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Decarbonizing the energy supply one pandemic at a time

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\textbf{ABSTRACT}

This study explores different energy consumption vectors during the first year of the COVID-19 pandemic in Portugal. Most of the workforce started working from home and resource consumption significantly shifted towards the domestic sector. The ensuing confinement protocols caused a shift in everyday life, which in turn significantly altered the energy supply and demand landscape. This event, although catastrophic in terms of loss of human life and economic development, can provide us with valuable data to study the potential of new strategies to achieve EU 2050 Energy goals. It was investigated whether the pandemic has opened a path and provided us with a partial answer to decarbonization in the form of home office practices as a possible energy efficiency measure. The present study shows that, in Portugal, there was a 15.7% reduction of primary energy consumption (accounting for electricity, natural gas and transport fuels) compared to 2019. The data suggest that actions targeting reduced mobility, such as home office practices and the decentralization of the workforce, could be a relevant energy efficiency measure.

\section{Introduction}

The decentralization of the workforce due to the COVID-19 pandemic caused a shift in energy demand towards the Domestic sector as home office practices became the new norm. This behavioural change can shine a light towards possible strategies for future energy management and provide us with a partial answer we have been seeking to the problem at hand, reducing our dependence on fossil fuels.

Energy consumption and generation, together with the associated pollutant emissions, have been one of the main concerns of the European Union (EU), echoed by numerous policies and directives aimed at reducing energy consumption and pollutant emissions. In the past few decades, there has been clear evidence of the impacts of anthropogenic emissions on climate leading to intensification of global warming and an increase in extreme weather events, with the energy generation sector being the largest contributor of global CO\textsubscript{2} emissions (IEA, 2020a). The EU 2050 energy and greenhouse gas emission (GHG) targets, reinforced in the Paris Agreement, are a direct response to this (European Commission, 2018). The main objectives are the decrease of emissions to the atmosphere and achieve the decarbonization of the energy supply to reduce our impact on the environment and keep the global temperature rise below 2 \degree C. Currently, there are some concerns about whether current policies are sufficient to achieve the long-term goals of net-zero GHG emissions by 2050 (H. de Coninck et al., 2018). Inevitably, energy systems, and how we use them, play a central role in achieving these long-term goals.

For the past 5 years (Table 1), both average final energy consumption (+1.3\% per year) and installed renewable capacity (+4.1\% per year) in Portugal have steadily increased. Yet, the contribution of renewable energy to final energy consumption has remained relatively constant, even decreasing in recent years (DGEG, 2020a).

This could be explained by the increase in renewable energy generation that, not following the same trend as installed power, became insufficient to cope with the increased energy demand. Nonetheless, the country has been striving towards decarbonization of the energy supply in compliance with the Paris Agreement and EU goals. With this in mind, the Portuguese National Energy and Climate Plan (PNEC) establishes a clear path towards these objectives, focused on increasing the renewable energy share and promoting the use of electricity as a replacement for fossil fuels, mainly in the transport, industry, domestic and services sectors (PNEC, 2030; 2021). Additionally, the plan references the role of citizens, adding that behavioural changes in our daily routine are key in

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fulfilling these objectives through more sustainable and energy-efficient practices.

On December 31st, 2019, the World Health Organization (WHO) reported on the initial spread of the novel COVID-19 virus in Wuhan, China (WHO, 2020). Three months later, on March 11th, 2020, WHO declared the global outbreak as a pandemic, which at this point had over 100,000 confirmed cases and more than 4,000 deaths (Ducharme, 2020; WHO, 2020). The following months, and ensuing confinement protocols, caused a shift in everyday life, with measurable impacts on our industries, economy, and the environment. As in many European countries, more than half of the population in Portugal went into confinement, halting the activity of many industries and services, and significantly changing the landscape of energy consumption and the environment (Le Quéré et al., 2020; Wang and Su, 2020; Werth et al., 2021). Although not by choice, but out of necessity, dramatic behavioural changes occurred during 2020 due to the pandemic that challenged the traditional work norm and opened a path to novel unconsidered strategies.

There has been an increasing number of publications related to the pandemic, with many focusing on the impact of COVID lockdown measures on energy production and demand. For instance, Werth et al. (2021) found that stay-at-home orders were the measure with the highest correlation to the energy system load reduction for a group of 16 European countries, while Rouleau et al. (Rouleau and Gosselin, 2021) reported a shift in housing energy consumption patterns with increased demand during the middle of the day. Additionally, some researchers have focused on the energy system flexibility and resilience, as well as energy market behaviour and social response to energy topics post-pandemic (Bienvenido-Huertas, 2021; Chen et al., 2021; Delgado et al., 2021; Halbrügge et al., 2021; Ruan et al., 2021). Finally, there are assessments of the regional energy landscape of different countries, where the pandemic has caused a significant increase in energy demand, especially in Brazil and Spain (Carvalho et al., 2020; Santiago et al., 2021), 18% in Kuwait (Albajery et al., 2020) and 23% in Italy (Rugani and Caro, 2020), among others (Abu-Rayash and Dincer, 2020; Ali et al., 2021; Aruga et al., 2020; Kulachinskaya et al., 2020; Mostafa et al., 2021; Wang and Zhang, 2021).

