A Methodology for Accounting the CO_2 Emissions of Electricity Generation in Finland

The contribution of home automation to decarbonisation in the residential sector

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Abstract— **To achieve the decarbonisation of the energy sector in Europe, the CO_2 emission profile of energy consumption must be fully understood. A new methodology for accounting for CO_2 emissions is required for representing the dynamics of emissions. In this article, a dynamic integration of CO_2 emissions due to the electricity production and trade was developed. Electricity consumption and related CO_2 emissions are studied for a typical Finnish household. A model detached house is used to simulate the effect of home automation on CO_2 emissions. Hourly electricity production data are used with an hourly electricity consumption profile generated using fuzzy logic. CO_2 emissions were obtained from recorded data as well as estimated based on monthly, weekly, and daily generated electricity data. The CO_2 emissions due to the use of electric appliances are around 543 kgCO_2/y per house when considering only the generated electricity, and 335 kgCO_2/y when balancing the emissions with exported and imported electricity. The results of the simulation indicate that home automation can reduce CO_2 emissions by 13%. Part of emission reduction was achieved through peak shifting, by moving energy consumption load from daytime to night time. The paper highlights the role of home automation in reducing CO_2 emissions of the residential sector in the context of smart grid development.**

Keywords-CO_2 emissions calculation, home automation, load shifting, modelling.

I. Introduction

In December 2011, the European Commission set clear goals in its Energy Roadmap 2050 COM(2011)885/2, to achieve a decarbonised society. Decarbonisation in this context means reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050. This will provide considerable challenges for electricity production, consumption and management. Smart grids represent one tool for achieving this target. Smart grids aim at increasing the energy efficiency of the network, peak load shaving, load shifting, and reduction of energy consumption. Smart buildings are expected to be an integral part of smart grids, with smart meters as the gateway allowing the entrance of smartness into the building. Smart meters receive and send information to and from the building for use such as in Home Area Networks, and grid handling. Ultimately, smart buildings will lead to the decarbonisation of the residential sector. A description of CO_2 emissions from the electricity generation in Finland has been presented in our earlier paper [1].

The role of the residential sector in reducing carbon emissions is paramount in the development of the future smart grid [2][3]. A massive deployment of smart meters is under way in Europe, which will facilitate digital measurements, and will allow a consequent access to energy consumption data to energy companies and authorities. Member States of the European Union (EU) have the obligation to implement smart meters covering 80 % of consumers by 2020 at the latest [4]. In contrast to the European Energy Efficiency Directive (2012/27/EU) [4], the Finnish Electricity Market law 588/2013 and its application Act 2009/66 on the electricity supply in the survey and measurement sets the deadline for 2014 [5]. Legal obligations to increase energy efficiency also provide a motivation to the deployment of renewable energy sources (RES) as a vector for energy production, both electrical and heating, in a large scale as well as in buildings. Home energy management systems can have a significant role in contributing to energy efficiency and cutting or shifting peak load. This can be achieved through an active collaboration of energy consuming systems and the information network on a local level [6]. Putting together smart grids, smart buildings, RES-based heat and electricity and energy efficiency, involve the development of a smart energy networks (SEN) capable of managing the energy system through constant monitoring.

The impact of energy efficiency on emissions from the residential sector has been a subject of much research (e.g., [7]-[10]). It has been shown that electric load shifting from the residential sector may reduce air pollution in urban areas [11]. To this effect, developing mathematical tools that are able to anticipate and cut emissions through the deployment of smart systems and home automation is of major importance.

This article aims at exploring the significance of home automation and its impact on the CO_2 emissions of a dwelling, and the possible ways home automation can contribute to decarbonisation. In the first Section of the paper, a description of CO_2 emissions from the production and the use of electricity in Finland will be presented. The second Section presents the methodology used for translating hourly carbon emissions to single households will be described. The third

Section shows and details the results from the simulations carried out on two chosen types of dwellings, which will be described and analysed.

II. Related Research

Research on smart houses and their development has been going on for quite some time. Smart homes can be broadly seen as buildings monitored and controlled for multiple purposes [2]. The energy management feature of smart homes is one aspect of the development. Algorithms for generating electricity consumption load profile have been developed on hourly and half-hourly bases [12], but also with a finer grid on a minute-basis [13]. These algorithms can be further used to emphasise the potential of energy in smart houses and their roles in improving energy efficiency, reducing energy consumption and CO_2 emissions from the energy used. More elaborate algorithms have also been developed, where the integration of each appliance within the dwelling has been modelled with a bottom-up approach [14][15]. Finally, the management of appliances within the dwelling may as well be implemented in simulation for optimizing their usage and enhancing demand-side management [16][17].

Previous studies have attempted to determine the impact of energy efficiency measures on CO_2 emissions from the residential sector [7]-[10]. Detailed algorithms for evaluating CO_2 emissions associated with electronic appliance usage have been proposed [18]. One of the main drawbacks of previous methods is that CO_2 emissions are based on a fixed coefficient, thus limiting the understanding of the CO_2 emission mechanism. The variation of electricity production and market dynamics have been ignored, resulting in a biased estimation of carbon dioxide emissions. A more dynamic model has been elaborated by Stoll et al. for estimating CO_2 emissions and their impact on demand response [19]. Although the research of Stoll et al. has based its dynamism on real dataset of energy production on an hourly basis for various countries, the CO_2 emissions related to the production of electricity are based on a fixed emission factor from the IEA annual report on CO_2 emissions [20]. Therefore, the dynamic has increased but variation due to the use of different fuel types were not present and, therefore, the estimation is severely biased. Fuel usage varies according to market prices, resource availability and climatic variations.

Consequently, studies on segmented electricity production, related CO_2 emissions, and the impact of home automation on the emissions are lacking.

III. Electricity consumption and Carbon Emissions in the residential sector

In terms of CO_2 emission reduction in the residential sector, the largest effort should be made in retrofitting buildings. The average renewal time of the residential sector is estimated to be around 70 years [7][12]. The influence of technology on CO_2 emissions needs to be highlighted. Consequently, technology upgrading can greatly influence the total CO_2 emissions of the residential sector. Lighting consumes over 30 % of the total electricity used in households [13][21]. The upgrade of lighting technology is one way for impacting energy consumption [14][15], but also for reducing carbon emissions [16][17][22]. Furthermore, home energy management systems will continue to play a role for increasing energy efficiency, reducing energy consumption [7][23] and allowing load shifting.

In Finland, electricity generation and consumption is being constantly surveyed, recorded and reported by Statistics Finland. In 2012, household appliances consumed 8 072 GWh of electricity [18][21]. At the same time, 2 579 781 households were registered in Finland [19][24], resulting in an average consumption per house of 3 129 kWh/y. There can be considerable deviation from this average value, if the households is in an apartment building or a detached house [20][25]. Furthermore, total electricity production in Finland was around 67.7 TWh in 2012, while the total consumption of electricity was around 82.9 TWh, and a total of 8.4 $MtCO_2$ were emitted. Therefore, it can be estimated that the share of electricity using devices in the total CO_2 emissions from electricity production and consumption are 1001 tCO_2/GWh_{pro} or 817 tCO_2/GWh_{cons}.

