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Action plan for the mitigation of greenhouse gas emissions in the hospital-based health care of the Hellenic Army

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Abstract Climate change is a growing threat for human health and well-being, one that will seriously impact and potentially disrupt all economic sectors and supply chains, such as trade, tourism, agriculture, forestry, and fisheries. The environmental impact of the delivery of medical and hospital care, which generates its own greenhouse gas emissions, needs to be examined and analyzed in detail in order to design and implement effective mitigation actions and measures. Hospital internal energy use processes include the energy consumed for hospital operation, such as lighting, heating, cooking, waste treatment, and other functions associated with the logistical and operational support of hospitals. The present research work, which follows the assessment undertaken in a previous study of the transport activities of the 401 Military General Hospital of Athens (401 MGHA), focuses on the carbon footprint of the stationary emission sources of the 401 MGHA; it serves as a second step in the development of an action plan for the mitigation of greenhouse gas emissions in the hospital-based health care of the Hellenic (Greek) Army. A portfolio of energy saving and emission reduction actions is proposed and mapped according to their abatement cost and greenhouse gas (GHG) reduction potential. The highest decrease of GHG emissions is expected to be materialized by the decarbonization of the Greek power sector due to the lignite phase-out and increased share of low carbon fuels and renewable energy sources. Significant emission reduction potential could also be achieved by the replacement of face-to-face hospital visits by telemedicine, primarily by reducing transport-associated emissions. Furthermore, a number of key performance indicators (KPI) are proposed as simple and easily monitored metrics of the hospital's performance towards its sustainable low carbon objectives. Specific KPIs per mitigation action are presented, as well as a general KPI that covers all mitigation actions and sources of emissions in the form of "tCO_2eq per patient" or "tCO_2eq per hospitalization day."

Keywords Carbon footprint · Climate change · Mitigation action plan · Greenhouse gas emissions · Hospital-based health care · Stationary emission sources · Key performance indicators

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Introduction

Driven by man-made greenhouse gas (GHG) emissions, climate change is the greatest threat humanity

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is facing today, while its effects are anticipated to worsen in the decades to come (IPCC, 2021). Scientists and analysts have cautioned that global warming is a future national security concern for humanity (Ostad-Ali-Askari et al., 2020; Talebmorad et al., 2021; Javadinejad et al., 2021). The main GHG in the Earth's atmosphere are carbon dioxide (CO_2), methane (CH4), ozone (O3), water vapor, nitrous oxide (N2O), and fluorinated gases. All these gaseous compounds are capable of absorbing and emitting infrared radiation, trapping heat in the lower atmosphere, while simultaneously allow an amount of heat to return back to space. In order to reduce emissions of the seven GHG covered by the United Nations Framework Convention on Climate Change (UNFCCC), which have been recognized as the prime manmade cause of global climate change (CO_2, CH4, N2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), Sulfur hexafluoride (SF6) and nitrogen trifluoride (NF3)), all nations have to develop environmentally friendly regulations, aiming to limit the increase of global average temperature. Based on the Paris Agreement, the 193 Parties that signed it have committed to report their national GHG emissions to UNFCCC and submit Nationally Determined Contributions (NDC) that they intend to achieve in the future years. Climate plans for reducing GHG emissions need to limit temperature rise to 1.5 °C, taking into consideration the financial and industrial circumstances of each country (UNFCCC, 2015).

The health care sector is a significant source of greenhouse gas (GHG) emissions and other pollutants (Dacones et al., 2021). Hospital-based health care is an energy-intensive sector that generates large quantities of GHG emissions. Hospitals generate and release GHG emissions in a variety of ways, including the transportation footprint from commuting employees and fleet management (Bozoudis & Sebos, 2021), the energy consumed for heating and cooling of the buildings, medical electronic devices and laboratory equipment, laundries, food preparation and cooking, and waste management and disposal. Hospitals and labs produce more than 5 million tons of waste annually, and emit 2 gigatons of CO_2 each year, 4.4% of the world's net GHG emissions (Budd, 2019). Despite the magnitude of health care resource use and associated emissions, there has been insufficient research into its environmental sustainability. The overarching principles and validated methodologies of sustainability science could be applied to the health sector, in order to critically assess the ways in which the current provision of health care creates emissions that undermine the health and well-being of current and future generations and to propose actions for their abatement (Sherman et al., 2019).

The UK's health care sector spends more than £400 million per year on energy, and the National Health Service (NHS) is responsible for 25% of all UK public sector emissions. The estimated carbon footprint of the NHS UK was 25.0 megatons of CO_2eq in 2019 (Purohit et al., 2021). In the USA, the health care system generates 8–10% of country's GHG emissions (MacNeil et al., 2017; Eckelman & Sherman, 2016). The USA is the world's highest emitter of health sector GHG, accounting for 27% of the global health sector carbon footprint. The US health care sector GHG emissions rose by 6% from 2010 to 2018, reaching 1692 kg per capita in 2018. (Eckelman et al., 2020).

The carbon footprint (CF) is the total GHG emissions that are produced by a country, a person, an organization, etc., over a specific period of time, indicated as carbon dioxide equivalent (CO_2eq) (Holmner et al., 2014). The decrease of the carbon footprint of large-scale organizations such as big hospitals could be considered a necessity for mitigating climate change (Karliner et al., 2019). According to the Health Care Without Harm (HCWH) non-profit coalition of hospitals, more than half of the health sector's CF comes from energy use, when measured across all the emission categories (scopes) of the GHG Protocol (HCWH, 2019). The Scope 1 GHG sources account for all direct emissions, including the health care facilities and health care owned vehicles that make up 17% of the sector's worldwide footprint. Scope 2 is the indirect emissions from purchased energy sources used by the health care organization, such as electricity, steam, cooling, and heating, comprising another 12% of the total CF. Scope 3 (all other indirect emissions) usually includes the greatest share of the carbon footprint, which is derived from the health care supply chain through the production, transport, and disposal of goods and services (food and pharmaceuticals supplies, medical devices, hospital equipment, etc.). In accordance with the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2018), health care administrators should work with their suppliers in order to achieve "net zero" emissions by 2050 or before.