This paper analyses electricity, natural gas and transport fuel (road, aviation and shipping) consumption for the first year of the pandemic, 2020, and compares the data with the previous year (2019). This will allow us to analyse the effects of the pandemic on various forms of energy, their demand throughout the year, and explore if there are any sectors where the concept of home office practices and changes to citizen behaviour could effectively be used in future policies to achieve the goals set out by the EU for 2030–2050 and beyond.

### 2. Data source and applied methodology

Data regarding electricity, natural gas and transport fuel consumption, as well as final energy consumption and renewable energy production, was compiled from various Portuguese energy agencies. Specifically, the data sources are the following:

| Source | Description |
|--------|-------------|
| REN (Redes Energeticas Nacionais) | Daily real-time information platform for Portugal's electricity grid. |
| IPMA (Instituto de Meteorologia de Portugal) | Weather information for Portugal. |
| DGEG (Direção Geral da Energia) | Monthly statistic reports for energy production and consumption. |
| EPE (Empresa de Emergência Pública) | Daily electricity data for both 2019 and 2020. |
| IBGE (Instituto Brasileiro de Geografia e Estatística) | Population and economic data. |

In addition, for integrated analysis, all energy data was converted to primary energy, expressed as tonnes of oil equivalent (toe), according to the conversion factors used by DGE, applicable to Portugal in 2019, as detailed in Table 2. In doing so, the different forms of energy are normalized, allowing for a more detailed and accurate comparison between them.

To further facilitate the analysis and discussion of the data, both years were divided into four time periods, detailed in Table 3, defined according to the government confinement strategies for Portugal during the pandemic. Additionally, except for Fig. 1, the values presented throughout the study were averaged according to the number of months in each period (also detailed in the following table). This method can influence the final values if different months are chosen for each period. The main priority in the selection of the periods in this analysis was to be the closest possible to the dates of the different containment strategies of the country. Different countries had different behaviours and measures during the pandemic, which should be taken into consideration when comparing the results shown here with other regions.

For each of the periods, there were different measures and infection mitigation strategies in place. For PC it was business as usual from the beginning of the year, with only a few cases reported at the beginning of March. After more cases were confirmed and infection numbers were increasing, SAH started, which is when a state of emergency was declared and stay-at-home orders were given by the government. During this time, the general population should only leave the house for supply, medical assistance and critical/authorized work. After a few weeks, the DC period began with some services starting to return to normal and businesses reopening, restrictions were put in place to which type of activities could be performed, as well as the number of people that could be present in closed spaces and outdoor gatherings. The deconfinement was done in three phases (May 4th, May 18th and June 1st), with each municipality applying additional measures on a case-by-case basis according to the number of active infections and i) annual final energy data from 2015 to 2019 from the Portuguese Directorate-General for Energy and Geology (DGEG) annual 2019 energy report (DGEG, 2020a). The values are annual totals of final energy consumption and the contribution of renewable energy production to that total, as well as the delta compared to the previous year;

### Table 1

| Energy Product | Conversion Factor |
|----------------|------------------|
| Electricity (GWh) | 86 |
| Natural Gas (10^6Nm³) | 0.97 |
| GPL (ton) | 1.099 |
| Petrol (ton) | 1.051 |
| Diesel (ton) | 1.018 |
| Jet Fuel (ton) | 1.027 |
| Shipping Fuel (ton) | 0.955 |

ii) monthly electricity, natural gas and transport fuel data for both 2019 and 2020, from the DGEG monthly statistic reports (DGEG, 2020b). This includes data for the total monthly electricity and natural gas consumption from each of the main energy sectors (Agriculture & Fisheries, Industry, Transport, Services and Domestic), as well as the monthly fuel consumption of the most common fuels for transport (GPL, Petrol, Diesel, Aviation fuel and Shipping fuel);

iii) daily electricity data for both 2019 and 2020 is from the REN (Redes Energeticas Nacionais) daily real-time information platform (RENNET, 2020), which is divided into total production, production by source and daily electricity demand;

iv) Weather information for 2019 and 2020 is from the yearly weather reports published by the Portuguese Institute for Sea and Atmosphere (IPMA) (IPMA, 2021, 2020).
Infection rate. Approaching the end of year and Christmas holidays, a new nationwide state of emergency is declared, with additional confinement measures for municipalities identified as “high risk” according to their infection rate. These additional measures lasted until new year celebrations to mitigate increased population mobility during and after the holidays.

