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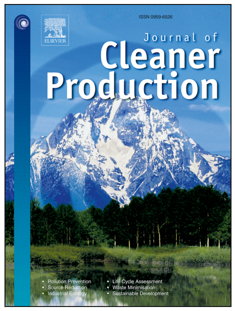


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PII: S0959-6526(18)33116-0

DOI: 10.1016/j.jclepro.2018.10.102

Reference: JCLP 14504

To appear in: *Journal of Cleaner Production*

Received Date: 25 June 2018

Revised Date: 2 October 2018

Accepted Date: 9 October 2018

Please cite this article as: Pulselli RM, Marchi M, Neri E, Marchettini N, Bastianoni S, Carbon accounting framework for decarbonisation of European city neighbourhoods, *Journal of Cleaner Production* (2018), doi: https://doi.org/10.1016/j.jclepro.2018.10.102.

# Carbon accounting framework for decarbonisation of European city neighbourhoods.

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**Abstract**

Strategies for climate change mitigation in European cities have become more urgent and require actions to proactively involve administrators, citizens and other stakeholders and let them cooperate to accomplish widely approved plans for decarbonisation. Nevertheless, considering the short term of political mandates and the instability of social-economic-legal variables in our changing world, urban planning practices will require more effective and rapid decision support systems to easily access and process information. The paper presents an optimised carbon accounting methodology to assess greenhouse gas (GHG) emissions in specific urban environments and inform urban policies and design. In particular, this procedure, substantially inspired by the IPCC standard methodology for GHG emissions inventory of Nations, constitutes the framework of a "mediate model" with a dual role: to both assess the Carbon Footprint of urban neighbourhoods and to estimate the effects, in terms of Carbon Footprint mitigation, of action plans addressed to carbon neutrality. For demonstration, the carbon accounting framework has been performed based on average European values. The procedure started by profiling the typical household as functional unit, whose carbon footprint has been estimated 6.93 t $CO_2$-eq/yr, referring to energy use for housing and mobility, domestic waste treatment and water use. The impact of the average European neighbourhood has been obtained by scaling up to 10,000 households (23,000 inhabitants) as benchmark for future applications. An additional outcome concerns the innovative spatial visualisation of results in terms of equivalent forestland (e.g. the emission of one average European household corresponds to the quantity of $CO_2$ yearly absorbed by 0.51 hectares of forest), that allows for understanding intensity and size of impacts in order to consistently support awareness raising initiatives targeting citizens and stakeholders and communication-dissemination activities.

**Keywords:** *Decision Support System; Carbon Footprint Offset; Energy Saving; Renewable Energy; Sustainable Mobility; Waste Management.*

## 1. Introduction

The European Union (EU) has ambitious plans to drive the transition towards climate neutral societies (EU, 2007; Skjærseth, 2016). The low-carbon economy roadmap states that EU should cut 80% of greenhouse gas (hereafter GHG) emissions (below 1990 levels) by 2050 (EU, 2011). Considering that the current global share of renewable energy is around 11% and the potential contribution of renewable sources is estimated around 60% (UN Human Settlements Programme, 2016), the world energy transition is still at its early stage.

In the last few years, the global population living in cities has been progressively growing: 54% of the world population was living in urban areas in 2014 and an increase up to 66% is expected by 2050 (UN, 2015). Cities represent more than 70% of global energy demand (UN Human Settlements Programme, 2016) and account for nearly three-quarters of anthropogenic GHG emissions (Kennedy and Sgouridis, 2011; Premalatha et al., 2013). Towns with high population density should be targeted through specific policies. The 90% decrease of GHG emissions from private and public buildings (EU, 2018) and the energy transition from fossil fuels towards fully electrified systems (EU, 2013) are among the objectives pursued. The chances to reach the goal will mostly depend on our ability to reimagine cities.

The Carbon Neutral Cities Alliance (CNCA) is among the world partnerships established to plan actions and achieve long-term carbon reduction goals (Lehmann, 2013; CNCA, 2018). In this regard, the Global Protocol for Community-Scale GHG Emissions Inventories (GPC), released by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), provides a worldwide standard approach for the GHG emissions accounting at the urban scale (GHG Protocol, 2014). In particular, it shows a robust framework for data collection in compliance with standard methodologies, e.g. 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 2006). According to the GPC, GHG emission sources can be located inside or outside the urban boundary and classified into three categories, namely scope 1 (emissions occurring within the city), scope 2 (electricity, steam, heat, and cold supplied by grids crossing city boundaries) and scope 3 (emissions occurring outside). Separate accounting of the three scopes avoids double counting. The GPC standard has been designed to aggregate various city and urban neighbourhood inventories at subnational and national levels in order to improve quality of data, measure the contribution of urban mitigation actions relative to regional or national GHG emissions reduction targets, identify innovative strategies for GHG mitigation (GHG Protocol, 2014).

Based on a survey of literature, a few studies and experiences have been published concerning assessments and interventions at the neighborhood scale. Koch et al. (2012) highlighted that solutions for GHG emissions reduction have been mostly developed at wider scales, although the intermediate scale of city neighbourhoods has a higher potential to accomplish concrete actions such as by designing high-performance buildings and settlements. Stephan et al. (2013) monitored energy consumption and GHG emissions of a representative low-density neighbourhood in Melbourne (AUS) and compared different scenarios depending on transport technologies, house size and typology. They demonstrate that higher population density (e.g. apartment buildings instead of detached houses) would decrease the energy demand of the neighbourhood by 20%. Marique and Reiter (2014) presented a simplified calculation method to investigate feasibility of zero emissions energy supply in existing neighbourhoods (both urban and rural) focussing on transportation and building energy sectors. An accurate equations framework for calculating GHG emissions reduction, energy saving and production of energy from renewable sources has been implemented in the methodological report for the Covenant of Mayors in Emilia Romagna (Regione

Emilia Romagna, 2013). Moreover, Marchi et al. (2018) presented an equations framework for calculating energy saving and waste reduction/management of the historic centre of Siena (Italy) based on statistical data scaled down by the regional contest (Bastianoni et al., 2014).

The aim of the present study is to propose a methodological approach for accounting GHG emissions and $CO_2$ absorptions in European neighbourhoods. The accounting method is reasonably based on the worldwide-accepted standard methodologies, particularly the 2006 IPCC Guidelines and the GPC (limited to scopes 1 and 2) (IPCC, 2006; GHG Protocol, 2014). Referring to average European activity data, the procedure starts from the assessment of GHG emissions provided by a single household and then estimates impacts at the neighbourhood level by scaling-up. A detailed equations framework has been provided concerning 25 measures and policies for decarbonisation to be potentially planned and accomplished. Compared to previous studies mentioned above, novelties consist in: profiling a single representative household as functional unit to scale up at the neighbourhood level (given the difficulty to assess direct data for cities or districts); operating a comprehensive carbon balance of the urban district taking into account a set of activity sectors, i.e. energy for housing, mobility of people, domestic waste and water, besides carbon uptake by local ecosystems (relevant aspects to plan energy policies); taking outcomes from the carbon accounting as the starting point to plan a progressive energy transition and design feasible decarbonisation scenarios. Moreover, a crucial aspect of the proposed method is the possibility to implement it in few working days, quickly collecting and processing data, and easily replicating the experience elsewhere.

This study is based on the experience of the City-Zen Project, funded by the European Commissions within the FP7-Energy-Smartcities-2013 program, addressed to zero energy cities (City-Zen Project, 2018).

## 2. Materials and methods

### 2.1 Carbon emissions accounting

The carbon accounting methodology shown in this study has been developed as part of the EU FP7 City-Zen Project (City-Zen Project) which, besides other tasks, aimed to establish a general approach for urban neighbourhood retrofitting in European cities for decarbonisation including the monitoring of carbon emissions and the estimate of the effects of mitigation measures. Built on few successful experiences of GHG inventories at subnational level (Bastianoni et al. 2014; Marchi et al., 2012), the procedure consists of an optimised assessment to inform urban design practices and provide credible and realistic results in a short time (likely in two/three working days). In other words, it is conceived as a mediate model that, through a scientific approach, acts as an intermediary with the society to inform policy makers, citizens and stakeholders about current situation and guide transition pathways. The accounting framework has been tested before its publication through a set of real residential neighbourhoods taken as test-beds during dedicated workshops, namely City-Zen roadshows (van den Dobbelsteen et al., 2018; Pulselli et al., 2018).

Even though it presents assumptions and approximations, it has demonstrated to be a promising tool for addressing choices, making decisions easier to understand and agreed.

First step of this procedure is to provide a clear picture of the state of the art of urban districts in terms of GHG emissions as the initial condition to start from and plan integrated measures for neighbourhood retrofitting towards carbon neutrality. The Carbon Footprint (hereafter CF), here interpreted as the final result of the carbon accounting framework, measures the GHG emissions in a given city, urban district or neighbourhood. It is given in tons of carbon dioxide equivalents (t $CO_2$-eq), corresponding to the quantity of the three main greenhouse gases released into the atmosphere, i.e. carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), multiplied by the respective 100-year Global Worming Potential ($GWP_{100}$): $CO_2$ $GWP_{100}$ = 1, $CH_4$ $GWP_{100}$ = 34 and $N_2O$ $GWP_{100}$ = 298 (IPCC, 2013). The GWP measures the potential greenhouse effect (heat trapping) of a gas relative to an equivalent mass of carbon dioxide 100 years after its release into the atmosphere (e.g. methane is 34 times more effective than carbon dioxide).

The Carbon Accounting procedure concerns the selection of specific emission factors (EFs) to estimate the GHG emissions of each activity; for example, fossil fuel consumption is one activity considered and the amount of GHG emitted per unit of combusted fuel is the related emission factor (EF). Most of the EFs, expressed in kg $CO_2$-eq /unit activity, have been assessed on the bases of the 2006 IPCC Guidelines (IPCC, 2006), except for those that require site specific information and direct measurements. In particular, the EF of electricity depends on the local (regional) electric grid obtained by a mix of primary sources and a share of renewables. Considering the crucial role of electricity use in energy policies, the specific EF has to be assessed as a mandatory step of the procedure.

The basic inventory of data concerns energy demand in buildings including details on energy sources (electricity, natural gas and other fuels), mobility of people (especially focussing on private car use), waste and water management. Most of the difficulty for carbon accounting in cities, urban districts or neighbourhoods is the lack of activity data directly monitored. Data is usually available at the regional, provincial or municipal level and lower spatial details are rarely monitored. Dealing with urban neighbourhoods, some information such as population density, number of families/households and a few others can be collected per census unit or building blocks through GIS datasets, when available, and can be used for scaling down the other measures by allocation (top-down approach). In the meanwhile, a bottom-up approach is also recommended by collecting site-specific information on people attitudes and architectural typologies of housing. As a functional unit in the accounting framework, one representative household must be identified through an accurate investigation and profiling. Data sources can include local surveys (e.g. interviews with residents, check of energy bills), statistical reports at the municipal or district level (e.g. administrative officers, service providers, energy label records, GIS datasets), research studies available in literature (e.g. local universities, energy diagnosis of buildings).

Once collected, activity data are properly elaborated and aggregated representing different urban activities as main emissions sources. In particular, in order to figure out and ex-ante evaluate possible interventions of urban retrofitting, the profile of the typical household will refer to energy use, mobility system, waste and water management:

- Energy use concerns energy for lighting and appliances, cooling, heating, domestic water heating and cooking including details on primary energy sources (e.g. electricity and the electric grid mix, natural gas, gasoil, other fuels). For example, it is important to know the mix of primary sources for electricity generation (this can be at the regional level), the share of renewables, the primary source for heating, Domestic Hot Water (DHW) and cooking in buildings.
- Mobility can be investigated based on the average use of passenger cars per year (travelled km/yr) and the number of cars per household. An alternative solution consists in considering commuting house-work and house-school distance by private car (in average 252 working days/year) or other transport, e.g. public transport, bikes, foot (in this case other private car uses, such as for extra-travelling, can be avoided).
- Waste management concerns the produced quantity of domestic waste (a quantity per capita is usually monitored at the municipal level and can be referred to the unit by considering the average number of people per household) and differentiated rates per treatment plant (waste to landfill, waste to incineration, organic waste to compost, recycling).
- Water use concerns quantity of tap water per capita per day.

