



Decrease in life expectancy due to COVID-19 disease not offset by reduced environmental impacts associated with lockdowns in Italy[☆]

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ABSTRACT

The consequence of the lockdowns implemented to address the COVID-19 pandemic on human health damage due to air pollution and other environmental issues must be better understood. This paper analyses the effect of reducing energy demand on the evolution of environmental impacts during the occurrence of 2020-lockdown periods in Italy, with a specific focus on life expectancy. An energy metabolism analysis is conducted based on the life cycle assessment (LCA) of all monthly energy consumptions, by sector, category and province area in Italy between January 2015 to December 2020. Results show a general decrease (by ~5% on average) of the LCA midpoint impact categories (global warming, stratospheric ozone depletion, fine particulate matter formation, etc.) over the entire year 2020 when compared to past years. These avoided impacts, mainly due to reductions in fossil energy consumptions, are meaningful during the first lockdown phase between March and May 2020 (by ~21% on average). Regarding the LCA endpoint damage on human health, ~66 Disability Adjusted Life Years (DALYs) per 100,000 inhabitants are estimated to be saved. The analysis shows that the magnitude of the officially recorded casualties is substantially larger than the estimated gains in human lives due to the environmental impact reductions. Future research could therefore investigate the complex cause-effect relationships between the deaths occurred in 2020 imputed to COVID-19 disease and co-factors other than the SARS-CoV-2 virus.

1. Introduction

The different rates of lethality associated with the COVID-19 disease in various geographical areas have been widely investigated by a growing number of studies. Some of them have focused on pre-existing conditions and comorbidities of the patients, e.g. [Zhu et al. \(2021\)](#), while others have hypothesized a link between environment and the onset of a more aggressive disease, e.g. [Bashir et al. \(2020\)](#).

It is well known that elderly patients, particularly the ones suffering from chronic diseases affecting respiratory tract, as well as the ones with an impaired functionality of immune system, have presented the worst outcome ([Cajamarca-Baron et al., 2021](#)). At the same time, many studies are being addressed in the field of genetics, aiming to identify if the genetic background may be responsible of a more severe disease in patients without significative comorbidities or risk factors ([Monticelli](#)

[et al., 2021](#); [Zanella et al., 2021](#)).

Conversely, the role of the environment has been considered by several authors, whose goal was to determine whether external factors, not directly related to the patients, may explicate the different incidence and lethality of the COVID-19 disease. It is not surprising that low-income countries suffered from COVID-19 more than the developed ones, both due to the low expenditure in health system and to the lack of effective preventive measures ([Coccia, 2021a, 2021b](#); [Doyle et al., 2021](#)). However, higher uncertainties exist about the role of meteorology and pollution in the diffusion and severity of the virus, such as in the case of Italy ([Coccia, 2021c](#)).

On one hand, a first factor (i.e. the faster spreading of the virus) has been linked to several conditions, such as weather, wind, temperature humidity and population density ([Coccia, 2021d](#); [Diao et al., 2021](#); [Haque & Rahman, 2020](#); [Rosario et al., 2020](#)). Moreover, interesting

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insights have been evidenced when different countries, as well as different regions within the same country, have been compared (Sarkodie & Owusu, 2020; Srivastava, 2020).

On the other hand, the augmented lethality associated with COVID-19 seems to have a direct correlation with air pollution, whose long-term exposure negatively acts through the impairment of primary immunity, the development of severe, respiratory tract comorbidities and chronic lung inflammation (Conticini et al., 2020; Whiteside & Herndon, 2020). Recent quantitative estimations from Pozzer et al. (2020) confirm that air pollution is an important cofactor to increase the risk of mortality from COVID-19, finding that particulate air pollution has contributed by ~15% to COVID-19 mortality worldwide. Similarly, Venter et al. (2020) estimate that reductions in air pollution (in particular with regard to PM_{2.5} and NO₂) during lockdown events across 34 countries have contributed to avoid a net total of 49,900 excess deaths and 89,000 pediatric asthma emergency room visits.

In this regard, a large body of research has recently evaluated the potential effect of air pollution on the increase of COVID-19 lethality in different geographical areas (Cole et al., 2020; Copat et al., 2020; Domingo & Rovira, 2020; Hendryx & Luo, 2020; Magazzino et al., 2020; Ogen, 2020; Yao et al., 2020). In Italy, contagious has rapidly spread starting from the end of February 2020, particularly in the North (Lombardy, Veneto and Emilia-Romagna), and recording much higher levels of lethality than in other countries and Italian regions (Coker et al., 2020; Fattorini & Regoli, 2020; Murgante et al., 2020; Perone, 2021; Zoran et al., 2020).

Chronic respiratory diseases, leading to frequent and prolonged hospital admissions and eventually death, do represent negative impacts or damages for human health caused, among others, by primary and secondary aerosols and ozone in the atmosphere associated with air pollution (van Zelm et al., 2016). Such a burden can be measured in Disability Adjusted Life Years (DALYs), a worldwide acknowledged indicator to quantify the burden of diseases, injuries and risk factors in one aggregated single metric based on the sum between the estimated “years of life lost” (YLLs) from premature death, and those of life lived in less than full health (WHO, 2018). Accordingly, DALYs can be utilised to help decision makers and the public understand the leading causes of health burden and whether improvement occurs over time (GBD 2017 Risk Factor Collaborators, 2018).

The effects of COVID-19 disease on public health are the subject of a vast number of studies aiming to assess the extent of the pandemic among various countries and populations. Excess deaths, premature deaths, and YLLs are the most employed indicators and accurately reflect the elevated lethality of SARS-CoV-2 (Aburto et al., 2021; Andrasfay & Goldman, 2021; Hanlon et al., 2020; Pifarré i Arolas et al., 2021; Rommel et al., 2021). Conversely, insufficient data are available to assess the long-term burden of COVID-19 and its disease extent in terms of reduction of DALYs, presumably due to the current uncertainty about the long-term damages of SARS-CoV2 in recovered patients. Similarly, no paper has to date investigated if the restrictive measures employed by the different Governments have led to public health significant modifications other than the crude number of new cases and/or new deaths due to COVID-19.

It is hence worth investigating the effects of the lockdown measures on the Italian burden of human health disease. Only a few papers have so far examined the relationship between the damage wrought by the SARS-CoV-2 pandemic on human health and other possible disease measures such as those quantified with the DALYs indicator. For example, some preliminary estimates of DALYs due to COVID-19 have been provided for Korea (Jo et al., 2020). Moreover, an estimated load of YLLs – which represents a key variable for the calculation of DALYs – due to COVID-19 has been used to measure the burden of the COVID-19 in the thirty countries with the highest incidence of COVID-19 (Oh et al., 2020). On top of this, the disability weight in the estimation of “years lost due to disability” (YLDs) –which represents the second key variable for estimating the DALYs indicator –has been assumed as an acute lower

respiratory infection, since a specific value for COVID-19 is still not available (Nurchis et al., 2020).

