Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
A multiscale integrated analysis of the COVID-19 restrictions: The energy metabolism of UK and the related socio-economic changes

Valeria Andreoni

Management School, University of Liverpool, Chatham Street, Liverpool, L69 7ZB, UK

ARTICLE INFO

Handling Editor: Bin Chen

Keywords:
MuSIASEM
Lockdown restrictions
Economic downturn
Energy use
Human activity
Green recovery

ABSTRACT

The COVID-19 pandemic and the related lockdown restrictions have imposed a wide range of impacts that need to be analysed based on the specific characteristics of countries. By comparing socio-economic and energy data for the four quarters of 2020 to the same period of 2019, the MuSIASEM approach is used, for the first time, to investigate the energy metabolism of UK during a period of economic downturn. Results show that the commercial and the public administration activities have been able to achieve energy efficiency increases, and the residential sector has accounted for energy-related economies of scale. The industrial and the other activity sectors, on the contrary, have raised the energy intensity of production. Comparted to time series data, scenarios, and modelling exercises, the MuSIASEM approach integrates a wide range of intensive and extensive variables across different scales of analysis and investigate how specific socio-economic and energy structures have reacted to the COVID-19 crisis. The methodology can be easily replicated for other case studies and results can support the design of recovery and sustainable transition strategies.

1. Introduction

Despite the increased environmental and policy concerns related to fossil fuel dependency, the energy systems of countries are still heavily reliant on non-renewable energy sources. According to data provided by Ritchie and Roser (2020), in 2019 fossil fuel accounted for 84.3% of the global primary energy produced, with peaks over 99% in Oman, Qatar, and United Arab Emirates. The increasing investments in renewable energy sources and the improvements in energy efficiency and use are just marginally compensating the energy consumption growth, that globally rise by 62.9% since 1990 (IEA, 2020a).

During the last few decades, a large set of studies have been devoted to analysing the energy dependency of societies and to discuss the impacts that economic growth, consumption possibilities, and technological effects could generate on the overall energy changes (Tutak and Brodny, 2021; Tutak and Brodny, 2022). The global energy review of the Environmental Energy Agency and the energy outlook of OECD are examples of well documented analysis on how energy accessibility is shaping the structures of societies and influencing the development opportunities of countries (IEA, 2021; IEA, 2020a). Within this context, increasing research has been recently devoted to investigating the metabolic patterns of societies by analysing how energy is used to sustain and expand a specific socio-economic structure. The Material and Energy Flow analysis (MEFA), together with the Multiscale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) are examples of that (Gerber and Scheidel, 2018).

By combining the traditional energy efficiency indicators with analysis on energy allocation and use, the metabolic approaches allow to investigate the way in which energy is used across time, dimensions, and scales (Fisher-Kowalski and Erb, 2016; Giampietro et al., 2009). In this respect, metabolic analyses have been devoted to cross-regional studies, sectoral uses, and historical changes (Falconi-Benitez, 2001; Iorgulescu and Polimeni, 2009; Silva-Macher, 2016; Andreoni, 2017; Parra et al., 2018). Most of them have however been focused on period of growth, where energy consumption has been analysed in relation to GDP increase. Fewer analyses have, on the contrary, investigated the energy consumption changes during period of crisis. As previously highlighted by Andreoni (2020) the possibility to examine the energy effects of economic downturn can complement the analysis focused on growth and provide a more exhaustive understanding of the energy dependency of societies. Within this context, the COVID-19 crisis, that emerged as a global outbreak in March 2020, represents an important opportunity to investigate energy allocation and use during period of severe economic disruptions. Following the pandemic declaration of the World Health Organization (WHO) many countries introduced a wide range of measures for pandemic prevention and control, with unprecedented...
restrictions on social mixing, travel, working patterns and business operations (Zambrano-Monserrate et al., 2020). The extensive lockdown constraints and the related production and consumption drop have then induced the largest economic crisis since the Great Depression of 1930s with a global GDP reduction of 3.3% in 2020 (World Bank website). Consequently, the overall energy demand declined by 4% and the energy-related CO₂ emissions by 5.8% (IEA, 2021). The prolonged macroeconomic disruptions, the reshaped investments toward medical and health related expenditures, together with the drop in the global oil price (Çelik et al., 2022), also induced conspicuous withdraws from renewable energy projects, that experienced an inverse trend compared to the pre-pandemic growth of renewable energy sources (Çelik et al., 2021; Jiang et al., 2021; Hosseini, 2020). In addition, the imposed lifestyle variations, and the enforced production constraints, contributed to change the energy consumption profiles of the industrial, commercial, and residential sectors, with consequent impacts on network distributions, power system operations, maintenance, and control (Huang et al., 2021; Santiago et al., 2021).