The framework for carbon accounting presented in this paper is actually focussed on housing (it does not consider tertiary sectors, industry and agriculture) and will be demonstrated by simulating an average European neighbourhood. Table 1 shows the EFs that were selected for processing the carbon accounting in European cities and the corresponding reference or assessment method.

TABLE 1

Compared to the GPC standard mentioned above (GHG Protocol, 2014), the performed GHG inventory applies a "territorial criterion" (IPCC, 2016). Most of the GHG emissions take place within the urban area and refers to the scope 1, being lifecycle processes (e.g. industrial manufacturing of goods such as domestic systems or private cars) left out from the system boundaries. Emissions due to electricity use from the National grid belong the scope 2 and LCA based EFs allowed for assessing the impact of infrastructures, including renewable energy sources (EFs 1-13 in Table 1 take into account lifecycle processes such as installation, maintenance and decommissioning of power plants and electricity grids). Emissions from solid waste and water treatment occur outside the urban area and refer to the scope 3.

The EFs 28-31 for solid waste treatment consider direct emissions due to waste decomposition and incineration, assuming impacts from manufacturing and management of treatment plants as negligible compared to the quantity of treated waste (Marchi et al., 2017a). The EF 32 for tap water is LCA based because it takes into account the relevant energy inputs to sewage treatment plants and water distribution networks (Cheng, 2002) that represent most of the impact associated to water use.

The territorial approach, followed in this study, avoids to pursue a wider responsibility criterion based on the Life Cycle Assessment of goods and materials used; GHG emissions referred to scope 3 are not usually required for reporting in territorial carbon balances, depending on purpose and audience.

Table 2 shows the specific assessment of the electricity emission factor for the EU-28 on the basis of the European electricity grid mix. The activity data related to electricity demand, production and import are obtained by the Eurostat Statistics database (Eurostat, 2015a). Despite this value can be taken by official sources (e.g. Covenant of Mayors, 2016), the direct assessment is shown as part of the framework because EFs for electricity at national and regional level are not always available or coherent and because the share of a simple and clear assessment makes results comparable to each other and the methodology fully replicable. Moreover, the awareness of the electricity grid mix at national or regional level is also important for planning policies locally.

TABLE 2

Based on average values in European Union, a typical European household have been profiled (Table 3). In particular, households in EU-28 have an average 2.3 inhabitants per house (Eurostat, 2016). The energy demand concerns almost 16,000 kWh/yr, of which about 4000 kWh/yr electricity for lighting and appliances, cooling/heating and water heating (hereafter DHW - domestic hot water) and cooking; about 12,000 kWh/yr heat by fossil fuels (EEA, 2016; Eurostat, 2015b). The impact of mobility was estimated by considering 1.15 passenger cars/household (Eurostat, 2015c) and average 14,000 km/yr passenger car use (ACEA), 45.7% of which are powered by gasoline, 52.4% by diesel, 1.8% Liquid Petroleum Gas (LPG) (Eurostat, 2015c). This corresponds to the average km travelled in 1 year including urban paths and long travels. Municipal waste production is average 476 kg per capita (Eurostat 2016), of which 28% landfilled, 27% incinerated, 16% organic composted and 29% recycled. Water use is around 160L/day per capita (EEA, 2016).

TABLE 3

## 2.2 Equations framework for the carbon mitigation accounting

The carbon emissions of the neighbourhood, assessed based on the procedure shown in the 2.1 section, represent the current state and the challenge to be faced by urban retrofitting. An integrated set of most common CF mitigation measures and policies has been identified as possible initiatives to progressively decrease impacts and finally achieve a condition of carbon neutrality.

The carbon accounting framework aims to ex-ante evaluate potential effects in terms of avoided GHG emissions of different measures for energy saving, energy transition to renewable resources, sustainable mobility, waste management and water resources. The goal of carbon neutrality can be pursued by evaluating alternative scenarios, made according to specific contextual conditions, also including compensation such as carbon uptake by urban ecosystems. The following equations framework in Table 4 shows the assessment method of a set of 25 CF mitigation measures in terms of avoided GHG emissions (namely $CF_{av.}$ in the equations). Potential effects of proposed solutions have been preliminary estimated based on most common parameter values in order to figure out expected ranges of avoided emission (see the “estimated parameter ranges” in the table). Mitigating actions concern different spatial scales of interventions, from the individual behaviour of citizens (namely behavioural in Table 4) to technical solutions (namely systemic/technological) for households, buildings, building blocks, streets and the whole neighbourhood. Moreover, they refer to different time scales of implementation considering short- (about 10 years), medium- (about 20 years) and long-term (about 30 years) scenarios. Short-term actions are those to be immediately launched while long-term refers to solutions that would need infrastructural intervention or deep cultural changes (e.g. transition to electric mobility).

TABLE 4

The first set of actions refers to energy savings in residential buildings.

Equation 1 concerns avoided CF due to cooling energy saving in buildings (i.e. electricity) based on the shading effect of vegetation or sun-screens and passive ventilation. Similarly, Equation 2 refers to, an increase of vegetation, trees and solar reflective surfaces at the street level, thus mitigating the Urban Heat Island Effect (UHIE). Passive systems therefore can be implemented autonomously by citizens (Eq.1) in buildings or include interventions of urban greenery and UHIE mitigation driven by local administrations (Eq.2).

Equation 3 accounts for the energy saving by building retrofitting through envelope insulation and double glazing; the same equation can also apply to domotic systems that allow for energy saving by smart thermostats automatically or remotely controlled. Equation 4 refers to the replacement of traditional light bulbs with LED lamps. Equation 5 quantifies the effects of energy saving by correct behaviors such as moderating the use of cooling-heating systems or buying more energy efficient appliances. These actions concern proactive initiatives of citizens induced by awareness raising campaigns, public subsidies or incentives for energy saving.

The second set of actions refers to energy generation from renewable sources.

The production of electricity from solar photovoltaic (PV) panels (Equation 6), wind (Equation 7) and hydro turbines (Equation 8) determines a GHG emissions mitigation at various scales (i.e. household, building, building block, street and neighbourhood) depending on the plant size (Equations 6-8). PV panels can be installed both on roofs or façades of single buildings (short time implementation scale) and in solar farms, operating in the regional district and envisioned as an outdoor energy industry (longer time scale). Micro-wind towers operate at household-building level, while mini- and big-wind towers or mini-hydro turbines can supply the energy demand of building blocks and neighborhoods.

Equations 9-11 concern heat or combined heat-electricity production by the installation of thermo-solar collectors, hybrid photovoltaic-thermal solar panels, heat pumps based on integrated renewable sources (such as geothermal as heat source and PV panels for electricity supply).

Equation 12 concerns the use of biomass for heat and power cogeneration. The biomass to energy cogeneration requires a specific plant and a biomass harvesting system, including a specific fraction of residues from agriculture and forestry. This system would potentially supply heat energy to District Heating Networks (DHN) and electricity to local or even national grids. In particular, Equations 13-14 estimate the CF mitigation due to DHN and electricity mini grids at the neighborhood scale. DHN can be high temperature grids supplied by a combination of heat sources such as biomass-to-energy plants, waste incineration, energy cascading from industrial processes, or low temperature grids supplied by thermo-solar collectors, geothermal based heat pumps, heat storages. The mini smart grid, fed by a combination of renewable energy generation plants at neighborhood level, including for example private or shared solar and wind-farms located in specific sites, is able to balance the inconstant electricity generation from renewable sources and the withdrawal by users through storage systems. As assumption for the CF mitigation accounting, DHN and smart grids are supposed to fully or partially support the energy demand (i.e. space/water heating and electricity, respectively) of an assigned number of households.

Equation 15 concerns the full transition to electric systems for space and water heating and cooking. It foresees an increase of electricity demand for heating systems (both space and water), besides cooking, assuming an average Coefficient of Performance of heat pumps (CoP = 4; Nordic heating, 2015). As a general result, net emissions are highly decreased by replaced fossil fuels despite the increased impact of electricity. The latter can be avoided by generation through renewable sources.

The third set of actions refers to sustainable mobility.

Equation 16 concerns biofuel production from biomass, mainly residues of the cultivated area. Bioethanol production for example is an option to develop urban agriculture in marginal areas and brownfields for energy purpose.

Equations 17-19 evaluate the energy saving due to remote working, walk to school-work (e.g. protected pathways), ride to school-work (e.g. protected cycling roads) and bike sharing, as well as car-pooling and the increased use of public transport (induced by the optimization of services or specific campaigns and incentives). These measures concern reduced impact of mobility based on improved infrastructures and induced behavioral changes of citizens.

Equation 20 foresees the transition to electric mobility. The benefit due to the decrease of fossil fuels use takes into account the increased consumption of electricity for vehicles, considering an additional electricity demand (average 16 $kWh_e$ per 100 km; ref. GAA, 2015).

The fourth set of actions refers to waste management. Equation 21 concerns a decrease of domestic waste production by dwellings and an increase of recycling rates. Emission reduction due to the increase of domestic waste recycling can be similarly assessed by considering the climate impact of recycling processes. These can be assumed as zero in order to enhance the effect of good practices of differentiation and recycling. Equation 22 concerns a decrease of the landfilled waste fraction and the increase of differentiated rates sent to incineration (waste to energy), composting (organic waste) and recycling. Equation 23 concerns the production of electricity and heat from waste incineration. The decrease of undifferentiated waste fraction conferred to landfill, the increase of incinerated waste and collected organic fraction provide lower impact of waste management, depending on more efficient infrastructures, services and behavioral changes of citizens.

The fifth set of actions refers to water resource management and carbon uptake by urban ecosystems. Equation 24 concerns an improved water management system. The effect of this measure concerns tap water saving by decreasing domestic consumption (behavioral attitude) or by installing water harvesting systems from roofs for gardening and other not drinkable uses.

Equation 25 determines the $CO_2$ removals from the atmosphere by absorption in plant biomass. The $CO_2$ uptake in the vegetation depends on the extension of green surfaces and the specific absorption capacity of different plant types in urban areas.

**2.3 GHG emissions reduction scenario**

For demonstration, an energy transition and CF mitigation scenario has been hypothesized referring to the average European (EU-28) neighbourhood (hypothetically 10,000 households, hosting 23,000 inhabitants). Scope of the scenario is to show one possible pathway, among others, to achieve a condition of carbon neutrality in the long run throughout a determined sequence of policies and measures among those shown in Table 4. Table 5 makes explicit the parameters used for estimating the effects of each measure including number of involved households and rates of energy saving, mobility shift, waste fraction and water use. The measures, analysed in the CF mitigation scenario, are listed from 01 to 15 in Table 5.

TABLE 5

The selected measures show a comprehensive strategy to implement action plans based on most common activities, starting first from solutions applicable in the short-term and then promoting initiatives with long-term horizon. In particular, the decarbonisation scenario has been structured into four steps:

a) Energy saving; waste reduction and water use decrease: combination of solutions to avoid energy waste and reduce resource use. Most common policies concern: energy performance in buildings through passive systems (01), improved insulation (02), higher efficiency of lighting (03); sustainable mobility by walk and bike (04) and by public transportation (05); optimized waste management by waste differentiation and recycling (06) and increased rate of incineration in waste-to-energy plants (07); water use reduction (08). These policies imply awareness raising campaigns or incentives/disincentives to induce behavioral changes of citizens as well as structural investments for the innovation of organization and processes.
b) Local exploitation of renewable energy sources: combination of solutions to generate energy from renewable sources including heat and electricity. The simulated policies include: installation of biomass-to-energy cogeneration plant (09) to supply an integrated DHN (10); electricity generation by PV on flat roofs (11) and wind turbines (12). Since measures 11 and 12 can concern different spatial scales (from the household to the neighborhood), the size of solar and wind systems have been hypothesized to supply the residual electricity demand of the neighborhood, including the additional demand due to the foreseen transition to fully electrical systems (following step c). They can be progressively installed during a reasonable time interval, first for the energy retrofitting of the neighborhood (short run) and then for its transition to electric systems (long run).
c) Transition to electrical systems for replacement of residual fuels: as a desirable vision of future city neighborhoods, the simulated policies forecast a transition to electrical systems in buildings, including space and water heating and cooking (13), and for mobility through the replacement of machines powered by fuels with electric cars, bikes and public transport (14). The additional

demand of electricity can be supported by renewable sources (actions 11 and 12). Besides the proactive involvement of citizens, these measures would require a significant innovation of infrastructures and processes that can be accomplished in the long term.

d) Removals of $CO_2$ emissions (carbon uptake by vegetation): an additional action for decarbonisation concerns the valorization of ecosystem services, such as $CO_2$ absorption. In particular, the residual GHG emission due to waste and water management (i.e. a kind of entropy that cannot be fully avoided) can be compensated by carbon uptake (15). Urban forestry is among the recommended actions to finally achieve a condition of carbon neutrality.