While research on incorporating COVID-19 effects in the DALY indicator is at its infancy, in the field of industrial ecology the life cycle assessment (LCA) method (ISO, 2006) is widely used to account for the cause-effect relationship between environmental issues, such as air pollution, and DALYs (De Schryver et al., 2009; De Schryver et al., 2011). LCA allows to assess the endpoint impact on human health of the global population in DALYs per mass unit of different pollutants emitted into the environment [i.e. DALY/kg emitted]. Therefore, by knowing how much impact has been generated in Italy during the year 2020, and comparing it with the impact from previous years, it is possible to understand whether (and to which extent) the stringent measures of lockdown of economic activities occurred in Italy over the course of 2020 have actually prevented further damage to human health (measured in DALYs).

Rugani and Caro (2020) have recently observed a meaningful carbon footprint reduction for the period March–April 2020 in Italy. Following their LCA approach, this paper aims to shed new light on the overall consequences of the lockdown measures for human health from the perspective of the avoided damage. More specifically, the objective has been to i) assess the environmental impacts on human health (and their effects in terms of DALYs) associated with the consumption of energy in Italy (i.e. assessment of country energy metabolism) during the whole year 2020, and ii) compare this record with equivalent records for the past 5 years. In so doing, the paper attempts answering to the question “how much benefit has the reduction in environmental impacts, occurring as a consequence of the lockdowns, provided, directly or indirectly, to human health?”.

2. Materials and methods

2.1. Research setting and data collection

The assessment methodology proposed in this paper represents a follow-up of the approach illustrated in Rugani and Caro (2020), in which the carbon footprint generated by the COVID-19 related lockdown measures in Italy was analysed. This was done by adopting an LCA approach to assess the monthly energy metabolism driving the Italian economy between January 2015 and May 2020. To go beyond that study, the focus here was to assess all the environmental impacts (not only those associated with greenhouse gas emissions) specifically relevant for human health over the same timeframe, but updating the data inventory until the December 31, 2020. By assessing the energy consumptions prior, during and after the lockdown period, and following Autumn’s restrictions therefore allowed to better understand the environmental consequences of such relevant event for the socio-economic system of the country.

In this regard, around thirty energy flows were considered, which were grouped in six main categories as follows: solid fossil fuels (SFF), oil and petroleum products (OPP), natural gas (GAS), renewables and biofuels (REN), non-renewable waste & heat (NRH), and electricity (ELE); see Table 1. The system boundaries thus included the whole national territory of Italy, disaggregating the inventory of energy metabolic flows by the 20 regions and 107 province areas of the country. As anticipated in Rugani and Caro (2020), accounting for the total energy consumptions of Italy allowed to consider the largest possible portion of environmental impacts seemingly generated at the national scale.

Fig. 1 depicts the two methodological steps followed in this study. Starting from Rugani and Caro (2020), an extension of the life cycle inventory (LCI) of each typology of energy flow reported in Table 1 was conducted (step 1 in Fig. 1), updating the collection of data until the end of December 2020 from national and international statistics (namely from databases of the Italian Ministry of Economic Development, Eurostat, Terna S. p.A., and ISTAT) with regard to the SFF, OPP, ELE and GAS categories. While in the case of REN and NRH categories, for which

Table 1
Framework for data collection and life cycle inventory of the Italian energy flows from January 2015 to December 2020.

Category	Typology	Spatial and temporal resolution
Solid fossil fuels (SFF)	Anthracite and other bituminous coal (incl. coking coal); lignite and agglomerates; coke oven coke; coal tar and ammonium sulfate; petroleum coke	Multiscale geographical resolution: country > region > province and metropolitan areas Time resolution: monthly ^b
Oil and petroleum products (OPP)	Liquefied petroleum gases (LPG); motor and aviation gasoline (excl. biofuel portion); kerosene (excl. biofuel portion); naphtha; gas oil and diesel oil (excl. biofuel portion); fuel oil; lubricants; bitumen; paraffin waxes and other oil products (among which white spirit and special boiling point industrial spirits)	consumption flows inventoried between January 2015 and December 2020
Natural gas (GAS)	-	
Electricity (ELE)	-	
Renewables and biofuels (REN) ^a	Solar thermal; geothermal; primary solid biofuels; charcoal; biogases; blended biogasoline; blended biodiesels; ambient heat (heat pumps)	
Non-renewable waste & heat (NRH) ^a	Industrial waste; heat (from co-generation and other)	

^a Data for the years 2019 and 2020 have been estimated according to the approach illustrated in Rugani and Caro (2020).

^b Data on electricity consumptions have been collected on a daily basis (see Supplementary Material SM1, Table S2).

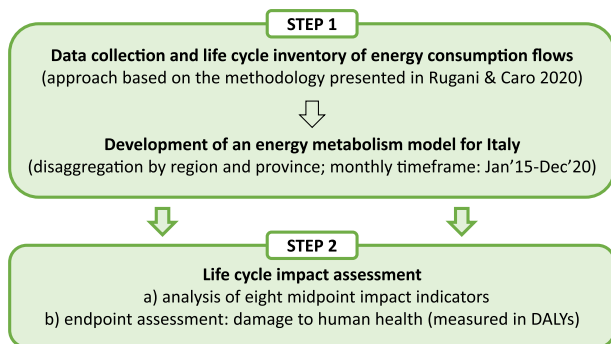


Fig. 1. Methodological steps; DALYs = Disability Adjusted Life Years.

data was not available, consumption flows were estimated using the same approach described in Rugani and Caro (2020). More details regarding the elaboration and adjustment of data, their reference sources and methodological assumptions, and the overall LCI of energy consumptions in time series can be found in the Supplementary Material SM1 (Tables S1-S3).

For the life cycle impact assessment (LCIA) phase (step 2 in Fig. 1), the latest version of the well-known and widely applied ReCiPe method was used (Huijbregts et al., 2016). Because the scope of this paper was centered around the human health aspects, only the LCIA indicators focusing on human health damage were selected. These rely upon the impact categories of global warming (GW), stratospheric ozone depletion (OD), ionizing radiation (IR), ozone formation (OF), fine particulate matter formation (PM), human carcinogenic and non-carcinogenic

toxicity (CT and NT, respectively), and water consumption (WC) (Huijbregts et al., 2016). As formalised in Section 2.2, midpoint impact indicators for these categories were quantified according to the characterisation phase of the LCA methodology (Hauschild et al., 2018; ISO, 2006). Their impact scores were then aggregated to measure the DALYs at the endpoint level. Ultimately, the estimated DALYs in each Italian region and province areas were qualitatively compared, and their consequences discussed against the number of deaths and hospitalizations in intensive care recorded from the beginning of the COVID-19 outbreak up to the end of December 2020.

2.2. Measures and data analysis procedure

Fig. 2 gives a detailed overview of the type of LCI input and output data collected and analysed in the present study, which represent the energy metabolism framework. In addition to Fig. 1, Fig. 2 depicts the links between those LCI flows and the LCIA indicators introduced in the previous Section.