Although existing studies have analysed the energy implications of the COVID-19 restrictions together with the potential impacts on power generation, green recovery strategies, and low-carbon energy transitions (Tian et al., 2022; Li et al., 2022; Dawn et al., 2022), limited analyses have been devoted to investigating the energy changes in relation to the socio-economic characteristics of countries (IEA, 2020d) and none have analysed the metabolic variations imposed by the COVID-19 restrictions. By considering the integrated relationships existing between socio-economic and energy variables at different scales of analysis, the metabolic approach can be used to investigate how the COVID-19 crisis has shaped energy allocation and demand. Results can provide a better understanding of the dynamic of energy use and can support the design of sustainable recovery strategies.

Within this context, the MuSIASEM technique is used in this paper to investigate the metabolic changes that have taken place in United Kingdom, a country that imposed some of the stricter and longer lockdown restrictions and that experienced one of the largest GDP drop across the advanced world economies (ONS, 2021). As reported in Fig. 1, beside the partial lockdown measures and the three-tier system that have been affecting different regions in different ways, the United Kingdom has experienced three national lockdowns between March 2020 and March 2021.

By combining the most update socio-economic and energy information provided by the Office for National Statistics, the metabolic impacts of the COVID-19 restrictions are analysed in this paper by comparing the quarters data of 2019 to the quarters data of 2020. The objective is to discuss energy allocation and use in relation to the socio-economic changes generated by the COVID-19 crisis. The main contributions of the paper can be listed as follow: First, a metabolic approach is used, for the first time, to investigate the energy implications of the COVID-19 restrictions. Compared to existing studies, that have mainly been focused on the analyses of specific energy markets, energy compartments and sectoral energy use (Tong et al., 2022; Su et al., 2022; Cihan, 2022), the MuSIASEM technique provides the possibility to integrate a wide range socio-economic and energy data at different scales of analysis (such as the sectoral and the national scale). Within this context, the MuSIASEM approach is particularly suitable to provide a comprehensive analysis of the trends taking place inside the system, as

![Fig. 1. Timeline of UK coronavirus lockdowns, March 2020 to March 2021](source: Institute for Government Analysis)
well as the role that external variables (such as crisis and resource constraints) can have on energy allocation and use (Lu et al., 2016; Han et al., 2018). In addition, the possibility to replicate the adopted methodology for other case studies, provides an important opportunity to compare and analyse how specific socio-economic and energy structures have performed in response to the pandemic crisis. Results can be used to support the definition of policies oriented to design sustainable recovery strategies specifically defined in line with the characteristics of the countries. Second, by extending the limited literature on energy metabolism during the period of economic downturn, the present paper provides a better insight of the energy dependency of society. Within this context, the paper contributes to extend the long-standing academic debate devoted to investigating the relationships existing between economic growth, energy use and related sustainability approaches (Khan et al., 2022; Mutumba et al., 2021). The manuscript is structured as follows: Section 2 provides a literature review of previous studies, methodologies, and results. Section 3 presents the methodology and the data that have been used in this paper. Section 4 discusses the main results and Section 5 concludes.

2. Literature review

During the last couple of years an increasing number of studies have been devoted to discussing the impacts of the COVID-19 crisis from a wide range of perspectives, such as mortality causes and trends (Arbel et al., 2022; Mannucci et al., 2020), inequalities (Sepulveda and Brooker, 2021; Hawkins et al., 2020), environmental impacts (Klemes et al., 2020; Andreoni, 2021), economic consequences (Teng et al., 2022; Arti and Parmar, 2021) and commodity prices (Liu and Chen, 2022; Hordofa et al., 2022). Extensive analyses have also been devoted to investigating the energy implications of the COVID-19 restrictions together with the potential impacts of the green recovery strategies (Dawn et al., 2022; Tian et al., 2022). Studies have for example focused on specific energy markets, energy compartments and sectoral energy use. Dutta et al. (2020), and Amamou and Barghaoui (2022) have for example investigated oil market during Covid-19 outbreak periods and highlighted extreme volatility and negative correlations between infection, mortality rate and crude oil price. Nyga-Lukaszewska and Aruga (2020), and Farid et al. (2021), on the contrary, identified a positive correlation with the natural gas price that, in line with the data provided by the IEA (2020e), accounted for a residential-related consumption increase. Studies have also been focused on electricity demand, with a wide range of scenario and data analyses investigating electricity consumption during the periods that preceded and that followed the introduction of the lockdown restrictions (Elavarasan et al., 2020; Bahmanyar et al., 2020; Jiang et al., 2021). Most of them concluded that the COVID-19 pandemic negatively affected the electricity use (Li et al., 2022). Similar trends have also been identified for the renewable energy sources, as the COVID-19 related restrictions have impacted on the supply of renewable energy components (Dolgui and Ivanov, 2021). In addition, the economic recession, and the reduction of public and market driven investments have slowed down the development of additional renewable capacity and the grid integration of renewable energy projects (Karmaker et al., 2021; Birol, 2020). Despite these negative trends, different studies have also investigated the opportunities of green recovery strategies, where fiscal and investment policies could be used to promote a low-carbon energy transition, defined in line with the 2030 Agenda and Paris Climate agreement (Werikhe, 2022; Hoang et al., 2021). Aktar et al. (2021) and Jiang et al. (2021) have for example review the COVID-19 energy related impacts and the emerging opportunities for a post-pandemic recovery. Quitzow et al. (2021) investigated the policy related responses of the major fossil fuel exporters and advocated international coordinated actions for the transition toward a post-carbon energy structure. Elavarasan et al. (2021) used a SWOT-AHP hybrid methodology to analyse sustainable energy changes and Hoang et al. (2021) specifically discussed the COVID-19 effects on renewable energy strategies. Both studies advised for integrated policy actions aiming to the achievement of long-term sustainability objectives.