Table 5 shows the size of every intervention in a sequence of simulated measures to test the carbon accounting framework. Most of the solutions concern a certain number of dwellings involved in order to estimate the effect of each measure based on the household as functional unit (bottom-up approach). This number is arbitrary but assumes reliable penetration rates (from 10% to 60%) of planned policies (100% is avoided to guarantee a prudential and more realistic approach). Some other policies refer to the neighborhood scale (top-down approach; e.g. solar and wind farms to support the comprehensive electricity demand). In this case the number of equivalent households allows to figure out the intervention size even if it has been determined based on the comprehensive demand of the neighborhood (this is especially useful after the transition to electrical systems and mobility). The simulation is coherent with the description given per each measure in table 4 (see the "estimated parameter ranges") and is useful to understand how the accounting system works simultaneously at different scales, from that of the household to the neighborhood and beyond.

## 3. Results

### 3.1 Carbon accounting of the average European household and neighbourhood

Table 6 shows the Carbon Footprint of the average EU-28 household, as well as the activity data and Carbon Footprint of the hypothetical neighbourhood. The assessment has been performed by referring to the EFs for different emission sources in Table 1, including electricity (Table 2).

The total impact, in terms of carbon emissions, for the typical household corresponds to 6.93 t $CO_2$-eq per year. Once profiled the typical house, the impact of the neighbourhood has been determined just by considering the number of households and results show the emission intensity per different sectors: energy use for housing and mobility, domestic waste and water management. In its present state, the gross emissions of the neighborhood are 69,256 t $CO_2$-eq.

TABLE 6

Table 6 shows both data referring to the single household and the neighbourhood. Since we hypothesized a neighbourhood of 10,000 households, CF values for the household and the neighbourhood may look redundant (just a multiple of 10 units) but the structure of this table is shown anyhow as useful requisite to perform the following assessment of CF mitigation measures allowing for easily estimating their effects depending on the spatial scale of interventions (some measures, such as the retrofitting of envelopes, refer to single households, and some other to the whole neighbourhood, e.g. renewable energy production). Both scales (the household and the neighbourhood) must be simultaneously taken into account to process data concerning CF mitigation measures within a correct systems approach.

**3.2 Carbon mitigation accounting**

The hypothetical scenario applying to the average European neighborhood presented in this study builds on a combination of 15 measures. Table 7 shows the estimated effects in terms of primary data and avoided GHG emissions, starting from the initial condition (69,256 t $CO_2$-eq for the EU-28 neighborhood, see also Table 6).

TABLE 7

This hypothetical scenario demonstrates that urban systems in Europe can be radically transformed through setting proper action plans applying to different sectors and relating to different spatial and time scales. The integrated set of interventions, including the generation of 50 GWh electricity by PV panels and wind farms (measures 11 and 12), brings the CF of the neighborhood to 2281 t $CO_2$-eq/yr (97% less than the initial impact). The sequence shows that actions concerning resource (waste and water) and energy saving can potentially decrease the CF by 35%, while renewable energy generation contributes by 38% and the transition to electrical systems by 24%. As a final step (measure 15), the forestation of 169 hectares, such as marginal areas or even remote brownfields, would allow for compensating the residual CF (3%) and potentially bring the neighborhood to carbon neutrality in the long run.

**3.3 Spatial visualisation of the carbon accounting**

Aiming at better understanding intensity and size of impacts, the quantity of greenhouse gases annually released into the atmosphere per household (6.93 t $CO_2$-eq) can be represented in terms of virtual forestland, the area covered by a relatively young forest that would be needed to absorb an equivalent amount of $CO_2$. The carbon emissions of the average European household correspond to the carbon uptake of 0.51 hectares of forestland. This assessment considers average 1.35 kg $CO_2$ $m^{-2}$ $yr^{-1}$ carbon uptake (item 35 in Table 1). Given the size of a football field is around 0.4 hectares, each house should have a backyard forest of 1.3 football fields.

Figure 1 shows on the same spatial scale an iconic layout of the hypothetical European neighbourhood (a common typology for urban sprawl: 150 hectares, hosting average 150 resident/ha density) and its 5130 hectares of virtual forestland. The area of forestland is about 34 times bigger than the surface of the neighbourhood itself.

FIGURE 1

The representation by means of squares (25 hectares each) allows the estimation of carbon mitigation effects that can be achieved by combining different measures (Figure 2). The sequence of actions would therefore progressively crunch the CF of the neighbourhood and show how the action plan would potentially bring impacts to zero. Moreover, the representation in grey scale allows to show the effect on different emission sources (i.e. electricity and natural gas for housing, fuels for mobility, waste and water) and to better understand transition processes: for example, every transition from fossil fuels to electric systems (e.g. heat pumps; electric mobility) provides the replacement of fossil fuels with electricity and therefore an increase of the electricity demand to be supplied by renewables.

FIGURE 2

During testing workshops in European Cities and presentation to wide audience, this visualisation has been enhanced by adding the icons of a pacman-like character, crunching the CF squares, and ghosts (when energy transitions call for additional electricity demand the ghost appears adding new squares), inspired by the famous videogame. This graphical visualisation in space of the CF of the neighbourhood has become an effective tool for communication and awareness raising among citizens and stakeholders during City-Zen roadshows (van den Dobbelsteen et al. 2018; Pulselli et al. 2018).

**4. Discussion**

The GHG emissions of a typical European neighbourhood have been estimated based on a bottom-up process, by assessing the CF of a single household (i.e. 6.93 t $CO_2$-eq/yr). This impact includes a limited set of activities, concerning housing (51.3% emission: 21.4% electricity, 29.9% fossil fuels), mobility (39.4%), domestic waste treatment (8.2%) and tap water use (1.1%). Presented results refer to average European values and can significantly change from case to case according to climate and physical conditions of the built environment, cultural, social and economic contexts. For example, cooling energy will be much higher in southern European countries where there is relatively lower heat demand while the latter will be much more relevant in the North. Age and quality of building envelopes highly condition the heat demand and also the possibility of interventions (e.g. historical centres would require very specific policies due to architectural conservation). Urban density and connecting infrastructures determine different impacts of mobility: low density neighbourhoods often require almost exclusively private car use by the residents and the GHG emissions due to fuels can easily overcome that of housing; on the contrary, high density neighbourhoods often allow for a higher concentration of urban utilities and services within a walking distance and more efficient public transportation systems and infrastructures. The impact of waste collection and treatment depends on individual behaviours (e.g. waste differentiation) but also on the waste management system adopted in the wider region. The proposed framework is able to detect the real state of carbon emissions, based on the inventory of site-specific data, and therefore the elaboration procedure that has been developed has a high potentiality of replicability in European neighbourhoods. Moreover, also the selection and design of mitigation measures depend on different urban contexts; for example the area of available flat roofs for PV installation, the energy potentials (e.g. wind speed, geothermal heat), the existing infrastructural facilities and services are site specific conditions that affect the plan and provide the real parameters to be processed in the equations framework.

Activity sectors included in the Carbon Accounting framework allow for assessing the contribution of most significant emission sources that can be the object of specific measures and therefore for planning strategies for decarbonisation concerning housing, mobility, waste and water resources and referring to different spatial and temporal scales. Moreover, results deal with daily life aspects that citizens know well and therefore contribute to raise awareness about their behaviour and the opportunity to change for the Planet. Besides others, measures such as greening and shading facades (measure 1 in Table 4), optimising the use of lights and appliances (measures 4 and 5 in Table 4), walking/cycling to school/work (measure 17 in Table 4), car-pooling (measure 18 in Table 4), using public transport (measure 19 in Table 4), could be potentially applied since tomorrow with no investments, just by inducing citizens to change their lifestyle. The role of communication, that the proposed framework contributes to support as shown in the 3.3 section, for the consciousness of citizens is therefore crucial.

The visualisation of results through the virtual forestland has been tested during the City-Zen roadshows (van den Dobbelsteen et al. 2018). It expresses the equivalent area covered by a growing forest to absorb GHG emissions provided by the neighbourhood and contribute to make outcomes from the Carbon Accounting spatially explicit and understandable: the forestland (5130 ha) is 34 times bigger than the area of the neighbourhood (150 ha). This communication outcome has looked as very surprising and worrying to the eyes of any audience. A necessary observation is that the forestland represented in Figure 1 does not provide the whole picture but just a part of it.

Some elements of the comprehensive Carbon footprint have not taken into account such as the impact of lifecycle processes for food and goods consumption. For example, the impact of mobility accounts for fuel use but not for the lifecycle processes of private cars (i.e. their manufacturing, maintenance and end-of-life). Moreover, the activity data of the inventory is currently limited to the residential sector: housing, private cars, domestic waste and water; indeed commercial or productive activities have not taken into account such as, for example, office buildings and shops or the street public lighting. Specific surveys on tertiary or industry located in the neighbourhood could be implemented and added into the assessment framework depending on data availability (not to give for granted). Consequently, we can reasonably imagine that the CF of neighbourhoods would be much increased, easily doubled or more, by including also these aspects in the assessment. Consequently new sets of scenarios and policies concerning dietary shifts, short-chain products, circular economy, should be investigated.

Furthermore, the same approach could be implemented with different or complementary indicators, together with the carbon footprint. One example is the traditional Ecological Footprint, as stated by the Global Footprint Network (Galli et al., 2016). Another example can concern an estimate of possible economic investments associated to each measure; this would allow for measuring the cost of decarbonisation scenarios and also evaluate the investment ratio (i.e. invested € per avoided kg of $CO_2$-eq). An input-state-output scheme as theorised by Pulselli et al. (2015) and Neri et al. (2017) to investigate sustainability of nations and regions can be also taken as reference for implementing a combined set of three systems indicators concerning input (resource use; the Carbon Footprint belongs to this item since it can be a proxy for energy use), state (social organisation, density and quality of infrastructures and services) and output (citizen welfare) focussing on any specific neighbourhood.

As stated before, the current framework has been tested during workshops throughout European cities (van den Dobbelsteen et al., 2018; Pulselli et al., 2018), under the City-Zen Project. The so called City-Zen roadshows has focused on specific neighbourhoods selected by the hosting municipality and have a strict timetable: field visit and site-specific data collection on Monday, 3 days elaboration from Tuesday to Thursday, final presentation of results on Friday morning. Outcomes include short-medium-long term measures and policies and the scenarios towards carbon neutrality in Figure 1 and 2. The short timing of workshops, made together with local stakeholders and facilitators, demonstrated that this Carbon Accounting mediate model can be a powerful tool for showcasing the effects of ambitious but reliable action plans for decarbonisation of neighbourhoods in different European cities and regional contexts.

## 5. Conclusion

The methodology presented in this study is conceived as a carbon accounting tool to understand the environmental implications of citizen behaviours and address choices for climate action in urban neighbourhoods. The different steps of the procedure go from the selection of Emission Factors, including the specific calculation of the electricity grid mix, to the assessment of the Carbon Footprint (CF), until the estimate of the Carbon Footprint mitigation effects of a hypothetical action plan. In particular, the equations framework proposed refers to a series of policies and measures for decarbonisation in built environments concerning energy for housing and mobility, waste and water management.

The assessment process has been demonstrated referring to a theoretical European neighbourhood (10,000 households; 23,000 inhabitants), based on average values from statistical datasets, in order to provide a reference benchmark for any kind of future application.

The CF per household, taken as functional unit, is 6.93 t $CO_2$-eq, equivalent to 0.51 hectares of forestland that corresponds to the extension of 1.3 football fields. This conversion into forestland provides an alarming representation of the impact of citizen lifestyles in contemporary cities, e.g. the virtual forestland of 5130 hectares is 34 times bigger than the neighbourhood area. Nevertheless, it also allows for visualising the effects of mitigation strategies concerning different spatial scales, from neighbourhoods to households until individual citizens, and temporal horizons (short-, medium-, long-term). This dynamic representation looks quite challenging and engaging to the eyes of any audience and can contribute to support awareness raising campaigns for the engagement of citizens and stakeholders.