IV. Methodology

Data acquisition consisted of analysing the electricity generation of all power plants in Finland, categorized according to their primary fuel, and the categories of power plants on an hourly basis. Secondly, the CO_2 emissions associated with the aforementioned categories were calculated on an hourly basis. Monthly CO_2 emissions are available from July 2011 to April 2014 [26]. It is then possible to evaluate the CO_2 emissions on an hourly basis by correlating the primary energy source for electricity generation and associated monthly CO_2 emissions.

A. Energy Data Collection

Data on electricity production and production forecast are to be reported to the grid aggregator of the Nordic network. Fingrid, the transmission system operator (TSO) of Finland releases information about the network operation and sources of electricity production on their network. In parallel, TSOs of all Nordic countries must report planned and unplanned interruption to the grid through the Urgent Market Message (UMM) system that allows for a better management of the electric grid. Data information on the electricity production systems have been recorded every 5 minutes from Fingrid. As Fingrid does not provide historical data on electricity production, the missing data are completed by two methods. Between 2010 to 2014, the use of historical daily information on the technology used for producing electricity, combined with the UMM system recorded by NordPool for integrating system failure into the data vector is used. The second method uses the monthly and weekly information for disaggregating the energy production data at the country level on an hourly basis.

1) Daily Energy

Information on daily power availability is reported by the Finnish Energy Industry Association. The information is split into five categories: nuclear power, combined heat and power (CHP), wind power, hydropower, and separate thermal power. As the characteristics of these technologies are different, the following assumptions have been made: nuclear power has a somewhat steady production of electricity; thermal power, which includes CHP electricity production and separate thermal power, have a production of electricity proportional to the total electricity production; and, hydro is used for balancing electricity production. The notations *h*, *w*, *d*, and *m* designate the hourly, weekly, daily, and monthly time step respectively, *i* is the energy technology used for producing the electricity, and *tot* stands for the total amount of a unit countrywide.

$$P_{h,tot} = P_{h,th-CHP} + P_{h,th-ind} + P_{h,nu} + P_{h,wi} + P_{h,hy} \quad (1)$$

Where P_h is the power produced on an hourly basis [MW], and *tot* stands for the total electricity produced, *nu* is nuclear power plants, *th* is thermal power plants, *wi* is wind power, and *hy* is hydropower.

Thermal power consists of CHP units from district heating and industrial sites, and the separate thermal units. Each unit runs proportionally to the total electricity produced balanced by the share of electricity brought by a unit as a ratio of power available. Therefore, the hourly production of electricity from thermal power plants $P_{h,th-i}$ can be written as:

$$P_{h,th-i} = \frac{P_{d,i}}{\sum_{i=1}^{5} P_{d,i}} \cdot P_{h,tot} \cdot \rho \quad (2)$$

Where $P_{d,i}$ is the daily power used as reported by the Finnish Energy Industry Association [27] for the a particular technology [MW], $P_{h,tot}$ is the total electricity production data provided by the TSO [MW], and ρ is the ratio of the weekly energy produced between the district heating and the industrial electricity produced [‘]. In case of separate thermal power or gas fired turbine, ρ is equal to 1.

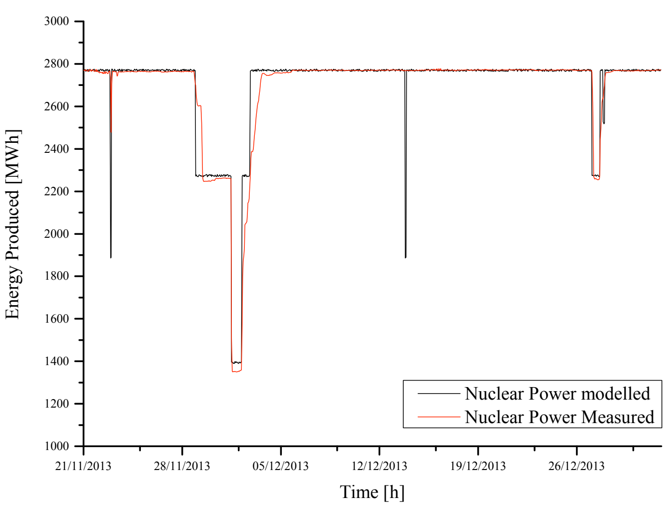


Figure 1. Measured and modelled data of electricity production from nuclear power plants

The flexibility of power production form nuclear power plants is rather low. Consequently, the output power is assumed to be constant with low random fluctuations as expressed in (3).

$$P_{h,nu} = P_{in,nu} \times \left(1 - R \sim U\left(\left[-2.8 \cdot 10^{-4}, 2.8 \cdot 10^{-4}\right]\right)\right) - P_{f,nu} \quad (3)$$

Where $P_{h,nu}$ is the hourly electricity produced by the nuclear park [MWh/h], P_{in-nu} is the global energy produced by the total power of the nuclear park [MWh/h], and P_{f-nu} is the power fault that occurs for each nuclear power station expressed in terms of energy evaluated from the UMM [MWh/h]. The standard variation of steady-state power output on an hourly basis from the nuclear power plants has been calculated from the measured data and is equal to 0.028 %. Fig. 1 illustrates the correlation between the previous equation and the measured data form Fingrid. It can be noticed that the inertia when a power plant is being disconnected has not been integrated, and thus bring a small bias. Notwithstanding, for the purpose of calculating the CO_2 emissions, this approximation is considered acceptable.

Wind power production is based on a generalised model [28] that takes into account the nominal wind power of a station and the characteristics of the wind turbine, and the wind park statues development in Finland as summarised in Table I. Consequently, wind power is calculated for a wind park A, where A is a 1-by-n matrix that varies depending on

TABLE I. WIND ENERGY PRODUCTION SYSTEMS IN FINLAND, BASED ON [29]

Year	WT_{in} [‘]	WP [kW]	WP_{min} [kW]	WP_{max} [kW]	WP_{in} [MW]
2000	63	602	65	1300	37.92
2001	63	614	65	1300	38.7
2002	64	666	200	2000	42.635
2003	74	664.1	200	2000	43.835
2004	92	869	75	2300	79.08
2005	94	898	75	3000	86.215
2006	96	898	75	3000	86.215
2007	107	1028	75	3000	110.015
2008	118	1212	75	3000	143.015
2009	118	1235	75	3000	147.015
2010	130	1475	75	3600	199.115
2011	131	1519	75	3600	198.99
2012	151	1700	75	3600	258
2013	209	1850	75	3600	447
2014	209	1850	75	3600	447

the daily available power for wind turbines WP_d, where n is defined using (4).

$$n = \left\lfloor WT_{in} \cdot \frac{WP}{WP_{in}} \right\rfloor \quad (4)$$

Where *WP* is the daily wind power available for producing energy. Each value of *n* is calculated as a uniformly distributed random number *X*:

$$X \sim U\left(\overline{WP}, b\right) \epsilon \left[WP_{min}, WP_{max}\right] \quad (5)$$

As hydropower is the most flexible type of energy production system, it is assumed that it is capable of producing the remaining energy needed for fulfilling the total electricity production reported by the TSO.

$$P_{h,hy} = P_{h,tot} - \sum P_{h,i} \quad (6)$$

2) Monthly and Weekly energy Data

Monthly and weekly energy data are used in the case where energy production before 2010 needs to be modelled. Before 2010, daily information on energy production systems is not available.