Analyses have also been produced to investigate the impacts of the COVID-19 pandemic on specific energy and sectoral compartments, such as electric vehicles (Wen et al., 2021), municipal buildings (Geraldi et al., 2021), social housing (Rouleau and Gosselin, 2021), residential consumption (Balest and Stawinoga, 2022), commercial buildings (Su et al., 2022) and industrial zones (Cihan, 2022). Most of these studies have used time series data, scenario, analysis, and econometric models, to investigate the trends, the drivers, and the impacts of changes. The International Energy Agency (2020b, 2020c, 2021) and the International Monetary Fund (IMF2021) have for example analysed the economic consequences and the energy demand across different sectors and countries, and some studies provided an overview of energy production, consumption, and prices for some of the main world countries. Gallo et al. (2021) for example, used time series and scenario analysis to investigate the COVID-19 effects on Italian power system, and Jia et al. (2021) used a multi-sector CGE model to analyse the impacts of oil price on Chinese economy, environment, and energy use. In addition, Guler et al. (2022) used panel unit root, panel causality and dynamic panel estimation tests to investigate the bi-directional causality between electricity consumption and economic growth for 30 European countries. None of the existing studies, has however been specifically devoted to investigating the energy effects in relation to the metabolic profile of countries. By using the MuSIASEM approach, that allows to investigate energy allocation and use in relation to various levels of socio and economic information, this paper provides a multiscale analysis of the energy changes. Compared to time-series data and regression methodologies, this approach allows to integrate a wide range of intensive and extensive variables across different socio-economic compartments and provides an explanatory overview of the relationships existing between human time, economic activities, and energy use. The possibility to analyse the impacts of changes across interrelated dimensions and scales, makes the MuSIASEM approach particularly suitable to support the definition of recovery strategies designed in line with the specific-socio economic and energy characteristics of countries.

3. Methodology and data

To investigate the metabolic changes that the COVID-19 restrictions have imposed to the socio-economic and energy structure of United Kingdom, the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is used in this paper. Based on the idea that economic systems are sustained by continuous throughput of inputs, such as energy, materials and labour, the metabolic approaches investigate the structure of societies by analysing how resources are allocated and used (Giampietro et al., 2012). By combining information across different dimensions (e.g., economy, demography, time allocation, energy sources) and scales (e.g., national, sectoral, residential, and paid activities), the MuSIASEM technique allows to investigate how socio-economic systems evolve and organize based on input availability and constraints (Giampietro and Mayumi, 2000a, 2000b; Giampietro et al., 2009). Compared to the traditional energy indicators, such as energy intensity (EI) and the Energy Returned on Energy Invested (EROI), the MuSIASEM approach specifically analyse how energy is used in relation to the socio-economic characteristics of the system and investigates the interlinkage effects across dimensions and scales (Giampietro et al., 2009; Gerber and Scheidel, 2018; Velasco-Fernandez et al., 2020a). During the last few decades, the MuSIASEM technique has been used to investigate a wide range of sustainability issues, such as energy production and use (Diaz-Maurin et al., 2018; Pierro et al., 2019; Al-Tamimi and Al-Ghamdi, 2020), urban development (Sicciliano, 2012; Han et al., 2018; Chen et al., 2021), land and water constraints (Serrano-Tovar et al., 2019; Rodriguez-Huerta et al., 2019), energy end-use (Velasco-Fernandez et al., 2018, 2020b) and input embedded into.
production, consumption and trade (Ripa et al., 2021; Perez-Sanchez et al., 2021).

By combining extensive and intensive variables derived from socio-economic, demographic, and energy data, the MuSIASEM approach allows to investigate how changes taking place in a specific dimension and scale can transform the entire system together with the composing parts (Giampietro and Mayumi, 2000a, 2000b, 2000c). Within this framework, the MuSIASEM technique results to be particularly useful to analyse how the socio-economic impacts of the COVID-19 restrictions have changed the energy allocation and use.

In line with the approach previously used to investigate the metabolic profile of countries during times of crisis (Andreoni, 2020), the levels and the extensive and intensive variables reported in Table 1 are used in this paper to analyse the metabolic profile of United Kingdom. Based on data availability and consistency, the sectoral activities included in this study are those reported in Table 2.

