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Review of Sustainable Energy Technologies and Financial Tools for Achieving Net-zero Emission Hospitals

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Abstract

Mitigation of climate change, which is a severe global environmental problem, requires the sharp decrease of greenhouse gas emissions. Hospitals and healthcare facilities consume large amounts of energy compared with other organizations while they mainly use conventional fuels and grid electricity. The aims of the current study are: a) to review the sustainable energy technologies which can be used in hospitals minimizing their carbon emissions due to energy use, and b) to review the existing financial tools which can support the investments of clean energy technologies in hospitals. Published literature indicates that several benign energy technologies have been used in hospitals in developed and less-developed countries. These include: a) energy saving technologies, b) renewable energy technologies, c) low carbon emission technologies, and d) technologies related with green transportation. The most of them are reliable, mature and cost-efficient. Their combined use results in lower carbon emissions in hospitals. Any remaining emissions can be offset with the existing carbon offsetting schemes. Various financial mechanisms can facilitate investments of clean energy technologies in hospitals. It is concluded that several benign energy technologies combined with carbon offsetting schemes can assist hospitals to zero their net carbon emissions due to energy use while the existing financial mechanisms can facilitate and support the required energy investments. The present study is useful to policy makers and hospital's authorities who are looking forward to minimize the carbon footprint in these organizations complying with current policies for achieving net zero carbon emission societies in the coming decades.

Keywords: carbon offsetting, financing, hospital buildings, low carbon energy technologies, net-zero emissions, renewable energies

1. Introduction

Hospital buildings consume large amounts of energy, compared to other buildings, to meet their energy requirements (*Gonzalez Gonzalez et al, 2018, Shen et al, 2019, Bawaneh et al, 2019*). They often use conventional fuels and energy while their carbon emissions are high. Their energy renovation is important to improve their energy and environmental sustainability complying with the global efforts for climate change mitigation and adaptation. Our work is focused on the investigation of using several sustainable energy technologies covering the energy requirements in hospitals and zeroing their net-carbon emissions due to energy use (*Vourdoubas, 2022*). These clean energy technologies include energy saving technologies, renewable energy technologies as well as low carbon emission technologies (*CADDET, 1977, Franco et al, 2017, Gurieff et al, 2020*). The possibility of using several financial mechanisms for supporting the clean energy investments in hospitals is also studied. These sustainable energy technologies are reliable, mature, well proven and cost-efficient. Our work is important since it indicates the benign energy technologies that can be used for reducing the carbon footprint in healthcare organizations helping them to increase their energy security, self-sufficiency and resilience. Energy renovation in hospitals will improve environmental health having positive impacts in local societies. It will show their commitment to improve the health of the planet additionally to treating human illness.

2. Literature Survey

The literature survey is separated in six sections including: a) Energy saving in hospitals, b) Use of renewable energies in hospitals, c) Use of low carbon technologies in hospitals, d) Sustainable transportation in hospitals, e) Offsetting carbon emissions in hospitals, and f) Financing clean energy investments in hospitals.

2.1 Energy saving in hospitals

CADDET, 1997 has reported on energy saving in hospitals. It was stated that hospitals have complex energy systems with high energy saving potential. Their energy saving potential is estimated at around 20% in Germany and 44% in Netherlands while 10% of energy saving can be achieved within one year. It is also mentioned that hospitals should appoint energy managers before initiating energy management programs. *Teke et al, 2014* have stated that hospitals can reduce their energy consumption by 20-40% while their energy cost has a share at 2-5% in their total operating cost. The authors mentioned various cost-efficient investments in hospitals as well as the most common energy saving measures used in them. They also stated that HVAC systems in India hospitals consume around 50% of their total electricity consumption. *Gatea et al, 2020* have stated that improvements in the building envelope, in the lighting system as well as in the HVAC system in hospitals result in lower energy consumption by around 20%. *World Health Organization, 2009* has studied the characteristics of a climate-friendly hospital. The study mentioned seven elements of it including: energy efficiency, green building design, alternative energy generation, transportation, food, waste, and water.