3. Results

3.1. Daily electricity demand

Fig. 1 shows the daily total electricity demand in Portugal, for both 2020 and 2019, and the difference between the two years. The plot is divided into the four main periods of 2020 (Table 1) according to the confinement dates and overall strategy for Portugal during the pandemic.

Electricity demand throughout 2020 followed a typical pattern for Portugal, with the highest demand in Winter and a decrease during the Spring and Summer seasons. Based on the values during the start of the year, 2020 was projected to surpass 2019 in terms of electricity demand (which is in agreement with yearly increases in energy demand), but due to the pandemic, the yearly average was 3.8% lower than 2019, a value comparable to the previous year, while Services and Domestic sectors continued the trend in DC and electricity demand remained within the same order of magnitude as the previous year, while Services and Domestic sectors began to normalize but were still significantly distant from 2019 values, at –13.1% and +12.5%, in that order, as many businesses and institutions remained in a home office format for the rest of the year. For NSE, most sectors experienced a decrease in electricity demand of 11.6% and an increase of 8.8%, respectively.

3.2. Electricity demand by activity sector

Fig. 2 shows the electricity demand by activity sector divided into each studied period during 2020 compared to the same value for the corresponding activity sector and period from 2019.

As expected, during PC, electricity consumption was similar to the previous year, with no significant variations. Starting with SAH, there was a significant drop in electricity demand, a drop that was not significant in every sector (except for Agriculture & Fisheries, which remained mostly constant throughout the entire year). Industry, Transport and Services electricity consumption decreased as Domestic increased, a parallel that remained true for the entire year. In SAH many industries were not working at full capacity or stopped entirely, causing a decrease of 12.6% in Industry electricity consumption, the highest decrease for the entire year for this sector. As with Industry, many services stopped during this time, which is reflected in the 31.6% decrease in Services electricity demand, the highest variation of all electricity sectors during the year. As expected, this was the period with the largest increase of building occupancy for households and consequently the largest increase for Domestic electricity consumption (23.2%). Although Transport in Portugal is not a highly electricity-dependent sector, many public transport options were not available during SAH, which is where most of the electricity consumption is allocated for this sector (trains and underground), registering a decrease in electricity consumption of 16.7%. The most notable difference in transport was in terms of fuel use (see section 3.4). As DC started, the Industry and Transport returned to near full capacity to decrease the negative economic impact of a prolonged shutdown, evidenced by the smaller difference during this time (–2.9% and –4.1%, respectively). The Services and Domestic sectors began to normalize but were still significantly distant from 2019 values, at –13.1% and +12.5%, in that order, as many businesses and institutions remained in a home office format for the rest of the year. For NSE, most sectors continued the trend in DC and electricity demand remained within the same order of magnitude as the previous year, while Services and Domestic had a decrease of 11.6% and an increase of 8.8%, respectively.

3.3. Natural gas consumption by activity sector

The 2020 natural gas consumption by activity sector and studied period, compared to 2019 values, is presented in Fig. 3. During PC, NG consumption was in line with 2019, with minor differences. As soon as the country went into the first lockdown (SAH) there is a 26.7% increase in Domestic NG consumption, which is to be
expected from the increased occupation of a residential building, since many day-to-day activities use NG, cooking and domestic water heating, for example. Since Industry and Services are very NG dependent, there was a 20.3%–32.4% decrease, respectively. As previously mentioned, during the SAH many industries and services were shut down completely, so these differences in NG were likely to follow the same pattern as electricity demand. For the DC period, NG consumptions started to normalize to 2019 values, although there was still a clear difference in the Services (14.6%) and Domestic (+14.5%) sectors. As industries restarted most of their activity mid-2020, by NSE the difference for this sector was minimal compared to 2019 in the same period, at 1.6%. Some services were still not fully operational, such as educational facilities and lodging, explaining the 11.8% decrease during this time. However, most were already functioning close to nominal capacity through online solutions or takeaway services, with some even increasing their activity to match increased demand, such as home delivery services. As for the Domestic sector, whoever could work remotely was asked to return to home office practices if they were not already doing so, which resulting in an 8.9% increased NG consumption compared to 2019, as residential occupancy was higher than the previous year.

3.4. Fuel consumption by petroleum derivative products

The values for fuel consumption by petroleum derivative products and period for 2020 and 2019 are shown in Fig. 4.