The electricity generated in Finland on an hourly basis is reported by the Finnish Transmission Service Operator – Fingrid since 2004 [30]. The data is split into two groups: electricity generated by power plants and the electrical load on the network taking into consideration the import and export of electricity. Moreover, the Finnish Industry Association (Energiateollisuus) recorded weekly electricity generated from 1990 [31], which is broken down by the technology used: wind, hydropower, nuclear, CHP industry, CHP district heating, conventional and gas turbine power plant. Finally, Fingrid informs in real-time the state of the network, using the same categories as mentioned above. Thus, for building up the hourly electricity generation by categories for the years 2010+, the weekly average electricity production by category is used, in parallel with the hourly electricity generated countrywide. The exported electricity is considered in the electricity generated and in corresponding CO_2 emissions. The imported electricity is considered as a share of CO_2 emissions from electricity consumption in Finland. In order to include the imported electricity into overall emissions from electricity consumption in Finland, it is necessary to know the energy mix for producing the electricity of the country from which Finland is importing. The hourly electricity generated from a particular energy source in the primary country is evaluated using (7).

$$P_{h,i} = \left(\frac{P_{w,i}}{P_{w,tot}} \cdot \frac{P_{in,i} - P_f}{P_{in,i}}\right) \cdot P_{h,tot} \quad (7)$$

Where $P_{h,i}$ is the electric energy generated by a given technology per hour [MWh/h], $P_{w,i}$ is the electric energy generated on a weekly basis by a given technology [MWh/w], $P_{w,tot}$ is the total amount of electricity produced in Finland per week [MWh/w], $P_{h,tot}$ is the total amount of electricity produced per hour [MWh/h], $P_{in,i}$ is the total installed power for the technology *i*, and P_f is the power fault that occur for each power station expressed in terms of energy evaluated from the UMM [MWh/h].

Nuclear power, wind power, and hydropower is evaluated using the same method as the one presented in the daily energy section, except that the weekly energy produced is used instead of the daily power available, as the value of WP in (4).

Once the hourly electricity generated by technology has been defined, it is possible to evaluate the hourly emissions from all the power plants.

B. Emission Data disaggregation

Emissions of CO_2 for electricity production consider only those directly related to the production of electricity: the net and gross emissions. Gross emissions consider only the emissions related to the electricity production within the country, while the net emissions evaluates the balance of emissions due to the import and export of electricity. Therefore, emissions related to fuel transportation or waste management are neglected. The power plants emitting CO_2 and equivalent greenhouse gases are thermal power plants. Thermal power plants can be divided into three distinctive categories in Finland. The first category integrates all power plants primarily used for producing heat for district heating. Electricity is therefore a by-product and varies depending on the thermal power need. The second category includes industries that produce electricity as a by-product from their activity. They may have seasonal variations depending on the industrial activities. The third category includes separate electricity production and groups all the thermal power plants that uses gas turbine, or is used for producing only electricity from thermal power plants. Some of the separate power plants are used for peak load hours, others for aiming at the stability of the grid, or simply to produce electricity. The following sections detail the composition of the conventional power plants in Finland and they are classified following the main fuel type. This description will help at disaggregating data from the energy source used for producing electricity from the above-mentioned three categories.

Data on energy source usage are available on a monthly basis since July 2011. Therefore, two cases are made distinct, the period from July 2011 to 2014 will be processed using the first methodology, and data from 2004 to July 2011 will be processed using the second methodology. The first methodology consists of calculating the monthly energy mix for each technology. This is to integrate the variation of raw material usage in the energy industry. The second methodology considers the measured energy data, the related calculated emissions, and the variation of outside temperature. From these two main variables, it is possible to correlate the variation of energy production and outside temperature to the emissions using a multi-linear regression model.

1) Emissions 2011 - 2014

The first two main categories of technologies that are used to produce electricity as a by-product are the electricity from the district heating, and industrial CHP units. The third category produce electricity during peak load hours or on a permanent basis: separate power plants. Each segment uses different sources of energy that are summarised in the Table II. Also, each segment can be represented in terms of number of units or power capacity. This is to differentiate and understand the emissions levels from the electricity production.

By using the distribution given in Table II and the monthly reported amount of raw energy used, the monthly emissions for each of conventional thermal power plant, separate thermal power plant excluding gas engines, gas power plant, CHP from district heating and CHP from industrial electricity production are calculated with:

$$Em_{m,x} = \left[1 - \frac{\begin{bmatrix} P_x \\ \vdots \\ \vdots \end{bmatrix}}{\begin{bmatrix} P_x \\ \vdots \\ \vdots \end{bmatrix} + \begin{bmatrix} P_y \\ \vdots \\ \vdots \end{bmatrix}} \right] \times \begin{bmatrix} P_{Em_{x+y}} \\ \vdots \\ \vdots \end{bmatrix} \tag{8}$$

Where $E_{m_{m,x}}$ is a n-by-1 matrix of the monthly emissions of the electricity production from district heating or from industry [$ktCO_2$/m], P is the installed power for each raw material where x and y stand for the district heating and the industrial sector [MW] respectively. Fig. 3 is the resulting monthly CO_2 emissions from iterating within above equation.

As part of its legal obligation, Finland reports CO_2 emissions from power plants, and energy intensive industry [33]. The Finnish Industry Association estimates monthly specific emissions related to electricity production, based on the type of fuel used by the energy industry [31]. By knowing the hourly electricity production from each sector, we can estimate the CO_2 emissions for each hour countrywide using (9) to (12).

$$E_{w,i} = a \cdot \left(\frac{P_{w,i}}{P_{m,i}} \cdot \frac{\delta_m}{7} \right) \tag{9}$$

Where a is evaluated using (10) if the full week is within the same month n, or (11) if the full week is between two months, n and $n+1$.

$$a = \frac{7E_{m,n}}{\delta_m} \tag{10}$$

$$a = \left(\delta_w \cdot \frac{E_{m,n}}{\delta_m} \right) + \left(\frac{E_{m,n+1}}{\delta'_m} \cdot (7 - \delta_w) \right) \tag{11}$$

Finally, the hourly emissions are given by,

$$E_{h,i-gen} = P_{h,i} \cdot \frac{E_{w,i}}{P_{w,i}} \tag{12}$$

Where $E_{h,i-i}$ is the emissions from the electricity generated hourly by the given technology [$ktCO_2$/h], and $E_{w,i}$ is the weekly emissions by technology segment [$ktCO_2$/w], δ_w is the day number within a week where Monday is 1 and Sunday is 7, δ_m and δ'_m are the number of days in the studied months, $E_{m,n}$ is the monthly CO_2 emissions for the month n. Fig. 2 illustrates the energy generated and its corresponding CO_2 emissions on an hourly basis for the year 2012 in Finland. It can be noticed that, although there is a strong correlation of CO_2 emissions to electricity generation, emissions may decrease even though the energy generation increases, due to the fact the energy mix is changing Fig. 2.