The energy metabolism framework in this study was built as a set of product systems p (those 28 products from SFF1 to NRH2 in Fig. 2). The matrix algebra principles generally applied in LCA for the LCI analysis (Heijungs & Suh, 2002) were used here as the basis of calculation, representing each p as a partitioned matrix (Eq. 1):

$$p = \begin{pmatrix} A \\ B \end{pmatrix} \quad (1)$$

composed by:

- a $n \times n$ Technology matrix $A = \begin{pmatrix} u_{1,1} & \dots & u_{1,n} \\ \vdots & \ddots & \vdots \\ u_{n,1} & \dots & u_{n,n} \end{pmatrix}$, which is square to

allow inversion, and includes a few thousands of unit processes u (i.e. UPs in Fig. 2) belonging to the economic systems (e.g. electricity, transport, construction, food, etc.). These are interconnected by means of average technology good and service flows (e.g. 100 kWh of electricity from the electricity production mix $u_{250,301}$ to the building construction unit $u_{781,45}$). This determines a large network of life cycles for each unit process with links specifying the quantity of each economic flow consumed;

- a $m \times n$ matrix $B = \begin{pmatrix} g_{1,1} & \dots & g_{1,n} \\ \vdots & \ddots & \vdots \\ g_{m,1} & \dots & g_{m,n} \end{pmatrix}$, so-called Biosphere, which

refers to the same type and number of unit processes from matrix A in the column but includes a different number of rows, which refer to hundreds of environmental interventions. These represent elementary flows of raw materials, such as biomass, freshwater, minerals, metals, and fossil fuels (natural gas, crude oil, coal, ...), renewable energy (wind, solar radiation, geothermal energy, ...), land, and pollutant emissions (to air, water and soil), as depicted in Fig. 2.

One general rule applies in LCI that can yield to the so-called “scaling vector” s , given a technology matrix A and a final demand vector f (an exogenously defined set of economic flows whose amount was determined according to Eq. (4)), which is followed by a second general rule that yields the inventory vector g given s and B (Heijungs & Suh, 2002) (Eq. 2a and 2b):

$$s = A^{-1} \times f \quad (2a)$$

$$g = B \times s \quad (2b)$$

Once defined A , B and f as illustrated below, equations (2a) and (2b) were combined to run the LCI analysis:

$$g_p = B \times A^{-1} \times f \quad (3)$$

For each product p of the energy metabolism framework, a final inventory vector g of environmental interventions was obtained for

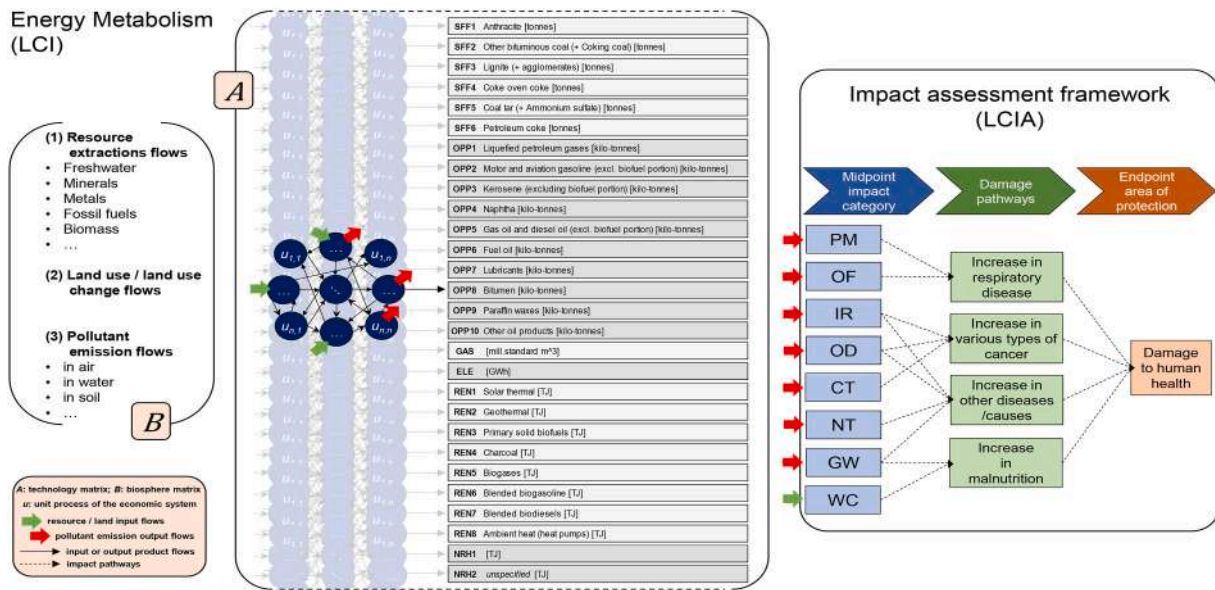


Fig. 2. Diagram of the analysed energy metabolism framework. LCI: life cycle inventory; LCIA: life cycle impact assessment, following Huijbregts et al. (2016)’s scheme; GW: global warming; OD: stratospheric ozone depletion; IR: ionizing radiation; OF: ozone formation; PM: fine particulate matter formation; CT: human carcinogenic toxicity; NT: non-carcinogenic toxicity, and WC: water consumption.

selected A and B matrices from the *ecoinvent* v3.6 database (ecoinvent, 2021) in the LCA software *SimaPro* v9 (PRéConsultants, 2021). More details about the choice and adaptation of the unit processes and associated matrices can be found in Rugani and Caro (2020).

The final demand f^{con} of each product p consumed by the annual energy metabolism of the Italian provinces r was calculated using Eq. (4). This considered the domestic production (*Dom*), import (*Imp*) and export (*Exp*) data flows of the same product p , collected from national and international statistics for each month from Jan-2015 to Dec-2020 (as indicated in Table 1):

$$f_{r,p}^{con} = Dom_{r,p} + Imp_{r,p} - Exp_{r,p} \quad (4)$$

Environmental impacts were afterwards quantified for each consumed product LCI of the energy metabolism. More specifically, as anticipated in Section 2.1 a set of characterization factors (CFs) were selected and applied to convert the LCI results (vectors g of the products p) to common or “equivalent” (unit-*eq.*) units of each selected impact category indicators in the so-called LCIA phase, first at midpoint and then at endpoint levels (Figs. 1 and 2).

In this regard, common units in LCIA allow the calculation of the impact category indicator result (ISO, 2006) using the following formula:

$$I_i = \sum_j \sum_p (CF_i^{mid})_j \times g_{j,p} \quad (5)$$

where I indicates the midpoint impact category of type i , measured here for each product p at midpoint level in kt CO₂-eq. (for GW), kt CFC11-eq. (for OD), GBq ⁶⁰Co-eq. (for IR), kt NO_x-eq. (for OF), kt PM_{2.5}-eq. (for PM), kt 1,4-DCB-eq. (both for CT and NT), and Mm³ (for WC) using precalculated conversion factors CF_i^{mid} (in unit of I_i /unit of g_j). These allowed to characterise the contribution of each environmental intervention j (in mass, volume, or energy units) to that midpoint impact category i in every product p consumed within the energy metabolism.

