air loop for cooling at 25°C. This network uses a mix of natural gas boilers, oil boilers, electrical heaters, and centralised district heating to provide heating services, refrigeration cycles to provide cooling services, and a mix of diesel and gasoline for mobility (Figure 2).

The second scenario looks at a potential future district energy network using CO_2 as the main heat transfer fluid. This network has only one loop: a vapour line at 15 °C, and a liquid line at 13 °C. Unlike water-based networks, CO_2 networks use phase change to realise heat transfer, and allow cooling applications to provide heating which cannot be accomplished with independent loops. Weber and Favrat (2010) introduced the idea of distributing CO_2 in district energy networks at an intermediate temperature, below the critical pressure of 74 bar. A pressure of 50 bar is selected for the system to stay in the saturation temperature range of 12 – 18 °C, as the system can take advantage of the small pressure difference between the phases to provide cooling services using gas expansion. The CO_2 networks use heat pumps to provide heating services, heat exchangers for cooling, and vapour compression chillers for refrigeration (Figure 2). For mobility, it is assumed that the demand is satisfied using electric vehicles with an average energy consumption for electric vehicles (Dimitrova, 2015).



(a) (b)

Figure 2: Current DHC network scheme (a), CO_2-based DHC network scheme (b)

Table 2: Energy demand per capita for different European zones

Zone	Building type	SH [kW/cap]	DHW [kW/cap]	AC [kW/cap]	REF [kW/cap]	El [kW/cap]	Mob [km/(cap y)]	WT [kg/(cap y)]
South	RE	0.266	0.104	0.000	0.000	0.186	16,460	747.52
	RR	0.118	0.102	0.000	0.000	0.182	16,460	747.52
	RN	0.145	0.104	0.000	0.000	0.185	16,460	747.52
	SE	0.202	0.069	0.235	0.049	0.177	16,460	747.52
	SR	0.091	0.070	0.918	0.050	0.175	16,460	747.52
	SN	0.103	0.060	0.993	0.047	0.214	16,460	747.52
CEast	RE	0.720	0.214	0.000	0.000	0.196	16,456	608.50
	RR	0.318	0.209	0.000	0.000	0.192	16,456	608.50
	RN	0.392	0.213	0.000	0.000	0.195	16,456	608.50
	SE	0.605	0.142	0.084	0.049	0.187	16,456	608.50
	SR	0.275	0.143	0.330	0.050	0.184	16,456	608.50
	SN	0.308	0.123	0.357	0.047	0.199	16,456	608.50
CWest	RE	0.500	0.182	0.000	0.000	0.254	17,877	688.50
	RR	0.221	0.178	0.000	0.000	0.248	17,877	688.50
	RN	0.272	0.181	0.000	0.000	0.252	17,877	688.50
	SE	0.396	0.121	0.072	0.049	0.241	17,877	688.50
	SR	0.180	0.122	0.281	0.050	0.238	17,877	688.50
	SN	0.202	0.105	0.304	0.047	0.257	17,877	688.50
North	RE	1.076	0.288	0.000	0.000	0.264	23,476	861.30
	RR	0.475	0.281	0.000	0.000	0.258	23,476	861.30
	RN	0.585	0.286	0.000	0.000	0.262	23,476	861.30
	SE	0.925	0.191	0.022	0.049	0.251	23,476	861.30
	SR	0.420	0.193	0.088	0.050	0.247	23,476	861.30
	SN	0.471	0.166	0.095	0.047	0.267	23,476	861.30

For both networks, a waste boiler is used to incinerate the municipal solid waste, and a steam network is integrated to recover the heat of the boiler, produce electricity and deliver heat at lower temperatures. This can be used to provide heating services and to vaporise CO_2, which is needed for heating in the case of the refrigerant-based network).

3. Results and discussion

3.1 Real/Sector profile of Geneva

First the real demand profile of the urban center is compared with the demand obtained using the sector profile. As observed in Figure 3, the energy service profile obtained using the sector profile proposed leads to results similar to the real resource consumption profile of Geneva. The errors for the different services vary between approximately 4 % for heating and 30 % for electricity consumption. The real consumption profile shows higher energy consumption for mobility since Swiss inhabitants travel more by car than average western European ones, and smaller electricity consumption due to the fact that the equipment used in Switzerland have, on average, a higher efficiency compared to western European ones.

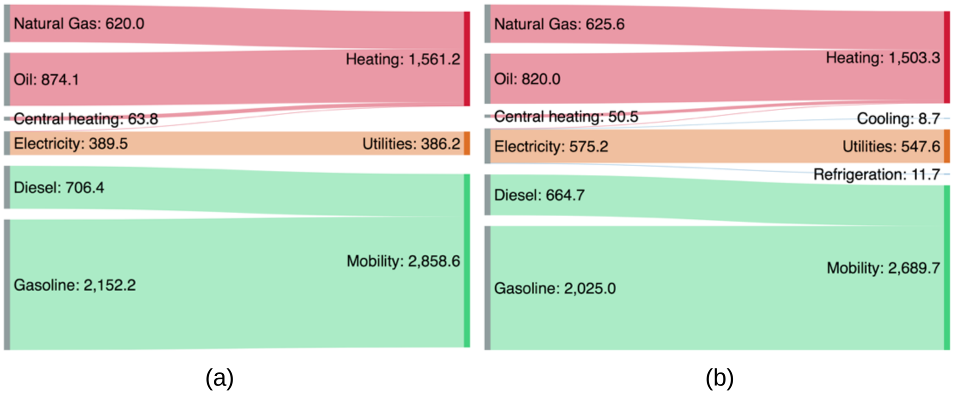


Figure 3: Real energy service profile (a) (Service cantonal de l'energie, Republique et canton de Geneve, 2009), Sector energy service profile (b) for Geneva

3.2 Sector profile applied to different DENs

Two DENs are compared in terms of energy consumption, cost, and CO_2 emissions to demonstrate the ability of the district profile to assess the potential of new technologies. Details on the energy technology efficiency of the CO_2 based network can be found in (Suciu et al., 2017). The network consumes electricity, with a buying price of 0.15 €/kWh (Henchoz, 2016) and CO_2 emissions of 362 kg/MWh (IPCC, 2005). The main assumptions made to compute the energy consumption, operating cost and CO_2 emissions (IPCC, 2005) for the current network can be found in Table 3.

Table 3: Main assumptions for energy consumption, economic and environmental analysis, current network

Service	Resource	Share [%]	Efficiency / COP / Consumption	Price [€/kWh]	CO_2 emissions [kg/MWh]
Heating	Natural gas	41.5	95.7% (Marechal, 2003)	0.05 (SFOS, 2015a)	201.2
	Oil	54.5	95.7% (Marechal, 2003)	0.08 (SFOS, 2015a)	278.7
	Central heating	3.5	-	0.11 (Henchoz, 2016)	-
	Electricity	0.5	-	0.15 (Henchoz, 2016)	362.0
Cooling	Electricity	100	AC: 8.65/REF: 4.02	0.15 (Henchoz, 2016)	362.0
Utilities	Electricity	100	-	0.15 (Henchoz, 2016)	362.0
Mobility	Diesel	26	6.63 L/100km (EIDG (UVEK),	1.56 (SFOS, 2015b)	266.8
	Gasoline	74	8.09 L/100km (EIDG (UVEK),	1.57 (SFOS, 2015b)	249.5

As seen in Figure 4, using a CO_2 based network leads to a reduction in energy consumption of approximately 70 %, operating cost reduction of 68 % and reduction in CO_2 emissions of approximately 59 %. Depending on the electricity supply, CO_2 networks could provide 100 % reduction in emissions when using carbon-free electricity.

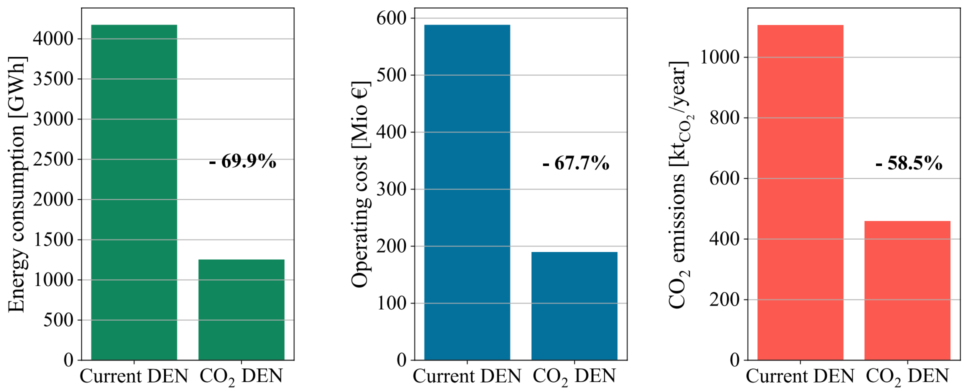


Figure 4: Energy consumption, operating cost, and CO_2 emissions comparison: current vs. CO_2 DEN

4. Conclusions

This paper aims at providing a residential energy and service sector profile for four different climate zones in Europe. The profile is validated using a typical European city, the city of Geneva. The differences between the real demand profile and the sector profile vary between 4 and 30 % for the different services, stemming from differences between the Swiss energy consumption profile and the average western European one. This model provides a fundamental element for quantitative, rational and accurate analysis of current and future energy systems related to urban population centres in Europe. Additionally, it provides opportunities for evaluating interconnections between cities and other economic sectors such as industry and electricity generation, thereby enabling application of optimization and system integration considering broader aspects of energy systems. The functionality and effectiveness of the profile was illustrated comparing an existing water/air-based district energy network with a potential low-temperature CO_2-based district network. The results show that the CO_2 network, compared to the network in place, leads to savings in energy consumption and operating cost of approximately 70 % and reductions in CO_2 emissions of up to 100 %, depending on the mix of electricity used. Future work will refine and test the profile in other settings to ensure its broad applicability throughout the European zones. An additional direction will include utilizing the residential sector profile to assess integration opportunities between services, and will demonstrate integration potentials for typical industries in the surroundings.

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