At the start of 2020, most of the fuel consumption was in line with the previous year, then in SAH the largest decrease of the year was registered. GPL, Petrol and Diesel, the three main fuels for road transport, decreased 8.6%, 38.2% and 31.5%, respectively. In the Aviation sector, which was severely affected by the pandemic during the entire year due to the closure of borders and national travel restrictions, there...
was a considerable 75.9% decrease in fuel consumption during DC, with no signs of recovery for the remainder of the year. Similar problems affected Shipping, since trading is dependent on travel and human interaction, supply chains were hindered due to the pandemic, evidenced by the decrease that started during SAH, most notably during DC with a 39.5% decrease in fuel consumption. Except for GPL demand, which remained significantly lower than 2019 throughout the entire year, none of the main fuels recovered from the mobility restrictions during 2020.

Petroleum derivatives are one of the main targets for policies in Portugal, especially road transport fuels. Diesel fuel, for example, has almost twice the primary energy consumption as the largest consumer in electricity and is higher than any natural gas consumer. Combined with other road transport fuels, this sector is one of the main contributors to carbon emissions and primary energy consumption in the country.

### 3.5. Total primary energy by activity sector

For an overall assessment and comparison of the energy consumption in 2020 and 2019, the total primary energy consumption for each activity sector and studied period is shown in Fig. 5.

In terms of total primary energy demand, the largest difference between 2020 and 2019 was for the Transport sector, with a decrease of 30.5% during the SAH period, which is equivalent to an average monthly decrease of 164 ktoe, which was the largest decrease in absolute values. Although the decrease in Services during the same period was comparable in percentage (31.8%), the reduction of primary energy in Transport is over three times higher than in Services (164 ktoe vs 44.7 ktoe, respectively). This reinforces the importance of exploring alternative policies for reducing transport fuel consumption, such as...
incentives to home office practices. Even comparing this with other sectors, such as Aviation which registered the largest percentage decrease of all sectors in all periods with –75.9% (102.2 ktoe), it is still only half of the decrease registered for Transport in absolute terms.

4. Discussion

4.1. Results discussion

There was a significant decrease in energy consumption during the time where mobility restrictions were in place, SAH and NSE being the most evident examples of this. Although the former is an extreme case and would not be an accurate case study or viable example for future strategies, the latter can be an interesting experiment in support of home office practices as an energy efficiency measure, since during this period there was lower energy consumption and a large portion of the population was working from home, yet the main services and industrial activities were still functional.

Electricity demand followed similar patterns to what would likely occur without government measures, but with overall lower values for most of the year, especially during SAH and NSE. There was a shift in electricity consumption towards the Domestic sector, while other sectors generally decreased during the year. This is to be expected since stay-at-home restrictions were in place during SAH and NSE, and even during DC a significant portion of the population was still at home.

As for natural gas, it is a valuable resource to many activities in the Industry, Services and Domestic sectors from energy production to household heating systems. The pandemic similarly affected natural gas consumption as electricity demand. Concerning NG consumption in the Domestic sector, higher NG use could be a result of a harsher winter. However, according to the Portuguese Institute for Sea and Atmosphere (IPMA), 2020 had the second hottest winter since 1931 and there was a low amount of precipitation, registering the highest average maximum temperature since 1931 and the third-highest average minimum temperature since the year 2000. The same can be said of 2019, which was also warmer and drier than average (IPMA, 2021, 2020). Therefore, the Domestic NG consumption increase is mostly attributable to increased building occupancy (i.e. increased activities such as cooking, domestic hot water use and normal space heating usage) and not increased use of heating systems due to colder weather.

The main petroleum products consumed in Portugal are for road Transport, Aviation and Shipping, all of which saw a drastic reduction in terms of demand during 2020. Since one of the main mitigation strategies for reducing the spread of an infectious disease is mobility restrictions, it is natural that fuels for transport would see a significant decrease during this time. Activity in the Aviation and Shipping sectors did not fully recover for the remainder of the year, and although they can represent a small portion of the Gross Domestic Product (GDP) in most countries, it is closely related to other activities such as manufacturing or freight transport and are highly dependent on fossil fuels with an almost one-to-one correlation between fuel use and activity. Fuel consumption data can already give us some insight on how home office practices could be helpful to achieve future energy goals, especially in sectors that have a high dependence on road transport fuels or other petroleum derivatives, since these products are normally hard to replace and represent large sources of carbon emissions. Total primary energy data supports this and suggests that policies targeting the Transport sector would be more effective and provide better results with a lower decrease in activity and should possibly be prioritized for reducing total primary energy consumption.

Overall, the combined reduction of primary energy in 2020, considering that average monthly values for each period, was 2636.5 ktoe, which is approximately 15.7% of the primary energy consumption in 2019, which is in line with the studies for other regions, mentioned at the end of Section 1, that reported an energy demand reduction of 13%-25%. This is a very large decrease and shows promising results when there is decreased activity in some sectors. From an economic standpoint, the country was severely impacted by the pandemic, with the national GDP falling 7.8%, more than double that of the economic crisis of 2008/2009 (INE, 2021a). However, energy intensity in Portugal also decreased from 0.0784 ktoe. Mt⁻¹ to 0.0698 ktoe. Mt⁻¹, which suggests that although the overall activity of the country decreased, it was more energy efficient (INE, 2021b), providing valuable insight towards decarbonization strategies.