Such factors were retrieved for this study from the ReCiPe method (Huijbregts et al., 2016), and represent the output of different impact characterisation models whose damage pathway is depicted in Fig. 2. More details about the features of those models and the derivation of the selected CF_i^{mid} can be found in Huijbregts et al. (2016). Results from applying Eq. (5) then served to estimate the effects on human health

caused by an increase in malnutrition, diarrhea, flooding, malaria, and heat stress, which can directly or indirectly be due to the selected midpoint environmental issues. To calculate such endpoint damage on human health, Eq. (6) was applied:

$$D = \sum_i \sum_p CF_i^{end} \times I_{i,p} \quad (6)$$

where D indicates the total damage to human health calculated in DALYs. In this case, midpoint to endpoint characterization factors (CF_i^{end}), in unit of DALYs/unit of I_i , were used to assess the environmental effects on the endpoint area of protection “Human Health” (Fig. 2) under the cultural perspective “Hierarchist”, which is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms (Huijbregts et al., 2016). A comprehensive description of each CF_i^{end} calculation procedure can also be found in Huijbregts et al. (2016). It is worth remarking that no edits or adaptations of the ReCiPe method were done in the present analysis, but the original numbers and the underpinning value choices and modelling steps for both midpoint and endpoint characterization factors were kept. The uncertainty associated with the use of those models is discussed in Section 3.

3. Results and discussion

Midpoint impacts were first assessed for the Italian energy metabolism considering each year between 2015 and 2020 (Figs. 3 and 4).

As shown in Fig. 3a, most of the indicators show a peak of decrease in April 2020, corresponding to the period of the year in which the largest business closures and confinements of people at home occurred. All the environmental impacts then grow constantly after the restart of socio-economic activities and larger commodity consumptions at the beginning of May 2020. In the latest part of the year, however, the effect of new (partial) lockdown measures – put in place to face a second wave of infections across some Italian regions and province areas – reduces the acceleration of environmental impacts from September to November 2020. This is the period of the year that usually sees a greater uprise in energy consumptions, as indicated by the analysis of past energy consumptions (see Supplementary Material SM1, Figure S1), which necessarily affects the impacts associated, in particular, with natural gas

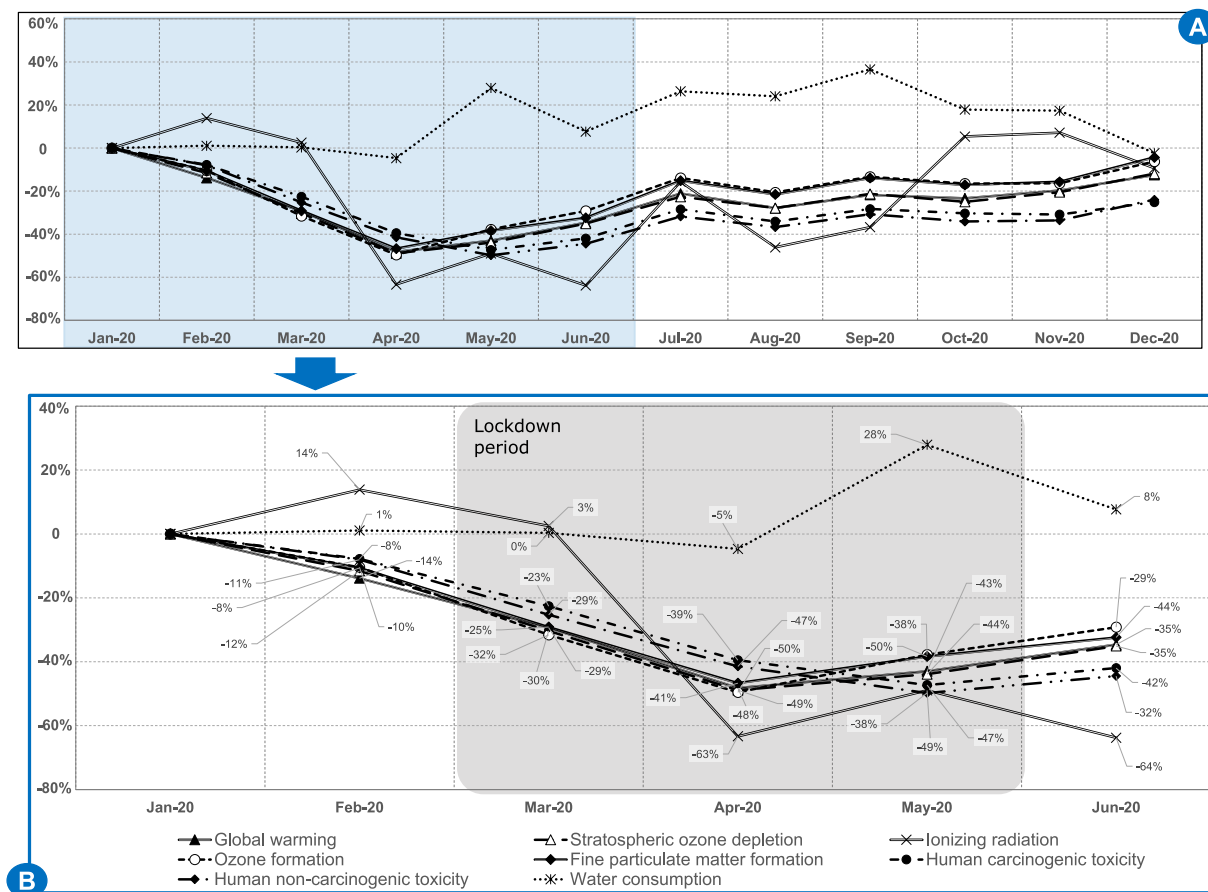


Fig. 3. A) Evolution of the midpoint impact indicator scores in 2020 (base-month: January); B) zoom on the trends prior, during and immediately after the first and most stringent lockdown period in Italy.

utilisation for heating purpose. Regarding the GW potential indicator, which is equivalent to the “carbon footprint”, such records are in compliance with the preliminary scenarios forecasted by Rugani and Caro (2020) for the whole year 2020.

When looking at the first six months of 2020 (Fig. 1b), the analysis estimates that the environmental impacts have been reduced by ~21% during the lockdown (occurring approximately during the three months of March, April and May 2020), as compared to the impacts calculated for the same three months of the preceding years from 2015 to 2019). This reduction rate represents the median value among the eight indicators assessed here. Accordingly, Fig. 3b suggests that during the lockdown period the reduction of the environmental impact has been very large for some categories (up to 50–60% less than in January 2020), such as GW, PM, OD and OF, which are typically related to the consumption of fossil fuels and the production of energy from biomass and non-renewable resources. Not surprisingly, the impacts then generally increase with the resumption of activities after the lockdown over June 2020, as previously mentioned.

The relative contributions of each category of energy metabolic flows to the annual impacts are shown in Fig. 4. The comparison of 2020’s records with the past records indicates a general decrease in the impact scores across all the analysed indicators occurring in 2020, compared to previous years. Such trends of impact avoided are mainly due to the occurrence of the lockdown measures that imposed to halt most of the economic activities in the country, among which the most polluting ones (e.g. mobility sector).