2.2 Use of renewable energies in hospitals

Franco et al, 2017 have reviewed the use of sustainable energy technologies in healthcare

facilities in the Global South. The authors stated that fossil fuels are the main energy sources used so far. However, the levelized cost of electricity of solar panels and wind turbines is currently low. They proposed the use of hybrid energy systems in healthcare facilities consisted of solar-PVs, wind turbines, electric batteries and diesel generators. *A report concerning the use of PV systems in healthcare facilities in rural areas in developing countries has been published, IEA, 2014.* The report stated that in medium and large healthcare facilities hybrid energy systems consisted of solar-PVs and diesel generators are the best option. It is also mentioned that in rural areas in developing countries it is important to provide sustainable financing for maintenance and spare parts replacement. *Poorya Ooshaksaraei et al, 2010* have studied the use of solar thermal systems for DHW production in hospitals in Malaysia. The authors implemented a case study in the hospital Universiti Kebangsaan Malaysia. They mentioned that the use of a solar thermal system reduces the LPG used previously for DHW production as well as the CO_2 emissions. *Sanchez-Barroso et al, 2020* have examined the potential saving in fuels with the use of solar thermal systems in hospitals in Extremadura, Spain. The authors studied 25 hospitals in this area. They stated that the use of solar thermal systems for DHW production in these hospitals, with solar fraction at 0.7, was profitable with payback period at around 4.29-4.74 years. *Sanz-Calcedo et al, 2011* have studied the use of biomass for heat generation in hospitals in Portugal. The authors stated that a solid biomass boiler at 430 KW was installed in Zafra hospital covering the needs of heating and DHW using olive stones. They mentioned that the payback period of the investment was at 5.4 years. *Vourdoubas, 2021* has studied the use of renewable energies for heat and cooling generation in hospitals. The author stated that solar energy, biomass and geothermal energy has been used so far in hospitals covering part or all of their heat and cooling requirements. *Vourdoubas, 2016* has studied the use of solid biomass for covering the heating needs in hospitals in Crete, Greece. The author stated that olive kernel wood is a byproduct of the olive oil producing industry in the island. Its good burning characteristics and its low price favor its use as a renewable and low-cost fuel in local hospitals.

2.3 Use of low carbon technologies in hospitals

Olufemi Oyewole Daramola, 2020 has reviewed the use of combined heat and power systems in hospital applications. The author stated that co-generation of heat and power (CHP) technology is a reliable source of heat and power in hospitals in UK to run their day-to-day operations. *A report related with the use of CHP technology in hospitals has been published, 2021.* The report stated that CHP systems can ensure that hospitals operate nonstop even during grid outages and natural disasters. It is also mentioned that more than 229 hospitals in USA have installed CHP systems with an average size at around 3.3 MW each. *Valancius et al, 2018* have studied the combined use of solar thermal and heat pump systems in Lithuanian hospitals. The author stated that seventeen Lithuanian hospitals have installed hybrid energy systems. They mentioned that the heat produced by the solar thermal systems varied between 263-433 KWh/m^2 of the solar mirror while the seasonal coefficient of performance of the heat pumps varied between 2.42-2.61. *Gurieff et al, 2020* have examined the possibility of creating energy hubs in community hospitals. The authors stated that public hospitals consume large amounts of energy while they have the opportunity to lead the transition to

renewable energy. They mentioned that hospitals have the opportunity to install various sustainable energy systems producing their own energy transforming them to clean energy hubs. *Vourdoubas, 2022* has investigated the possibility of using fuel cells for co-generation of heat and power in Venizelio hospital in Crete, Greece. The author stated that a fuel cell at 1 397 KW can produce annually 4 895 MWh_{el} and 4 895 MWh_{th} covering all the electricity and heat requirements producing excess heat at 2 451 MWh_{th}. He also mentioned that a smaller size fuel cell combined with a solar-PV system can cover all the energy requirements in the hospital without producing any excess energy. *The retrofitting of Toronto general hospital using district heating has been reported, 2017*. The hospital has replaced the electrically driven chiller plant with one that utilizes Enwave's district cooling loop also known as "deep lake cooling". *The use of district energy in hospitals and healthcare facilities has been reported, vicinity.us*. It is stated that the use of district energy in hospitals has many benefits including lower operating cost, increased reliability and energy resilience as well as support of sustainability goals. *Kyriakakos et al, 2000* have studied the intelligent management of distributed energy resources in hospitals. The authors stated that hospitals can produce on-site energy and use energy storage systems. They can also promote energy efficiency interventions. It was mentioned that intelligent energy management systems could control the operation of different distributed generation systems in hospitals.

2.4 Sustainable transportation in hospitals

van Gogh et al, 2005 have studied the concept of electric ambulance. The authors stated that emergency transportation by ambulances equipped with internal combustion engines has various problems. They proposed four types of electric ambulances which could overcome the disadvantages of conventional ambulances. *La Monaka et al, 2022* have reviewed the electric vehicle charging services. The author stated that clear roles should be assigned to the private and public funders to develop the infrastructure for large-scale EV development. They also mentioned that installing and maintaining charging infrastructure remains expensive. *Ryder et al, 2016* have examined the use of plug-in electric vehicle's charging in hospitals. The authors stated that hospitals providing plug-in electric vehicle's charging stations for employees send a strong and visible sign of a hospital's commitment to sustainability and public health.

2.5 Offsetting carbon emissions in hospitals

Scott et al, 2021 have proposed the promotion of carbon offsetting through nature-based solutions for mitigating climate change. The authors stated that nature-based solutions should be the first choice for offsetting carbon emissions. *Tsai et al, 2020* have studied several carbon emission reduction incentives and schemes including carbon tax, carbon trading and carbon offset. The author stated that there are two markets for carbon offsetting including: a) the large compliance market, and b) the smaller voluntary market.

2.6 Financing clean energy investments in hospitals

Carbonari et al, 2015 have studied the use of Energy Performance Contracting (EPC) for energy retrofitting in hospitals. The authors stated that involvement of Energy Service

Companies (ESCOs) can offer the necessary energy expertise and the required capital for energy renovation in hospitals. *Pantaleo et al, 2014* have analyzed the ESCO business model for biomass heating and CHP in Italy. The authors stated that involvement of ESCOs in biomass heating and in CHP in Italy is desirable while the use of biomass for heat generation is highly profitable. *Financing hospital energy sustainability has been reported, 2022***.** It is stated that energy sustainability in hospitals can be promoted with: a) energy saving, b) on-site clean energy generation, and c) buying clean energy from others. It is mentioned that implementation of sustainable energy projects in hospitals can be realized with energy performance contracting and involvement of Energy Service Companies.

Aims of the current research are:

a) To present several sustainable energy technologies that can be used in hospitals,
b) To present the possibilities of carbon offsetting in hospitals, and
c) To present several financing schemes that can be used for financing sustainable energy investments in hospitals.

3. Methodology

The text is structured as follows. After the sections of introduction and the literature survey the results are presented in six sections as follows. In the first three sections the use of energy saving technologies, the renewable energy technologies and the low carbon emission technologies in hospitals are stated. In the next three sections the reduction of transportation-related carbon emissions, the carbon offsetting schemes and the financing of green energy investments in hospitals are mentioned. The text is ending with discussion of the findings, the conclusions drawn and citation of the references used in the study.

4. Results

4.1 Energy saving in hospitals

Energy savings in hospitals can be achieved with various ways. Old hospital buildings constructed with the old building codes have high potential of heat savings. Old lighting and HVAC systems have low energy efficiency and they can be replaced with more efficient systems. It has been estimated that most hospitals have an energy reduction potential at around 20-40%. The main sectors with high potential of energy saving in hospitals include:

a) **The building envelope**. Buildings in many hospitals have been constructed with old building codes having poor energy performance. Improvements in building's envelope can reduce significantly the requirements for heating and cooling,
b) **The HVAC system**. HVAC systems in hospitals utilize 50% or more of their total electricity consumption. Improvements of HVAC systems can significantly reduce the energy demand,
c) **The lighting system**. Many hospitals have old, energy inefficient lighting systems. Their replacement with new systems having low energy consumption can reduce significantly the total energy use,

d) **Better use of medical equipment**. Medical equipment utilizes significant amounts of energy either during their operation or during stand-by mode.
e) **Better control of various parameters**. Installation of sensors and appropriate control of various parameters including lighting, heating and cooling in hospitals can reduce their energy demand, and
f) **Behavior changes**. Behavior changes of staff, patients and visitors result in energy saving in hospitals. The cost of behavior changes is low compared with the previously mentioned methods.

4.2 Use of renewable energies in hospitals

Several renewable energies can be used in hospitals. Solar photovoltaic energy for electricity generation, solar thermal energy for domestic hot water production and solid biomass for heat generation are frequently used. Few applications of biogas for heat generation or for CHP, small wind turbines for electricity generation and direct geothermal fluids have been also reported.

4.2.1 Use of solar photovoltaic energy

Use of green solar electricity is attractive provided that solar radiation at hospital's site is satisfactory. Use of solar-PVs in hospitals has many economic and environmental benefits while it can help their clean energy transition reducing or zeroing their net carbon footprint due to energy use. Various solar photovoltaic systems have been installed in many hospitals located either in areas with electric grids or in areas without grid's infrastructure worldwide. Taking into account that hospitals consume approximately two and half times more energy than other buildings the use of solar-PV systems can reduce the annual electricity bill allowing them to invest more resources on patient-care. Solar-PV systems can be combined with other low or zero carbon emission energy technologies, like wind turbines and co-generation systems, covering the most or even all of the annual electricity demand in hospitals.

4.2.2 Use of solar thermal energy

Hospitals utilize thermal energy in various sectors like in patient's rooms, in cooking, in the laundry, in cleaning, in steam production etc. In many cases hot water at around 60-70^{o}C can cover the most of their heating needs. It is estimated that the average hot water requirements in a hospital is at around 160 lt/day per patient. Hot water at low or medium temperatures can be produced with various types of solar thermal systems while in countries with satisfactory annual solar irradiance the use of solar thermal systems is technically and economically attractive. Solar thermal technology producing hot water is mature, reliable, well known and cost-efficient. When used in hospitals it replaces fossil fuels reducing their carbon emissions due to energy use as well as the annual operating expenses due to diesel oil and natural gas consumption. Therefore, the use of solar thermal technology in hospitals has positive economic and environmental impacts. These energy systems when combined under some circumstances with absorption chillers can also provide space cooling in hospitals. Solar thermal systems producing hot water are attractive when:

A) The water heating demand is constant throughout a year,

B) The climate is sunny with satisfactory annual solar irradiance, and

C) The cost of conventional fuels is high or unstable.

Solar thermal energy can cover a large part of hot water demand in hospitals and in many existing applications it can cover 10-30% of their total heating needs. Using hybrid energy systems, including solar thermal energy, biomass, fossil fuels and ambient heat with heat pumps, all the hot water requirements in hospitals can be covered.

4.2.3 Use of solid and gaseous biomass

Solid biomass can be used by burning in space heating and hot water production covering the needs in various sectors in hospitals. Since heat has a high share in the total energy mix in hospitals, which could exceed 50%, biomass could cover the most of their annual energy requirements. Various sources of solid biomass including agricultural and forest residues, by-products and wastes as well as wood pellets have been used for heat generation. Several biomass burning systems have been used in hospitals producing either steam or hot water. Solid biomass should not be transported from long distances for economic and environmental reasons. Burning of solid biomass produces flue gases that should be processed minimizing their environmental impacts at hospital's areas. The composition of the flue gases and the contained pollutants depend on the type of biomass source and the burning technology. In any case proper filters should be used removing the pollutants from the exit gases according to the legal regulations. Apart from other pollutants carbon dioxide (CO_2) is contained in the exit gases which is emitted into the atmosphere. Biomass burning though is considered to have neutral impacts to greenhouse effect since the CO_2 emitted into the atmosphere is removed by plant photosynthesis producing an equal quantity of the biomass burnt. Apart from solid biomass biogas is also used for heat generation or co-generation of heat and power in hospitals. Biogas is produced by anaerobic digestion of organic matter and contains mainly methane and carbon dioxide. Various types of liquid and solid organic wastes are currently used for biogas production resulting in the reduction of their organic load. When a hospital is located nearby a biogas production plant the biogas can be used for energy generation covering part of its energy demand.

4.2.4 Use of wind energy and geothermal energy

When the annual mean wind speed at hospital's site is satisfactory small wind turbines can be used in-situ generating electricity. Hybrid electricity generation systems consisted of wind turbines and solar-PV panels, backed up with diesel generators and electric batteries, can provide electricity in healthcare facilities located in areas without electric grid infrastructure mainly in poor and developing countries.

Geothermal fluids can be used directly for heat production in hospitals. Medium enthalpy geothermal fluids with temperatures at around 80-120^{o}C can cover a large share of the annual heating demand in hospitals particularly regarding space heating and domestic hot water production. When geothermal fluids are located nearby to hospitals, they can be used for hot

water production with heat exchangers. The utilized geothermal fluid is rejected back into the geothermal field while the hot water is transported with well insulated pipes at the hospital and used there for heat production. The use of renewable energy technologies in hospitals are presented in table 1.

Table 1. Use of renewable energy technologies in hospitals

Energy technology	Energy or fuel used	Energy generated	Energy efficiency (%)
Solar thermal panels	Solar energy	Heat	30-40
Solar photovoltaic panels	Solar energy	Electricity	15-18
Wind turbines	Wind energy	Electricity	25-35
Biomass Burning	Solid or gaseous biomass	Heat and electricity	60-80
Heat recovery from geothermal fluids	Low enthalpy heat of geothermal fluids	Heat	70-80

Source: Various authors

4.3 Use of low carbon emission energy technologies in hospitals

Various low carbon emission energy technologies have been successfully used in hospitals providing heat, cooling and electricity. These technologies comprise:

a) Heat and power co-generation systems,
b) Heat pumps,
c) Fuel cells, and
d) District heating and cooling systems.

The main characteristics of these technologies are their high energy efficiency and the low carbon emissions.

4.3.1 Use of heat and power co-generation systems in hospitals

Heat and power co-generation systems generate simultaneously heat and power using either fossil fuels or renewable energies. They can cover part or all of the heating and electricity demand in hospitals, while nowadays they have extensive applications in many sectors including hotels, hospitals, large-scale buildings as well as in industry and greenhouses. Apart from heat and power generation they can be used in space cooling, that is also required in hospitals, using a thermal absorption chiller operating as tri-generation systems. Hospitals are ideal candidates for using this technology since they operate continuously, 24/7, all over the year consuming both heat and electricity. CHP systems can provide continuously and reliably

space heating, steam, domestic hot water and electricity in hospitals in a cost-efficient way. Their overall energy efficiency is high at 80-85%, or even at 90% while they can reduce the environmental impacts in hospitals due to energy use. CHP systems encompass various technological systems co-producing heat and electricity including internal combustion engines, gas turbines, micro-turbines, fuel cells, and Stirling engines. The most common fossil fuel used in CHP systems is natural gas while few systems consume light or heavy oil or even coal. They can also utilize biomass like agricultural and forest residues, by-products and wastes, bioethanol, bio-diesel or biogas produced from various organic wastes. The use of CHP systems in hospitals is currently increasing due to their economic and environmental benefits as well as to high reliability. They can provide heat and electricity to healthcare facilities during severe storms and disasters increasing their resilience in extreme weather events.

4.3.2 Use of heat pumps in hospitals

Heat pumps are heat and cooling production devices which are currently used in many applications including hospitals. They are capable to generate three or more times more heat and cooling than the consumed electricity being more energy efficient than other heating and cooling systems. Their use in hospitals is increasing while they are capable to cover part or all of the demand in air-conditioning and domestic hot water production. Various applications of heat pumps' utilization in hospitals have been reported. Ground source heat pumps used for heating and cooling in hospitals offer significant financial and environmental benefits. Heat pumps have been also used for heat recovery from air-compressors producing hot tap water in the summer having a low payback period.

4.3.3 Use of fuel cells in hospitals

Fuel cells are modern, sustainable and very efficient energy systems having increasing applications in many sectors particularly when both heat and power are required. Although their installation cost is still high their promotion is accelerated with governmental support and financial subsidies. Among other applications fuel cells are increasingly used in hospitals covering part of the heating and electricity requirements. Their use has many benefits while they contribute in the reduction of carbon emissions due to energy use that is important for climate change mitigation. Fuel cells are devices that convert the chemical energy of a fuel that is either pure Hydrogen (H_2) or H_2 derived from natural gas or biogas into electricity via electrochemical reactions. H_2 in fuel cells reacts with oxygen producing water and energy. They do not have moving parts being a reliable source of power. A fuel cell system is an energy generator consisted of three parts: an anode, a cathode and an electrolytic material. Various types of fuel cells are available in the market and each type operates slightly different.

4.3.4 Use of district heating and cooling systems in hospitals

District heating and cooling is an old and sustainable energy technology which is broadly used nowadays in hospitals, as well as in other applications, for space heating, cooling and hot water production. Their use has many economic and environmental advantages. Depending on the fuel used district heating and cooling can positively contribute in lowering or zeroing the

carbon footprint in hospitals due to heat and cooling consumption. District heating systems have three major components:

a) A thermal energy generating plant,

b) Well insulated distribution piping for the hot water. Usually the pipes are placed underground, and

c) Building interconnections (valves, heat exchangers, meters).

The main fuels used in district heating systems comprise fossil fuels while natural gas has the largest share among them. Other fuels used include waste heat, grid electricity as well as various renewable energies like solar thermal energy, biogas, solid biomass, geothermal energy etc. The low carbon emission technologies used in hospitals are presented in table 2.

Table 2. Low carbon emission energy technologies used in hospitals

Energy technology	Energy or fuel used	Energy produced	Energy efficiency (%)
Heat and power co-generation systems	Natural gas, oil, biogas	Heat, electricity	80-90
Heat pumps	Ambient heat, electricity	Heat, cooling	300-600
Fuel cells	Natural gas, hydrogen, biogas, methanol	Heat, electricity	80-85
District heating, district cooling	Oil, natural gas, biomass, biogas	Heat, cooling	80-90

Source: Various authors

4.4 Low carbon transportation in hospitals

Hospitals utilize fuels covering the transportation needs of vehicles including emergency care services as well as transportation of their staff, patients and visitors. Fossil fuels based on petroleum products including gasoline, diesel oil and natural gas are mainly used in vehicles. Transportation has a share at around 10-20% in the total operational GHG emissions in hospitals. Their high dependency on fossil fuels increases their vulnerability regarding future price increases of petroleum-based products. “Greening transportation” is necessary for achieving climate-friendly healthcare facilities with net zero annual carbon emissions due to energy use.

Transportation-related carbon emissions in hospitals are produced:

a) From the ambulances,

b) From the vehicles used by their staff, patients and visitors,

c) From vehicles used by the staff providing external healthcare services at patients' homes.

There are several methods which can reduce the transportation-related carbon emissions in hospitals including:

a) Reduction of emissions due to staff's transportation,

b) Reduction of emissions due to patient's and visitor's transportation, and

c) Reduction of emissions due to patient's transportation with emergency services, and

d) Reduction of emissions due to healthcare delivery at patient's homes.

Alternative transportation methods comprise:

a) Selection of transportation modes with less carbon emissions,

b) Use of more energy efficient ambulances,

c) Use of ambulances fueled with unconventional fuels including electricity. Ambulances fueled by unconventional fuels include hybrid ambulances, ambulances using gaseous or liquid bio-fuels like biogas, bio-ethanol and bio-diesel, pure electric ambulances with re-chargeable batteries and electric ambulances with fuel cells fueled by hydrogen. Providing unconventional fuels to vehicles pre-supposes that hospitals should create the necessary infrastructure for using new alternative fuels including storage tanks for bio-fuels and hydrogen as well as electric battery's re-charging stations,

d) Providing electricity with on-site electric battery chargers to electric vehicles used by the staff, patients and visitors. "Green electricity" generated by solar-PV panels installed at hospital's site can be used for re-charging the batteries of electric vehicles, and

e) Selection of low carbon emissions transportation modes from hospital's staff when providing on-house healthcare to patients.

4.5 Carbon offsetting schemes in hospitals

Offsetting carbon emissions can help private or public organizations, including hospitals and healthcare facilities, to achieve the net zero carbon emissions target. The organization after reducing its energy consumption and replace part of fossil fuels used with renewable energies can offset any remaining carbon emissions purchasing carbon credits from carbon emission trading schemes. Offsetting carbon emissions is an additional tool for companies and organizations facilitating and assisting them to zero their net carbon emissions according to climate change mitigation targets. The concept of offsetting carbon emissions with three mechanisms was firstly proposed by UN under the Kyoto protocol in 1997. These three mechanisms are: a) the clean development mechanism (CDM), b) the joint implementation

(JI), and c) the emissions trading (ET). Nowadays various organizations create and realize carbon offsetting projects in developing countries and sell part of them to those who are voluntarily willing to reduce or zero their net carbon emissions. Carbon pricing is an important instrument that corresponds to the external costs of greenhouse gas emissions. It has a fundamental role in the transition to the net zero carbon emission economy. It has been proposed that a fair price of carbon credits depends on the type of carbon offsetting projects varying from 8.20 €/tonCO_2 for energy efficiency projects, to 8.10 €/tonCO_2 for renewable energy projects and 13 €/tonCO_2 for forest management projects. The current voluntary carbon market is small but is expected to grow fast. The current carbon offsetting price at 3-5 \$/tonCO_2 is considered very low and unsustainable while prices in 2030 are foreseen to be much higher at around 20-50 \$/tonCO_2 or up to 100 \$/tonCO_2 (*Future demand, supply and prices for voluntary carbon credits, 2021*).

4.6 Financing clean energy investments in hospitals

Hospital's buildings consume large amounts of energy compared with other public and private buildings. Improving their energy sustainability and decreasing their carbon footprint requires renewal of their old and polluting energy systems. The cost of retrofitting their buildings as well as of replacing their old and inefficient energy equipment is high. Financing the implementation of clean energy projects with own resources might not be feasible in many cases. Healthcare facilities should try to find the best financial options supporting clean energy investments for the successful and profitable realization of the projects. There are several financing schemes supporting sustainable energy investments in hospitals which can be used in a flexible way. They can be categorized as internal, external and mixed. All alternative financing possibilities should be examined and assessed for finding the optimum solution in a specific hospital. The main financing possibilities that can be used either alone or combined together are:

a) Financing with hospital's own funds,

b) Financing with bank loans,

c) Financing from energy service companies (ESCOs),

d) Financing from public funds, either national or international, subsidizing clean energy investments,

e) Financing from external donors and charities,

f) Financing from energy cooperatives,

g) Financing through crowd-financing, and

h) Financing through tax exemptions.

The financing options chosen depend on the scale and the nature of the specific project. Usually, large clean energy investments in hospitals require more than one financial tool. A clean energy investment can be partly financed with own capital, bank loans and governmental subsidies. The payback period of clean energy investments in healthcare

facilities depends on the specific project and usually is in the range of 5-20 years.

5. Discussion

Hospitals are complex organizations operating continuously all over the year while their energy consumption is high compared with other organizations. Our study indicates that the use of sustainable energies in hospitals can minimize or zero their net carbon emissions due to energy use. These technologies comprise: a) energy saving technologies, b) renewable energy technologies, c) low carbon emission technologies, and d) green transportation. Any remaining carbon emissions can be offset by the existing mechanisms zeroing their net carbon footprint. Our findings indicate that the required clean energy technologies are mature, reliable and cost-efficient while the existing financial mechanisms can facilitate and support clean energy investments in hospitals. Several sustainable energy technologies generating heat and electricity resulting in low carbon transportation have been used so far in many hospitals worldwide verifying their viability and usefulness. It should be mentioned that some of the energy technologies mentioned in our study, including solar and wind energy technologies, can be used in healthcare facilities only when the energy source is available in satisfactory quantities nearby them. Further research should be focused on realizing various case studies in hospitals and healthcare facilities verifying that clean energy technologies combined can reduce or zero the net carbon emissions due to energy use in these organizations.

6. Conclusions

Hospitals are complex organizations consuming large amounts of energy and emitting large amounts of GHGs. They mainly consume conventional fuels and grid electricity. The use of sustainable energy technologies in hospitals has been investigated. These include energy saving technologies, renewable energy technologies, low carbon emission technologies and green technologies in transportation. Several combinations of benign energy technologies in hospitals and healthcare facilities can achieve the desired result minimizing or zeroing their carbon footprint. Their use combined with carbon offsetting can zero their net carbon emissions due to energy use. These benign energy technologies are mature, reliable, well-proven and cost-efficient. Clean energy investments in hospitals can be supported by several existing financial mechanisms which facilitate their implementation. The abovementioned benign energy technologies have been used separately so far in many healthcare facilities worldwide increasing their energy resilience and their adaptability to climate change mitigation complying with global efforts for climate change mitigation and transition to a net-zero carbon society. Our work contributes in the clean energy transition of hospitals reducing their dependence on fossil fuels. It indicates that the existing clean energy technologies can support energy renovation in hospitals in a cost-efficient way helping them to promote both environmental and human health.

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