The combination of the assessment process with the visualisation of outcomes establishes an effective “mediate model” able to inform participative design processes and drive the energy transition of European cities. It is intended as a replicable methodology to be transferred and applied to European neighbourhoods and glaringly kick-off their decarbonisation processes.

**Acknowledgments**

The present study has been developed for implementing the activities of the City-Zen Project that has received funding from the European Union's Seventh Programme for research; technological development and demonstration under grant agreement No 608702. In particular, the authors thank the colleagues of the City-Zen roadshow team for their precious work and support and the equipe of researchers of the Ecodynamics Group for their constant collaboration.

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**TABLES**

Table 1: Emission factors and corresponding reference - assessment method.

| Item | | EF | Unit | Note |
|---|---|---|---|---|
| **n.** | **Electricity grid mix** | | | |
| 1 | electricity (LCA based) | 0.375 | kg$CO_2$-eq/$kWh_e$[a] | European electricity grid mix, year 2015 (Table 2) |
| 2 | thermoelectricity: natural gas (LCA based) | 0.443 | kg$CO_2$-eq/$kWh_e$ | Various combined cycle turbines (Sovacool, 2008) |
| 3 | thermoelectricity: petroleum (LCA based) | 0.778 | kg$CO_2$-eq/$kWh_e$ | Various generators and turbine types (Sovacool, 2008) |
| 4 | thermoelectricity: coal (LCA based) | 1.050 | kg$CO_2$-eq/$kWh_e$ | Various generator types (Sovacool, 2008) |
| 5 | nuclear (LCA based) | 0.066 | kg$CO_2$-eq/$kWh_e$ | Various reactor types (Sovacool, 2008) |
| 6 | renewable: PV (LCA based) | 0.032 | kg$CO_2$-eq/$kWh_e$ | Polycrystalline silicone (Sovacool, 2008) |
| 7 | renewable: solar thermal (LCA based) | 0.013 | kg$CO_2$-eq/$kWh_e$ | 80 MW – parabolic trough (Sovacool, 2008) |
| 8 | renewable: wind (LCA based) | 0.010 | kg$CO_2$-eq/$kWh_e$ | 1.5 MW – onshore (Sovacool, 2008) |
| 9 | renewable: hydroelectric (LCA based) | 0.012 | kg$CO_2$-eq/$kWh_e$ | Reservoir, 3.1 kW, 10 g $CO_2$-eq/kWh; run-of-river, 300 kW, 13 g $CO_2$/kWh (Sovacool, 2008) |
| 10 | renewable: geothermal (LCA based) | 0.380 | kg$CO_2$-eq/$kWh_e$ | Ecoinvent 3 (2015) |
| 11 | renewable: biomass (LCA based) | 0.028 | kg$CO_2$-eq/$kWh_e$ | Short rotation forestry steam turbine (Sovacool, 2008) |
| 12 | renewable: biogas (LCA based) | 0.011 | kg$CO_2$-eq/$kWh_e$ | Anaerobic digestion (Sovacool, 2008) |
| 13 | renewable: hydrogen (LCA based) | 0.664 | kg$CO_2$-eq/$kWh_e$ | Fuel cell (Hydrogen from gas reforming (Sovacool, 2008) |
| | **Primary energy for heating** | | | |
| 14 | natural gas/buthane | 0.252 | kg$CO_2$-eq/$kWh_h$[b] | Our assessment: Heat power 9,6kWh/$m^3$; 80% efficiency |
| 15 | natural gas/buthane | 1.933 | kg$CO_2$-eq/$m^3$ | IPCC (2006) |
| 16 | gasoil/diesel | 3.195 | kg$CO_2$-eq/kg | IPCC (2006) |
| 17 | gasoil/diesel | 2.650 | kg$CO_2$-eq/L | Our assessment: 0,835kg/L |
| 18 | gasoil/diesel | 0.281 | kg$CO_2$-eq/$kWh_h$ | Our assessment: Heat power 11,36kWh/kg |
| 19 | LPG[c] | 2.984 | kg$CO_2$-eq/kg | IPCC (2006) |
| 20 | LPG | 0.263 | kg$CO_2$-eq/$kWh_h$ | Our assessment: Heat power 11,36 kWh/kg |
| 21 | biomass, biogas | 0.114 | kg$CO_2$-eq/$kWh_h$ | Ecoinvent 3 (2015) |
| | **Mobility** | | | |
| 22 | travelled km by car (petrol) | 0.172 | kg$CO_2$-eq/km | IPCC (2006) |
| 23 | travelled km by car (diesel) | 0.169 | kg$CO_2$-eq/km | IPCC (2006) |
| 24 | travelled km by car (LPG[a]) | 0.133 | kg$CO_2$-eq/km | IPCC (2006) |
| 25 | car passenger (diesel) | 0.140 | kg$CO_2$-eq/(km person) | Our assessment: average 1.2 person/vehicle |
| 26 | bus (diesel) | 0.337 | kg$CO_2$-eq/km | Our assessment: average 8 km/L |
| 27 | bus passenger | 0.021 | kg$CO_2$-eq/(km person) | Our assessment: average 14 person/bus |
| | **Urban Waste** | | | |
| 28 | waste-to-energy (incineration) | 0.652 | kg$CO_2$-eq/kg | Includes paper, plastic, textile, nappies, other. |
| 29 | waste-to-landfill | 1.160 | kg$CO_2$-eq/kg | IPCC WASTE MODEL |
| 30 | organic waste-to-compost | 0.091 | kg$CO_2$-eq/kg | waste to composting. EF = 0,05 g $CH_4$/kg waste and 0,30 g $N_2O$/kg waste ($CH_4$: ANPA CTN-ACE, 2002; $N_2O$: IPCC, 2006) |
| 31 | recycled waste | 0.000 | kg$CO_2$-eq/$kWh_h$ | |
| | **Water** | | | |
| 32 | water management (LCA beded) | 0.585 | kg$CO_2$-eq/$m^3$ | extended to the lifecycle of tap water |
| | **Carbon uptake by urban ecosystems** | | | |
| 33 | grass and herbaceous plants (green roofs and facades) | 0.330 | kg$CO_2$/$m^2$ | STELLA model, based on IPCC 2006 (Marchi et al., 2015) |
| 34 | urban agriculture (vegetable gardens and grains, e.g. wheat) | 0.970 | kg$CO_2$/$m^2$ | STELLA model, based on IPCC 2006 (Marchi et al., 2015) |
| 35 | urban forestry | 1.350 | kg$CO_2$/$m^2$ | Our assessment based on IPCC 2006 with annual increase and growing stock from the forest inventory (INFC, 2005) |
| 36 | fruit trees | 0.560 | kg$CO_2$/$m^2$ | IPCC (2006) |

[a] $kWh_e$ = kWh of electricity produced.
[b] $kWh_h$ = kWh of heat produced.
[c] LPG = Liquid Petroleum Gas.

Table 2: Emission Factor (EF) of electricity, based on the European electricity grid mix (2015) (source of activity data: Eurostat, 2015a).

| EU-28 2015 | LCA based EF | Activity data | % | GHG EMISSION |
|---|---|---|---|---|
| **GENERAL ACTIVITY DATA** | **$kgCO_2$-eq/kWh** | **kWh** | **%** | **kg $CO_2$-eq/yr** |
| **ELECTRICITY DEMAND** | _ | **2.74E+15** | 100.0% | _ |
| **ELECTRICITY PRODUCTION** | _ | **3.23E+15** | 118.0% | _ |
| **NET INPORT** | 0.578 | 1.43E+13 | 0.5% | 8.24E+12 |
| **TERMO-ELECTRICITY** | | **1.41E+15** | **51.3%** | **1.13E+15** |
| natural gas | 0.443 | 5.30E+14 | 19.3% | 2.35E+14 |
| petroleum products[a] | 0.778 | 8.43E+13 | 3.1% | 6.55E+13 |
| Solid fossil fuels (mainly coal) | 1.050 | 7.91E+14 | 28.9% | 8.31E+14 |
| **RENEWABLES** | | **9.71E+14** | **35.4%** | **2.10E+13** |
| solar thermal | 0.013 | 5.59E+12 | 0.2% | 7.27E+10 |
| solar photovoltaic panel (PV) | 0.032 | 1.02E+14 | 3.7% | 3.27E+12 |
| wind | 0.010 | 3.02E+14 | 11.0% | 3.02E+12 |
| hydroelectric | 0.012 | 3.71E+14 | 13.5% | 4.45E+12 |
| geothermal | 0.380 | 6.52E+12 | 0.2% | 2.48E+12 |
| biomass[b] | 0.028 | 1.17E+14 | 4.3% | 3.27E+12 |
| biogas | 0.011 | 6.09E+13 | 2.2% | 6.70E+11 |
| hydrogen | 0.664 | 5.67E+12 | 0.2% | 3.77E+12 |
| **NUCLEAR** | | **8.57E+14** | **31.3%** | **5.66E+13** |
| nuclear | 0.066 | 8.57E+14 | 31.3% | 5.66E+13 |
| **TOTAL** | **0.375** | **3.25E+15** | | **1.22E+15** |

[a] Petroleum products contain crude oil, petroleum products and waste (non-renewable).
[b] Biomass contains Solid biofuels excluding charcoal, municipal waste (renewable) and liquid biofuels.

Table 3: European household consumptions (source of activity data: Eurostat, 2015a,b, c, 2016; EEA, 2016).

| Human activity | Unit | EU-28 HOUSEHOLD | Percentage |
|---|---|---|---|
| | | Activity data | |
| **ENERGY** | **$kWh_e$[b]/yr** | **15,704** | |
| **Electricity** | **$kWh_e$/yr** | **3,969** | 100% |
| lighting, appliances | $kWh_e$/yr | 2,385 | 60% |
| cooling | $kWh_e$/yr | 78 | 2% |
| cooking | $kWh_e$/yr | 439 | 11% |
| heating | $kWh_e$/yr | 612 | 15% |
| DHW | $kWh_e$/yr | 439 | 11% |
| RES[a] electricity | $kWh_e$/yr | 16 | 0% |
| **Fuels** | **$kWh_h$[c]/yr** | **11,735** | 100% |
| Natural Gas – heating | $kWh_h$/yr | 4,299 | 37% |
| Natural Gas – DHW | $kWh_h$/yr | 957 | 8% |
| Natural Gas – cooking | $kWh_h$/yr | 282 | 2% |
| Petroleum – heating | $kWh_h$/yr | 2,024 | 17% |
| Petroleum – DHW | $kWh_h$/yr | 282 | 2% |
| Petroleum – cooking | $kWh_h$/yr | 110 | 1% |
| RES[a] – heating | $kWh_h$/yr | 3,232 | 28% |
| RES – DHW | $kWh_h$/yr | 502 | 4% |
| RES – cooking | $kWh_h$/yr | 47 | 0% |
| **MOBILITY** | **km/yr** | **16,100** | **100%** |
| passenger car – petrol | km/yr | 7,406 | 46% |
| passenger car – diesel | km/yr | 8,372 | 52% |
| passenger car – LPG | km/yr | 322 | 2% |
| **URBAN WASTE** | **kg/yr** | **1,095** | **100%** |
| % waste-to-landfill | kg/yr | 308 | 28% |
| % waste-to-energy | kg/yr | 292 | 27% |
| % organic | kg/yr | 179 | 16% |
| % recycling | kg/yr | 315 | 29% |
| **WATER** | **$m^3$/yr** | **134** | **100%** |
| $m^3$ per yr (house) | $m^3$/yr | **134** | 100% |

[a] RES = Renewable Energy Sources.
[b] kWh of electricity produced (hereafter $kWh_e$).
[c] kWh of heat produced (hereafter $kWh_h$).
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Table 4: Equations framework for the estimate of avoided GHG emission ($CF_{av.}$ [kg $CO_2$-eq]) by Carbon Footprint mitigation/compensation measures.