The quarterly data for Gross Domestic Product (GDP) provided by the Office for National Statistics (ONS, 2020) have been the main source of economic information. The energy consumption collected by the Department of Business, Energy and Industrial Strategy has been used to account for the Total Energy Throughput and for the energy allocated to the production and to the residential sectors. The total human time available for every quarter of 2019 and 2020 has been derived by accounting for the total population at the beginning of the year plus the monthly data on birth and death for England, Wales, Scotland, and Northern Ireland. For 2019 and for the first quarter of 2020, the net migration data provided by ONS have also been included. Due to the lack of specific information related to the migration rate of the period affected by the COVID-19 restrictions, the following adjustments have been used to estimate the population of the last three quarters of 2020: the migration data provided by ONS for the period June 2019–June 2020 have been adjusted to take into account that during the second quarter of 2020, the number of long-term work and study visas have been reduced by around 90%, and reduced by around 35% during the last two quarters of 2020 (ONS, 2021a). Due to lack of information related to the emigration rate, the population data has not been specifically adjusted to that. However, given the travel restrictions imposed as international travel bans or as advice against non-essential travel, the possible overestimation of the UK population is expected to be marginal (UK Home Office, 2020). The total human time allocated to the paid and to the household sectors have been accounted based on the seasonally adjusted average weekly working hours provided by Office for National Statistics.

4. Results

According to data reported in Fig. 2, UK population has grown year-on-year since 1982 reaching more than 67 millions inhabitants at the beginning of 2020. The increasing contribution that the net migration has made since the beginning of the 1980s (Fig. 2). As a consequence, the total human activity (THA) available during the four quarters of 2020 has been lower than that available in 2019, with the largest increase in England. The mortality rate, that in April 2020 growth by more than 73% compared to the previous month, induced a sharp reduction of the inhabitant population (ONS, 2021a; 2021b). According to data reported in Fig. 3, in the second quarter of 2020, UK population inverted the growing trend experienced since the beginning of the 1980s (Fig. 2). As a consequence, the total human activity (THA) available during the four quarters of 2020 has been lower than that available in 2019, with the largest increase in England.

| Level N-1 – Paid and household sector | Level N-2 – Paid sectors |
|-------------------------------------|-------------------------|
| THA - Total human activity is measured in hours (h) and accounts for the share of human time allocated to the paid sector (h) | | 
| HA_Pw - Human activity paid work is the human time allocated to the paid sector (h) | HA_Pw - Hours allocated to the i sector (i: agricultural, industrial, commercial, public administration and other activities) |
| HA_HH - Human activity household is the human time allocated to the household sector (h) | |
| HA_Pw/THA - accounts for the share of human time allocated to the paid sector | ETPw - Energy throughput paid work. Accounts the energy used in the paid sector (MJ) |
| HA_HH/THA - accounts for the share of human time allocated to the household sector | ETPw/HAHw - Energy used by the i sector (i: agricultural, industrial, commercial, public administration and other activities) |
| | ETRw_HH - Energy throughput household. Accounts the energy used in the household sector (MJ) |
| | ETPw/HAHw |
| | EMRw - Energy consumed per hour in the paid sector (ETPw/HAHw) |
| EMRw_Pw - Energy consumed per hour in the paid sector (ETPw/HAHw) | |
| | EMRw_HH - Energy consumed per hour in the household sector (ETPw/HAHw) |
| | |
| GDPw - Value added generated by the i sector (i: agricultural, industrial, commercial, public administration and other activities) |
| GDP/H - Accounts for the contribution provided by every i sector to the total GDP generation (i: agricultural, industrial, commercial, public administration and other activities) |

Note: Extensive variable in black and intensive variables in blue

Table 1: Extensive and Intensive MuSIASEM variables.

| Level N – National level | Level N-1 – Paid and household sector | Level N-2 – Paid sectors |
|--------------------------|-------------------------------------|-------------------------|
| THA - Total human activity is measured in hours (h) and accounts for the share of human time allocated to a countries’ population for one year (Population*24 h*365days) | HA_Pw - Human activity paid work is the human time allocated to the paid sector (h) | HA_Pw - Hours allocated to the i sector (i: agricultural, industrial, commercial, public administration and other activities) |
| HA_HH - Human activity household is the human time allocated to the household sector (h) | |
| HA_Pw/THA - accounts for the share of human time allocated to the paid sector | ETPw - Energy throughput paid work. Accounts the energy used in the paid sector (MJ) |
| HA_HH/THA - accounts for the share of human time allocated to the household sector | ETPw/HAHw - Energy used by the i sector (i: agricultural, industrial, commercial, public administration and other activities) |
| | ETRw_HH - Energy throughput household. Accounts the energy used in the household sector (MJ) |
| | ETPw/HAHw |
| | EMRw - Energy consumed per hour in the paid sector (ETPw/HAHw) |
| EMRw_Pw - Energy consumed per hour in the paid sector (ETPw/HAHw) | |
| | EMRw_HH - Energy consumed per hour in the household sector (ETPw/HAHw) |
| | |
| GDPw - Value added generated by the i sector (i: agricultural, industrial, commercial, public administration and other activities) |
| GDP/H - Accounts for the contribution provided by every i sector to the total GDP generation (i: agricultural, industrial, commercial, public administration and other activities) |