4.2. Implications of home office practices in primary energy consumption

It is still unclear what the broader effects of office decentralization and adoption of home office practices would be in regards to primary energy consumption, especially since the case presented in this study is an isolated and extreme pandemic event. Nonetheless, there is evidence in the data that suggests home office practices could become an interesting avenue to explore in decarbonization and reduction of carbon emissions in the transport sector. At this time, the available data is limited and insufficient to extrapolate the results from this study to a broader national strategic perspective, however, a simplified set of scenarios were outlined to perform an estimate of home office practices in transport use to compare some of the most common commuting practices.

The scenarios are based on distance and office trips and were built to study the differences in primary energy consumption between a worker in an urban scenario with daily commutes to the office (i.e. local worker) and a home office worker that goes to the office up to four times a month (i.e. remote worker). An overview of the scenarios is shown in Table 4, including mode of transport, the number of trips and total distance travelled each month. The following assumptions were the basis for the construction of the scenarios:

- Local worker travels to the office every day, lives closer to the office than the remote worker, and uses the bus for daily commuting, with each round trip being 10, 25, 50 or 100 km, which are represented by scenarios LW-B-10, LW-B-25, LW-B-50 and LW-B-100, respectively;
- Remote worker lives further away since they are not required to be in the office every day and moved away from an urban centre to reduce housing costs;

| Worker type | Scenario name | Mode of transport [MJ. (passenger.km)⁻¹] (IEA, 2020b) | Total km travelled per month [r² of trips] |
|-------------|---------------|-----------------------------------------------|-----------------------------------------|
| Local Worker | LW-B-10/25/50/500 | Bus [0.7] | 200 [20]/500 [20]/1000 [20]/2000 [20] |
| Remote Worker | RW100-C-1/2/4 | Car [1.8] | 100 [1]/200 [2]/400 [4] |
| Remote Worker | RW300-C-1/2/4 | Car [1.8] | 300 [1]/600 [2]/1200 [4] |
| Remote Worker | RW600-C-1/2/4 | Car [1.8] | 600 [1]/1200 [2]/2400 [4] |
| Remote Worker | RW100-B-1/2/4 | Bus [0.7] | 100 [1]/200 [2]/400 [4] |
| Remote Worker | RW300-B-1/2/4 | Bus [0.7] | 300 [1]/600 [2]/1200 [4] |
| Remote Worker | RW600-B-1/2/4 | Bus [0.7] | 600 [1]/1200 [2]/2400 [4] |
| Remote Worker | RW100-T-1/2/4 | Train [0.2] | 100 [1]/200 [2]/400 [4] |
| Remote Worker | RW300-T-1/2/4 | Train [0.2] | 300 [1]/600 [2]/1200 [4] |
| Remote Worker | RW600-T-1/2/4 | Train [0.2] | 600 [1]/1200 [2]/2400 [4] |
- Remote worker has round trips from their residence to the office of 100, 300 or 600 km, represented by the scenarios RW100, RW300 and RW600, respectively;
- Within each RW scenario, the worker performs monthly, biweekly or weekly trips to the office by car, bus or train.

The total primary energy consumption of each of the scenarios was calculated using their energy intensity and total monthly distance travelled. It is of note that, according to (IEA, 2020b) the energy intensity of aviation is the same as passenger cars, 1.8 MJ/(passenger km)\(^{-1}\), therefore any conclusions that can be reached for cars is also comparable to air travel. Table 5 shows the results from the energy consumption calculations of each scenario.

The results show that a local worker living close to the office (LW-B-10) would have lower energy consumption than the closest remote worker using a car for a monthly trip (RW100-C-1) but have a higher energy consumption compared to the same remote worker using a bus up to biweekly office trips (RW100-B-2), as well as up to weekly trips using a train (RW100-T-4). The train option could still be beneficial if the remote worker lives up to 300 km away from the office and only requires one monthly trip (RW600-T-1).

With the local worker further away from the office other options could become viable, even when using the car. For example, compared to working in a large city (scenarios LW-B-25 and LW-B-50), a remote worker would have comparable or lower energy consumption while performing up to four 100 km trips (RW100-C-4) and even a monthly 300 km trip by car (RW300-C-1). From LW-B-25 onward, all train travel options (except RW600-T-4) have a lower energy consumption than the local worker.