| Equations | | Symbols | Estimated parameter ranges | Type of action |
|---|---|---|---|---|
| ***SET OF ACTIONS: ENERGY SAVING IN BUILDINGS*** | | | | |
| Eq. 1 | $Shading\ and\ passive\ ventilation\!:\ CF_{av.} = (n \times E_c \times e_c) \times EF_{kWh_e}$ | $n$ = number of households [n];<br>$E_c$ = cooling energy demand per household [$kWh_e$/yr];<br>$e_c$ = rate of cooling energy saving due to shading and passive ventilation [%];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | $n$ = 1 household;<br>$Ec$ = 78 $kWh_e$/yr (Table 3);<br>$e_c$ = from 10% to 50% (ref. Agrawal et al. 2012).<br><br>Estimated $CF_{av}$:<br>2.93 – 14.63 kg $CO_2$-eq/house | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological; behavioral. |
| Eq. 2 | $UHIE\ mitigation\ by\ vegetation\!:\ CF_{av.} = (n \times E_c \times e_c) \times EF_{kWh_e}$ | $n$ = number of households [n];<br>$E_c$ = cooling energy demand per household [$kWh_e$/yr];<br>$e_c$ = rate of cooling energy saving due to UHIE mitigation by vegetation [%];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | $n$ = 1 household;<br>$Ec$ = 78 $kWh_e$/yr (Table 3);<br>$e_c$ = from 5% to 20% (ref. Akbari et al. 2012).<br><br>Estimated $CF_{av}$:<br>1.46 – 5.85 kg $CO_2$-eq/house | Spatial scale:<br>street, neighborhood.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 3 | $Building\ envelope\ retrofitting\ and\ domotic\ systems\!:\ CF_{av.} = [(n \times E_c \times e_c) \times EF_{kWh_e}] + [(n \times H_h \times e_h) \times EF_{kWh_h}]$ | $n$ = number of households [n];<br>$E_c$ = cooling energy demand per household [$kWh_e$/yr];<br>$e_c$ = rate of cooling energy saving [%];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2);<br>$H_h$ = heat demand for heating per household [$kWh_h$/yr];<br>$e_h$ = rate of heating energy saving [%];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14). | $n$ = 1 household;<br>$Ec$ = 78 $kWh_e$/yr (Table 3);<br>$H_h$ = 6,323 $kWh_h$/yr (Table 3, excluded RES).<br><br>*Building envelope retrofitting:*<br>$e_c$ = from 20% in warm to 80% in cold climate, mainly depending on proper ventilation and threshold values (ref. Qian and Lee, 2014);<br>$e_h$ = from 30% to 60% (ref. Qian and Lee, 2014).<br>*Domotic systems:*<br>$e_c$ and $e_h$ = around 10% (ref. NV energy, 2018; Smart Home, 2017).<br><br>Estimated $CF_{av}$:<br>*Building envelope retrofitting* → 483.87 – 979.44 kg $CO_2$-eq/house<br>*Domotic systems* → 162.26 kg $CO_2$-eq/house | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 4 | $Led\ lamps\!:\ CF_{av.} = [n \times I \times (P_0 - P_n) \times t] \times EF_{kWh_e}$ | $n$ = number of households [n];<br>$I$ = number of light bulbs per household [n];<br>$P_0$ = power of traditional light bulbs [kW];<br>$P_n$ = power of LED lights [kW];<br>$t$ = operating time [h/yr];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | $n$ = 1 household;<br>$I$ = estimate 10 light bulbs per household;<br>$P_0$ = 80 W;<br>$P_n$ = 8 W (90% less) (ref. Frank et al., 2015; King and Perry, 2017);<br>$t$ = 438 hours/yr (average 4 hors/day x 3% of 10 lamps x 365 days.<br><br>Estimated $CF_{av}$: | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological. |

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| | | | 118 kg $CO_2$-eq/house | |
| Eq. 5 | *People behavioural change*: $CF_{av.} = [(n \times E_d \times e) \times EF_{kWh_e}] + [(n \times H_d \times h) \times EF_{kWh_h}]$ | $n$ = number of households [n];<br>$E_d$ = electricity demand per household [$kWh_e$/yr];<br>$e$ = rate of electricity saving by behavioural change [%];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2);<br>$H_d$ = heat demand for cooking, heating and domestic hot water per household [$kWh_h$/yr];<br>$h$ = rate of heating energy saving by behavioural change [%];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14). | $n$ = 1 household;<br>$E_d$ = 3,953 $kWh_e$/yr (Table 3, excluded RES);<br>$H_d$ = 7,954 $kWh_h$/yr (Table 3, excluded RES);<br>$e$ and $h$ = from 5% to 10% (ref. Darry, 2006).<br><br>Estimated $CF_{av}$:<br>174.34 – 348.68 kg $CO_2$-eq/house | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>behavioral. |
| ***SET OF ACTIONS: ENERGY GENERATION FROM RENEWABLE SOURCES*** | | | | |
| Eq. 6 | *PV panels*: $CF_{av.} = (S \times P \times Y \times a) \times EF_{kWh_e}$ | $S$ = surface of roofs or walls covered by PV panels [$m^2$/household];<br>$P$ = installed power [kW/$m^2$];<br>$Y$ = production yield [$kWh_e$/kW];<br>$a$ = exposition plan coefficient;<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | $S$ = 12 $m^2$/household or estimate 1000 $m^2$ in sun farms;<br>$P$ = 0.12 to 0.25 kW/$m^2$;<br>$Y$ = from 2.5 $MWh_e$/yr in N-EU (Belfast - IE), to 3.2 in C-EU (Paris - FR), until 3.9 (Rome - IT) and 4.8 $MWh_e$/yr (Palermo - IT) in S-EU (ref. EU JRC, 2018);<br>$a$ = 1 (slope <70°, as in the case of roofs) or 0.7 (slope >70° , as in the case of walls).<br><br>Estimated $CF_{av}$:<br>*On roofs or walls* ⟶ 843.75 – 1,102.50 kg $CO_2$-eq/house.<br>*In sun farms* ⟶ 70,312.50 – 91,873 kg $CO_2$-eq. | Spatial scale:<br>*On roofs or walls* ⟶<br>household, building.<br>*In sun farms* ⟶<br>neighborhood.<br><br>Temporal scale:<br>*On roofs or walls* ⟶ short term.<br>*In sun farms* ⟶ medium term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 7 | *Wind turbine*: $CF_{av.} = (n_{wt} \times P \times v \times t) \times EF_{kWh_e}$ | $n_{wt}$ = number of installed wind towers [n];<br>$P$ = standard power [kW];<br>$v$ = capacity factor due to wind speed variability;<br>$t$ = operating time [h/yr];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | $n$ = 1 micro wind tower, 1 mini or big wind tower;<br>$P$ = 1-5 kW for micro-wind towers (6-9 m towers embedding 1-7 m turbines), 20-200 kW for mini-wind towers (10-30 m towers embedding 1-20 m towers), 1-3 MW for big-wing towers (60-120 m towers embedding 55-80 m turbines) (ref. OE, 2018);<br>$v$ = from 0.8 to 0.85 (ref. SEI, 2018);<br>$t$ = 3285 h/yr (i.e. 365 day/yr × 10 h/day × 90% day/yr due to maintenance).<br><br>Estimated $CF_{av}$:<br>*Micro wind tower* ⟶ 1,256.51 – 6,282.56 kg $CO_2$-eq/wind tower;<br>*Mini wind tower* ⟶ 25,130.25 – 251,302.50 kg $CO_2$-eq/wind tower;<br>*Big wind tower* ⟶ 1,047,093.75 – 3,141,281.25 kg $CO_2$-eq/wind tower. | Spatial scale:<br>*Micro wind tower* ⟶<br>household, building.<br>*Mini wind tower* ⟶<br>building block, street.<br>*Big wind tower* ⟶<br>neighborhood.<br><br>Temporal scale:<br>*Micro-Mini wind tower* ⟶<br>short term.<br>*Big wind tower* ⟶<br>medium term.<br><br>Type of solution:<br>systemic/technological. |

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| Eq. 8 | $Mini\ hydro\ plant\colon\ CF_{av.} = (n_{ht} \times P \times w \times t) \times EF_{kWh_e}$ | $n_{ht}$ = number of installed hydro turbines;<br>$P$ = standard power [kW];<br>$w$ = capacity factor due to water load variability;<br>$t$ = operating time [h/yr];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$]<br>(Table 2). | $n$ = 1 hydro turbine;<br>$P$ = from 100 kW to 1 MW (ref. LifeGate, 2018);<br>$w$ = 0.85 (ref. LifeGate, 2018);<br>$t$ = from 3000 to 5000 h/yr.<br>Standard 100 kW hydro-turbine can provide up to 350 MWh/yr.<br><br>Estimated $CF_{av}$:<br>65,625 – 1,593,750 kg $CO_2$-eq | Spatial scale:<br>building block, street, neighborhood.<br><br>Temporal scale:<br>short -medium term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 9 | $Thermo\_solar\ collector\colon\ CF_{av.} = (n_{PV} \times S \times Y_h) \times EF_{kWh_h}$ | $n_{PV}$ = number of installed solar collectors [n];<br>$S$ = exposed surface [$m^2$];<br>$Y_h$ = heat production yield [$kWh_h/m^2$];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14). | $n$ = 1 household;<br>$S$ = 2 $m^2$ per household (ref. Tian and Zhao, 2013; University of Strathclyde, 2018);<br>$Y_h$ = from 2.9 $kWh_h$/day in N-EU to 6.3 $kWh_h$/day in S-EU and from 1000 $kWh_h/(m^2$ yr) in N-EU to 2200 $kWh_h/(m^2$ yr) in S-EU (ref. University of Strathclyde, 2018).<br><br>Estimated $CF_{av}$:<br>504 – 1,108.80 kg $CO_2$-eq/house. | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 10 | $PV\ thermo\ hybrid\ panel\colon\ CF_{av.} = [(n_{PVt} \times S \times Y_e) \times EF_{kWh_e}] + [(n \times S \times Y_h) \times EF_{kWh_h}]$ | $n_{PVt}$ = number of PV-thermo hybrid solar panels;<br>$S$ = exposed surface [$m^2$];<br>$Y_e$ = electricity production yield [$kWh_e/m^2$];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$]<br>(Table 2);<br>$Y_h$ = heat production yield [$kWh_h/m^2$];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14). | $n$ = 1 household;<br>$S$ = 2 $m^2$ per household (ref. Tian and Zhao, 2013; University of Strathclyde, 2018);<br>$Y_e$ = from 1000 $kWh_e/m^2$ in N-EU to 2200 $kWh_e/m^2$ in S-EU (ref. Bosanac et al., 2003);<br>$Y_h$ = from 1000 $kWh_h/m^2$ in N-EU to 2200 $kWh_h/m^2$ in S-EU (ref. Bosanac et al., 2003; Baig et al., 2013).<br><br>Estimated $CF_{av}$:<br>1,254 – 1,758.80 kg $CO_2$-eq/house. | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 11 | $Renewable\ source\ based\ heat\ pumps\colon\ CF_{av.} = [(n \times H_{hw} \times y) \times EF_{kWh_h}] - (E_{hp} - PV_e)$ | $n$ = number of households [n];<br>$H_{hw}$ = heat demand for heating and hot water per household [$kWh_h$/yr];<br>$y$ = rate of heat energy saving [%];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14);<br>$E_{hp}$ = electricity demand to supply the heat pump [$kWh_e$/yr];<br>$PV_e$ = electricity supply by integrated PV [$kWh_e$/yr]. | $n$ = 1 household;<br>$H_{hw}$ = 7,562 $kWh_h$/yr (Table 3, excluded RES and heat for cooking);<br>$y$ = 4%; e.g. 2500 $kWh_e$/yr to supply about 10,000 $kWh_h$/yr (ref. Self et la., 2013).<br>Geothermal heat pumps can exploit horizontal heat exchangers (around 120% of household surface, until 60 cm depth) or vertical systems (around 110 m depth) (ref. Energy Expert, 2011);<br>$E_{hp}$ = 0 $kWh_e$ (assumed totally supported by PV panels)<br>$PV_e$ = 3,025 $kWh_e$.<br><br>Estimated $CF_{av}$:<br>1,905.62 kg $CO_2$-eq/house. | Spatial scale:<br>household, building.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 12 | $Biomass\ to\ energy\ cogeneration\colon\ CF_{av.} = [(B \times HP_b \times y \times b) \times EF_{kWh_h}] + [(B \times Y_e \times e) \times EF_{kWh_e}]$ | $B$ = quantity of biomass [t];<br>$HP_b$ = heat power of biomass [$kWh_h$/t];<br>$y$ = heat production yield [%]; | $B$ = 1 t biomass<br>$HP_b$ = 2500 $kWh_h$/1 t wood chips;<br>$y$ = from 30% (bio-residues) to 90% (wood chips) | Spatial scale:<br>neighborhood. |