Table 2: Economic activities.

| Economic activities | UK Standard Industrial Classification (SIC) Hierarchy |
|---------------------|-----------------------------------------------|
| Agriculture         | A                                             |
| Industrial          | B, C, D, E, F                                 |
| Commercial          | G, H, I, J, K, L, M, N                       |
| Public administration| O, P, Q                                       |
| Other activities    | R, S, T                                       |

Source: Industrial classification activities available at: Standard industrial classification of economic activities (SIC) - GOV.UK (www.gov.uk).
The reduction of the immigrant population, mainly characterized by working-age individuals, together with the increased unemployment rate (4.5% in 2020 compared to 3.8% in 2020) (ONS, 2021c) have induced a percentage reduction of the human time devoted to the paid activities (HApw) that has been largely higher than the reduction of the household time (HAhh) (Fig. 4). During the first national lockdown, where most of the production activities have been forced to shut down, the total human time devoted to the working sector has reduced by more than 16.3% compared to the same period of the previous year. However, given the fact that the average working hours provided by ONS are not adjusted for the workers who were temporarily away from work (such as benefiting from the furlough scheme provided by the UK government) the effective working time reduction has probably been higher than that included in the official statistics. That is because, according to data reported by ONS (2021c), the Coronavirus Job Retention Scheme (CJRS), announced by the UK Government on March 20, 2020 and extended until September 2021, has involved a wide percentage of the UK workforce, ranging between the 28.8% in May 2020 and 8.3% in October 2020. In addition, during the third quarter of 2020, the high unemployment rate (4.7%) and the decrease mortality of the non-working age population has contributed to slightly increase the household time that accounted for a 0.2% rise compared to the same period of 2019.

When considering the allocation of time across activities of the paid sector (Fig. 5), all the five compartments considered in this paper experienced working time reduction, with the largest drop taking place in the commercial sector, accounting for more than half (51.2%) of the human activity reduction (HApw). According to data provided by ONS (2021d) this sector had the largest redundancy rate, accounting for 60.4% of the total redundancies of 2020 and experiencing a 133.2% redundancy increase compared to 2019. The forced shut down imposed to the retail, accommodation and food services activities have largely affected the entire commercial sector and contributed to the overall redundancy increase. Together with the art, entertainment and recreation activities, this sector has also accounted for some of the higher percentage of the total workforce furloughed (46% for the art, entertainment, and recreation activities and 31% for the accommodation and food services activities, in July 2020) (ONS, 2021d).

When considering the economic performances, the industrial sector had the largest reduction in the percentage contribution to GDP generation (Fig. 6 and Table 3). By including manufacturing and construction, the industrial sector has been largely affected by the extensive lockdown restrictions that particularly during the fist pandemic wave, imposed the forced shut down of the non-essential production. According to the data provided by ONS (2020f), during the second quarter of 2020, these two sectors had a GDP drop of 23.4% and 36.2% compared the same period of 2019. The distribution and hospitality sector also accounted for a 36.7% reduction. On the contrary, the public administration and the commercial activities increased the percentage contribution to GDP.
administration activities in line with the working from home recommendation has allowed to sustain the core function of the public administration and other activities sectors. On the contrary, the transport activities, including non-essential shops and hospitality, experienced a recovery once the restrictions were eased. The retailer sector, for example, had a seasonally adjusted indexed volume of sales that in October 2020 was 29 points higher than in April 2020. On the contrary, the public administration and defence have seen a constant growth through the pandemic (ONS, 2021g).

In line with the GDP trend, the total energy throughout (TET), summarizing the energy used to sustain the socio-economic structure of the UK, has largely reduced during the entire duration of the COVID-19 crisis (Fig. 7). During the second quarter of 2020, the TET was 29.2% lower than in the same period of the previous year and the total energy used reduced by 12.7% between January and December 2020. The largest drop has taken place in the commercial sector, that including the transport activities experienced the some of the most extensive reductions (Table 4).

According to data provided by the Department for Business, Energy and Industrial Strategy (2021a), the transport demand dropped 28% compared to 2019 and the aviation sector experienced the largest reduction with a 60% drop. In addition, the complete shut down of non-essential shops and hospitality largely contributed to reduce the overall energy use. The working from home recommendation and the non-use of office spaces influenced the lower energy consumption of the public administration and other activities sectors. On the contrary, despite the warmer weather of 2020, the domestic energy demand used reduced by 12% between January and December 2020. The extension of energy used to sustain the socio-economic structure of the household sector has largely reduced summarizing the impact of production drop and increased unemployment rate. As reported above, however, if the

| Table 3 | Percentage variation of economic sectors to GDP contribution. |
|---------|----------------------------------------------------------|
|         | Q1          | Q2          | Q3          | Q4          |
| Agriculture | 13.06       | 11.56       | 7.01        | 6.33        |
| Industries  | –40.09      | –47.39      | –40.70      | –38.80      |
| Commercial  | 14.10       | 10.71       | 10.44       | 7.65        |
| Public admin.| 19.77       | 47.72       | 33.61       | 40.00       |
| Other activities | 10.76       | –24.51      | –6.75       | –15.84      |