Of all the scenarios the best and worst in terms of primary energy consumption are the one monthly trip by train from a remote worker with a distance travelled of 100 km (RW100-T-1, 0.5 \(10^{-3}\) toe) and a remote worker using a car for a weekly trip to the office with 600 km per trip (RW600-C-4 103.2 \(10^{-3}\) toe). In most situations, if the worker lives close to a train or bus station they are both better options than using the car. The energy reduction benefits of train travel are tenfold compared to using the car, and approximately 70% less energy consumption than using the bus. However, this is due to most trains using electricity as a power source, contrary to cars and buses that mostly use fossil fuels. Nonetheless, the estimate provides a good comparison between different perspectives, and while the future of transport is currently skewed towards electric or soft mobility in the early to mid-term, this data still allows us to make a case for home office practices and reducing trips to the office.

There are a few limitations of a straightforward estimate such as the one presented here. When studying the broader effects of home offices practices as an energy efficiency measure by analysing primary energy consumption in Portugal during the first year of the COVID-19 (2020) pandemic. The year was divided into four time periods, chosen according to the pandemic response strategies in place, namely pre-confinement (PC), stay-at-home orders (SAH), deconfinement (DC) and a new state of emergency (NSE). All the main activity sectors, except for Domestic, registered a significant primary energy demand decrease during the year. This was due to mobility restrictions and the closure of many businesses during the SAH, part of the DC and the NSE periods, as a large portion of the population started working from home in March 2020.

Compared to 2019, the greatest differences mostly occurred during the SAH period, which was the initial containment period of the virus, when most businesses closed, part of the industry shut down and when the largest portion of the population was home. The most relevant variations for each energy type were:

- Electricity decreased 31.6% and 12.6% for Services and Industry, respectively, during SAH (Transport decreased 16.7% but in absolute terms, the value is very low, only 0.8 ktoe), and increased 23.2% for Domestic, in the same period.
- Natural gas consumption followed a similar pattern to electricity demand, with a decrease of 32.4% for Services and 20.3% for Industry, and an increase of 26.7% for Domestic, all during the SAH period.
- Petroleum products consumption saw a decrease of 31.5% in Diesel demand during SAH, while during DC Aviation and Shipping fuel consumption decreased 71.5% and 39.5%, respectively.

Reviewing the combined variation of primary energy demand, the Transport sector (sum of electricity, NG, GPL, Diesel and Petrol) registered the largest variation, with an average decrease of 164 ktoe during

### Table 5
Primary energy consumption of the different commuting scenarios, colour coding is green for lower values, white for average and red for higher values.

| Scenarios | B-10 | B-25 | B-50 | B-100 | C-1 | C-2 | C-4 | B-1 | B-2 | B-4 | T-1 | T-2 | T-4 |
|-----------|------|------|------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| LW        | 3.3  | 8.4  | 16.7 | 33.4  | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| RW100     | -    | -    | -    | 4.3   | 8.6 | 17.2| 1.7 | 3.3 | 6.7 | 0.5 | 1.0 | 1.9 |
| RW300     | -    | -    | -    | 12.9  | 25.8| 51.6| 5.0 | 10.0| 20.1| 1.4 | 2.9 | 5.7 |
| RW600     | -    | -    | -    | 25.8  | 51.6| 103.2| 10.0| 20.1| 40.1| 2.9 | 5.7 | 11.5|
SAH, followed by Aviation during DC with an average decrease of 118.3 ktoe, and finally Industry with a 62.8 ktoe average decrease in the SAH period. Currently, we have the technology required for the adoption of home office practices as a permanent option, and it is widely available at a global scale, especially in developed and developing countries. This would signify decreased mobility of the population due to the decentralization of the workforce, and as the present data and estimate suggest, strategies targeting the transport fuel sectors would yield favourable results. These sectors are highly dependent on petroleum derivatives, which are hard to effectively replace while maintaining the same level of activity and represent one of the largest sources of carbon emissions. Therefore, home office practices could be considered a viable energy efficiency measure for achieving future decarbonization goals, since the same level of services can be provided (taking the NSE period as an example), while decreasing primary energy demand and shifting some of the consumption to sectors where the energy source is already highly renewable (i.e., electricity in the Domestic sector).

However, there are downsides to this solution, and it would not be a simple process. For example, engaging in home office practices while also having a centralized office is a flawed solution, because it would mean a duplication of energy consumption by having equipment powered on in both places, therefore some initial planning is required to properly implement these solutions and avoid such situations. Additionally, in Portugal, like many other countries in the EU (e.g., Bulgaria, Greece and Italy), energy poverty is a major problem affecting a large portion of the population who are unable to keep their homes adequately warm or live in dwellings with leakages and other structural issues, which could be further aggravated if citizens exchange comfort for decreased utility bills. Finally, the social aspect of having a decentralized office could be a major factor hindering these measures from being successful, since increased isolation and decreased social interactions could in some cases lead to widespread mental health issues and decreased productivity. These issues are still understudied and up for debate, further research is required to study the balance between sustainability, productivity and wellbeing.