As previously mentioned, the lockdown measures (especially those put in place during March and April 2020) have generated an overall reduction of the midpoint impacts across all indicators, which ranges from ~2.6% in the case of CT and NT, to ~13.2% in the case of IR

(Fig. 4). Interestingly, the latter reflects the reduction in the consumption of imported electricity produced with nuclear energy (such as from France and Switzerland), which substantially reduces the impact due to upstream life cycle treatments of tailing from uranium milling (occurring in different places outside Italy where nuclear energy resources are generated). In contrast, for the other impact categories (GW, OD, OF, and PM) the impact decreases by around 6% on average, in line with the general decrease in fossil fuels use associated with the lockdown measures, from which those impacts mainly depend upon. These figures are obtained when comparing the total impact recorded between January and June 2020 against the mean impact in the same period from 2015 to 2019. In absolute terms, such reductions are even more meaningful. For example, compared to the same timeframe (Jan–Dec) in 2019, the lockdown measures occurring in 2020 have allowed to save ~54 Mt CO₂-eq. (i.e. ~900 kg CO₂-eq. per capita in 2020), ~120 kt NO_x-eq. (i.e. ~2 kg NO_x-eq. per capita in 2020), and ~39 kt PM_{2.5}-eq. (i.e. ~650 g PM_{2.5}-eq. per capita in 2020).

When looking at the shares of each energy category, the impacts due to electricity (ELE) consumptions dominate across the indicators of IR, CT and NT, followed by OPP and, to a lesser extent, GAS consumption-related impacts. In the case of ELE, this is mainly due to the diversity of pollutant emissions generated during the production of electricity or along its life cycle upstream. In contrast, the consumption of fuels mainly generates pollution throughout their combustion processes, as reflected by the large contributions of the GAS, OPP and REN categories to the three impact indicators of GW, OD and PM. Finally, it is worth noticing that the impact due to WC tends to increase differently from other impacts (Fig. 3), and results to be larger in 2020 than in previous years (by ~6% as indicated in Fig. 4). This is due to the impact characterisation modelling assumptions made by ReCiPe of considering the

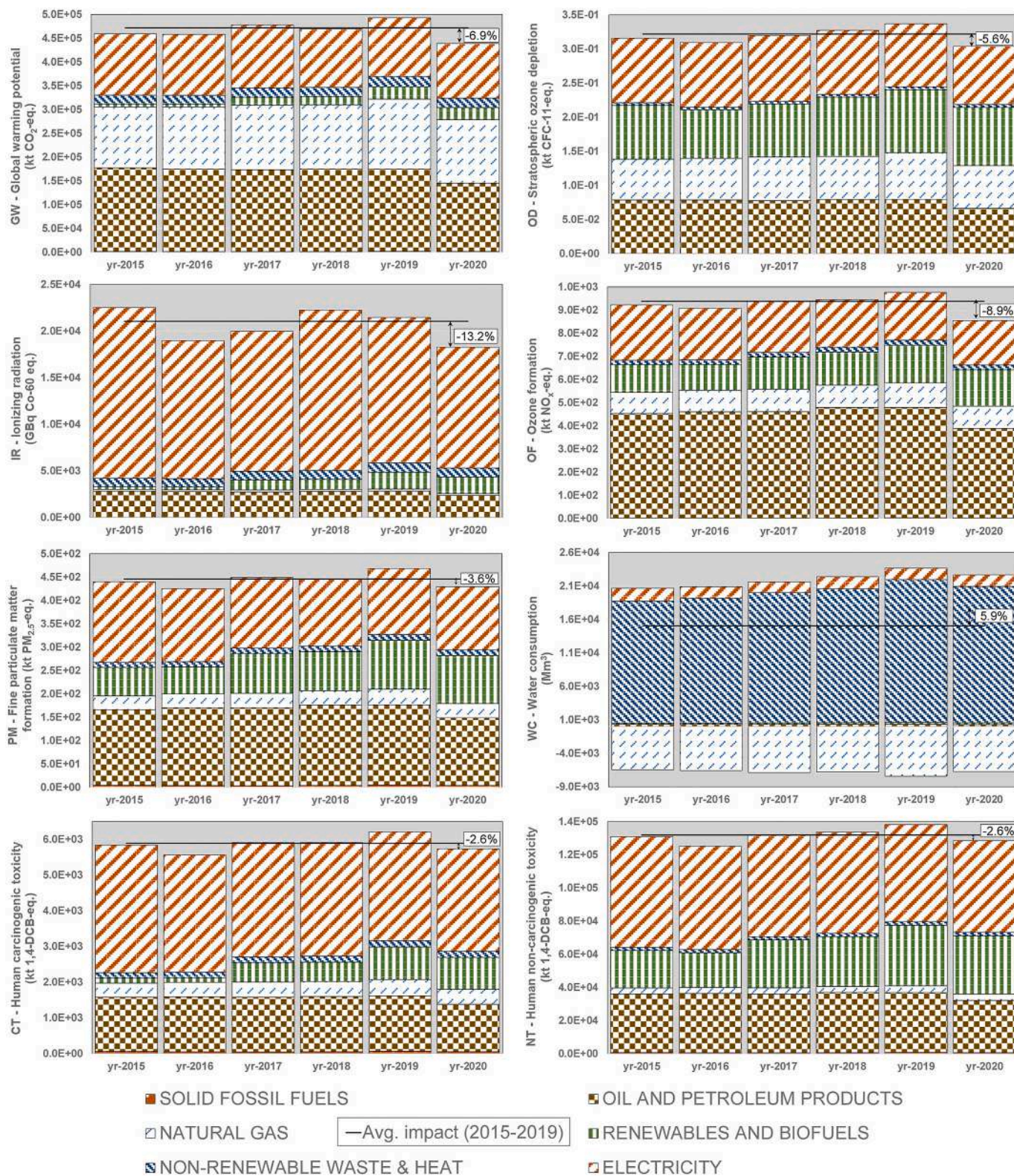


Fig. 4. Comparison of yearly impact scores for a selected set of midpoint LCIA indicators.

release of water back into the environment “beneficial” and not detrimental for such resource availability. In this case, it happens that the impact of the water emitted from upstream processes of the natural gas supply-chain (in particular with regard to some electricity production systems linked to the GAS system life cycles) is estimated with a negative characterisation factor. As a result, WC undergoes less evident decreases

than other indicators, although in absolute terms the WC impact recorded for 2020 is lower by ~360 Mm³ than that estimated for 2019 (Fig. 4), which makes saving ~6 m³ per capita.