| | | | | |
|---|---|---|---|---|
| | | *b* = heat self-consumption rate [%];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14);<br>$Y_e$ = electricity production yield [$kWh_e$/t];<br>*e* = electricity self-consumption rate [%];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | (ref. EAL, 2011);<br>*b* = average 80% of produced heat;<br>$Y_e$ = 1000 $kWh_e$/1 t wood chips;<br>*e* = average 75% of produced electricity (ref. EAL, 2011).<br><br>Estimated $CF_{av}$:<br>469.95 – 772.35 kg $CO_2$-eq/t biomass. | Temporal scale:<br>Medium term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 13 | $Distric\ heating\ Network\ (integrated\ renewable\ sources){:}\ CF_{av.} = [(n \times H_h \times h) + (n \times H_w \times w)] \times EF_{kWh_h}$ | *n* = number of households [n];<br>$H_h$ = heat demand for heating per household [$kWh_h$/yr];<br>*h* = rate of heat energy saving [%];<br>$H_w$ = water heating demand per household [$kWh_h$/yr];<br>*w* = rate of water heating energy saving [%];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14). | *n* = 1 household;<br>$H_h$ = 6,323 $kWh_h$/yr (Table 3, excluded RES);<br>*h* = 90% (ref. Ancona et al., 2015);<br>$H_w$ = 1,239 $kWh_h$/yr (Table 3, excluded RES);<br>*w* = 80% (ref. Ancona et al., 2015).<br><br>Estimated $CF_{av}$:<br>1,683.84 kg $CO_2$-eq/house. | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>Medium-long term.<br><br>Type of solution:<br>systemic/technological. |
| Eq. 14 | $Mini\ grid\ (integrated\ renewable\ sources){:}\ CF_{av.} = (n \times E_d) \times EF_{kWh_e}$ | *n* = number of households [n];<br>$E_d$ = electricity demand per household [$kWh_e$/yr];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | *n* = 1 household;<br>$E_d$ = 3,953 $kWh_e$/yr (Table 3, excluded RES);<br>Electricity mini grids is supplied by a combination of renewable energy generation plants (ref. Ancona et al., 2015).<br><br>Estimated $CF_{av}$:<br>1,482.36 kg $CO_2$-eq/house. | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>Medium-long term.<br><br>Type of change:<br>systemic/technological. |
| Eq. 15 | $Transition\ to\ electric\ systems{:}\ CF_{av.} = [(n \times H_d \times e) \times EF_{kWh_h}] - [(n \times E_d \times i) \times EF_{kWh_e}]$ | *n* = number of households [n];<br>$H_d$ = heat demand for cooking, heating and domestic hot water per household[$kWh_h$/yr];<br>*e* = rate of energy saving [%];<br>$EF_{kWh_h}$= EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14);<br>$E_d$ = electricity demand per household [$kWh_e$/yr];<br>*i* = increase of electricity demand [%];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | *n* = 1 household;<br>$H_d$ = 7,954 $kWh_h$/yr (Table 3, excluded RES);<br>*e* = 100%<br>$E_d$ = 3,953 $kWh_e$/yr (Table 3, excluded RES);<br>*i* = 180% (for heating and domestic hot water) and 50% (for cooking): overall 230% (ref. Nordic heating, 2015).<br><br>Estimated $CF_{av}$:<br>1,405.05 kg $CO_2$-eq/house. | Spatial scale:<br>household, building, neighborhood.<br><br>Temporal scale:<br>long term.<br><br>Type of solution:<br>systemic/technological, behavioral. |
| ***SET OF ACTIONS: SUSTAINABLE MOBILITY*** | | | | |
| Eq. 16 | $Biofuel\ production{:}\ CF_{av.} = (B_h \times Y_{eth} \times HP_{eth} \times D) \times EF_{km_{diesel}}$ | $B_h$ = harvested biomass [t];<br>$Y_{eth}$ = ethanol production yield [L/t];<br>$HP_{eth}$ = bioethanol heat power [$kWh_h$/L];<br>D = travelled km by private car per fuel unit [km/$kWh_h$];<br>$EF_{km_{diesel}}$= EF travelled km by private car [kg $CO_2$-eq/km] (Table 1, e.g. Item 23). | *B* = 1 t biomass;<br>$Y_{eth}$ = average from 1.4 L/t to 10 L/t for grain and maize (ref. Ghisolfi, 2008);<br>$HP_{eth}$ = 7520 $kWh_h$/L<br>*D* = average 2 km/$kWh_h$ (Cheung et al., 2015);<br>Bio-ethanol production yield in t/ha is: 22 t/ha for reed, 10 t/ha for sorghum, 1.4 t/ha for rapeseed, 1.63 t/ha for grain and 3.3 t/ha for maize (ref. Ghisolfi, 2008).<br><br>Estimated $CF_{av}$: | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>medium term.<br><br>Type of solution:<br>systemic/technological. |

| | | | | |
|---|---|---|---|---|
| | | | 3,558.46 – 25,417.60 kg $CO_2$-eq/t biomass. | |
| Eq. 17 | $Remote\ work\ \&\ bike/walk\ to\ school, work: CF_{av.} = (n_p \times \frac{u}{p} \times d \times t \times a) \times EF_{km_{diesel}}$ | $n_p$ = number of persons reached by specific measures (e.g. free Wi-Fi neighborhood, protected pathway to walk or ride around a school or working place, bike sharing system) [n];<br>$u$ = percentage of persons engaged that really change their behavior [%];<br>$p$ = average number of persons per vehicle [n];<br>$d$ = return commuting distance in working days [km/day];<br>$t$ = number of working days per yr [days/yr];<br>$a$ = rate of abandon of private car (e.g. working days walking or riding instead of driving) [%];<br>$EF_{km_{diesel}}$= EF travelled km by private car [kg $CO_2$-eq/km] (Table 1, e.g. Item 23). | $n_p$ = 1 person reached by specific measures;<br>$u$ = 10% (ref. Shaheen and Lipman, 2007);<br>$p$ = 1.15 person (Eurostat, 2015c);<br>$d$ = 10 km;<br>$t$ = 252 working days/yr;<br>$a$ = 80% working day walk & bike instead of driving (ref. Poundex, 2008).<br><br>Estimated $CF_{av}$:<br>28.39 kg $CO_2$-eq/person | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological; behavioral. |
| Eq. 18 | $Car\ pooling: CF_{av.} = (n_p \times d \times t \times a) \times EF_{km\ passenger}$ | $n_p$ = number of persons engaged besides drivers [n];<br>$d$ = average return commuting distance by car [km/day];<br>$t$ = number of working days per yr [days/yr];<br>$a$ = rate of abandon of private car (e.g. working days choosing car-pooling instead of driving) [%];<br>$EF_{km\ passenger}$ = EF passenger by diesel car [kg $CO_2$-eq/(km person)] (Table 1, Item 25). | $n_p$ = 1 of engaged person;<br>$d$ = 40 km (ref. Manzini and Pareschi, 2012);<br>$t$ = 252 working days/yr;<br>$a$ = 80% working day car-pooling instead of driving (ref. Manzini and Pareschi, 2012).<br><br>Estimated $CF_{av}$:<br>1,428.96 kg $CO_2$-eq/person | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systemic/technological; behavioral. |
| Eq. 19 | $Public\ transport: CF_{av.} = (n_p \times d \times t \times a \times p) \times (EF_{km\ passenger} - EF_{km\ bus\ passenger})$ | $n_p$ = number of engaged persons [n];<br>$d$ = return commuting distance in working days [km/day];<br>$t$ = number of working days per yr [days/yr];<br>$a$ = rate of abandon of private car (e.g. working days taking public transport instead of driving) [%];<br>p = rate of new passengers that avoid car use [%];<br>$EF_{km\ passenger_{diesel}}$ = EF passenger by diesel car [kg $CO_2$-eq/(km person)] (Table 1, Item 25);<br>$EF_{km\ bus\ passenger}$ = EF passenger by bus [kg $CO_2$-eq/(km person)] (Table 1, Item 27). | $n_p$ = 1 engaged person;<br>$d$ = 50 km/day;<br>$t$ = 252 working days/yr;<br>$a$ = 80% working day public transport instead of driving (ref. Yan and Crookes, 2009);<br>$p$ = 80% avoided use of private car (ref. Yan and Crookes, 2009).<br><br>Estimated $CF_{av}$:<br>959.62 kg $CO_2$-eq/person | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>Short-medium term.<br><br>Type of solution:<br>systemic/technological; behavioral. |
| Eq. 20 | $Transition\ to\ electric\ mobility: CF_{av.} = [(n_v \times d) \times EF_{km}] - [(n_v \times d \times E_v) \times EF_{kWh_e}]$ | $n_v$ = number of replaced vehicles;<br>d = total travelled distance by car per year [km/yr];<br>$EF_{km}$= EF travelled km by private car (diesel as average) [kg $CO_2$-eq/km] (Table 1, Item 23); | $n_v$ = 1 replaced vehicles;<br>$d$ = 14,000 km/yr (ref. Eurostat, 2015c);<br>$E_v$ = 16 $kWh_e$/100 km (ref. GAA, 2015).<br><br>Estimated $CF_{av}$:<br>1,526 kg $CO_2$-eq/vehicle | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>long term. |

| | | | | |
|---|---|---|---|---|
| | | $E_v$ = electricity demand per km travelled by electric vehicles [$kWh_e$/km];<br>$EF_{kWh_e}$= EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2). | | Type of solution:<br>systemic/technological; behavioral. |
| ***SET OF ACTIONS: WASTE MANAGEMENT*** | | | | |
| Eq. 21 | $Waste\ reduction\ \&\ increased\ recycling{:}\ CF_{av.} = \{[(n \times W \times w_l) \times r \times EF_l] + [(n \times W \times w_i) \times r \times EF_i] + [(n \times W \times w_o) \times r \times EF_o]\} - [(n \times W) \times r_r \times EF_r]$ | *n* = number of households [n];<br>*W* = collected waste per household [t/yr];<br>$w_l$ = current waste fraction disposed to landfill [%];<br>$w_i$ = current waste fraction to incineration [%];<br>$w_o$ = current waste fraction to composting plants [%];<br>*r* = rate of waste reduction [%];<br>$r_r$ = rate of increased waste recycling [%];<br>$EF_l$ = EF waste treated in landfill [kg $CO_2$-eq/kg] (Table 1, Item 29);<br>$EF_i$ = EF waste treated in incinerators [kg $CO_2$-eq/kg] (Table 1, Item 28);<br>$EF_o$ = EF organic waste treated in composting plants [kg $CO_2$-eq/kg] (Table 1, Item 30);<br>$EF_r$ = EF of recycling waste [kg $CO_2$-eq/kg] (assumed = 0, Table 1, Item 31). | *n* = 1 household;<br>*W* = 1095 kg/yr: 406 kg waste / person; 2.7 person / household (Table 3);<br>$w_l$= 28% (Table 3);<br>$w_i$ = 27% (Table 3);<br>$w_o$ = 16% (Table 3);<br>r = -10% reduction (ref. Marchi et al., 2017a; 2018)<br>$r_r$ = +20% increase (i.e.49% *vs* 29% in Table 3) (ref. Marchi et al., 2017a; 2018);<br><br>Estimated $CF_{av}$:<br>98 kg $CO_2$-eq/house | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systematic/technological; behavioral. |
| Eq. 22 | $Dicrease\ of\ lanfilled\ waste\ fraction{:}\ CF_{av.} = [(n \times W \times w_l) \times l \times EF_l] - \{[(n \times W \times w_i) \times i \times EF_i] + [(n \times W \times w_o) \times o \times EF_o] + [(n \times W \times w_r) \times r \times EF_r]\}$ | *n* = number of households [n];<br>*W* = collected waste per household [kg/yr];<br>$w_l$ = current waste fraction disposed to landfill [%];<br>$w_i$ = current waste fraction to incineration [%];<br>$w_o$ = current waste fraction to composting plants [%];<br>$w_r$ = current recycled waste fraction [%];<br>*l* = reduction of landfilled waste fraction [%];<br>*i* = increase of incinerated waste fraction [%];<br>*o* = increase of composted waste fraction [%];<br>*r* = increase of recycled waste fraction [%];<br>$EF_l$ = EF waste treated in landfill [kg $CO_2$-eq/kg] (Table 1, Item 29);<br>$EF_i$ = EF waste treated in incinerators [kg $CO_2$-eq/kg] (Table 1, Item 28);<br>$EF_o$ = EF organic waste treated in composting plants [kg $CO_2$-eq/kg] (Table 1, Item 30);<br>$EF_r$ = EF of recycling waste [kg $CO_2$-eq/kg] (assumed = 0, Table 1, Item 31). | *n* = 1 household;<br>*W* = 1095 kg/yr : 476 kg waste / person; 2.3 person / household (Table 3);<br>$w_l$= 28% (Table 3);<br>$w_i$ = 27% (Table 3);<br>$w_o$ = 16% (Table 3);<br>$w_r$ = 29% (Table 3);<br>*l* = -10% reduction (i.e. 18% *vs* 28% in Table 3) (ref. Marchi et al., 2017a; 2018);<br>*i* = +10% increase (i.e. 37% *vs* 27% in Table 3) (ref. Marchi et al., 2017a; 2018);<br>*o* = +10% increase (i.e. 26% *vs* 16% in Table 3) (ref. Marchi et al., 2017a; 2018);<br>*r* = +10% increase (i.e. 39% *vs* 29% in Table 3) (ref. Marchi et al., 2017a; 2018).<br><br>Estimated $CF_{av}$:<br>11 kg $CO_2$-eq/house | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>short term.<br><br>Type of solution:<br>systematic/technological; behavioral. |
| Eq. 23 | $Waste\ to\ energy{:}\ CF_{av.} = \{[(n \times W \times w_i) \times HP_w \times y \times EF_{kWh_h}] + [(n \times W \times w_i) \times Y_e \times EF_{kWh_e}]\} - [(n \times W \times w_i) \times EF_i]$ | *n* = number of households [n];<br>*W* = collected waste per household [t/yr];<br>$w_i$ = current waste fraction to incineration [%]; | *n* = 1 household;<br>*W* = 1095 kg/yr : 476 kg waste / person; 2.3 person / household (Table 3);<br>$w_i$ = 27% (Table 3) | Spatial scale:<br>neighborhood.<br><br>Temporal scale: |