The emissions due to the electricity imported are added to the primary emissions from the electricity generated within the country. The CO_2 emissions from the electricity generated dedicated to the export is then subtracted from the hourly emissions $E_{h,c1}$. In order to account the net CO_2 emissions from the electricity load in the country, the emissions from each country with which Finland is trading electricity are evaluated, meaning Norway, Sweden, Russia and Estonia. As the hourly energy mix is not known for each country, a general coefficient of CO_2 emissions has been considered for 14 $kgCO_2/MWh_{pro}$ for Norway, 21 $kgCO_2/MWh_{pro}$ for Sweden, 417 $kgCO_2/MWh_{pro}$ for Russia and 1 059 $kgCO_2/MWh_{pro}$ for Estonia [20].

The share of CO_2 emissions coming from each trading country is evaluated using (13).

$$E_{h,c_n} = \sum_{i=2}^{n} \frac{P_{h,net-c_i}}{P_{h,load}} \cdot E_{c_i} \tag{13}$$

Where $E_{h,ci}$ is the hourly emissions for each participating country to the electricity trade [$kgCO_2$/h], $P_{h,load}$ is the hourly electric load on the Finnish network [MWh/h], $P_{h,net-ci}$ is

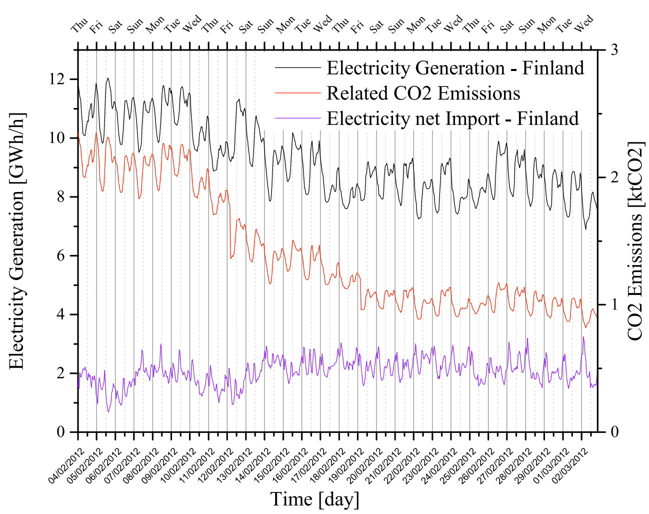


Figure 2. Hourly electricity generation, net import and their related CO2 emissions from 4.02-02.03.2012

TABLE II. INDUSTRIAL PARK PRODUCING ELECTRICITY FROM CHP UNITS IN FINLAND FROM INDUSTRIAL AND DISTRICT HEATING POWER PLANTS, BASED ON [32]

Industry CHP				District Heating CHP				Separate Power Plants			
Ass. Cat	Declared Main Fuel	Nbr of PP	Total Power	Ass. Cat	Declared Main Fuel	Nbr of PP	Total Power	Ass. Cat	Declared Main Fuel	Nbr of PP	Total Power
Peat	Peat	16	643.2	Natural Gas	Natural gas	17	1239.4	Oil	Medium heavy distillates	20	1098.9
Biomass	Industrial wood residues	19	462.6	Peat	Peat	19	1102.24	Peat	Peat	1	154
Natural Gas	Natural gas	10	427.3	Biomass	Forest fuelwood	7	57.7	Oil	Heavy distillates	6	342
Others	Other by-products and wastes used as fuel	1	7	Coal	Hard coal and anthracite	7	1647.1	Oil	Light distillates	3	16.9
Biomass	Forest fuelwood	2	63	Oil	Medium heavy distillates	2	2.9	Coal	Hard coal and anthracite	5	1751
Biomass	Black liquor and concentrated liquors	16	1152.3	Biomass	Industrial wood residues	3	142.5	Coal	Blast furnace gas	2	95.8
Others	Other non-specified energy sources	1	3.9	Others	Other by-products and wastes used as fuel	1	9	Natural gas	Natural gas	2	2.7
Coal	Hard coal and anthracite	1	4.2	Oil	Heavy distillates	2	177				
Biomass	By-products from wood processing industry	1	64	Others	Biogas	1	14.42				
Oil	Heavy distillates	3	13.8								
Others	Exothermic heat from industry	2	39.3								
Oil	Light distillates	1	1								
Others	Biogas	3	4.9								

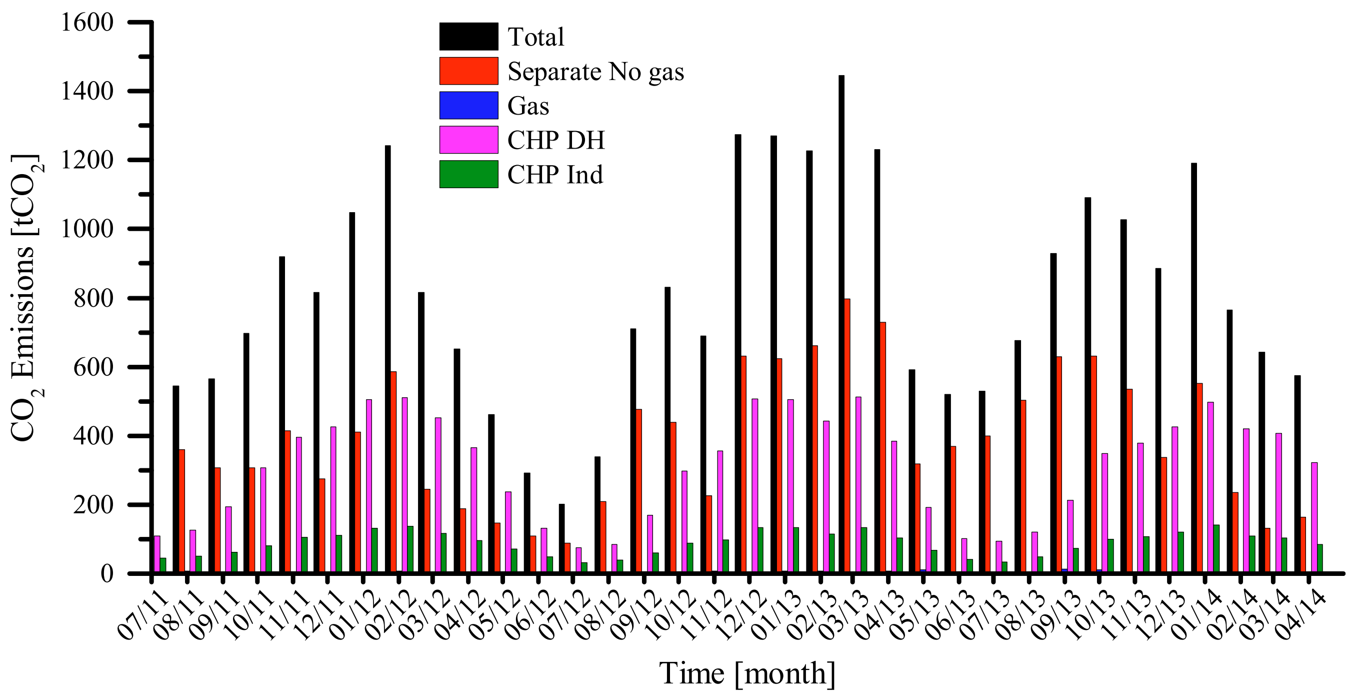


Figure 3. CO_2 emissions in Finland from conventional thermal power plants excluding gas engines, gas power plants, CHP from district heating and CHP from industrial electricity production, based on [32].

the net balance of electricity traded between Finland and the country n [MWh/h] in case of export or the difference between electricity generated and the electricity exported in the case of Finland, and E_{c_i} is the coefficient of CO_2 emissions for the corresponding country [$kgCO_2$/MWh]. In case $P_{h,net-c_i}$ is negative, the coefficient of CO_2 emissions is equal to $E_{h,i-gen}$ as the emissions from the Finnish production is exported as well, otherwise, E_{c_i} takes the value defined by the IEA.