The extension economic losses of the art, entertainment, and recreation activities largely influenced the drop of the other activities sector, that has been the second most affected compartment after the industrial sector. According to data of ONS (2021g), despite the relaxation of the lockdown restrictions, the enforced social distance measures, and the related reduction in the numbers of sale has largely affected the profitability of the entertainment industry, with a turnover, that for the cinema, was 58% lower in September 2020 compared to the same period of 2019. For the entire duration of the pandemic, the GDP production has been lower that generated during the same quarters of 2019 with an overall 10% reduction. According to data reported in Fig. 7, the largest GDP drop has taken place during the second quarter of 2020, when the value added production shrank by around 20% compared to the same period of the previous year. During the third quarter of 2020, the progressive relaxation of the lockdown restrictions contributed to a partial recovery. However, according to data provided by ONS (2021g), by September 2020, the value added generation was still down 8.2% compared to February. The industrial and the other activities sectors performed the largest GDP drop (Table 4), while the commercial activities, including non-essential shops and hospitality, experienced a recovery once the restriction were eased. The retail sector, for example, had a seasonally adjusted indexed volume of sales that in October 2020 was 29 points higher than in April 2020. On the contrary, the public administration and defence have seen a constant growth through the pandemic (ONS, 2021g).

In line with the GDP trend, the total energy throughout (TET), summarizing the energy used to sustain the socio-economic structure of the UK, has largely reduced during the entire duration of the COVID-19 crisis (Fig. 7). During the second quarter of 2020, the TET was 29.2% lower than in the same period of the previous year and the total energy used reduced by 12.7% between January and December 2020. The largest drop has taken place in the commercial sector, that including the transport activities experienced the some of the most extensive reductions (Table 4).

According to data provided by the Department for Business, Energy and Industrial Strategy (2021a), the transport demand dropped 28% compared to 2019 and the aviation sector experienced the largest reduction with a 60% drop. In addition, the complete shut down of non-essential shops and hospitality largely contributed to reduce the overall energy use. The working from home recommendation and the non-use of office spaces influenced the lower energy consumption of the public administration and other activities sectors. On the contrary, despite the warmer weather of 2020, the domestic energy demand used reduced by more than 2% as people were forced to stay at home. This trend is also summarized by the Exosomatic Metabolic Rate (EMR) of the paid and residential sectors. According to data reported in Fig. 9, the quantity of energy used per unit of time devoted to the paid activities has largely reduced summarizing the impact of production drop and increased unemployment rate. As reported above, however, if the

| Table 4 | Percentage variation GDP, TET and THA (2020 compared to 2019). |
|---------|----------------------------------------------------------|
|         | % Δ GDP | % Δ TET | % ΔTHA |
| Agriculture | –1.4  | –5.7   | –16.6  |
| Industries  | –47.3 | –8.5   | –6.3   |
| Commercial  | –0.2  | –24.9  | –10.8  |
| Public admin.| 21.3  | 2.4    | –8.1   |
| Other activities | –17.3 | –8.0   | –13.9  |
| Paid sector  | –9.9  | –17.6  | –9.4   |
| Household sector | 2.1   | 2.1    | –1.4   |
73.9% energy efficiency change. The extensive production drop of the industrial activities and the related 8.5% reduction of energy used has moved from 1.76 (MJ/£) in 2019 to 3.06 (MJ/£) in 2020 (Fig. 10). In a similar way, the almost complete shutdown of the art, entertainment and recreation sector contributed to increase the energy intensity of the other activities compartment (11.3%), that despite the extensive value generation drop (−17.3%) still had to sustain fixed energy costs. On the contrary, the commercial and the public administration sectors, had a reduction in the quantity of energy used per unit of GDP produced. The possibility to work from home and to substitute most of the non-essential shopping activities with on-line sale, has allowed these sectors to sustain the generation of economic values while reducing the energy used in office spaces and retail stores. According to data reported in Fig. 10 the energy intensity of these two sectors has been reduced by 24.9% and 20.3%, respectively.

In a similar way, the Exosomatic Metabolic Rate (EMR) of the commercial sector has been reduced, summarizing a drop in the energy used per unit of human time (Fig. 11). On the contrary, all the other sectors, with exception of industry, have experienced an exosomatic metabolic rate increase, summarizing that the fixed energy costs have not been proportionally reduced in line with the reduction of the working time. According to data reported in Table 4, for these sectors the reduction of THA has been percentage higher than the reduction in the total energy used (TET). On the contrary, the extensive production drop of the industrial activities and the relative 8.5% reduction of energy used has been higher than the percentage variation of the total human time (−6.3%) summarizing an exosomatic metabolic rate increase. As reported above, however, these results might be affected by the fact that the furlough data have not been included in the working hour adjustment provided by ONS.

5. Conclusion

The COVID-19 crisis and the related lockdown restrictions have forced a reduction of activities and a consequent energy consumption drop. During the last nine months of 2020, the total energy throughput of UK reduced by more than 17% and the value added decreased by 12.5% compared to the same period of the previous year. Despite this overall reduction trend, extensive differences have characterized the performances of sectors, and some of them have adjusted better than others to the pandemic challenges. The public administration activity for example been able to account for an overall GDP increase, with a related variation in the percentage contribution to the total value-added generation. The increased demand for human health, social work, and defence related activities, together with the possibility to manage most of the public administrative procedures in line with the working from home recommendation have allowed to sustain the core functions of the public sector without reducing the generation of value. On the contrary, the forced shutdown of non-essential productions and recreational activities have induced extensive economic losses for the industrial and the other activities sectors. For the commercial compartment, the possibility to rapidly convert the business practices to on-line shopping and sales has contributed to limit the revenue drop. When considering the related energy use, the commercial sector has also been able to account for the largest energy reductions. Characterized by relatively low energy structural costs, this sector has been able to decrease the energy demand...
by more than 24% and to increase the economic energy efficiency of production by almost 25%. On the contrary, the extensive energy fixed costs of the industrial sector, have induced a much smaller reduction of the energy demand, that decreased by 8.4% despite the 47% of GDP drop. When considering the domestic sector, the increased unemployment rate and the working from home recommendation have induced an overall energy consumption rise, that despite the favourable weather condition, increased by more than 2% compared to the same period of 2019. As a consequence, the exosomatic metabolic rate has slightly increase. As reported above, this result is however affected by the lack of inclusion of the furlough data into the working hour statistics. In this case, the increase of the domestic human time could have highlighted energy-related economies of scale, as more people of the same household would have shared the domestic energy use.

As reported above, a wide range of studies have investigated the impacts of the COVID-19 pandemic for different sectors, countries, and variables. Time series and scenario analysis have been used together with different modelling approaches. However, none of the existing analyses have used a metabolic approach to relate the impacts to the socio-economic and energy characteristics of countries. By integrating a wide range of intensive and extensive variables at different scales of analysis, the MuSIASEM approach is particularly suitable to investigate how different countries have been affected by the same pandemic crisis. Within this context, the possibility to replicate the MuSIASEM technique for a wide range of world areas represents an important opportunity to analyse the role that metabolic profiles can have in amplifying (or reducing) the impacts induced by the COVID-19 pandemic. The results presented in this paper can help us to understand how specific sectors and areas. Despite the existing limitations, results are in line with the analysis included in the Green Recovery Strategy of the UK Government. Both studies highlight the extensive energy dependency of UK society and a promising potential for energy efficiency improvements, as demonstrated by the fact that the imposed operational restrictions have been able to generate a percentage reduction of energy use that has been higher than the percentage of GDP drop. The possibility to work from home, the consequent reduction of working related journeys, the shut-down of office and retailer spaces, together with the increased on-line sale have highlighted possibilities for business models able to generate economic value with lower energy uses. The need to reduce the fix energy costs of industrial production and the energy consumption of built spaces have also been highlighted as green development priorities of the net zero carbon emissions objective of 2050. Within this context, the extensive constraints of the unexpected COVID-19 pandemic could than provide opportunities for sustainable changes. The approval of the Next Generation EU and the large investments that developed and developing countries are devoting to renewable sources and energy efficiency increase, have highlighted the importance of green development plans in the definition of the post-pandemic recovery. Within this context, the metabolic approach and the related MuSIASEM technique can be used to investigate how changes taking place across dimensions and scales can impact on energy allocation and use, and specifically support the definition of strategies designed in line with the socio-economic characteristics of countries. In addition, when data will be available, metabolic analysis could also be performed to investigate the structural changes induced by the green recovery strategies and the sustainability transition of countries.

CRediT authorship contribution statement

Valeria Andreoni: Conceptualization, Data curation, Methodology, Writing – review & editing.

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.