As a follow-up of the midpoint impact assessment, DALYs due to the consumption of energy in each region and province areas of Italy were then estimated. Fig. 5 compares the distribution of the DALYs impact

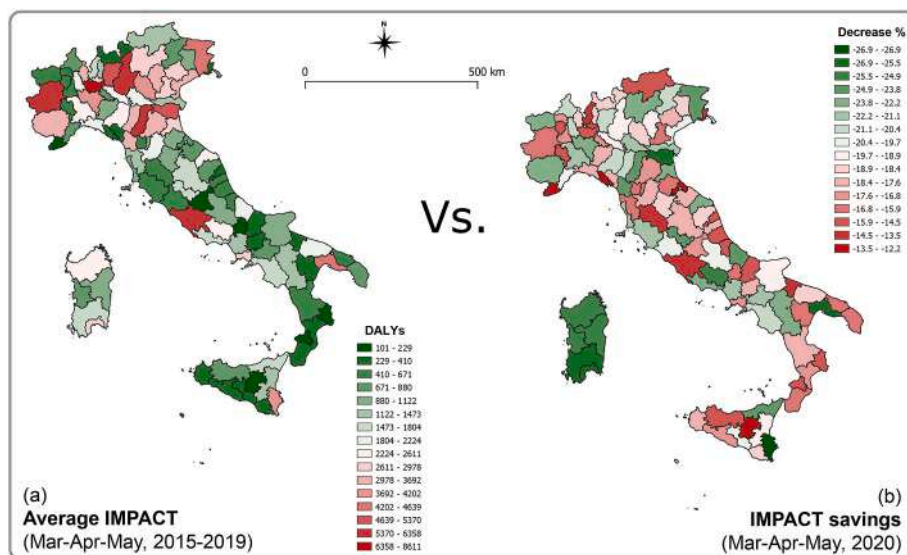


Fig. 5. (a) Average distribution of the endpoint impacts (in DALYs) across the 107 province areas of Italy in the timeframe 2015–2019. (b) Avoided DALY impacts during the lockdown period (between March and May 2020), calculated in % against the past timeframe. The raw dataset on DALYs by province area is available in the Supplementary Material SM1 (Table S4).

over the timeframe March–May from 2015 to 2019 (considering the average among these years) against the distribution of the avoided impact generated during the lockdown in 2020, presented in % values.

Highest impacts and savings are mostly concentrated in the Northern regions, even if high avoided DALY scores are recorded in several province areas of Southern Italy and the islands. This is mainly due to two factors: a higher population density, which implies more extensive consumptions of energy, and a larger presence of the heavy and most pollutant industry. Accordingly, it is not surprising to observe the highest relative contributions to the impact reductions (up to 27%, i.e. ratio between the impact between March and May 2020, and the average impact between the same periods over the timeframe 2015–2019) in those areas (such as most of Sardinia’s provinces) with the lowest environmental impacts and population densities.

More specifically, the highest avoided impacts are recorded in the

province areas of Modena, Milan and Ferrara, with scores of ~1540, ~1330 and ~1300 saved DALYs during the first lockdown period (March–May 2020). However, those areas also reflect the highest DALYs impacts in 2020 when compared to past records, in compliance with other literature findings showing that the majority of infected individuals and deaths in the first wave of COVID-19 pandemic appeared in industrialized regions with high levels of air pollution (Coccia, 2020a, 2021e). In contrast, the Southern province areas of Enna, Crotone and Vibo Valentia have generally low impacts (less than 130 DALYs in 2020) but also the lowest savings (less than 20 avoided DALYs in 2020 when compared to the average 2015–2019 values).

Compared to past records (average impacts between 2015 ad 2019), DALYs avoided likely because of the lockdown measures are estimated to be around 40,000 in the whole country over the entire year 2020, although most of them (around 93% of the annual impact) are saved

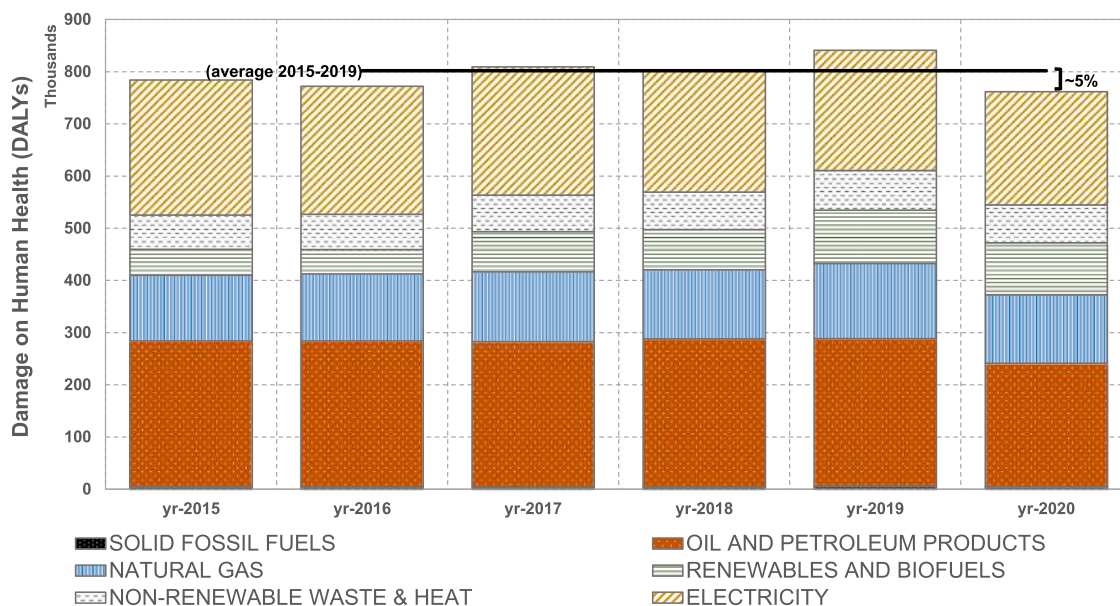


Fig. 6. Impact scores in DALYs recorded in 2020, compared with those from previous years.

during the first semester (further confirming the meaningful effect of the lockdown occurred in March–April 2020). Overall, this represents ~5% of the average annual DALYs impact from 2015 to 2019, whereby in the whole year 2019 the energy metabolism has generated an impact of around 840,000 DALYs. If the comparison were done with those 2019 DALYs, the saving would double to almost 80,000 avoided DALYs. Fig. 6 shows the trend of such records and confirms that the most relevant contributions to the impacts are associated with the consumption of OPP, ELE and GAS.

It is worth mentioning that the potential damage to human health, measured with the single score indicator of DALYs, is mainly due to the contribution of GW and PM impact categories. These weight to the global DALYs score each by ~44% (on average among the energy categories and flows). Therefore, the damage on human health measured with DALYs is mostly dependent upon the impact due to greenhouse gases and particulate matter pollution, which in the ReCiPe method mainly contribute to malnutrition and respiratory diseases, respectively.

Beyond the findings obtained, it is worth mentioning that some uncertainty associated with these impact characterisation models does occur, which should be taken into consideration. As anticipated by the ReCiPe method's developers, there is a substantial difference between the uncertainty and meaning associated with the midpoint and the endpoint characterizations. While the midpoint approach has a stronger relation to the environmental flows and a relatively low uncertainty than the endpoint one, the latter is more uncertain than the former for what concerns the assessment of DALYs, but provides better information on the environmental relevance of environmental flows (Huijbregts et al., 2016). This is a typical issue in LCA, where uncertainty can be mainly imputed to data and models, both at the level of LCI and LCIA (Bamber et al., 2019; Igos et al., 2019; Lloyd & Ries, 2007; Michiels & Geeraerd, 2020; Schaubroeck et al., 2020). Despite their importance, no quantitative characterisation or analysis of uncertainty was performed in the present study because:

- (i) at the level of LCI, statistical data to build the energy metabolism inventory were retrieved from official statistics/databases and used as such, with no relevant manipulation to change their quality. A probability distribution could be applied to obtain variability ranges for the collected data, which could then be used to perform a sensitivity analysis or a Monte Carlo sampling as it is often done in LCA (Heijungs, 2019). However, this could introduce further uncertainty in the LCI results since the actual quality of those statistical data is unknown and was out of scope to investigate on it. Because the goal of the proposed assessment was on past trends analysis only, if the datasets collated here are used to perform future scenarios or predictive modelling and evaluations (see further considerations in Section 4), then it is recommended to conduct a quantitative uncertainty analysis. The advantages and drawbacks of applying probability distribution models in the ecoinvent database (used in this paper) have been already investigated in the literature and can be used as a methodological source (Muller et al., 2014).
- (ii) at the level of LCIA, the original ReCiPe method was rigorously adopted without intervening on the quality and type of data underpinning the characterisation models, such as for recalculating DALYs. Therefore, all possible uncertainties inherent to those models are necessarily propagated in the results of the present study. No LCIA method is free of shortcomings, and the uncertainty caused by using different LCIA methods could be significantly large (Chen et al., 2021). Because ReCiPe is one of the most used LCIA method globally, its application in the present study is thus justified with the awareness about its limitations (more discussion on this issue are provided in Section 4).

To the net of their uncertainty, the LCIA outcomes of this study suggest to investigate, at least preliminary and qualitatively, the

potential relationships between the DALYs indicator and the disease due to COVID-19. Fig. 7 compares the number of deaths and hospitalisations occurred across the 20 Italian regions until the end of December Vs. the DALYs estimated for the same timeframe (but starting in January 2020) and areas (note that the number of hospitalisations corresponds to the one of the first peak in March 2020). Both visually and numerically (Pearson correlation index = 0.93 and 0.88 between DALYs and deaths, and hospitalisations, respectively) a relevant parallel exists between the two sets of numbers, which suggests that the higher the environmental impact to human health due to energy consumption within a certain region, the higher the number of people affected by a more severe disease. This confirms several recent observations about the relationship between the high penetration of the virus in the population of Northern Italy with the low air quality of those regions (Coker et al., 2020; Fattorini & Regoli, 2020; Mirri et al., 2020; Murgante et al., 2020; Zoran et al., 2020), although it must be stated that the impacts estimated with the DALYs indicator in this paper are not necessarily occurring *in loco* (according to the undertaken life cycle approach).

Nevertheless, such a finding can help to move towards a better understanding of the link between the COVID-19 consequences on human health and their possible inclusion in an index of burden of disease such as the DALY. Accordingly, this study provides additional or complementary outcomes to the preliminary findings of some recent literature studies that investigate the correlation between the components of, or the drivers for, the DALYs measure at country scale and the observed COVID-19 mortality rates. For example, a significant correlation between dementia DALYs and COVID-19 cases has been found when analysing data from around 200 countries, suggesting that dementia is a strong predictor of COVID-19 mortality (Azarpazhooch et al., 2020). Moreover, recent evidence on the relations between dietary factors and the global infection and mortality rates of COVID-19 confirms that malnutrition has an important effect on the immune system and disease vulnerability of peoples, whereby poor dietary habits are considered to be the second-leading risk factors for mortality and DALYs (Abdulah & Hassan, 2020). The reduced atmospheric pollution associated with the effects of lockdown in many countries has generated benefits in terms of reduced damages (accounted for in mortality, morbidity and disease factors with associated DALYs); and this damage avoided has been even quantified in monetary terms for several urban contexts (Bherwani et al., 2020). In the case of Italy, however, the total cost of lost productivity due to COVID-19 premature mortality has been estimated to be around 300 M€ (Nurchis et al., 2020). The same study has calculated a DALY rate equal to 2.01 DALYs per 1000 persons, with the estimated burden of disease being the highest among people aged 80–89 years. Moreover, the results presented here are in the same order of magnitude, showing an overall impact saving of ~66 DALYs per 100,000 persons (i.e. ~13 DALYs per 1000 persons generated during the whole year 2020 in Italy, and ~3 DALYs per 1000 persons saved most likely because of the lockdown – compared to the average impact in March–May from 2015 to 2019, which represents ~26% of that burden).

In the future these and other environmental assessment data should be duly integrated in the national yearly statistics to rebalance the current estimations of the “absolute” impact of the COVID-19 pandemic. For example, the benefits to human health associated with the avoided DALYs could be put in relation with the recent findings from ISTAT regarding the 10-years monitoring program “BES” (Benessere Equo e Sostenibile) on “fair and sustainable wellbeing” in Italy (ISTAT, 2021). This report clearly states that the positive evolution of life expectancy observed between 2010 and 2019, albeit with apparent geographic and gender inequalities, has been severely curbed by COVID-19: the disease has drastically reduced, if not eliminated in Northern Italy and partially in other areas of the country, the gains in expected years of life accrued during the last decade. However, this estimate does not consider the complexity of cause-effect relationships between the deaths in 2020 and co-factors other than the SARS-CoV-2 virus. It does not incorporate in turn the beneficial effects for human lives due to the reduced