Finally, the hourly emissions E_h are determined as the sum of the hourly emissions for each participating country to the electricity trade E_{h,c_i} as shown in (14).

$$E_h = \sum_{i=1}^{n} E_{h,c_i} \quad (14)$$

The emission data in Fig. 2 are then translated to a single house where the hourly electricity consumption profile has been previously generated using (8).

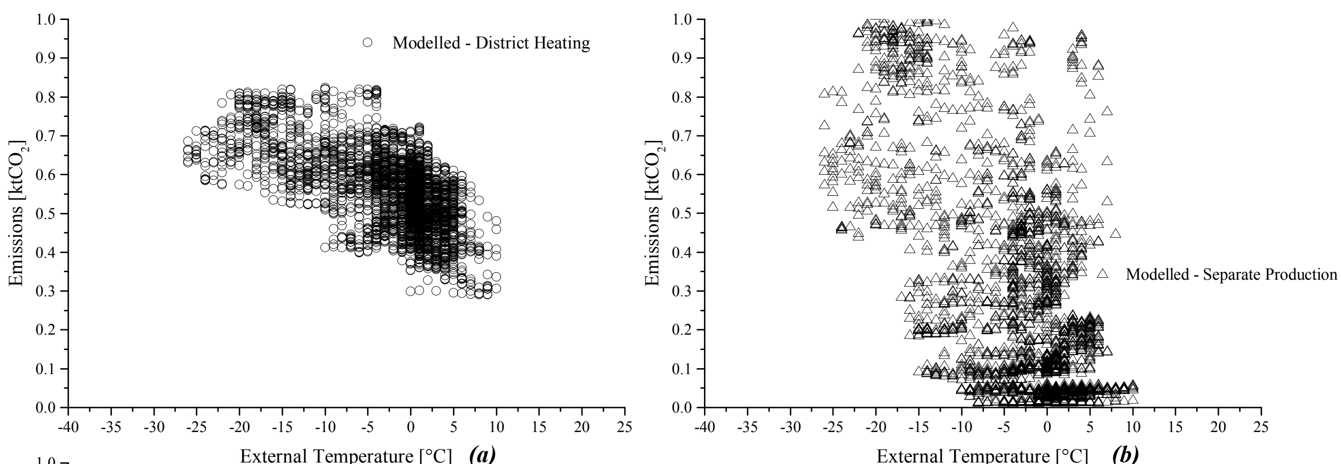
$$E_{h,house} = \sum_{j} \frac{P_{j,house}}{P_{h,tot}} \cdot E_h \cdot 10^3 \quad (15)$$

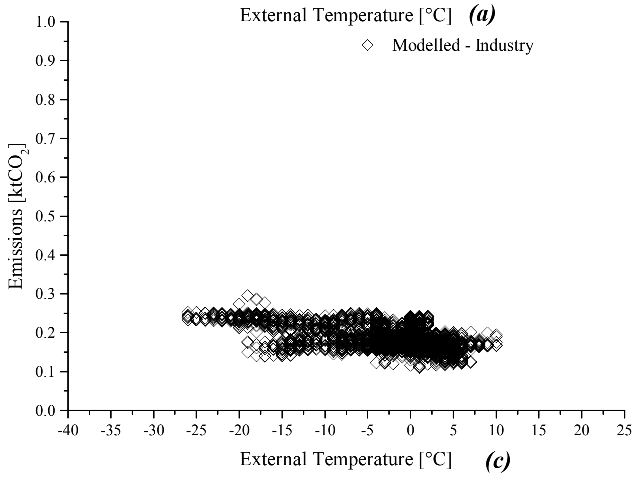
Where $E_{h,house}$ is the hourly emissions from the house [$kgCO_2$/h], and $P_{j,house}$ is the total hourly electricity consumed by the house excluding the electric heating [kWh/h]. Two cases are differentiated: CO_2 levels towards the production of electricity within the primary country, and the net CO_2 emissions level considering the import and export. In the first case, P takes the value of the total electricity produced in the primary country $P_{h,tot}$. In the second case, P takes the value of the total load on the electric grid of the primary country $P_{h,load}$.

The results give an estimate of CO_2 emissions related to the electricity consumption in a private household on an hourly basis. This model is then applied to an average Finnish dwelling previously modelled, in order to estimate the daily CO_2 emissions.

a) Gross emissions from DH

In order to extend the research on multiple years, measured data of electricity production have been considered alongside with the monthly emission data and the resulting hourly emission data generated using the method previously explained. From the hourly CO_2 emissions calculated, the correlation between energy production and external temperature has been evaluated. It appears that the variation of CO_2 emissions and air temperature has a good correlation with a Pearson coefficient R of -0.627 as Fig. 4 and Fig. 5 illustrates. Therefore, the multi-linear regression with a R-square of 0.993 can be written as follows,





Model		Unstandardized B	Unstandardized Std. Error	R-Square
Emissions Separate Thermal power	(Constant)	5.078E-03	3.47E-04	0,997059
	T	6.481E-04	4.82E-05	
	En_{Sep}	6.739E-04	9.56E-06	
	En_{Gas}	4.902E-01	3.59E-02	
Emissions District Heating	(Constant)	2.098E-03	9.64E-04	0,992977
	En_{DH}	2.715E-04	4.86E-07	
	T	-2.367E-04	2.65E-05	
Emissions Industry	(Constant)	2.088E-04	2.99E-04	0,993087
	T	-6.695E-05	7.10E-06	
	En_{Ind}	1.151E-04	1.90E-07	

Figure 4. Calculated emissions from the measured power produced by separate thermal power plant and the multilinear regression used to model the corresponding emissions as factors of the external temperature and the measured power produced.

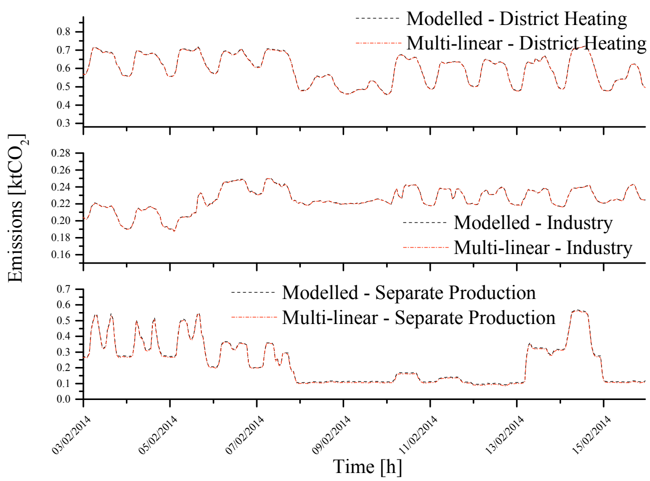


Figure 5. Correlation between the modelled emissions from the energy production level and the multi-linear regression.

$$E_{m_{DH}} = -2.37 \cdot 10^{-4} T + 2.72 \cdot 10^{-4} E_{n_{DH}} + 2.098 \cdot 10^{-3} \quad (16)$$

Where $E_{m_{DH}}$ is the CO_2 emissions from the DH industry [$kgCO_2$], and T is the external temperature [°C].

b) Gross emissions from Industry

Similarly, the emissions from the electricity produced from industrial processes correlate with the variation of external temperature, with a Pearson coefficient of -0.527. The resulting equation considers the variation of external temperature and electricity production level. (17) gives the emission from this industrial segment with a R-square of 0.993.

$$E_{m_{Ind}} = -6.7 \cdot 10^{-5} T + 1.15 \cdot 10^{-4} En_{Ind} + 2.09 \cdot 10^{-4} \quad (17)$$

Where $E_{m_{ind}}$ is the CO_2 emissions from the industrial processes [$kgCO_2$], and T is the external temperature [°C].

c) Gross emissions from separate thermal power

The third segment integrates two types of electricity production technologies: the gas turbine that has a minor role in producing electricity, and condensing power plants using oil, coal, and peat as main fuels that represent the main source of electricity.

$$E_{m_{Sep}} = 6.48 \cdot 10^{-4} T + 6.74 \cdot 10^{-4} En_{Sep} + 0.490195 En_G + 5.078 \cdot 10^{-3} \quad (18)$$

Where $E_{m_{sep}}$ is the CO_2 emissions from the separate thermal power plants [$kgCO_2$], and T is the external temperature [°C].

2) Gross and Net emissions from Finnish electricity

The emissions were detailed by technology at the country level; therefore, it is possible to speak about gross emissions of CO_2 from the electricity production. As it has been mentioned earlier, imported electricity has also been considered in the evaluation of CO_2 emissions from households. Emissions in a country vary daily, weekly and seasonally. Overall, net emissions are always lower than gross emissions due to the fact that Finland imports less CO_2-intensive electricity than it exports. Fig. 6 illustrates the variation of gross and net CO_2 emissions and the deviation between both emissions.

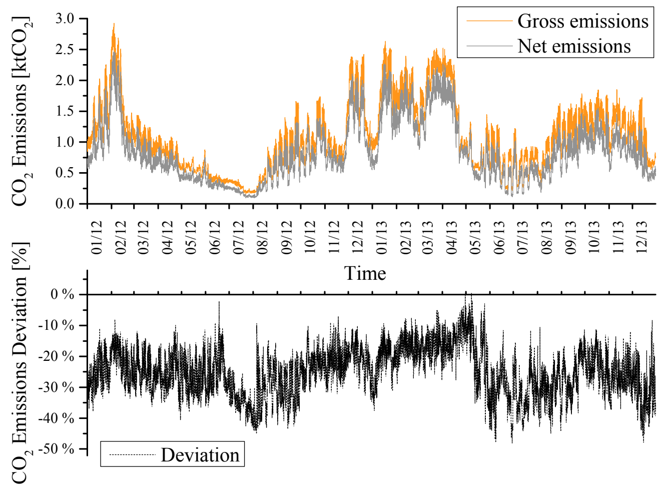


Figure 6. CO_2 emission variations between gross and net emissions including exported and imported electricity.

The deviation between net and gross emissions varies from +0.56 % to -48.13 % with a median value of -24.71 %. This means that the balance of imported and exported electricity is environmentally beneficial for Finland. The import and export mix also varies hour-by-hour. Nevertheless, a trend can be observed on a yearly basis; Finland is importing mainly (97 %) from Sweden and Russia while exports are mainly focused on Estonia and Sweden. Norway, which has the lowest CO_2 emissions factor, plays a minor role in the Finnish electricity mix due to the lack of high voltage transmission line north-south, and the sparse population in Northern Finland.

Depending on how the emissions are accounted, very different results can be obtained from the study of households. Therefore, two cases will be studied; one with gross and another with net emissions.

V. Smart House Emissions

The emissions related to electricity consumption from the residential sector can be determined based on the emissions from the production and trade of electricity, and were estimated hour-by-hour. For this purpose, an electricity consumption model was built for simulating various types of detached houses with multiple configurations such as the number of household members, number and types of appliances with their related energy efficiency factor and so on. A detached house, home to 4-persons has been simulated, with various types of technologies installed in it [34]. Inhabitants are rated depending on their willingness to respond positively to an action. Green users are considered to have a positive response up to 70% of the time, orange users 50% and brown users 30%. This research is focusing on green users while previous results of users' influence on home automation consider all three [34].

A. Electrical and electronic devices in the house

The house electricity demand profile is drawn on an

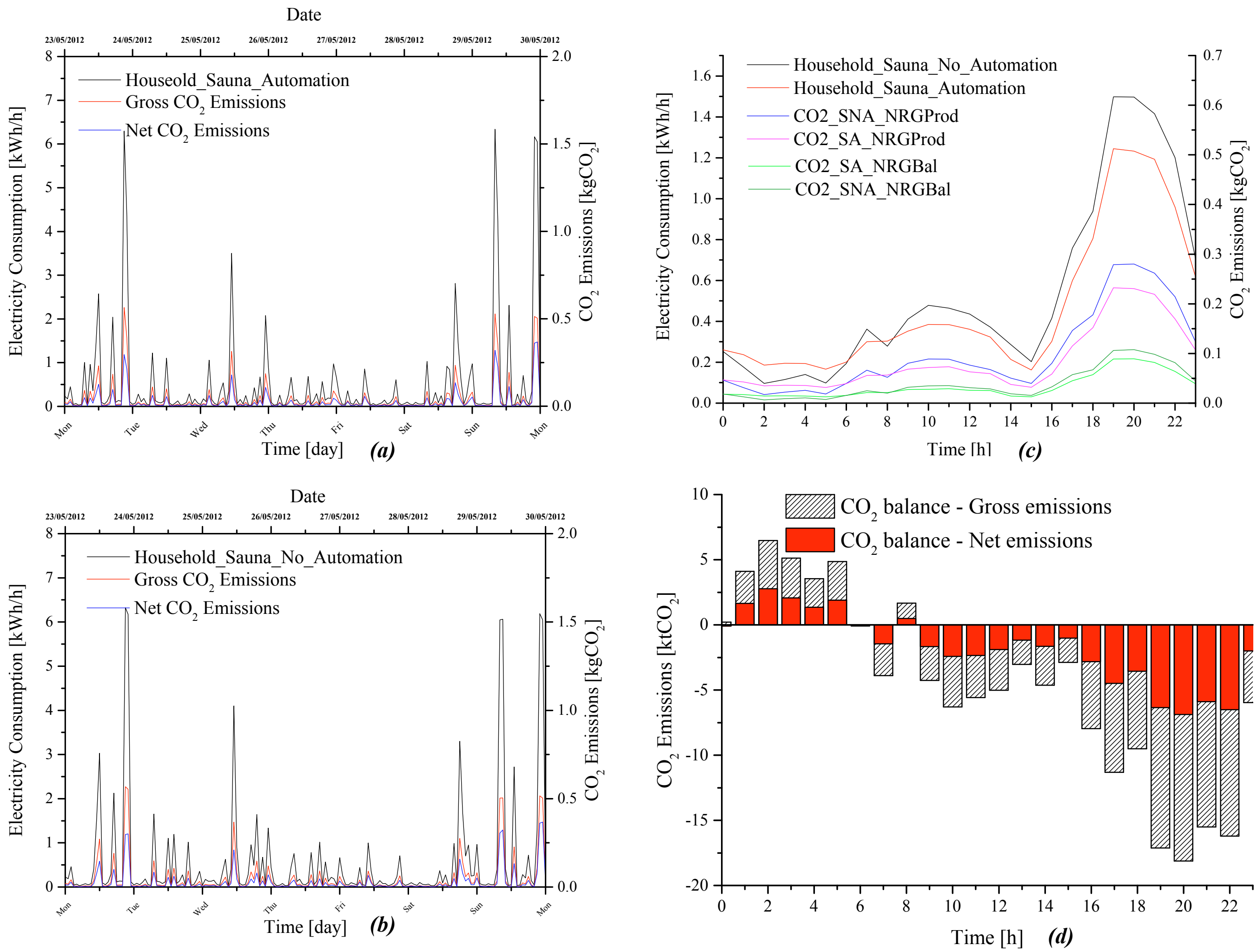


Figure 7. Electricity consumption with its related CO_2 emissions for (a) a dwelling with automation and (b) a dwelling without automation, (c) Daily electricity consumption profiles and (d) the related CO_2 emissions balance between both houses in terms of gross and net emissions

hourly basis using different components for evaluating the electricity consumption from appliances, without primary and secondary electric heating systems. Two dwellings were studied: one with home automation and one without home automation, and the difference in their CO_2 balance was evaluated.

The modelled house contains twenty-one appliances, all of them labelled A or B [14]. The house, being in Finland, has an electric sauna stove of 6 kW. The overall electricity consumption of appliances in this modelled house is 4 501 kWh/y, which correlates with the findings of the European ODYSSEE MURE project and that of the Sähkötohtori Analysis [25]. The measured data were obtained from detached houses in Oulu, Finland, which were equipped with a 10 kW sauna stove.

B. Impact of the simulated home automation on the emissions

The model showed that the CO_2 emissions are highly dependent on electricity consumption levels. Depending on the energy mix for electricity production at a given time, CO_2 emission levels may even be lower at peak hours and thus not proportional to consumption levels. Two models have been developed. In the first case, the CO_2 emissions from the house are accounted relatively to the electricity production only. In the second case, the CO_2 emissions are balanced with the electricity exported and imported. Fig. 7 represents the energy consumption for the two cases: with home automation (Fig. 7 (a)), and without home automation (Fig. 7 (b)). The electricity consumption shown was extracted for a randomly selected week in May 2012, starting on Monday, the 23rd of May.

1) Case 1: Emissions related to electricity production

The houses in the two cases are similar in their characteristics such as number and types of appliances, number of inhabitants, dimensions, users' habits. The CO_2 emission levels vary from 0.06 to 0.20 $kgCO_2/kWh$. The levels depend on the energy mix of Finland's electricity generation. Consequently, the hourly-based emissions peak at 1.93 $kgCO_2/h$ for the house without home automation and

1.81 kgCO_2/h for the one with home automation. In the first case, the related energy demand was 10.03 kWh/h and in the second 9.42 kWh/h. The maximum electricity consumptions are 12.33 kWh/h, and 10.16 kWh/h. The emission peaks are somewhat related to the level of electricity consumption but also to the energy mix for electricity generation. The use of home automation may reduce the instantaneous peak of CO_2 emissions. The daily electricity profile of the houses and CO_2 balance between the two cases are represented in Fig. 7 (c). The difference in the profile of the two modelled houses result in a 592 kWh/y reduction of total electricity consumption. In terms of CO_2 emissions, the house that is not equipped with a home automation emits 543 kgCO_2/y, while the house with home automation emits 473 kgCO_2/y. The amount of CO_2 saved represents 12.78 % of original emissions.

Home automation shifted some of the electricity consumption from the evening peak to the night. It resulted in a decrease of CO_2 emissions in the evening down to 37 % from the original levels, and an increase of 51 % of CO_2 emissions overnight (Fig. 7 (d)). Considering, however, that the emissions overnight are about 0.1 kgCO_2/h on average, this can be regarded as a relatively small, cumulative amount.

The emissions increased overnight by 3 to 5 kgCO_2, and reduced by 17 kgCO_2 on average over the whole year during the evening. While the home automation was not optimised for reducing CO_2 emissions but rather for cutting peak load consumption, it resulted in the decrease of CO_2 emissions as well. Notwithstanding, it is to be seen that the emissions related to electricity generation countrywide vary throughout the day. Fig. 8 represents the summed CO_2 emissions per hour on the left axis and the hourly average profile of CO_2 emissions on the right axis for the year 2012 from the electricity produced in Finland. The CO_2 emissions during the peak hours are 0.95 ktCO_2/h on average, and add up to a total of 346 ktCO_2 between 6 and 7 pm. The lowest point on the daily plot of CO_2 emissions occurs around 2 and 3 am, with an average emission of 0.8 ktCO_2/h and a corresponding emission for this hour throughout the year is 294 ktCO_2.

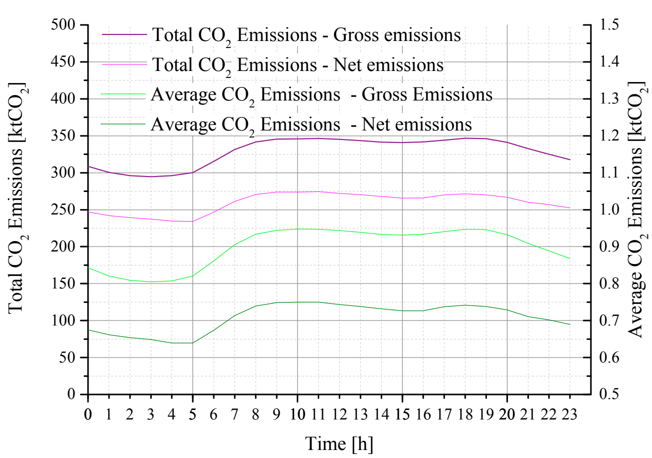


Figure 8. Total and average daily profile of the carbon dioxide emission in 2012, Finland

2) Case 2: Emissions related to net load

The CO_2 emissions in this second case were found much lower than in Case 1. Firstly, the total CO_2 emissions factor $E_{h,i\text{-}gen}$ has slightly decreased. This can be interpreted as an improvement in the net CO_2 emissions from electricity at the country level. This is explained by the fact that Finland is importing its electricity mostly from Sweden, and Sweden has an average emission factor around 7 times smaller than that of Finland. On the other hand, Finland is exporting electricity with a relatively high emission factor. As well, the emissions from Finnish electricity have been calculated for every hour and, therefore, there are peaks of CO_2 emissions. Conversely, the electricity from the neighbour countries are applied a constant factor, thus this bring a bias result. Nonetheless, the exchange of electricity is beneficial for Finland in terms of CO_2 emissions. In this case, the house had a 335 kgCO_2/y emission without home automation, and 293 kgCO_2/y with home automation. This means a difference of about 38 % between Case 1 and Case 2. This also indicates that CO_2 emissions can be interpreted very differently, depending on whether the emissions associated with exported electricity are subtracted from the total CO_2 emissions of the country or included in it. Similarly to Case 1, the peaks of CO_2 emissions are reduced, and are about 24 % lower than in Case 1. In Case 2, the CO_2 peak for the house without home automation is 1.46 kgCO_2/h, and 1.37 with home automation.

At the system level, the total and average hourly CO_2 emissions have decreased as well. In case the exported and imported electricity are accounted in net emissions, the low peak occurs between 4-5 am with an average emissions of 0.64 ktCO_2 and the high peak period occurs between 10-11 am with an average emissions of 0.75 ktCO_2 and cumulates to 275 ktCO_2 in same hour. Regarding the shift of CO_2 emissions due to the home automation device and the feedback strategies used for informing the private consumers, it has decreased by 6 kgCO_2 in the evening and has risen by 2.7 kgCO_2 in the night time. The quantities of CO_2 shifted, as presented in Fig. 6 (d), and are different from Case 1 and Case 2, as the CO_2 emission profiles for both cases are different (see Fig. 8).

VI. Discussion

The methodology developed in this article allows the integration of physical electricity production variation and resource usage. The emission factor is re-calculated every month for each technology, thus better reflecting the seasonal variations compared to a fixed emission factor. The gross emission factor can be calculated from 2004, but net emissions from electricity production are only available since 2012. This method has the advantage to use publicly available information with an hourly window grid. Nevertheless, the method presented is restricted to data availability from country-to-country. It is thus challenging to evaluate the replicability level of the method.

When studying the impact of home automation, both cases

TABLE III. CO_2 EMISSIONS SUMMARY FOR THE TWO STUDIED CASES

	CO_2 emissions relative to		
	Electricity produced (Gross Emissions)	Net electricity consumed (Net Emissions)	Unit
Min. $E_{h,i\text{-}gen}$	0.06	0.04	$kgCO_2/kWh$
Max. $E_{h,i\text{-}gen}$	0.20	0.19	
Max $E_{h,house}$ SA	1.81	1.37	$kgCO_2/h$
Max $E_{h,house}$ SNA	1.93	1.46	
Max $P_{i,house}$ SA	12.33	12.33	kWh/h
Max $P_{i,house}$ SNA	10.16	10.16	
Total $E_{h,house}$ SA	543	335	$kgCO_2/a$
Total $E_{h,house}$ SNA	473	293	
Max Average $E_{h,i\text{-}gen}$	0.95	0.75	$ktCO_2$
Min Average $E_{h,i\text{-}gen}$	0.8	0.64	
Max Sum $E_{h,i\text{-}gen}$	346	275	
Min Sum $E_{h,i\text{-}gen}$	294	234	

showed that load shifting can contribute to 12.7 % decrease in CO_2 emissions. However, there is a difference depending on whether the balance of import and export is considered. As well, consumer awareness and their willingness to comply is also a factor in the potential for reducing CO_2 emissions. Table III summarises the results from the CO_2 emissions and the electricity consumption from both houses. It is necessary to point out the importance of methods evaluating emissions on the results. It is paramount that the countries involved use the same methodology for their CO_2 evaluation. In this study, Finland is mostly importing electricity from Sweden and Russia and exporting to Norway and Estonia. For Sweden, this means importing "polluted" electricity and exporting cleaner electricity to Finland. Consequently, for Finland, the shifting of CO_2 emissions is greater when compared to the emissions of gross electricity production. It also needs to be pointed out that the house simulator can be used for either optimising electricity consumption or CO_2 emissions or both. In our case, the multi-objective algorithm was developed for optimising electricity consumption, but it also resulted in emission reductions. To optimise for CO_2 reduction, would be an additional challenge. In addition, an added level of complexity is whether export/import net emissions are considered or not.

VII. CONCLUSION AND FUTURE WORK

The article detailed the CO_2 emissions of electricity generation in Finland. Firstly, CO_2 emissions from electricity production and trade have been evaluated using a methodology developed within this research. Then, monthly, weekly, and daily data of electricity generation were used to calculate corresponding CO_2 emissions into hourly data. This was used to evaluate the CO_2 emission profile of households. The model was based on hourly electricity load profiles previously built. The methodology developed reflects the seasonal variations as well as the monthly fluctuation in resources usage from the power plants. It, in turn, increases the reliability for evaluating the CO_2 emissions due to the electricity consumption.

Secondly, the CO_2 emissions associated with imported and exported electricity generation were accounted as well. Both cases show the same peak distribution in their daily profile. Notwithstanding, emissions will depend on the fuel used at a particular hour. Therefore, the relationship between electricity production, import and export is not straightforward. The cumulated CO_2 emissions overnight from the electricity produced in Finland stand at around 290 $ktCO_2/h$, while the peak reaches 345 $ktCO_2/h$. Considering the import and export of electricity, and their related CO_2 emissions, the peak dropped to 230 $ktCO_2/h$ overnight, and the high peak is at 275 $ktCO_2/h$.

Although the home automation was not optimised for emission reduction, the CO_2 emissions are somewhat proportional to electricity consumption levels. The study showed that home automation might reduce the carbon dioxide emission by 12.7 % while influencing the private consumers' everyday routine. The CO_2 emissions have been reduced most substantially during the evening peak, by 18 $kgCO_2/h.y^{-1}$ in the first case and by 6 $kgCO_2/h.y^{-1}$ in the second case, while the emissions at night time have increased from 3 to 5 $kgCO_2/h.y^{-1}$ on average. Although the CO_2 emissions related to electricity consumption from appliances are strongly correlated, the energy mix for producing this electricity needs to be considered and thus optimised for reducing the carbon footprint of households.

Consequently, smart buildings within a smart grid may not only participate in load shifting and increase energy efficiency or decrease electricity consumption, but they can also significantly contribute to the reduction of CO_2 emissions. It will, in turn, impact the total CO_2 emissions of the country and will assist in achieving the decarbonisation goal of the EU.

The limitation of this research is that there was no information available on the variation of the energy mix from exporting countries and, therefore, import electricity had to be considered with a yearly constant CO_2 emission factor. Secondly, in the case of Finland, a more detailed estimation would require knowing the energy mix hour-by-hour, rather than estimating it from the monthly average. However, currently, this information is not available in Finland.

Further research will investigate the impact of private consumers in correlation with home automation for reducing the CO_2 emissions of households. In addition, a full assessment considering district-heating systems ought to be done, in order to achieve full integration of smart buildings in a SEN. Finally, the multi-objective algorithms will have to be further developed and improved on.

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