Home office practices could be beneficial for existing and planned policies/directives in the EU regarding the energy sector, energy use and increasing clean and safe energy availability. The most relevant being the “Clean Energy for all Europeans” package, which is a part of the agreement for a new energy rulebook based on proposals published by the European Commission in the past few years. The package includes several legislative acts related to the energy sector, from building performance to the energy market, that have a direct link to the topic explored in this study. For example, starting with the energy performance in buildings directive (Directive (EU) 2018/844), which outlines the long-term renovation strategy for the national stock of residential and non-residential buildings, taking a step towards zero-energy buildings. This directive could reduce some of the problems related to energy poverty, specifically household heating and cooling, which would propel the widespread implementation of home office practices by making it a more attractive and viable option for workers. Another aspect of the package is related to the promotion of the use of renewable energy (Directive (EU) 2018/2001, with a target of 32% renewable sources in the energy mix), which combined with an increase in energy efficiency could aid in increasing the contribution of renewable energy in final energy consumption, doubling down on efforts to decarbonize the energy supply. Finally, the directive that aims at increasing energy efficiency (Directive (EU) 2002/2001) would greatly benefit from home office, since the core principle of this practice is to decrease primary energy consumption while maintaining the same level of activity without compromising economic development.

CRediT authorship contribution statement

M.A. Russo: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. L. Ruivo: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. D. Carvalho: Writing – review & editing, Supervision. N. Martins: Conceptualization, Methodology, Writing – review & editing, Supervision. A. Monteiro: Writing – review & editing, Supervision.

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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References

Abu-Rayash, A., Dincer, I., 2020. Analysis of mobility trends during the COVID-19 coronavirus pandemic: exploring the impacts on global aviation and travel in selected cities. Energy Res. Soc. Sci. 68, 101699 https://doi.org/10.1016/j.erss.2020.101699.
Alhajeri, H.M., Almutairi, A., Alenezi, A., Alshammari, F., 2020. Energy demand in the state of Kuwait during the covid-19 pandemic: technical, economic, and environmental perspectives. Energies 13, 4570. https://doi.org/10.3390/en13114370.
Ali, G., Abbas, S., Qamer, F.M., Wong, M.S., Rasul, G., Ashraf, S., Shahzad, N., 2021. Environmental impacts of shifts in energy, emissions, and urban heat island during the COVID-19 lockdown across Pakistan. J. Clean. Prod. 291, 125806 https://doi.org/10.1016/j.jclepro.2021.125806.
Aruja, K., Islam, M.M., Jannat, A., 2020. Effects of COVID-19 on Indian energy consumption. Sustain. Times 12, 1–16. https://doi.org/10.3390/sut12145616.
Benedenbader-Huertas, D., 2021. Do unemployment benefits and economic aids to pay electricity bills remove the energy poverty risk of Spanish family units during lockdown? A study of COVID-19-induced lockdown. Energy Pol. 150, 112117 https://doi.org/10.1016/j.enpol.2020.112117.
Carvalho, M., de Delgado, D.B., de Lima, K.M., de Cancela, M., dos Siqueira, C.A., de Sousa, D.L.B., 2020. Effects of the COVID-19 pandemic on the Brazilian electricity consumption patterns. Int. J. Energy Res. 1–7. https://doi.org/10.1002/er.5877.
Chen, C., Li, J., Shuai, J., Nelson, H., Walzem, A., Cheng, J., 2021. Linking social-psychological factors with policy expectation: using local voices to understand solar PV poverty alleviation in Wuhan, China. Energy Pol. 151, 121610 https://doi.org/10.1016/j.enpol.2021.121610.
de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J.C., Ley, D., Mehlisch, R., Newman, P., Revokatova, A., Schultz, S., Steg, L., S, T., 2018. Strengthening and implementing the global response. Glob. Warm. 1.5°C: An IPCC spec. Rep. Impacts glob. Warm. 1.5°C above pre-industrial levels relat. Glob. Grehn. Gas emis. Pathways, context strength. Glob. Res. Thetin Clim. Chang. 132.
Delgado, D.B. de M., Lima, K.M. de, Cancela, M. de C., Siqueira, C.A., dos S., Carvalho, M., Souza, D.L.B. de, 2021. Trend analyses of electricity load changes in Brazil due to COVID-19 shutdowns. Elec. Power Syst. Res. 193 https://doi.org/10.1016/j.epsr.2020.107009.
Direc¸çao Geral de Energia e Geologia (DGE), 2020a. Balanço Energetico Sintético 2019. https://www.dgeg.gov.pt/pt/estatistica/energia/balancos-energeticos/balancos-energeticos-sinteticos/.
Direc¸çao Geral de Energia e Geologia (DGE), 2020b. Estimativas r´apidas de consumo energ´etico. https://www.dgeg.gov.pt/pt/estatistica/energia/publicacoes/estimativas-rapidas-de-consumo-energetico/.
Du charm, J., 2020. World Health Organization Declares COVID-19 a ‘Pandemic.’ Here’s what That Means. https://time.com/5791661/who-coronavirus-pandemic-declaration/.
European Commission, 2018. A Clean Planet for All A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy 1–29. Halbriegge, S., Schott, P., Weiβzahli, M., Buhl, H.U., Frigden, G., Schöpf, M., 2021. How did the German and other European electricity systems react to the COVID-19 pandemic? Appl. Energy 285, 116370. https://doi.org/10.1016/j.apenergy.2020.116370.
International Energy Agency (IEA), 2020a. Global CO2 emissions by sector. https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2018.