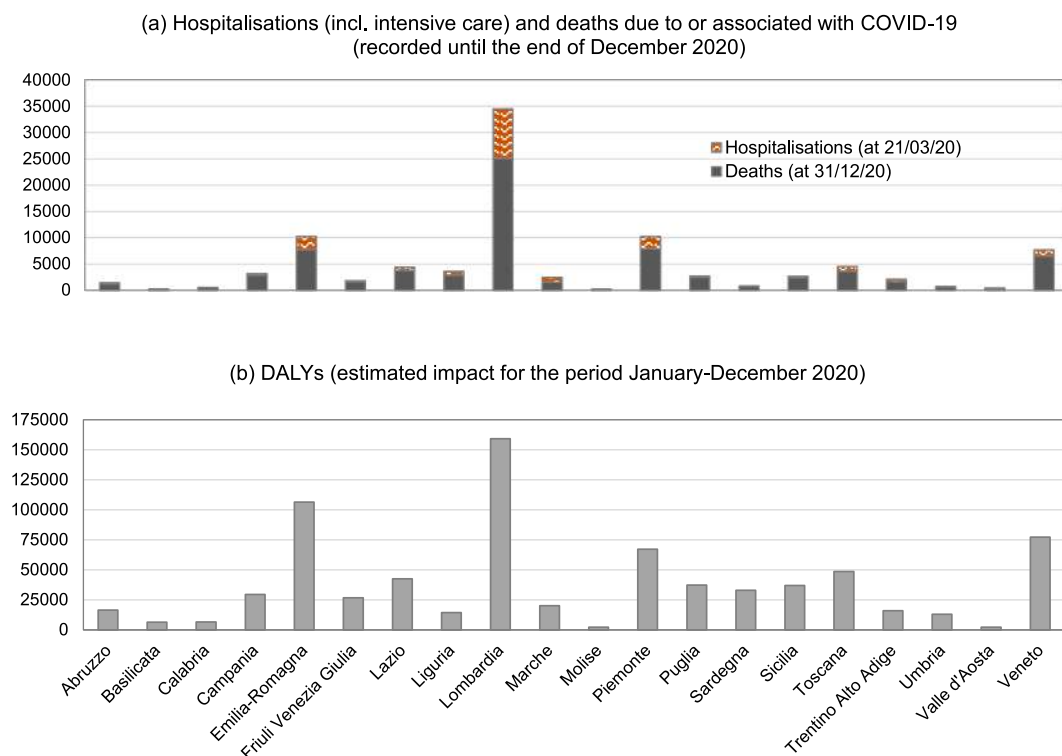


Fig. 7. (a) Number of hospitalisations (at the peak day of the first COVID-19 wave, i.e. 21st March 2020) and deaths associated with COVID-19 disease, recorded at 31/12/20 (source: [Ministero della Salute, Dipartimento della Protezione Civile](#)), and (b) spatial distribution across the Italian regions of the DALYs impact in 2020.

environmental impacts on human health.

4. Conclusions and outlook

The effects on human health due to COVID-19 pandemic are currently under investigation across several domains of research, including the environmental science. The high number of deaths and hospitalisations recorded so far in Italy and worldwide are certainly an index of the severity of this virus. However, the role of environmental impacts due to, among others, air pollution (mainly associated with respiratory stressors such as $PM_{2.5}$) as co-factors for the amplification of the virulence is still not enough investigated.

Through the lens of the energy metabolism, which roots into the life cycle thinking principles, this paper highlights one potentially relevant issue for human health worsening due to environmental pollution. Interestingly, the reduction of environmental impacts estimated here seems to have only marginal beneficial effects for human health, since the magnitude of the officially recorded casualties is substantially larger than the gains in human lives. This finding answers the question posed in Introduction (last sentence in Section 1): despite the measures of lockdown in Italy have seemingly reduced the environmental impact potentially harmful for human health, this is way lower than the extent of COVID-19 disease effects on people, either in terms of deaths or loss in life expectancy. As made evident by recent literature ([Pozzer et al., 2020](#); [Venter et al., 2020](#)), considering the relationship between environmental pollution and human health will be crucial in the future to ensure the necessary environmental quality standards as a basis for mitigating the risk of new virus pandemics and therefore human casualties.

So far, no relationships have been identified between the global burden of diseases, injuries and risk factors represented by the DALYs indicator, and the effects of the COVID-19 disease on the number of years of life lost from premature death and/or the years of life lived in less than full health. This will represent a subject of future research on human health. Nevertheless, by looking at the saved DALYs due to the

measures of lockdown in Italy, this paper has shed new light on the opportunity that such measures, although dramatically severe for the society and the economic productivity, may provide back in terms of human health quality.

On top of this consideration, some uncertainty and limitations may potentially hinder the originality linked to the implementation of an energy metabolism analysis framework combined with an LCA approach. First, no distinction between impacts occurring in Italy and impacts occurring outside has been made. This hampers to understand how the actual distribution of the impacts occurs, regarding air pollution due to combustion processes, and to which extent these impacts eventually take place in Italy or elsewhere. Consequently, results shown in the maps of Fig. 5 must be interpreted as the penetration of the impact due to the regional economic systems, since they reflect the distribution of the energy consumptions due to domestic production and imports and exclude the impacts due to exported energy flows; other caveats associated with the energy metabolism approach have been thoroughly described in [Rugani and Caro \(2020\)](#). Moreover, no regionalized characterisation factors have been considered to estimate the DALYs, as well as other possible midpoint impacts, reducing the assessment representativeness. It has been observed that applying region-specific characterization factors can lead to significantly different outcomes of an LCA, such as an over- or underestimation of damage of up to 2 orders of magnitude ([van Zelm et al., 2016](#)). Despite these limitations, the consumption approach used in the present analysis, which is compliant with the principles of LCA, may help to anticipate the environmental burden that national statistics and environmental authorities will disclose in the upcoming years through the territorial emissions data associated with domestic production sources. It is worth remarking that such an approach is not predictive though since it has only focused on analysing time series of recently observed data. The development of sustainability policies for the post COVID-19 period should necessarily look at such past trends. However, they should also benefit, with duly considerations about their uncertainty, from the findings obtained by using other methodologies for predictive modelling and analysis. In this regard,

recent literature offers insightful perspectives on how to anticipate possible occurrence of future casualties, on which future energy demands and consequently environmental impacts may be related. For example, Tutsoy and co-authors have shown how the use of parametric models for predicting and analysing COVID-19 casualties (Tutsoy et al., 2021; Tutsoy et al., 2020), even more when coupled with artificial intelligence techniques (Tutsoy, 2021), can provide insights on how to minimize the impact of restrictive measures during pandemics by considering the multi-dimensional contribution of non-pharmacological policies such as lockdowns, schools' closure, curfews, etc. Incorporating such knowledge on the complexity of the COVID-19 socio-economic impact mechanisms into the business, industry and public authority policy framework will be key for guiding sustainable energy productions and consumptions in the post COVID-19 era (Aktar et al., 2021; Mofijur et al., 2021). For Italy – but that can be generalised to other countries – a novel predictive Index of contagious integrating multiple factors (not necessarily associated with pharmacological determinants) advocates that the capacity to prevent future infectious diseases may depend on how life sciences and non-pharmaceutical interventions to reduce human-to-human transmission of viral agents will be able to encompass socioeconomic, commercial, demographic and environmental factors (Coccia, 2020b).

In this regard, it is worth remarking that long-term damages of SARS-CoV2 in organs and systems, such as lung fibrosis (Udwadia et al., 2021) and neuropsychiatric disturbances (Willi et al., 2021), have been extensively hypothesized and evidenced also in young patients (Willi et al., 2021), but they are far from being fully defined in terms of pathogenesis and epidemiology. The exact comprehension of the mechanisms leading to chronic diseases, such as pulmonary fibrosis and end-stage renal disease, as well as their incidence in patients previously affected by COVID-19, will be key in determining how DALYs relate to this condition. Given the upsurge of interdisciplinary studies around COVID-19, synergic advances are expected – and would be recommended – in the next future from Science, Policy and the Society as a whole. Those will offer an unprecedented platform of knowledge, experience and evidences about the long-term effects of COVID-19 on individuals and their socioeconomic systems. Beneficial effects of such effort would be to foster, improve and support the analysis of the environmental implications related to economic systems developments, as well as the implementation of sustainability policies aiming at preventing both human and ecosystem health damages likewise.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2021.118224>.

Author statement

B.R.: Conceptualisation, Methodology, Data curation, Formal analysis and Writing – original draft preparation; E.C. Conceptualisation, Validation and writing D.C.: Conceptualisation, Validation and writing;

B.F.: Validation, Writing – review & editing.

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