The total GHG emissions of Greece were 85,631 kt CO_2eq in 2019, and the GHG emissions per capita were about 7.98 tons CO_2eq per capita (Sebos et al., 2016; EEA, 2020). Nevertheless, despite the significance of hospital-based health care GHG emissions and their increasing trend (Dacones et al., 2021, Eckelman et al., 2020), there are no comprehensive studies in the scientific and other technical literature to measure and assess the contribution of the Greek health care sector to the country's national emissions. It is also necessary to develop action plans to mitigate emissions from the health care sector, in order to be in line with the overall national strategy targeting climate-neutrality by mid-century, and standardized metrics and protocols are needed to define environmental performance and monitor progress (Sherman et al., 2019).

The objective of this article is to create the necessary framework in terms of GHG accounting methodologies, activity data, baseline emissions, portfolio of mitigation actions, and standardized metrics for tracking progress, required for the development of an action plan for the reduction of GHG emissions in the hospital-based military health care. The carbon footprint of the 401 Military General Hospital of Athens (401 MGHA, Greece), the largest military hospital of Greece, is estimated for the first time. The analysis of GHG emissions and relative activity data is done between January and December 2018. Based on this analysis, Key Performance Indicators (KPIs) are proposed as simple metrics for the evaluation of the hospital's performance in relation to a portfolio of GHG mitigation actions, and the achievement of its low carbon and sustainability objectives. In addition, a mapping of the proposed GHG mitigation actions is made with respect to their abatement cost in relation to their GHG reduction potential. This mapping could facilitate the selection of and investment decisions about actions to reduce the GHG emissions of the health care sector.

Case study

The 401 military general hospital of athens (401 MGHA)

The 401 Military General Hospital of Athens (401 MGHA) is the largest military hospital of the Hellenic (Greek) Army. It has a capacity of 550 beds for patients and up to 1000 personnel, both military and civilians, and is located at Katehaki Avenue in Athens, Greece, since 1971. It was founded in 1904 as one of the biggest health care services in Greece. The military doctors and nurses of the 401 MGHA are among the best professionals in the Greek health care sector.

In 2018, 16,000 patients were hospitalized, and 230,000 patients visited the hospital (630 visits daily on average). The 401 MGHA is also a medical research center with engagement in training activities. It is also a member of the "IMIHO — Interconnection of Military Hospitals" portal, a medical information web exchange among South Eastern Europe military hospitals that specialize in humanitarian activities.

Carbon footprint calculations

The CF of the energy processes of the 401 MGHA was estimated based on data for the year 2018. The carbon footprint was estimated in carbon dioxide equivalent (CO_2eq) units, which describe different GHGs using a common unit of measure. For any quantity and type of greenhouse gas, CO_2eq signifies the amount of CO_2 that would have the same Global Warming Potential (GWP). The GWP of a GHG indicates the amount of warming a gas causes over a given period of time, normally 100 years. This analysis used the GWPs from the Fourth Assessment Report of Contribution of Working Group I to the Intergovernmental Panel on Climate Change (IPCC, 2007), which are currently used for reporting national GHG inventories to UNFCCC.

Energy consumption

Electricity The health care sector consumes significant quantities of energy (Eckelman & Sherman, 2016). The electricity consumption of the 401 MGHA is growing steadily. The total of 8,472,700 kWh purchased electricity in 2018, accounted for over half of the hospital's energy costs. With the increased use of special medical equipment, stationary air conditioners, refrigerators, cooking and laundry machines, and daily usage of 42,000 light bulbs for the artificial lighting of the buildings (a total area of 95,722 square meters), all of which rely on electricity, consumption is set to increase. The GHG conversion factor for 2018 was 0.6227 kg CO_2eq/KWh (MEEN, 2020), and therefore, the total GHG emissions were 5275.3 tCO_2eq.

Fossil fuels The fossil fuel consumption for central heating and other internal uses is as follows:

a. The natural gas consumption of the 401 MGHA for the year 2018 was 13,200,000 KWh (or 47.52 TJ). The GHG conversion factor is 55.72 tCO2eq/TJ (MEEN, 2020). The GHG emissions associated with natural gas were 2647.8 tCO2eq.
b. The diesel oil consumption in 2018 was 22,000 lt. The GHG conversion factor is 73.78 tCO2eq/TJ, and the net calorific value is 42.80TJ/kt (MEEN, 2020). The GHG emissions associated with diesel were 58.4 tCO2eq.

The total GHG emissions for the year 2018 were 2706.2 tCO_2eq.

Fluorinated gases

Fluorinated gases (or f-gases) are a family of synthetic gases containing fluorine. They are powerful greenhouse gases that trap heat in the atmosphere and contribute to global warming. Their GWP (please refer to "Carbon footprint calculations") may be thousands times higher than CO_2, which makes them the most potent and longest lasting GHG emitted by human activities. Fluorinated gases are used in products such as refrigerators, air-conditioners, foams, and aerosol cans. Emissions from these products are caused by gas leakage during the manufacturing process as well as throughout the product's life. Fluorinated gases are also used for the production of metals and semiconductors (Müllerová et al., 2020; Sebos et al., 2020). For the estimation of the CF of the 401 MGHA, the GHG emissions from refrigeration and air-conditioning systems are calculated.

The most common f-gases are hydrofluorocarbons (HFCs), which contain hydrogen, fluorine, and carbon. A large number of blends containing HFCs are used in refrigeration and air conditioning applications. GHG emissions associated with f-gases can be estimated in different ways with varying degrees of complexity and data intensity. For the case of the CF of the 401 MGHA, a detailed analysis was performed and the following data per application were obtained:

- activity data (number of refrigerators, air-conditioning systems, etc.),
- initial charge and type of refrigerant blend,
- type of HFCs used in blends, and
- emission factor per application, which is the annual leakage of refrigerant.

The operating and servicing GHG emissions associated to refrigeration and air conditioning applications was estimated by applying the following equation:

$$\text{GHG Emissions(tCO2eq)} = AD \times M \times x \times GWP/1000 \tag{1}$$

where:

- AD: activity data (number of refrigerators, air-conditioning systems, etc.),
- GWP: global warming potential of the HFCs used in refrigerant blends; e.g., for the case of HFC134a, GWP is 1430 kgCO2eq/kgHFC134a,
- x: emission factor or product life factor (% of initial charge per year), and
- M: initial charge.

In the following sections, a detailed analysis of the calculation of emissions associated with fluorinated gases is presented for the following applications:

a. Residential/domestic refrigerators,
b. Commercial refrigerators (including food processing and cold storage),
c. Residential and commercial air-conditioning, including heat pumps, and
d. Chillers.

Residential/domestic refrigerators The 401 MGHA has approximately 205 domestic refrigerators (small capacity, lower than 150 lt). According to the National Inventory Report (NIR) of Greece for GHG emissions (MEEN, 2020), 47% of domestic refrigerators contain HFC-134a (1,1,1,2-tetrafluoroethane, CH2FCF3), with a GWP of 1430 kgCO2eq/kgHFC134a, and 53% contain R600a (isobutene, CH(CH3)2 CH3) with a GWP equals to 3 kgCO2eq/kgR600a. The same allocation per type of refrigerant is assumed for the 205 domestic refrigerators of the hospital, i.e., 96 units contain HFC-134a and 109 units R600a. The operating and servicing GHG emissions associated to domestic refrigerators were estimated by the application of Eq. (1).

Based on the NIR of Greece, the emission factor x is considered to be 0.25% of the initial charge per year and the initial charge M = 0.225 kg (MEEN, 2020).

Therefore:

1. HFC-134a emissions = 205 units × 47% × 0.225 kg HFC134α/unit × 0.25% × 1430 (kgCO2eq/kgHFC134a) = 77.5 kgCO2eq
and
2. R600a emissions = 205 units × 53% × 0.225 kg R600α/unit × 0.25% × 3 (kgCO2eq/kgR600a) = 0.2 kgCO2eq

The total emissions of the domestic refrigerators for the year 2018 were 77.7 kgCO2eq or 0.0777 tCO2eq.

Commercial refrigerators (including food processing and cold storage) The 401 MGHA has 20 commercial type food and medicine refrigeration systems, with medium capacity (between 250–340 lt). These 20 units contain the blended refrigerant R-404A, which is comprised of HFC-125, HFC-143a, and HFC-134a (weight ratio: 44/52/4). These HFCs have different GWPs. The GWP of HFC-125 is 3500, for HFC-143a is 4470, and for HFC134a is 1430. Based on the weight ratio of the refrigerant blend and the GWP of each individual gas, the GWP of the R-404A is estimated to be 3921.6 kgCO2eq/kg R-404A.

The average initial charge M (kg) of the refrigerators is 13.1 kg, and is calculated based on site activity data, as follows:

- 1 out of 20 units contains 2 kg refrigerant (5%),
- 11 out of 20 units contain 20 kg refrigerant (55%),
- 8 out of 20 units contain 5 kg refrigerant (the 40%).

The emission factor x (% of initial charge/year) was obtained from the NIR of Greece, and it is 0.5% initial charge/year (MEEN, 2020). Taking into consideration the above parameters, the GHG emissions of the commercial refrigerators were estimated to be 5.1 tCO_2eq, by the application of Eq. (1).

Residential and commercial air-conditioning, including heat pumps Air conditioning in hospitals accounts for a large proportion of their electricity consumption. The 401 MGHA is equipped with 420 stationary air conditioning 12,000 btu units. These air conditioners contain the blended refrigerant R-407C, which is comprised of HFC-32, HFC-125, and HFC-134a (weight ratio: 23/25/52). These HFCs have different GWPs: the GWP of HFC-32 is 675, for HFC-125 is 3500, and for HFC134a is 1430. Based on the weight ratio of the refrigerant blend and the GWP of each individual gas, the GWP of the R-407C is estimated to be 1773.85 kg CO_2eq/kg R-407C.

The average initial charge and emission factor were obtained from the NIR of Greece. The initial charge is $M = 1.5$ kg, and the emission factor $x = 0.5\%$ (MEEN, 2020). Taking into consideration the above parameters, the GHG emissions of the air conditioners were estimated to be 5.6 tCO_2eq, by the application of Eq. (1).

Chillers Eight chillers are installed in the 401 MGHA for the air conditioning of hospital buildings, as follows:

- 4 units with total initial charge 175 kg of R-407C (HFC-32/HFC-125/HFC-134a),
- 2 units with total initial charge 50 kg of HFC-134a, and
- 2 units with total initial charge 200 kg of R-410a (weight ratio: 50/50 of HFC-32/HFC-125).

Based on the NIR of Greece, the emission factor for the blend of HFCs is 5% initial charge/year. The GWP for the R-407C is 1773.25, for HFC-134a is 1430, and for R-410a is 2087.5.

The GHG emissions per refrigerant type are calculated as follows:

- R-407C emissions = 4 × 175 × 15% × 1773.25/1000 = 186.190 tCO2eq
- HFC-134a emissions = 2 × 50 × 15% × 1430.00/1000 = 21.450 tCO2eq
- R-410a emissions = 2 × 200 × 15% × 2087.50/1000 = 125.25 tCO2eq

The total emissions of the chillers for the 2018 were 332.9 tCO_2eq.

Solid waste disposal

Hospitals produce millions of tons of waste globally. The hospital waste that is disposed to solid waste disposal sites (SWDS) produces and emits mainly CH4 to the atmosphere (Bakopoulou et al., 2005). The estimation of the CH4 emissions is calculated by the application of the First Order Decay methodology (FOD) (Kallinikos et al., 2016). In particular, a mass balance approach is used that involves the estimation of the degradable organic carbon (DOC) content of the solid waste, and based on this the CH4 emissions that can be generated by the waste are estimated.

In 2018, the 401 MGHA produced and disposed of 360 tones (t) municipal solid waste, 113.64 t non-toxic medical solid waste, and 19.07t of toxic medical waste, totaling 492.71 t of solid hospital waste. The CH4 emissions from SWDS for a single year can be estimated using the equation below (MEEN, 2020):

$$\text{CH4 emissions} = W_T \times \text{DOC} \times \text{DOC}_f \times \text{MCF} \times F \times 16/12 \times (1 - OX) \times (1 - R) \quad (2)$$

where:

- WT is the mass of waste disposed (disaggregated for paper, food waste and non-food waste) in the reference year (kt/year).
- DOC is the degradable organic carbon. Based on the NIR of Greece, the following DOC values were used: 0.4 for paper, 0.15 for food waste, and 0.2 for non-food waste.
- DOC_f is the fraction of the degradable organic carbon that decomposes under anaerobic conditions. It reflects the fact that some degradable organic carbon does not degrade, or degrades very slowly, under anaerobic conditions in the SWDS. The recommended default value for DOC_f by IPCC (IPCC, 2006) is 0.5 (under the assumption that the SWDS environment is anaerobic as in the case of Athens SWDS).
- MCF is the methane correction factor. The MCF for anaerobic decomposition is 1 for managed SWDS.
- F is the fraction of CH4 in landfill gas. Most waste in SWDS generates a gas with approximately 50% CH4. Only material including substantial amounts of fat or oil can generate gas with substantially more than 50% CH4, which is not the case of solid waste from the hospital. Therefore, the use of the IPCC default value for the fraction of CH4 in landfill gas (0.5) is followed in the calculation (IPCC, 2006).
- 16/12 is the molecular weight ratio CH4/C.
- OX is the oxidation factor. The OX reflects the amount of CH4 from SWDS that is oxidized in the soil or other material covering the waste. The use of the oxidation value of 0.1 is justified for covered, well-managed SWDS, as in the case of Athens SWDS, to estimate both diffusion through the cap and escape by cracks/fissures.
- R is the recovered CH4 (kt/year). Based on the NIR of Greece, it is 43% for year 2018.

Taking into consideration the above parameters, we can calculate emissions as follows:

- CH4 emissions (paper) = 0.034 kt/year.
- CH4 emissions (food waste) = 0.013 kt/year.
- CH4 emissions (non-food waste) = 0.017 kt/year.

The total emissions from the solid hospital wastes in 2018 were 64.0 tCO_2eq.

Results and discussion

Hospital carbon footprint

The carbon footprint of the stationary emission sources of the 401 Military General Hospital of Athens (401 MGHA) is presented in Table 1.

Electricity consumption constitutes the category with the highest contribution (62.9%) to the hospital's carbon footprint of stationary emission sources, followed by fossil fuels with 32.2%.

According to a previous paper by the authors (Bozoudis & Sebos, 2021), the footprint of transport activities in 2018 was 1402.0 tCO_2eq, and therefore, the total carbon footprint of the 401 MGHA in 2018 was 9791.2 tCO_2eq. The movement of patients to and from the hospital is the main emission source category (85.9% of transport emissions), followed by the ambulance services with 7.5%. Transport related to waste disposal and procurement contributes to 3.7% and 2.4%, respectively, while the share of the staff's transportation is limited to 0.5% (Bozoudis & Sebos, 2021).

Table 1 The carbon footprint of the stationary emission sources of the 401 Military General Hospital of Athens

Energy usage	GHG emissions (tCO_2eq)	Share (%)
Electricity	5275.3	62.9
Fossil fuels	2706.2	32.2
Refrigerators	5.2	0.1
Air-conditioning systems	338.5	4.0
Waste disposal	64.0	0.8
Total	**8389.2**	**100**

The uncertainty of the estimated carbon footprint is an essential element of a complete inventory of greenhouse gas emissions. Uncertainty in emission estimates is a function of the uncertainty of input data, i.e., activity or emission factors, used to compile the inventory. The uncertainty of emission estimates of the 401 MGHA is expected to be similar to that of the respective source categories from the national GHG inventory, given that activity data information and emission factors from the Greek NIR (MEEN, 2020) were used for the estimation of the CF. It could be considered that the uncertainty will be even lower because detailed site-specific activity data was collected and assessed in the analysis of the CF of 401 MGHA.

The uncertainty assessment of the CF is presented in Table 2. The uncertainty of emission estimates is around 3.4%, which could be considered satisfactory based on international practice (IPCC, 2006). It should be noted that the source categories with the highest uncertainty (i.e., emissions from refrigerators, air-conditioning systems, and waste disposal) have a small effect on the overall uncertainty, due to the low level of emissions from these sources.

Hospital key performance indicator

Climate change is a long-term process. The aim of the Greek National Energy and Climate Plan (NECP) is to reduce GHG emissions by 2030 by more than 56% compared to emissions in 2005 (to reach about 60.1 $MtCO_2eq$ in 2030) (MEEN, 2019). In 2018, the GHG total emissions of Greece were 92.3 $MtCO_2eq$. Therefore, the reduction target of NECP is equivalent to a reduction target of 35% by 2030 compared to 2018 levels. This is a mid-way target, which is currently underway, in order to move to a climate neutral economy by 2050 (MEEN, 2019).

Hospitals require energy in order to remain in operation on a 24/7 base. Moreover, the GHG emissions from transport activities of the hospitals (the movement of patients/visitors/staff to and from the hospital, the ambulance services, etc.) are very high. The estimation of the GHG emissions in hospitals would be a feasible starting point (the baseline) to develop action plans for reducing their energy consumption and operational costs. The calculation of the hospital's impact on the environment can be done by its staff with the support of many available computing tools, as well as easily collected activity data, needed for validation (Bakopoulou et al., 2005).

The administration of 401 MGHA, by considering the high energy demand and the annual GHG emissions of the hospital, can develop and implement a portfolio of energy saving and emission reduction actions, in order to make the gradual transition to low carbon energy and transportation possible.

It is recommended to develop and use specific KPIs as metrics, in order to monitor and annually evaluate the progress in reducing the carbon footprint of hospital GHG emissions. Working with this metric, the 401 MGHA Energy Management Team can

Table 2 Uncertainty assessment of the carbon footprint of 401 MGHA

Energy usage	GHG emissions (tCO_2eq)	Uncertainty of emission source	Combined uncertainty as % of total emissions
Electricity	5275.3	1%	0.54%
Fossil fuels	2706.2	2%	0.55%
Transport activities	1402.0	2%	0.29%
Refrigerators	5.2	50%	0.03%
Air-conditioning systems	338.5	50%	1.73%
Waste disposal	64.0	40%	0.26%
Total	**9791.2**		**3.39%**

enforce policies and procedures in reducing hospital GHG emissions by determining what mitigation actions should be taken. A general KPI, which covers all mitigation actions and sources of emissions, could be in the form of "tCO_2eq per patient" or "tCO_2eq per hospitalizations' days."

Action plan

The total GHG emissions of 401 MGHA in 2018 and the strategic national goal in 2030 are presented in Table 3. It is assumed that GHG emissions of 401 MGHA in 2030 should be reduced by 35%, similar to the national target. Therefore, GHG emissions in 2030 should be reduced by about 3400 tCO_2eq compared to 2018 levels.

Electricity

Electrification can reduce the hospital's GHG emissions in the near future, depending on the resources used by the Greek electrical grid operators. The European Union currently seeks to decarbonize the electricity generation sector and Greece makes great strides in reducing coal and increasing the amount of electricity generated by low carbon fuels and renewable resources (MEEN, 2019; González-Sánchez et al., 2020).

Greece has set ambitious GHG mitigation goals for its power sector (NECP), including the total phase-out of the lignite-fired plants by 2028 combined with an increased investment scheme in renewable energy sources (RES) and broader interventions for more efficient energy usage (Stamopoulos et al., 2021). More specifically, a critical element in the context of the NECP is the highly ambitious but realistic program for sharply and definitively reducing the share of lignite in power generation, i.e., the so-called lignite phase-out, by putting a complete end to the use of lignite for power generation in Greece by 2028 (MEEN, 2019). This transformation in power generation is planned to take place through an increasing utilization of RES potential of Greece to exceed 60% RES share in electricity consumption by 2030. In this context specific initiatives are already being promoted and implemented by the government, e.g., simplifying and speeding up the licensing framework, ensuring optimal integration of RES in electricity networks, operating storage systems, and promoting electromobility (MEEN, 2019, Stamopoulos et al., 2021).

The increase of renewable energy sources and gas-fired plants, and the shutting down of lignite-fired power plants in the country by 2028 will have a positive impact on reducing indirect GHG emissions in all economic sectors, including the health care sector. The electricity consumption in the 401 MGHA in 2018 was 8,472,700 kWh and was responsible for 5275.3 tCO_2eq, 53.9% of the hospital's total GHG emissions. These GHG emissions will be significantly reduced by 2030, because the GHG conversion factor for 2030 will be reduced to 0.3566 kgCO2eq/KWh compared to 0.6227 kgCO2eq/KWh in year 2018 (MEEN, 2019). This means that the annual

Table 3 Proposed GHG emission reductions by the year 2030

Transport activities/energy usage	GHG emissions (tCO_2eq) in 2018	Estimated GHG emissions (tCO_2eq) in 2030 (−35%)	GHG reduction (tCO_2eq)
Electricity	5275.3	3428.9	−1846.4
Fossil fuels	2706.2	1759.0	−947.2
Movement of patients to and from the hospital	1204.6	783.0	−421.6
Air-conditioning systems	338.5	220.0	−118.5
Ambulance services	105.4	68.5	−36.9
Solid waste disposal	64.0	41.6	−22.4
Vehicles engaged to the disposal of hospital waste	51.2	33.3	−17.9
Suppliers	34.1	22.1	−11.9
Staff's movement	6.7	4.4	−2.3
Refrigerators	5.2	3.4	−1.8
Total	9791.2	6364.2	−3426.9

GHG emissions from the electricity consumption of 401 MGHA will be significantly reduced during the following years, because of the diversification of the energy mix of power sector in Greece. The GHG emissions will be approximately 3021.4 tCO_2eq by 2030 (−2253.9 tCO_2eq lesser GHGs), assuming that the electricity consumption will be the same in 2030 as in 2018.

The 401 MGHA Energy Management Team could use a simple KPI, i.e., annual electricity consumption and associated GHG emissions, to monitor the performance on energy savings and relevant avoided emissions. The electrification of the 95,722 m^2 hospital buildings by using existing technologies is a mitigation option that will reduce the annual operating cost of the hospital, too. However, the team should balance the electricity prices and the available annual budget with the cost of replacing existing technologies in the older buildings. The installation of energy efficient appliances will be more attractive economically in future new buildings of the 401 MGHA.

There are many other low-cost actions to reduce emissions and save money by reducing the annual energy (electricity) costs, improve the energy performance, and restrain the GHG emissions of the 401 MGHA, through efficiency and conservation measures. This can be done by implementing simple "green actions" on high-efficiency lighting, switching computers and medical equipment off when not in use and educating the staff on how to reduce energy consumption. A "turn the thermostats down and light switches off" policy with posters up in the staff areas and stickers above windows, light switches, air conditioning, and electricity-consuming medical equipment can lead to important energy savings and persuade the employees to participate and be environmentally conscious.

Moreover, the hospital administration should consider installing roof-mounted PV energy systems and/or parking lot PV canopy installations. This is a long-term mitigation strategy, in order to set a goal to meet 100% of the hospital's electricity demand with renewable energy, and become a net zero energy hospital by 2030 or sooner.

Fossil fuels

The 401 MGHA uses natural gas for central heating and other internal uses of the hospital, which, albeit low carbon, is still a fossil fuel associated with carbon emissions and other pollutants that can harm human health. It is cost effective, plentiful, cleaner, and more efficient than diesel oil but still produces 32.2% of the GHG emissions of the 401 MGHA.

The hospital's energy management team can develop a KPI metric to monitor and evaluate annually the consumption of natural gas, its cost, and the footprint of its GHG emissions. Working with this metric, the team should investigate alternative options for reducing GHG emissions and their relative cost, by using electricity for heating, cooling and transportation.

The diesel oil currently used for the hospital's transport activities (ambulances and other hospital vehicles) will gradually be replaced by plug-in electric vehicles (PEVs) and electric vehicles (EVs) over the long term. The 401 MGHA energy management team should proceed with the procurement of one or more PEVs (ambulances) and build a charging station for PEV-driving employees to help promote driving electric vehicles and reduce their carbon footprint.

Transportation of patients to and from the hospital

In 2018, the hospitalized patients at the outpatient clinic of the 401 MGHA and their visitors exceeded 230,000 people, which amount to more than 630 visits per day, on average. The GHG emissions per mode of transport and patient have been calculated in a previous paper by the authors. The use of private cars is responsible for around 94% of GHG emissions caused by the transportation of patients and visitors to and from the hospital (10.8 kgCO2eq/patient). The authors proposed in a previous study (Bozoudis & Sebos, 2021) a number of actions to mitigate GHG emissions from transport activities, such as the development and broader use of telemedicine, which is the application of ICT technologies to provide health services from distance. Telemedicine could play a critical role in the transition to a net carbon-zero health care sector. Purohit et al. (2021) estimated that the carbon footprint savings could range between 0.70 and 372 kg CO_2e per consultation. A 2018 NHS Midlands and Lancashire commissioned report estimated that the UK's West Midlands could reduce emissions by 533,535 kg CO2eq annually by shifting 15% of all hospital follow-up consultations to telemedicine (NHS, 2018). In another study in the central Catalan region of Spain, 3248.3 g of carbon dioxide were avoided by avoiding a total of 9034 face-to-face hospital visits through telemedicine services in the primary care centers (Vidal-Alaball et al., 2019). The extent of carbon footprint reduction through telemedicine is dependent on the population density of the region, as well as on transport infrastructure (Whetten et al., 2019).

Other actions that have been proposed by the authors (Bozoudis & Sebos, 2021) are setting limitations or banning free parking inside the hospital premises, providing incentives for the use of public transport and other more "active" means of transport, such as walking or cycling, use of biofuels in ambulances, and training on eco-driving.

The proposed KPI to monitor the effect of mitigation actions for transport activities is the ratio of GHG emissions per patient.

Air-conditioning systems and refrigerators

The hospital administration should gradually replace the stationary air conditioning systems and freezers with appliances that are more energy efficient. These expected savings in energy and emissions are also cost effective. The proposed KPI metric to monitor and evaluate the performance of this action is the annual consumption and cost of electricity consumed by the relevant appliances of the 401 MGHA.

Other mitigation actions

The Greek Government's National Energy and Climate Plan (NECP) includes specific interventions for better management of wastes (including the health care sector) (MEEN, 2019). The hospital administration should capitalize on available information technologies and develop electronic platforms in order to reduce the use of printing paper. In addition, they should promote composting of food waste, recycling, and re-use in order to minimize the amount of non-medical solid waste disposal.

The hospital administration could establish a green public procurement scheme and evaluate future vendors by adopting environmental criteria for products and services. Moreover, a modified, more vegetable-based hospital menu for in-patients, employees and visitors will reduce meat on hospital menus, with an important impact on the hospital's carbon footprint.

The 401 MGHA can reap many of the benefits from applying an ISO environmental management standard from the ISO 14000 family. These standards can provide the criteria for an effective environmental management plan, and map out an operational framework that the team can follow.

Hospital buildings should maintain appropriate internal temperatures in areas with different temperature needs, such as in emergency rooms and clinics, in contrast with the waiting rooms and the administration offices. The energy team of the hospital should make a chart showing the desired temperatures for each area in the hospital, from the lowest to the top floors of the building. They could try to minimize losses by using automatic doors in frequently used hospital entrances.

The cost of reducing GHG emissions

The most economically efficient way to mitigate GHG emissions is to select mitigation actions with marginal benefits associated with emission reduction higher or equal to marginal costs. The Marginal Abatement Cost (MAC) curves follow this concept. The most prominent MAC curve is the well-known McKinsey curve. The MAC curves plot the abatement cost of an action versus its abatement potential or emission reductions. Mitigation actions may have a negative abatement cost, which translates to both emission reduction and cost savings at the same time (Gillingham & Stock, 2018).

The future GHG emissions of the 401 MGHA will be reduced by about 30% without any intervention by the hospital administration. This reduction will be implemented by the change of the carbon footprint of the Greek energy mix for electricity production, which will be highly decreased by the lignite phase-out in 2028 and the high shares of renewables (MEEN, 2019).

Figure 1 presents the mitigation measures discussed in this section grouped by their abatement cost and abatement GHG reduction potential, similarly to the MAC curve.

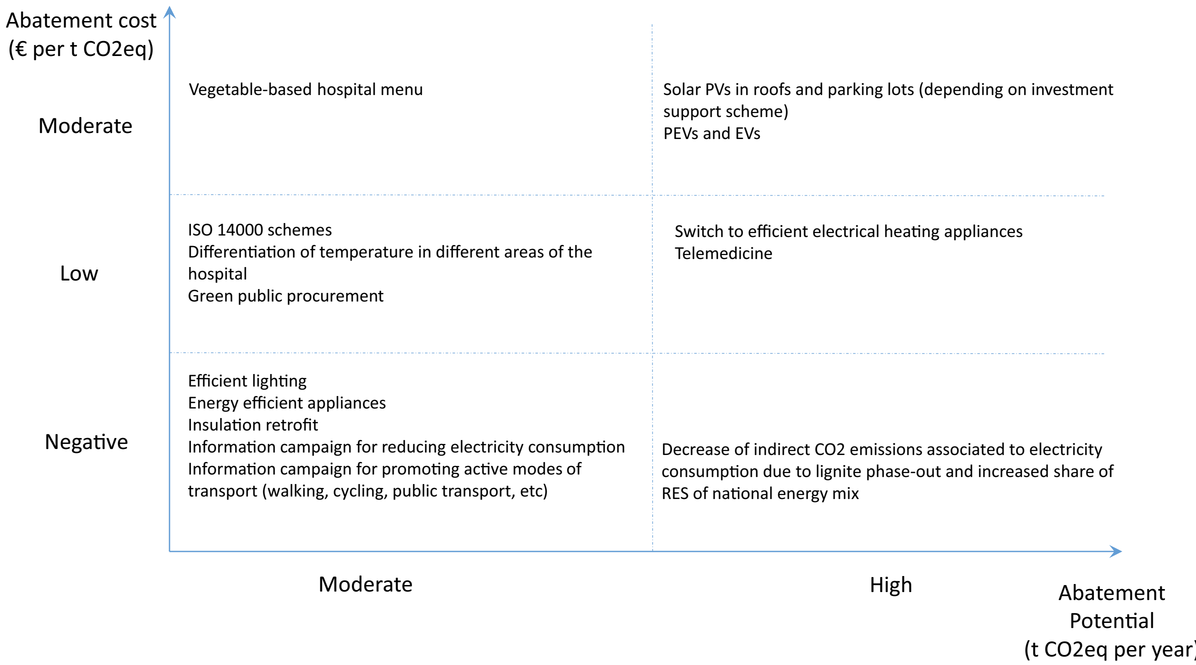

Fig. 1 Proposed mitigation actions characterized by their abatement cost and abatement GHG reduction potential

Conclusions

The estimation of the CF of the stationary emission sources in this study, in combination with the estimation of the CF of transport activities of the 401 MGHA (Bozoudis & Sebos, 2021), constitutes the baseline for the development of an action plan for the mitigation of GHG emissions, the reduction of energy use and operating annual budget in the hospital-based health care of the Greek Army. The analysis in this paper shows that the major contribution to the CF of the hospital comes from the indirect GHG emissions due to the consumption of electricity. The other important sources of GHG emissions are associated with the consumption of natural gas and diesel (around 28%) for heating purposes and transport activities (14%). The contribution of each emission source to the hospital's CF is similar to the emission profiles of other health care sectors reported by other researchers (Eckelman et al., 2020; Purohit et al., 2021).

The phase-out of lignite-fired power plants in Greece by the year 2028, in combination with the increase of the share of power production from renewable and low-carbon sources, will lead to a significant reduction of the indirect GHG emissions associated with the consumption of electricity from the national grid. In addition, the benefits of telemedicine and its critical role in the transition to a net carbon-zero health care sector were emphasized. Several other mitigation measures of GHG emission sources have been proposed, which were mapped according to their abatement cost and GHG reduction potential, such as efficient lighting, insulation retrofit, green public procurements, information campaigns, etc. Most of these measures will have the co-benefit of reducing the hospital's annual operating budget. Furthermore, as has been pointed out by many researchers, the actions to reduce GHG emissions have an additional co-benefit, which is the opportunity to improve public health through reduced air pollution, increased physical activity by the adoption of more active modes or transport, such walking and cycling, and improved diet with lower environmental impacts (Milner et al., 2020).

The authors have also proposed a framework of KPIs that can be used as metrics to monitor and evaluate the progress in reducing the carbon footprint of hospital GHG emissions. In addition to the two general KPIs, "tCO_2eq per patient" and "tCO_2eq per hospitalizations' days," which cover all mitigation actions and sources of emissions, a number of KPIs specific to the source of GHG emissions or mitigation action were proposed in order to assist hospital administration in monitoring GHG sources and assessing the effectiveness of mitigation actions. The development of robust and standardized metrics to define environmental performance and monitor progress is a critical element of any mitigation action plan. This approach could also be used to assess the performance of individual clinicians, hospitals, and health care systems (Sherman et al., 2019).

The European Union (EU) aims to move to a net zero GHG emissions by 2050 in order to achieve the goals of the Paris Agreement. Greece has set a strategic aim of 56% GHG reduction by 2030, compared to the 2005 levels (equivalent to a reduction of 35% compared to 2018). The mitigation actions proposed in this paper are sufficient to deliver a reduction of GHG emissions by more than 3400 tCO_2eq annually, which corresponds to a reduction consistent with the national target of 35% compared to 2018 levels. Thus, the Hellenic Army health care sector can reduce its carbon footprint, and promote its environmental friendly perspective under its Corporate Social Responsibility.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

References

Bakopoulou, S., et al. (2005). Medical waste management in Greece: The case of Thessaly region. *Sustainable Development and Planning II, 1*, 565, 571–573.

Bozoudis, V., & Sebos, I. (2021). The carbon footprint of transport activities of the 401 Military General Hospital of Athens. *Environmental Modeling and Assessment, 26*(2), 155–162. https://doi.org/10.1007/s10666-020-09701-1

Budd, K. (2019). Hospitals race to save patients — and the planet. [online]. https://www.aamc.org/news-insights/hospitals-race-save-patients-and-planet. Accessed 20 September 2021.

Dacones, I., Cave, C., Furie, G.L., Ogden, C. A., & Slutzman, J. E. (2021). Patient transport greenhouse gas emissions from outpatient care at an integrated health care system in the Northwestern United States, 2015–2020. *The Journal of Climate Change and Health*, *3*, 100024. https://doi.org/10.1016/j.joclim.2021.100024

Eckelman, M., & Sherman, J. (2016). Environmental impacts of the U.S. health care system and effects on public health. *PLoS One, 11*(6). [online]. https://doi.org/10.1371/journal.pone.0157014. Accessed 20 September 2021.

Eckelman, M., Huang, K., Lagasse, R., Senay, E., Dubrow, R., & Sherman, J. D. (2020). Health care pollution and public health damage in the United States: An update. *Health Affairs, 39*(12), 2071–2079. https://doi.org/10.1377/hlthaff.2020.01247

European Environmental Agency. (2020). Country profiles — Greenhouse gases and energy. [online]. https://www.eea.europa.eu/themes/climate/trends-and-projections-in-europe/climate-and-energy-country-profiles/country-profiles-greenhouse-gases-and-1. Accessed 20 September 2021.

Gillingham, K., & Stock, J. H. (2018). The cost of reducing greenhouse gas emissions. [online]. https://pubs.aeaweb.org/pdfplus/ https://doi.org/10.1257/jep.32.4.53 *Journal of Economic Perspectives, 32*(4), 53–72.

González-Sánchez, M., & Martín-Ortega, J. L. (2020). Greenhouse gas emissions growth in Europe: A comparative analysis of determinants. *Sustainability, 12*, 1012. https://doi.org/10.3390/su12031012

Health Care Without Harm, HCWH. (2019). Health care's climate footprint. [online]. https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_092319.pdf. Accessed 20 September 2021.

Hellenic Republic, Ministry of Environment and Energy, MEEN. (2020). National Inventory Report (NIR) of Greece for Greenhouse and other Gases for the Years 1990–2018. 119, 417, 530–531.

Hellenic Republic, Ministry of the Environment and Energy, MEEN. (2019). The National Energy and Climate Plan (NECP). [online]. https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en. Accessed 20 September 2021.

Holmner, A., Ebi, K.L., Lazuardi, L., Nilsson, M. (2014). Carbon footprint of telemedicine solutions - Unexplored opportunity for reducing carbon emissions in the health sector. *PLoS One, 9*(9). [online]. https://doi.org/10.1371/journal.pone.0105040. Accessed 20 September 2021.

IPCC. (2006). Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.). IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Published: IGES, Japan.

IPCC. (2007). Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2021). The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

IPCC. (2018). Global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Javadinejad, S., et al. (2021). The analysis of the most important climatic parameters affecting performance of crop variability in a changing climate. *International Journal of Hydrology Science and Technology, 11*(1). https://doi.org/10.1504/IJHST.2021.112651

Kallinikos, L., et al. (2016). Greenhouse gas emissions trends from waste in Greece. In: P. Grammelis (Ed), *Energy, Transportation and Global Warming. Green Energy and Technology*. Springer, Cham. https://doi.org/10.1007/978-3-319-30127-3_12

Karliner, J., et al. (2019). Health care's climate footprint. 5, 8, 36. [online]. https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_090619.pdf. Accessed 20 September 2021.

MacNeill, A. J., et al. (2017). The impact of surgery on global climate: A carbon foot printing study of operating theatres in three health systems. *The Lancet Planetary Health*. Accessed 20 September 2021.

Milner, J., et al. (2020). Health benefits of policies to reduce carbon emissions. *BMJ Clinical Research, 368*, l6758. https://doi.org/10.1136/bmj.l6758

Müllerová, M., Krtková, E., & Rošková, Z. (2020). F-gases: Trends, applications and newly applied gases in the Czech Republic. *Atmosphere, 11*, 455. https://doi.org/10.3390/atmos11050455

NHS Midlands and Lancashire Commissioning Support Unit. (2018). The potential economic impact of virtual outpatient appointments in the West Midlands - A scoping study. [online]. www.strategyunitwm.nhs.uk/sites/default/files/2018-11/180813_Economic%20Impact%20of%20OP%20Appointments%20for%20WM%20CCGs_FINAL.pdf. Accessed 27 January 2021.

Ostad-Ali-Askari, et al. (2020). Effect of climate change on precipitation patterns in an arid region using GCM models: Case study of Isfahan-Borkhar Plain. Natural Hazards Review. *ASCE-American Society Civil Engineering Publisher, 21*(2). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000367

Purohit, A., Smith, J., & Hibble, A. (2021). Does telemedicine reduce the carbon footprint of healthcare? *A Systematic Review Future Healthcare Journal, 8*(1), e85–e91. https://doi.org/10.7861/fhj.2020-0080

Sebos, I., et al. (2016). Mitigation and adaptation policies related to climate change in Greece. In: P. Grammelis (Ed.) Energy, transportation and global warming. *Green Energy and Technology* (pp. 35–49). Springer, Cham. https://doi.org/10.1007/978-3-319-30127-3_4

Sebos, I., Progiou, A., & Kallinikos, L. (2020). Methodological framework for the quantification of GHG emission reductions from climate change mitigation actions. *Strategic Planning for Energy and the Environment, 39*(1–4), 219–242. https://doi.org/10.13052/spee1048-4236.391411

Sherman, J. D., MacNeill, A., & Thiel, C. (2019). Reducing pollution from the health care industry. *Journal of the American Medical Association, 322*(11), 1043–1044. https://doi.org/10.1001/jama.2019.10823

Stamopoulos, D., et al. (2021). Does investing in renewable energy sources contribute to growth? A preliminary study on Greece's National Energy and Climate Plan. *Energies, 14*, 8537. https://doi.org/10.3390/en14248537

Talebmorad, H., et al. (2021). Evaluation of the impact of climate change on reference crop evapotranspiration in Hamedan-Bahar plain. *International Journal of Hydrology Science and Technology., 11*(3), 333–347. https://doi.org/10.1504/IJHST.2021.114554

United Nations Climate Change. (2015). The Paris Agreement. [online]. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. Accessed 20 September 2021.

Vidal-Alaball, J., Franch-Parella, J., Lopez Seguí, F., Garcia Cuyàs, F., & Mendioroz Peña, J. (2019). Impact of a telemedicine program on the reduction in the emission of atmospheric pollutants and journeys by road. *International Journal of Environmental Research Public Health, 8, 16*(22), 4366. https://doi.org/10.3390/ijerph16224366

Whetten, J., Montoya, J., & Yonas, H. (2019). Access to better health and clear skies: Telemedicine and greenhouse gas reduction. *Telemedicine Journal and E-Health, 25*(10), 960–965. https://doi.org/10.1089/tmj.2018.0172