| | | | | |
|---|---|---|---|---|
| | | $HP_w$ = heat power of waste [$kWh_h$/t];<br>$y$ = heat production yield [%];<br>$EF_{kWh_h}$ = EF natural gas for heating [kg $CO_2$-eq/$kWh_h$] (Table 1, Item 14);<br>$Y_e$ = electricity production yield [$kWh_e$/t];<br>$EF_{kWh_e}$ = EF electricity [kg $CO_2$-eq/$kWh_e$] (Table 2);<br>$EF_i$ = EF waste treated in incinerators [kg $CO_2$-eq/kg] (Table 1, Item 28). | $HP_w$ = 600 $kWh_h$/t of waste (ref. Siena Ambiente, 2015);<br>y = 70%;<br>$Y_e$ =500 $kWh_e$/t of waste (ref. Siena Ambiente, 2015).<br>A plant that burn in average 70,000 t of waste/yr produces 35,00 $MWh_e$ and 42,000 $MWh_h$.<br><br>Estimated $CF_{av}$:<br>67,450 kg $CO_2$-eq/house | Medium term<br><br>Type of solution:<br>systemic/technological. |
| ***SET OF ACTIONS: WATER RESOURCE MANAGEMENT & CARBON UPTAKE BY URBAN ECOSYSTEMS*** | | | | |
| Eq. 24 | $Water\ use\ reduction\ \&\ rainwater\ harvesting\!:\ CF_{av.} = n \times w \times r \times EF_w$ | $n$ = number of households [n];<br>$w$ = water use per household [$m^3$/yr];<br>$r$ = tap water saving rate [%];<br>$EF_w$ = EF tap water use [kg $CO_2$-eq/$m^3$] (Table 1, Item 32). | $n$ = 1 household;<br>$w$ = 134 $m^3$/yr (Table 3);<br>$r$= 40% (ref. Deng et al., 2016).<br><br>Estimated $CF_{av}$:<br>31.36 kg $CO_2$-eq/house | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>Short term.<br><br>Type of solution:<br>systematic/technological; behavioral. |
| Eq. 25 | $Green\ areas\!:\ CO_2 uptake = GS \times EF_E$ | $GS$ = Green space surfaces [$m^2$];<br>$EF_E$ = Emission removals by ecosystems relative to different plant species (e.g. grass, herbaceous plants, vegetable gardens, urban forestry, fruit trees) [kg $CO^2/m^2$] (Table 1, Item 33-36). | $GS$ = 1 $m^2$;<br>$EF_E$ = grass and herbaceous plants in roofs, facades, lawns-flowerbeds-vegetable gardens (in average 0.65 kg $CO_2/m^2$), fruit trees (0.56 kg $CO_2/m^2$) and urban forestry (1.35 kg $CO_2/m^2$).<br><br>Estimated $CF_{av}$:<br>Table 1, Item 33-36 | Spatial scale:<br>neighborhood.<br><br>Temporal scale:<br>medium term.<br><br>Type of solution:<br>systemic/technological. |

Table 5: Parameters used for the assessment of the selected CF mitigation measures.

| n. | CF mitigation measure | Symbol | Value | Description | Eq. n. (Table 4) |
|---|---|---|---|---|---|
| **a) Saving electricity, fuels, waste and water** | | | | | |
| 01 | Building shading and UHIE mitigation | $n$ | 6000 | Involved households | 1-2 |
| | | $e$ | -10% | Rate of cooling energy saving | |
| 02 | Building envelope retrofitting | $n$ | 4000 | Involved households | 3 |
| | | $e_c$ | -80% | Rate of cooling energy saving | |
| | | $e_h$ | -60% | Rate of hating energy saving | |
| 03 | LED lamps | $n$ | 4500 | Involved households | 4 |
| | | $l \times (P_0\text{-}P_n) \times t$ | 318 kWh/house | Lighting energy saving | |
| 04 | Bike/walk to school-work | $n$ | 1500 | Involved households | 17 |
| | | $u/p \times d \times t \times a$ | 16100 km/house | Avoided distance travelled by car | |
| 05 | Public transport | $n$ | 4000 | Involved households | 19 |
| | | $d \times t \times a \times p$ | 16100 km/house | Avoided distance travelled by car | |
| 06 | Waste reduction and increased recycling | $n$ | 10,000 | Involved households | 21 |
| | | $r$ | -10% | Reduced (landfilled) waste production | |
| 07 | Lower landfilled and incinerated waste | $n$ | 10,000 | Involved households | 22 |
| | | $l$ | -60% | Reduction of landfilled waste | |
| | | $i$ | -30% | Reduction of incinerated waste | |
| | | $o$ | 30% | Increase of composted waste | |
| | | $r$ | 70% | Increase of recycled waste | |
| 08 | Water use reduction | $n$ | 10,000 | Involved households | 24 |
| | | $r$ | -40% | Tap water saving rate | |
| **b) Installation of varies renewable energy sources** | | | | | |
| 09 | Biomass to energy cogeneration | $B \times HP_b \times y \times b$ | 10,000 MWh | Heat production (i.e. 1000 equivalent houses) | 12 |
| | | $B \times Y_e \times e$ | 4500 MWh | Electricity production (i.e. 1100 equivalent houses) | |
| 10 | District Heating Network | $n$ | 1800 | Involved households | 13 |
| | | $h$ | -90% | Rate of heat energy saving | |
| | | $w$ | -80% | Rate of water heating energy saving | |
| 11 | PV on roofs | $S \times P \times Y \times a$ | 30,000 MWh | Renewable energy production (i.e. 7500 equivalent households) | 6 |
| 12 | Wind turbines | $n_{wt} \times P \times v \times t$ | 20,000 MWh | Renewable energy production (i.e. 5000 equivalent households) | 7 |
| **c) Electrification of the residual fuels** | | | | | |
| 13 | Transition to electric systems | $n \times E_h \times e$ | 42,000 MWh | Residual energy demand (i.e. 3500 equivalent households) | 15 |
| | | $n \times E_d \times i$ | 11,000 MWh | Additional electricity demand (i.e. 2700 equivalent households) | |
| 14 | Transition to electric mobility | $n$ | 4500 | Involved households | 20 |
| | | $d$ | 16100 km/house | Avoided distance travelled by car | |
| | | $E_v$ | 7000 MWh | Additional electricity demand (i.e. 1700 equivalent households) | |
| **d) Removals of GHG emissions (Carbon uptake by vegetation)** | | | | | |
| 15 | Carbon uptake by ecosystems | $GS$ | 169 ha | Forestland needed to compensate the residual CF | 25 |

Table 6: Carbon Footprint of the EU-28 household and Activity data and Carbon Footprint of EU-28 neighbourhood of 10,000 households.

| **Human activity** | **EU-28 HOUSEHOLD** CF kg $CO_2$-eq | Unit | **EU-28 NEIGHBOURHOOD** Activity data | **EU-28 NEIGHBOURHOOD** CF t $CO_2$-eq | **Percentage** |
|---|---|---|---|---|---|
| **ENERGY (housing)** | **3,554** | **$kWh_e^b$/yr** | **157,040,000** | **35,547** | 51.33% |
| **Electricity** | 1,481 | **$kWh_e$/yr** | **39,690,000** | 14,813 | 21.39% |
| lighting, appliances | 894 | $kWh_e$/yr | 23,850,000 | 8,937 | 12.90% |
| cooling | 29 | $kWh_e$/yr | 780,000 | 292 | 0.42% |
| cooking | 165 | $kWh_e$/yr | 4,390,000 | 1,645 | 2.38% |
| heating | 229 | $kWh_e$/yr | 6,120,000 | 2,293 | 3.31% |
| DHW | 165 | $kWh_e$/yr | 4,390,000 | 1,645 | 2.38% |
| RES[a] electricity | 0 | $kWh_e$/yr | 160,000 | 0 | 0.00% |
| **Fuels** | 2,073 | **$kWh_h^c$/yr** | **117,350,000** | 20,734 | 29.94% |
| Natural Gas - heating | 1,082 | $kWh_h$/yr | 42,990,000 | 10,820 | 15.62% |
| Natural Gas - DHW | 241 | $kWh_h$/yr | 9,570,000 | 2,409 | 3.48% |
| Natural Gas - cooking | 71 | $kWh_h$/yr | 2,820,000 | 710 | 1.02% |
| Petroleum - heating | 569 | $kWh_h$/yr | 20,240,000 | 5,693 | 8.22% |
| Petroleum - DHW | 79 | $kWh_h$/yr | 2,820,000 | 793 | 1.15% |
| Petroleum - cooking | 31 | $kWh_h$/yr | 1,100,000 | 309 | 0.45% |
| RES - heating | 0 | $kWh_h$/yr | 32,320,000 | 0 | 0.00% |
| RES - DHW | 0 | $kWh_h$/yr | 5,020,000 | 0 | 0.00% |
| RES - cooking | 0 | $kWh_h$/yr | 470,000 | 0 | 0.00% |
| **MOBILITY** | **2,728** | **km/yr** | **161,000,000** | **27,281** | 39.39% |
| passenger car - petrol | 1,274 | km/yr | 74,060,000 | 12,740 | 18.40% |
| passenger car - diesel | 1,411 | km/yr | 83,720,000 | 14,113 | 20.38% |
| passenger car - LPG | 43 | km/yr | 3,220,000 | 427 | 0.62% |
| **WASTE** | **564** | **kg/yr** | **10,948,000** | **5,642** | 8.15% |
| % waste-to-energy | 357 | kg/yr | 3,081,862 | 3,575 | 5.16% |
| % waste-to-energy | 190 | kg/yr | 2,920,926 | 1,904 | 2.75% |
| % organic | 16 | kg/yr | 1,794,377 | 163 | 0.23% |
| % recycling | 0 | kg/yr | 3,150,834 | 0 | 0.00% |
| **WATER** | **79** | **$m^3$/yr** | **1,343,200** | **786** | 1.13% |
| $m^3$ per yr (house) | 79 | $m^3$/yr | 1,343,200 | 786 | 1.13% |
| **TOTAL** | **6,926** | | | **69,256** | |

[a] RES = Renewable Energy Sources.
[b] kWh of electricity produced (hereafter $kWh_e$).
[c] kWh of heat produced (hereafter $kWh_h$).