International Energy Agency (IEA), 2020b. Energy intensity of passenger transport modes, 2018. https://www.iea.org/data-and-statistics/charts/energy-intensity-of-p-assenger-transport-modes-2018.

National Statistic Institute (INE), 2021a. Gross domestic product per capita. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&contexto=pl&indicadorCod=0090888&efTab=tab0.

National Statistic Institute (INE), 2021b. Gross domestic product at current prices. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&contexto=bd&selTab=tab2&xlang=en.

Portuguese Institute for Sea and Atmosphere (IPMA), 2020. Resumo climatológico ano 2019 Portugal 1–20. https://www.ipma.pt/pt/publicacoes/boletins.jsp?cmbDep=cli&cmbTema=pc&idDep=cli&curAno=2019.

Portuguese Institute for Sea and Atmosphere (IPMA), 2021. Resumo climatológico ano 2020 Portugal 1–9. https://www.ipma.pt/pt/publicacoes/boletins.jsp?cmbDep=cli&cmbTema=pc&idDep=cli&curAno=2020.

Kulachinskaya, A., Akhmetova, I.G., Kulkova, V.Y., Ilyashenko, S.B., 2020. The challenge of the energy sector of Russia during the 2020 COVID-19 pandemic through the example of the republic of tatarstan: discussion on the change of open innovation in the energy sector. J. Open Innov. Technol. Mark. Complex. 6, 60. https://doi.org/10.3390/joitmc6030060.

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., DeGol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Change 10, 647–653. https://doi.org/10.1038/s41558-020-0797-z.

Mostafa, M.K., Gamal, G., Wafiq, A., 2021. The impact of COVID-19 on air pollution levels and other environmental indicators - a case study of Egypt. J. Environ. Manag. 277, 111496 https://doi.org/10.1016/j.jenvman.2020.111496.

Plano Nacional Energia, 2021. El clima 2021-2030 (PNEC 2030). https://www.portugalenergia.pt/sector-energetico/bloco-3/.

Redes Energéticas Nacionais (REN), 2020. Estatística diária - SEN. https://www.centrodeinformacao.ren.pt/EN/Pages/CHomePage.aspx.

Rouleau, J., Gosselin, L., 2021. Impacts of the COVID-19 lockdown on energy consumption in a Canadian social housing building. Appl. Energy 287, 116565. https://doi.org/10.1016/j.apenergy.2021.116565.

Ruan, G., Wu, J., Zhong, H., Xia, Q., Xie, L., 2021. Quantitative assessment of U.S. bulk power systems and market operations during the COVID-19 pandemic. Appl. Energy 286, 116354. https://doi.org/10.1016/j.apenergy.2020.116354.

Rugani, B., Caro, D., 2020. Impact of COVID-19 outbreak measures of lockdown on the Italian Carbon Footprint. Sci. Total Environ. 737, 139806 https://doi.org/10.1016/j.scitotenv.2020.139806.

Santiago, I., Moreno-Munoz, A., Quintero-Jiménez, P., García-Torres, F., Gonzalez-Redondo, M.J., 2021. Electricity demand during pandemic times – a case study of China. Sci. Total Environ. 728, 138915 https://doi.org/10.1016/j.scitotenv.2020.138915.

Wang, Q., Zhang, F., 2021. What does the China’s economic recovery after COVID-19 pandemic mean for the economic growth and energy consumption of other countries? J. Clean. Prod. 295, 126265 https://doi.org/10.1016/j.jclepro.2021.126265.

Werth, A., Gravino, P., Prevedello, G., 2021. Impact analysis of COVID-19 responses on energy grid dynamics in Europe. Appl. Energy 281, 116045. https://doi.org/10.1016/j.apenergy.2020.116045.

World Health Organization, 2019. Coronavirus Disease 2019 (COVID-19): Situation Report, vol. 51. World Health Organization, Geneva PP - Geneva.

World Health Organization, 2020. Interactive COVID-19 timeline. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline.