CARBON AND ENVIRONMENTAL FOOTPRINT OF CITIES AND COMMUNITIES: A LIVING LABS EXPERIENCE

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ABSTRACT

The paper first provides an overview of the environmental footprints used to assess the impacts of human activities on the environment. The Horizon 2020 I-CHANGE project, dealing with the challenge of engaging and promoting the active participation of citizens to address climate change, sustainable development and environmental protection, is then introduced. Finally, the environmental footprint methodologies are applied on the basis of information collected from the Living Labs about daily activities, traffic simulation results and statistical data to compute specific footprints in base case and alternative scenarios for different Living Labs in the I-CHANGE project.

Keywords: carbon footprint, environmental footprint, Living Lab, traffic simulation, energy consumption, waste management, air pollutants emissions, biometeorological indicators.

1 INTRODUCTION

Several methods, tools and indicators, developed over the years, are available to measure and quantify the impacts of human activities on the environment. This quantification provides the basis for development of required interventions for mitigation and therefore help in decision-making. The term environmental footprint is an umbrella term [1] for the different footprint concepts that have been developed during the past two decades, including carbon footprints. An environmental footprint family is composed of a set of indicators that helps to evaluate the pressure of human activities on the environment from different angles [2].

There is a large body of literature (especially scientific papers and reports) utilising the term footprint, and it is still exponentially growing. The majority of the papers limited their focus on carbon, water and ecological footprints. However, because of complex environmental problems that are resulting from various pressures, a concept of footprint family has recently emerged and is being further refined on a variety of different bases. In the paper by Vanham et al., the authors have defined a family of environmental footprints, identified overlaps between different footprints and analysed how they are related to nine planetary boundaries (thresholds within which humanity can survive, develop and thrive for generations to come) [1]. Additionally, they have also assessed how the footprint family is helpful in measuring progress towards the Sustainable Development Goals (SDGs) [3]. Recently, a review paper presented almost a similar framework [4]. Fig. 1 presents the illustration of different footprints, their overlaps and also their relationship with planetary boundaries.

Based on Fig. 1, each footprint represents a particular environmental concern and attempts to quantify either resource appropriation (resource use) or emissions generated or both [5].

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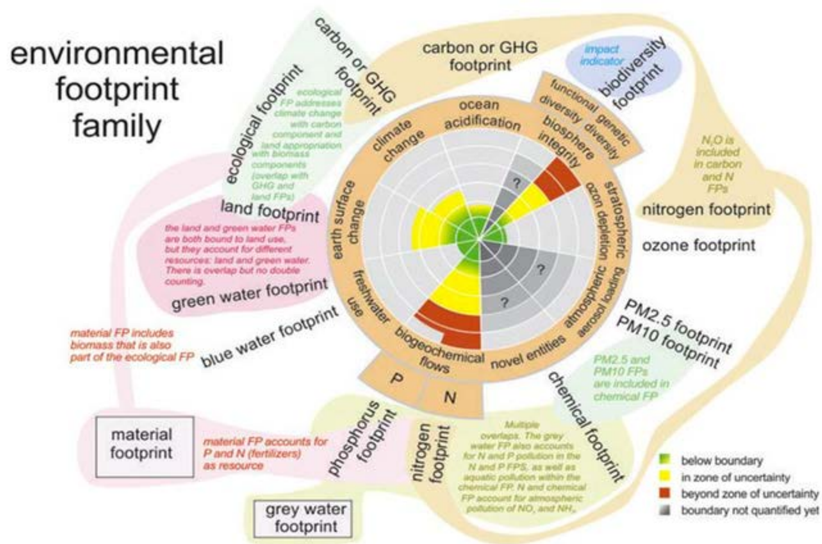

Figure 1: Environmental footprint family [1].

Footprints are usually estimated for products at any stage of their production to end user consumption, for individuals, communities (residing at street level or villages to global level), for companies or economic sector [6]. Because of this flexibility in the estimation process at various levels, the quantification process involves understanding the product development process along with its transportation and consumption patterns. Also, if it is for individuals, then it is required to obtain information in a way that their lifestyle is appropriately understood. Therefore, the development of their quantification methodology requires involving a variety of stakeholders, civil society, industrial stakeholders and decision makers [5].

2 I-CHANGE PROJECT

2.1 The project concept

The Horizon 2020 I-CHANGE project deals with the challenge of engaging and promoting the active participation of citizens to address climate change, sustainable development and environmental protection in the framework of the European Green Deal, the European Climate Pact and the European Biodiversity Strategy for 2030.

The overall concept is based on the idea that citizens and civil society have a central role in the definition of environmental protection and climate action and their direct involvement is essential to drive a true shift and promotion of changes of behaviours towards more sustainable patterns.

The project follows the EU Horizon 2020 Innovation actions type of funding scheme and addresses the Topic LC-GD-10-3-2020 ‘Enabling citizens to act on climate change, for sustainable development and environmental protection through education, citizen science, observation initiatives, and civic engagement’.

I-CHANGE represents a change of paradigm achievable through a multi-disciplinary and participatory approach. The project addresses the environment and climate challenges from two perspectives: (1) Empowerment through knowledge acquired through hands-on participation in the monitoring and assessment; and (2) Understanding the role and the impact of individual choices (behaviour, lifestyle and consumptions) in the daily life and its consequences on the environment. To shape this vision the development of the I-CHANGE action leverages on three main pillars:

- Climate change awareness: I-CHANGE promotes the knowledge of science and the understanding of physical, socio-economic and cultural processes, to raise awareness and educate citizens to be engaged in the actions toward climate neutrality.
- Active participation of citizens: I-CHANGE is based on the active participation of citizens in collecting, monitoring and better observation of the environment and of their environmental impacts within a set of Living Labs (LLs) located in different socio-economic contexts, belonging to countries with different levels of climate change awareness and affected by a wide range of climatic conditions in and outside Europe.
- Improvement of data usability and interoperability with existing and future datasets.

I-CHANGE is conducted by a consortium of universities (University di Bologna, Italy; Tel Aviv University, Israel; University College Dublin, Ireland; University de Barcelona, Spain; Wageningen University, Netherland; and Universities Hasselt, Belgium), research centres (Centro Internazionale in Monitoraggio Ambientale – Fondazione CIMA Italy; CNR Consiglio nazionale delle ricerche, Italy; Luonnonvarakeskus, Finland; West African Science Services Centre on Climate Change; and Adapted Land Use, Ghana), not-for-profit organisations (Fonden Teknologiradet, Denmark and DEN Institute, Belgium), international organisations (European Centre for Medium-Range Weather Forecasts, UK) and SMEs (Techne Consulting, Italy; Kajo pro, Slovakia; and CMF Climate Media Factory UG Haftungsbeschrankt gmbh, Deutschland).

2.2 The Living Labs

At the centre of the I-CHANGE project, there are the eight LLs, located in geographical areas impacted by different hazards and challenges connected to climate change. Fig. 2 depicts the LLs locations and reports on their environmental issues.

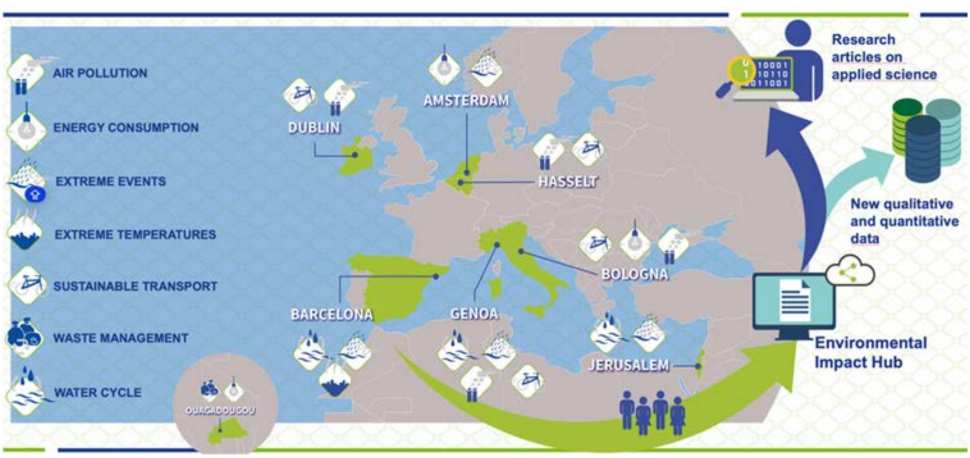

Figure 2: I-CHANGE LLs locations and main topics of interest.

Based on the aforementioned data and topics investigated in the LLs (Table 1), the following ones were considered relevant for the calculation of carbon and environmental footprints: Energy consumption, sustainable transport and waste management.

Table 1: Type of data planned or collected in I-CHANGE LLs.

Living Lab	**Data**
Amsterdam	Temperature, humidity, CO_2, concentration, sound level at 5 min interval for Netatmo: temperature, humidity, wind speed, rain, radiation and turbulent fluxes (including CO_2) + traverse observations of temperature, humidity, wind speed, long and shortwave radiation, indoor temperature.
Barcelona	Temperature, humidity, precipitation, barometric pressure, PM concentration and CO_2.
Bologna	Data from Meteotracker and Smart Citizens Kit; Meteorological data (temperature, wind, precipitation, relative humidity) from ARPAE; traffic flow data; population data; other open data or collected through specific campaigns (e.g. mapping of existing NBS. Data from high-end sensing technologies (sonic anemometers, thermal cameras, ceilometer, net radiometer).
Dublin	Weather station; Air pollution from EPA and local council stations; data from Smart Citizens Kit and Telraam traffic counters.
Genoa	Temperature, relative humidity, precipitation; Data from Meteotracker and Smart Citizens Kit; fuel consumptions; water consumptions.
Hasselt	Temperature, barometric pressure; change of transport mode; pollutants concentrations.
Jerusalem	Temperature, pressure, humidity, radiation, altitude, air pollution, cellular signal power.
Ouadagougou	LCE analysis: waste type and quantity. Compliance with waste sorting, Quantity of waste reused or recycled. HRA analysis: rainfall, sea-surface temperature, relative humidity, precipitable water, wind speed and direction, evapotranspiration, water level.

An important target of LLs activities are the extreme events studies, whose frequency is increasing due to climate change [7]. In this regard, a group of LLs (Genoa, Barcelona, Amsterdam, Bologna and Jerusalem) is collecting a wide range of meteorological parameters. To improve the suitability of the environmental footprint definition for these I-CHANGE LLs, as will be shown later in Section 2.4, we have extended its original definition to include a set of selected biometeorological indicators to report a synthetic picture of impact of environmental and weather conditions, particularly extreme temperatures, on health. The indexes addressed individual’s perceived temperature, based upon the air temperature and humidity and/or wind speed.

2.3 Carbon and environmental footprints definition

2.3.1 Carbon footprint

Since the target of the project is citizens/individual behavioural change, the carbon footprint evaluation is conducted in accordance with the approach followed in the Covenant of Mayors

[8], i.e. an emission inventory approach. The I-CHANGE calculation uses specific activity level and both:

- Standard emission factors: Emissions are evaluated using methodologies and emission factors from IPCC Guidelines for National Greenhouse Gas Inventories [9]; the methodology covers all the CO_2 emissions related to energy consumption within the territory of the city/region, either directly due to fuel combustion within the city/region or indirectly via fuel combustion associated with electricity and heat/cold usage within their area. Emissions are reported as:
    - o CO_2 only emissions, the most important greenhouse gas;
    - o CO_2 equivalent emissions, including the evaluation of the emissions of CH_4 and N_2O using the global warming potential (GWP) with time horizon of 100 years [10]:

$$1 \text{ Mg } CO_2 = 1 \text{ Mg } CO_{2\text{-eq}}$$

$$1 \text{ t } CH_4 = 21 \text{ Mg } CO_{2\text{-eq}}$$

$$1 \text{ t } N_2O = 310 \text{ Mg } CO_{2\text{-eq}}.$$

- LCA (life cycle assessment) emission factors: They take into consideration the overall life cycle of the energy carrier. This approach accounts not only for the emissions of the final combustion, but also for all the emissions of the supply chain; it includes emissions from exploitation, transport and processing (e.g. refinery) steps in addition to the final combustion; this hence includes also emissions that take place outside the location where the fuel is used; in absence of specific national or local emission factors, will be used the LCA emission factors given in Covenant of Mayors guidelines, based on JRC European Reference Life Cycle Database ELCD.

As for emissions, the model used in the project:

- evaluates emissions from activities data coming from LLs activities and traffic simulation realised in the project;
- uses emission factors from Covenant of Mayors guidelines or specific emission factors in the area of LLs;
- calculates emissions as:

$$E_k = A_{ij} F_{ik}$$

where:

- A_{ij} is the indicator of the activity i in the territorial unit j;
- F_{ik} is the emission factor for different carbon footprint indicators k for activity i (expressed in grams per unit of activity);
- k is the carbon footprint indicator used: CO_2, CO_{2eq}, CO_{2eq} LCA.

In Table 2 the CO_2 fuel standard emission factors used are reported [11]; furthermore, specific emission factors in the area of LLs are used for Bologna road traffic [12], Amsterdam electricity use [13] and natural gas combustion [14].

2.3.2 Air pollution environmental footprints

I-CHANGE approach is to evaluate in an integrated way emissions inventory and carbon footprint.

Table 2: CO_2 standard emission factors [11].

Fuel	**CO_2 standard emission factors (Mg/MWh(**	**CO_{2eq} standard emission factors (Mg/MWh)**	**CO_{2eq} LCA emission factors (Mg/MWh)**
Motor gasoline	0.249	0.250	0.299
Gas oil, diesel	0.267	0.268	0.305
Natural gas	0.202	0.202	0.237

The air pollution environmental footprint defined starting from emission inventories are the following ones [15]:

- Acidification potential. The reference substance is SO2 and specific weight coefficient factors are defined to convert emissions of specific substance to SO2:

$$AP = f_{SOx} \times E_{SOx} + f_{NOx} \times E_{NOx} + f_{NH3} \times E_{NH3}$$

The equivalency factors are given by: $f_{SOx} = 31.25$; $f_{NOx} = 21.74$; $f_{NH3} = 58.82$.

- Tropospheric ozone formation potential. The indicator includes the emissions of ozone precursors each weighted by a factor prior to aggregation:

$$TOFP = f_{NMVOC} \times E_{NMVOC} + f_{NOx} \times E_{NOx} + f_{CH4} \times E_{CH4} + f_{CO} \times E_{CO}$$

The equivalency factors are given by: $f_{NMVOC} = 1$; $f_{NOx} = 1.22$; $f_{CH4} = 0.014$; $f_{CO} = 0.11$.

- Aerosol formation potential. The indicator includes the emissions of primary PM_{10} and of PM_{10} gaseous precursors each weighted by a factor prior to aggregation:

$$AFP = E_{PM10} + f_{SOx} \times E_{SOx} + f_{NOx} \times E_{NOx} + f_{NH3} \times E_{NH3}$$

The equivalency factors are given by: $f_{SOx} = 0.54$, $f_{NOx} = 0.88$, $f_{NH3} = 0.64$.

2.3.3 Biometeorological footprints

For the LLs focusing on extreme events, especially temperature, the following footprints indicators are selected:

- Apparent temperature [16] estimates the physiological discomfort due to exposure to weather conditions:

$$AT\ (°C) = -2.7 + 1.04 \times T + 2.0 \times e / 10 - 0.65 \times v$$

- Thom index or Discomfort index [17] evaluates the sensation of heat or cold perceived by the human body:

$$DI = T - (0.55 - 0.0055 \times RU) \times (T - 14.5)$$

- Humidex [18] evaluates the climatic comfort in relation to humidity and temperature:

$$H = T + (0.5555 \times (e - 10))$$

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- Wind chill [19] expresses the cooling sensation caused by the combined effect of temperature and wind:

$$WC = 13.12 + (0.6215 \times T) - (11.37 \times v^{0.16}) + (0.3965 \times T \times v^{0.16})$$

where: T (°C) = ambient temperature; RU (%) = relative humidity; e (hPa) = vapour pressure; v (km/h) = wind speed.

A ranking based on thresholds defined in the literature for temperature, discomfort and humidex is reported in Table 3. A ranking of risk of freezing is reported in Table 4.

Table 3: Physiological temperature, discomfort and humidex thresholds.

Risk description	Temperature	Discomfort	Humidex
Comfort	AT < 27°C	DI < 21	H < 27°C
Caution	27 ≤ AT < 32	21 ≤ DI < 27	27 ≤ H < 30
Extreme caution	32 ≤ AT < 40	27 ≤ DI < 29	30 ≤ H < 40
Danger	40 ≤ AT < 54	29 ≤ DI < 32	40 ≤ 55
High danger	AT ≥ 54	DI ≥ 32	H ≥ 55

Table 4: Ranking of risk of freezing.

Interval	Risk description
−27 ≤ WC < 0	Low risk of freezing
−39 ≤ WC < −27	Risk: Exposed skin can freeze in 10–30 minutes
−47 ≤ WC < −39	High risk: Exposed skin can freeze in 5–10 minutes
−54 ≤ WC < −47	Very high risk: Skin exposed it can freeze in 2–5 minutes
WC < −55	Extremely high risk

3 RESULTS

The I-CHANGE Project applied the methodology described above to compute carbon footprint, environmental footprint, air pollutants and SLCFs emissions using driving forces data gathered within I-CHANGE LLs activities.

Besides application and detailed calculation of all the indicators in the baseline scenario on the basis of data gathered within the I-CHANGE LLs, the project also evaluates their reduction when implementing two traffic policy scenarios in three selected cities within the I-CHANGE LLs, namely Bologna, Dublin and Hasselt (provision of bicycle infrastructure and introduction of low emission zone (LEZ) for Bologna and Dublin, and restriction of traffic in school streets and introduction of remote working hours for Hasselt).

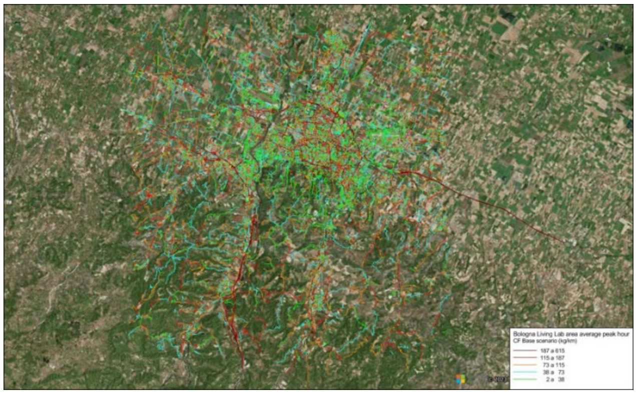
Furthermore, the methodology was applied on the basis of energy consumption (electricity and heat) in the residential sector for the Amsterdam LL. Finally, the methodology was customised to evaluate the impact of waste management for the LL of Wascal in Burkina Faso.

All the data and results are available in the specific software model tool E^2GovCmty developed in the project.

3.1 Carbon footprint

The carbon footprints calculation methodology defined in Section 2.3.1 was applied to Bologna, Dublin, Hasselt (road traffic), Amsterdam (residential energy consumptions) and

Ouagadougou (waste management) case studies. An example of calculation for the Bologna, Dublin, Hasselt area starting from the traffic simulations in the base case conducted in the project is reported in Fig. 3.



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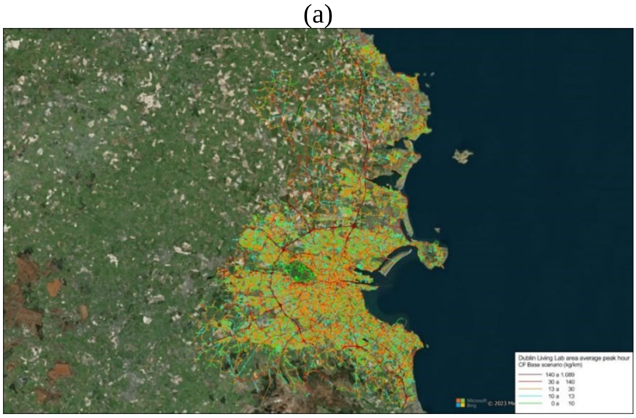

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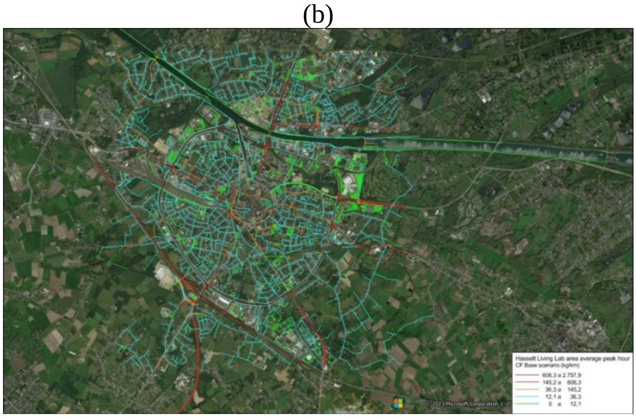


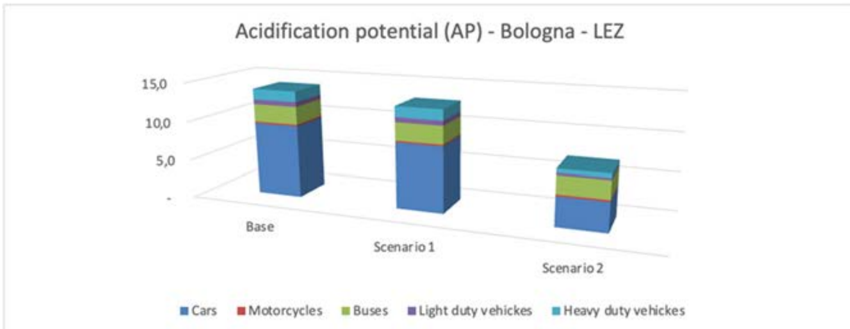
(c)

Figure 3: Carbon footprint (kg/km) evaluated starting from traffic simulations in the LLs area for the peak hour in the current Base case scenario. (a) Bologna; (b) Dublin; and (c) Hasselt.

The proposed measures for road traffic have a reduced impact on the carbon footprint of transport sector.

3.2 Air pollution environmental footprints

The air pollution environmental footprints calculation methodologies defined in Section 2.3.2 were applied to Bologna, Dublin, Hasselt and Amsterdam case studies. Some examples of calculation of air pollution environmental footprints starting from the traffic simulations in the base case and policy scenarios conducted in the project is reported in Fig. 4.



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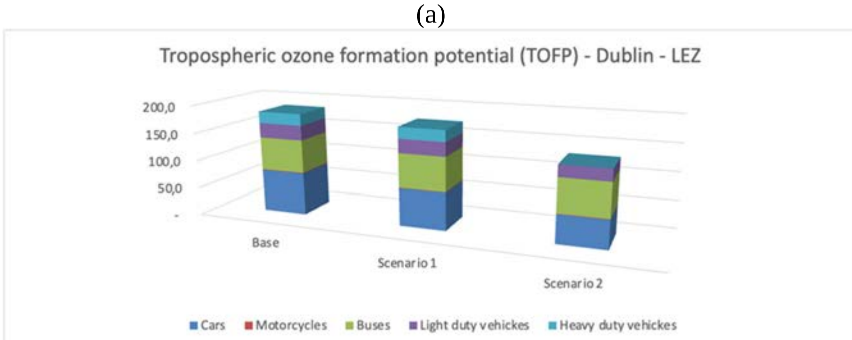

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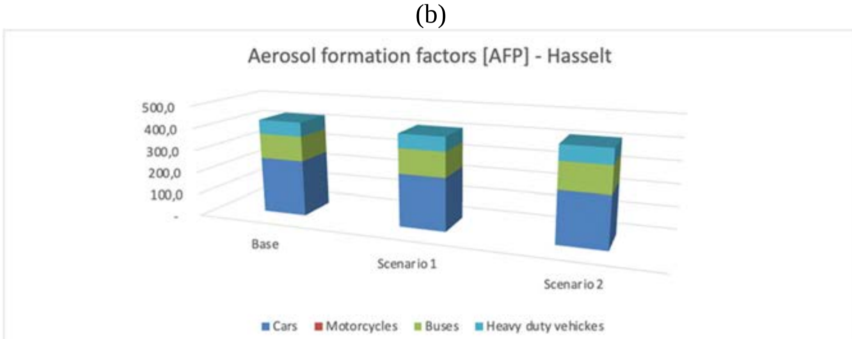

(c)

Figure 4: Example of air pollution environmental footprints from traffic simulations in the LLs LEZ area (base case and two traffic policy scenarios). (a) Bologna; (b) Dublin; and (c) Hasselt.

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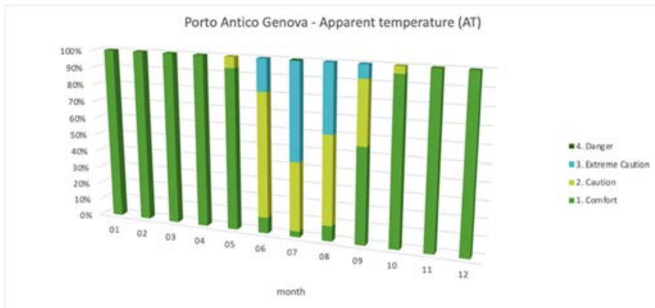
The traffic scenarios that introduce a LEZ for vehicles up to Euro 4 in Bologna and Dublin can lead to a non-negligible reduction in pollutant emissions (in particular nitrogen oxides) and are already planned in most cities to contribute to the challenges that the European Union has launched with the proposal for a new directive on air quality [20]; the overall effect on Hasselt of the scenarios is negligible, possibly because of the reduced size of the interventions and their limited effect on shift to pro-environmental transport modes.

3.3 Biometeorological footprints

Moreover, as a group of I-CHANGE LLs is mostly focused on extreme events and measurement of meteorological parameters such as air temperature, precipitation, relative



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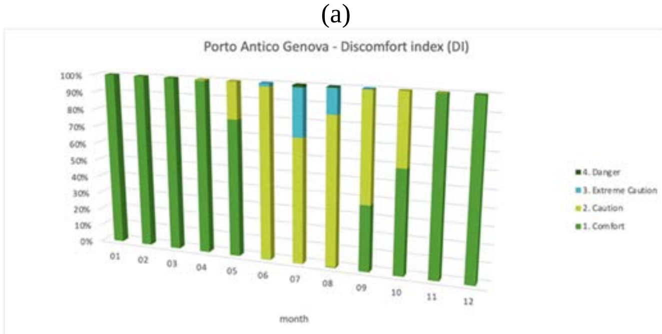

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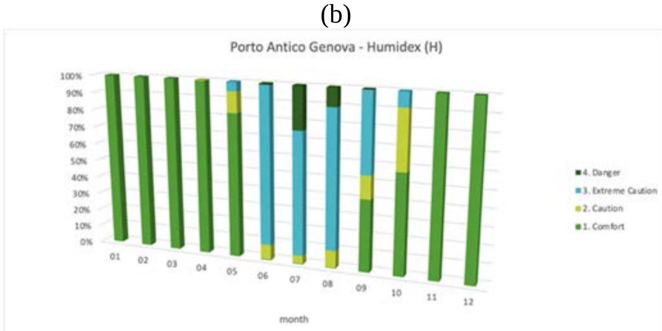

(c)

Figure 5: Example of biometeorological environmental footprints distributions as calculated from monitoring data in Genoa Living Lab. (a) Apparent temperature (AT); (b) Discomfort index (DI); and (c) Humidex (H).

humidity, wind speed and direction, the 'classical' Environmental Footprint definition has been extended as discussed in Section 2.3.3 to include a set of biometeorological selected to report a synthetic picture of impact of climate on health. On the basis of data gathered from the Genova LL, the footprints were evaluated in collaboration with the LL team and reported as frequency distribution of the footprint (Fig. 5).

Their application in Genoa LL allows an evaluation of the spatial and temporal distribution of the events, giving the possibility of drawing recommendations to citizens.

4 CONCLUSIONS

The main conclusions of these activities inside the I-CHANGE project are:

- Carbon footprint and air pollution emission factors appropriate to the activities of the LLs in the project have been introduced.
- A robust methodology for evaluating carbon footprint and short-lived climate forcers and air pollutants emissions starting from the data collected in the LLs of the project has been defined.
- Air pollution environmental footprints and environmental biometeorological footprint indicators appropriate to the activities of the LLs in the project have been introduced.
- A specific model (named E^2GovCmty) to support detailed calculations has been implemented.
- The methodology has been applied to data gathered from the LLs in the project.
- The methodologies and tools developed in this work represent a valid support to evaluate the impact of collective and individual behavioural changes and to formulate solid advanced policies using the input data from the LLs.
- The biometeorological indicators introduced are appropriate for assessing to provide some practical recommendations to citizens during specific periods and in specific locations.
- The emissions calculated has been subsequently utilised as input data to evaluate the impacts of behavioural changes on atmospheric concentrations of air pollutants, greenhouse gases and SLCFs. In particular, dispersion modelling simulations have been conducted to evaluate the impacts of traffic policy scenarios in terms of reductions of atmospheric concentrations of air pollutants and greenhouse gases against the baseline.

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