References

Aktar, M.A., Alamb, Md M., Al-Amin, A.Q., 2021. Global economic crisis, energy use, CO2 emissions, and policy roadmap amid COVID-19. Sustain. Prod. Consum. 26, 770–781.
Al-Tamimi, A., Al-Ghamdi, S., 2020. Multiscale integrated analysis of societal and ecosystem metabolism of Qatar. Energy Rep. 6 (1), 521–527.
Amanou, S.A., Bargaoui, S.A., 2022. Energy markets responds to Covid-19 pandemic. Renew. Resour. Pol. 76, 102551.
Andreoni, V., 2017. Energy metabolism of 28 world countries: a multi-scale integrated analysis. Ecol. Econ. 142, 56–69.
Andreoni, V., 2020. The energy metabolism of countries: energy efficiency and use in the period that followed the global financial crisis. Energy Pol. 139, 111304.
Andreoni, V., 2021. Estimating the European CO2 emissions changes due to COVID-19 restrictions. Sci. Total Environ. 769, 145115.
Arbel, Y., Fialkoff, C., Kerner, A., Kener, M., 2022. Do COVID19 infection rates change over time and space? Population density and socio-economic measures and regressors. Cities 20, 103400.
Arbi, V., Parma, J., 2021. Disease, downturns, and wellbeing: economic history and the long-run impacts of COVID-19. Explor. Econ. Hist. 79, 101381.
Bahlamyar, A., Etehbari, A., Ernst, D., 2020. The impact of different COVID-19 containment measures on electricity consumption in Europe. Energy Res. Soc. Sci. 68, 101683.
Balest, J., Stanwraga, A.E., 2022. Social practices and energy use at home during the first Italian lockdown due to COVID-19. Sustain. Cities Soc. 78, 103536.
Birol, F., 2020. Pay Clean Energy at the Hearth of Stimulus Plans to Counter the Coronavirus Crisis-Analysys-IEA. IEA.
Çelik, D., Meral, M.E., Waseem, M., 2021. Restrictions and driving forces for renewable energy production development and electrical energy demand in general and during COVID-9. In: The 12th International Symposium on Advanced Topics in Electrical Engineering. March 25-27, 2021. Bucharest, Romania.
Çelik, D., Meral, M.E., Waseem, M., 2022. The progress, impact analysis, challenges and new perceptions for electric power and energy sectors in the light of the COVID-19 pandemic. Sustain. Energy, Grids Networks 31, 00728.
Chen, L., Xu, L., Velasco-Fernandez, R., Giampietro, M., Yang, Z., 2021. Residential energy metabolic patterns in China: a study of the urbanization process. Energy 215 (A), 119021.
V. Andreoni

Sepulveda, E.R., Brooker, A.S., 2021. Income inequality and COVID-10 mortality: age-stratified analysis of 22 OECD countries. SSM – Population Health 16, 100904.
Serrano-Tovar, T., Penate Suarez, B., Musicki, A., de la Fuente Bencomo, J.A., Cabello, V., Giampietro, M., 2019. Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. Sci. Total Environ. 689, 945–957.
Siciliano, G., 2012. Urbanization strategies, rural development and land use changes in China: a multiple-level integrated assessment. Land Use Pol. 29 (1), 165–178.
Silva-Macher, J.C., 2016. A metabolic profile of Peru: an application of multi-scale integrated analysis of societal and ecosystem metabolism (MusiASEM) to the mining sector’s exosomatic energy flows. J. Ind. Ecol. 20 (5), 1072–1082.
Su, Y., Cheng, H., Wang, Z., Wang, L., 2022. Impacts of the COVID-19 lockdown on building energy consumption and indoor environment: a case study in Dalian, China. Energy Build. 263, 112055.
Teng, B., Wang, S., Shi, Y., Sun, Y., Wang, W., Hu, W., Shi, C., 2022. Economic recovery forecasts under impacts of COVID-19. Econ. Modell. 110, 105821.
Tian, J., Yu, L., Xue, R., Zhuang, S., Shan, Y., 2022. Global low-carbon energy transition in the post-COVID-19 era. Appl. Energy 307, 118205.
Tong, Y., Wan, N., Dai, X., Bi, X., Wang, Q., 2022. China’s energy stock market jumps: to what extent does the COVID-19 pandemic play a part? Energy Econ. 109, 105937.
Tutak, M., Brodny, J., 2021. Assessing the level of energy and climate sustainability in the European union countries in the context of the European green deal Strategy and Agenda 2030. Energies 14 (6), 1767.
Tutak, M., Brodny, J., 2022. Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment, and conventional energy sources. A 20-year perspective. J. Clean. Prod. 345, 131076.
UK Home Office, 2020. Statistics Relating to COVID-19 and the Immigration System. May 2020. Available at: Statistics relating to Covid-19 and the immigration system, May 2020 (publishing.service.gov.uk).
Velasco-Fernandez, R., Dunlop, T., Giampietro, M., 2020a. Fallacies of energy efficiency indicators: recognizing the complexity of the metabolic pattern of the economy. Energy Pol. 137, 111089.
Velasco-Fernandez, R., Giampietro, M., Bukkens, S.G.F., 2018. Analyzing the energy performance of manufacturing across levels using the end-use matrix. Energy 161, 559–572.
Velasco-Fernandez, R., Perez-Sanchez, L., Chen, L., Giampietro, M., 2020b. A becoming China and the assisted maturity of the EU: assessing the factors determining their energy metabolic patterns. Energy Strategy Rev. 32, 100562.
Wen, W., Yang, S., Zhou, P., Gao, S.Z., 2021. Impacts of COVID-19 on the electric vehicle industry: evidence from China. Renew. Sustain. Energy Rev. 144, 111024.
Werikhe, A., 2022. Towards a green and sustainable recovery form COVID-19. Current Research in Environmental Sustainability 4, 100124.
World Bank website: GDP Growth (Annual %) Data (worldbank.org).
Zambrano-Monserrat, M.A., Ruano, M.A., Sanchez-Alcalde, L., 2020. Indirect effects of Covid-19 on the environment. Sci. Total Environ. 728, 138813.