Table 7: GHG emissions reduciton due to the activaiton of environmental policies.

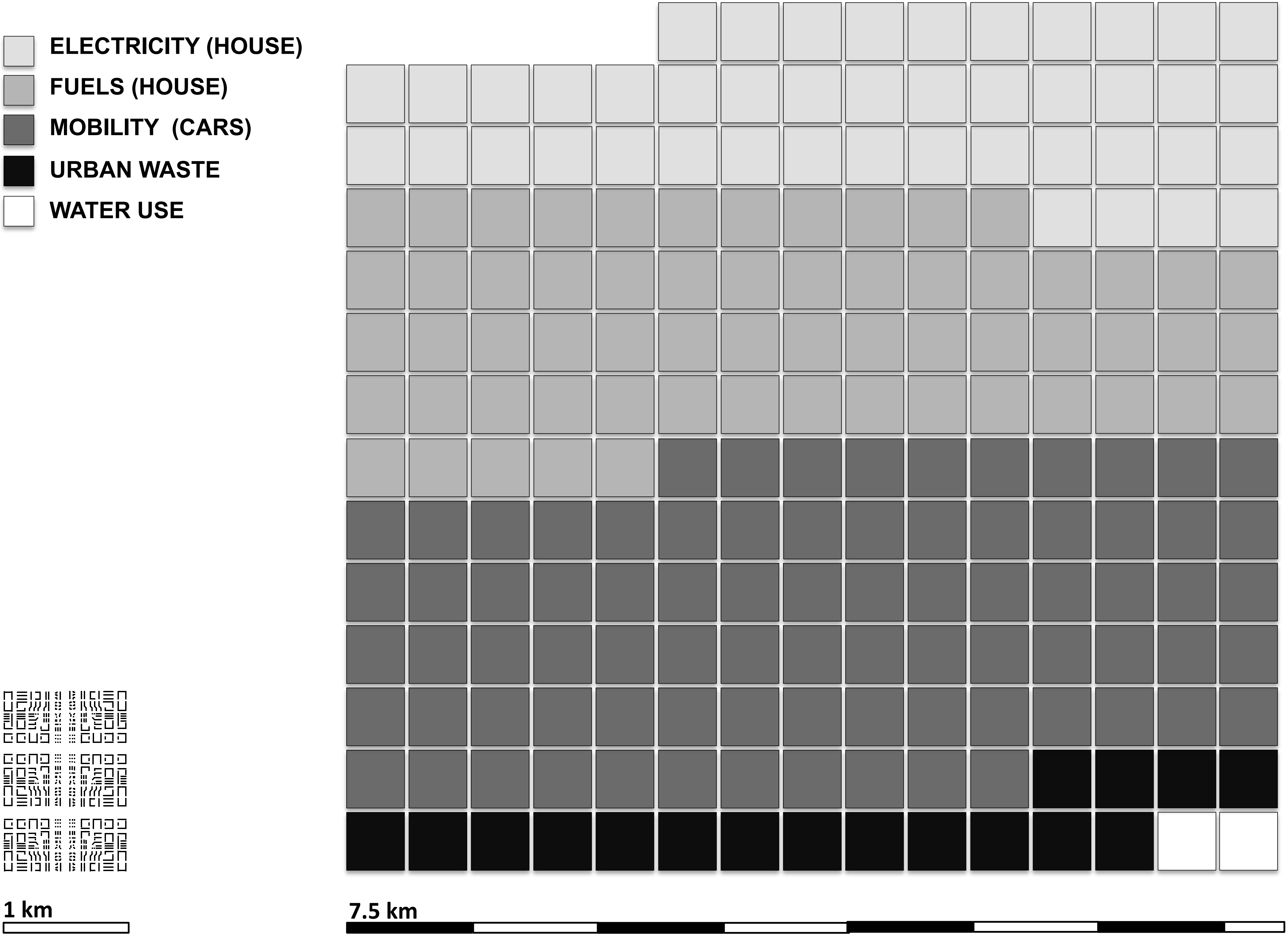
| n. | CF mitigation measure | Electricity | Lighting, appliances | Cooling | Cooking | Heating | DHW | RES electricity | Fuels | Heating | DHW | Cooking | Mobility | Waste | Water | $CF_{av.}$ | CF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $MWh_e$/yr | $MWh_e$/yr | $MWh_e$/yr | $MWh_e$/yr | $MWh_e$/yr | $MWh_e$/yr | $MWh_e$/yr | $MWh_h$/yr | $MWh_h$/yr | $MWh_h$/yr | $MWh_h$/yr | km/yr | t/yr | $m^3$/yr | t $CO_2$-eq/yr | t $CO_2$-eq/yr |
| **0** | **Neighbourhood at the current state** | 39,690 | 23,850 | 780 | 4,390 | 6,120 | 4,390 | 160 | 117,350 | 63,230 | 12,390 | 3,920 | 161,000,000 | 10,948 | 1,343,200 | **69,256** | 69,256 |
| **a) Saving electricity, fuels, waste and water** | | | | | | | | | | | | | | | | | |
| 01 | Building shading and UHIE mitigation | -47 | | -47 | | | | | | | | | | | | **-18** | 69,238 |
| 02 | Building envelope retrofitting | -1,718 | | -250 | | -1,469 | | | -15,175 | -15,175 | | | | | | **-4,607** | 64,631 |
| 03 | LED lamps | -1,431 | -1,431 | | | | | | | | | | | | | **-536** | 64,095 |
| 04 | Bike/walk to school, work | | | | | | | | | | | | -24,150,000 | | | **-4,092** | 60,003 |
| 05 | Public transport | | | | | | | | | | | | -64,400,000 | | | **-10,912** | 49,091 |
| 06 | Waste reduction and increased recycling | | | | | | | | | | | | | -1,109 | | **-1,287** | 47,804 |
| 07 | Lower landfilled and incinerated waste | | | | | | | | | | | | | -2,725 | | **-2,669** | 45,135 |
| 08 | Water use reduction | | | | | | | | | | | | | | -537,280 | **-314** | 44,821 |
| **b) Installation of varies renewable energy sources** | | | | | | | | | | | | | | | | | |
| 09 | Biomass to energy cogeneration | -4,501 | | | | | | -4,501 | -10,023 | -8,536 | -1,487 | | | | | **-4,293** | 40,528 |
| 10 | District Heating Network | | | | | | | | -12,027 | -10,243 | -1,784 | | | | | **-3,136** | 37,392 |
| 11 | PV on roofs | 30,000 | | | | | | -30,000 | | | | | | | | **-11,197** | 26,195 |
| 12 | Wind turbines | 20,000 | | | | | | -20,000 | | | | | | | | **-7,465** | 18,730 |
| **c) Electrification of the residual fuels** | | | | | | | | | | | | | | | | | |
| 13 | Transition to electric systems | 11,190 | | | | | | | -42,156 | -33,512 | -6,567 | -2,078 | | | | **-6,796** | 11,934 |
| 14 | Transition to electric mobility | 7,001 | | | | | | | | | | | -72,450,000 | | | **-9,653** | 2281 |
| **d) Removals of GHG emissions (Carbon uptake by vegetation)** | | | | | | | | | | | | | | | | | |
| 15 | Carbon uptake by ecosystems | | | | | | | | | | | | | | | **-2281** | 0 |

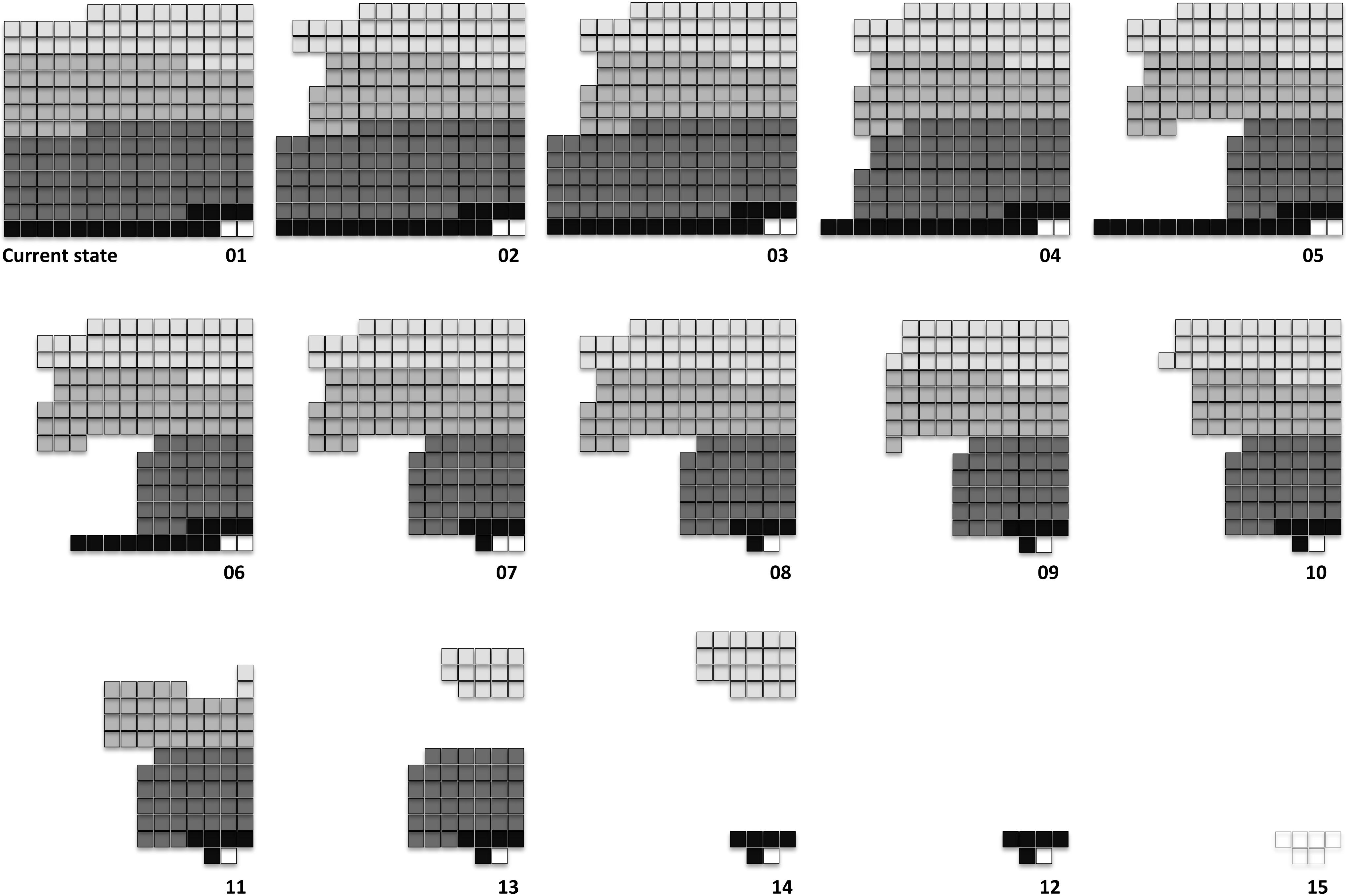
**FIGURE CAPTIONS**

Figure 1: Carbon Footprint offset, i.e. virtual forestland (5130 ha) of the average European neighbourhood (23,000 inhabitants, 150 ha).

Figure 2: Visualisation of the long term Carbon Footprint mitigation scenario based on virtual forestland of the average European neighbourhood (23,000 inhabitants)[a].

[a] Numbers refer to the measures listed in Table 7; the number 0 is the current state; the number 15 represents the compensation by carbon uptake (needed forestation area).
Action 01 does not provide visible effects in decreasing GHG emissions, compared to the current state.
Action 12 is postponed after actions 13 and 14 that require an increase of electricity demand.


ELECTRICITY (HOUSE)
FUELS (HOUSE)
MOBILITY (CARS)
URBAN WASTE
WATER USE
1 km
7.5 km


Current state
01
02
03
04
05
06
07
08
09
10
11
13
14
12
15

**Research highlights**

A mediate model is developed to assess GHG emissions of urban neighborhoods.

Processed data refers to an average European neighborhood as reference benchmark.

The model assesses Carbon Footprint mitigation scenarios to inform urban design.

A spatial visualization of GHG emissions reduction shows effects of planned measures.