

## Article

# Healthy Power: Reimagining Hospitals as Sustainable Energy Hubs

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**Abstract:** Human health is a key pillar of modern conceptions of sustainability. Humanity pays a considerable price for its dependence on fossil-fueled energy systems, which must be addressed for sustainable urban development. Public hospitals are focal points for communities and have an opportunity to lead the transition to renewable energy. We have reimagined the healthcare energy ecosystem with sustainable technologies to transform hospitals into networked clean energy hubs. In this concept design, hydrogen is used to couple energy with other on-site medical resource demands, and vanadium flow battery technology is used to engage the public with energy systems. This multi-generation system would reduce harmful emissions while providing reliable services, tackling the linked issues of human and environmental health.

**Keywords:** energy transitions; hydrogen; energy storage; vanadium; flow battery; industrial ecology; co-benefits; multi-generation; power-to-X; energy networks

## 1. Introduction: Health and Energy

The energy systems most modern economies rely on are outmoded and unhealthy, which has multiple significant negative impacts. In addition to anthropogenic climate change caused by greenhouse gas emissions, nitrogen and sulfur oxides and carbon particulates damage ecosystems and are harmful to human health. Excess mortality from outdoor air pollution due to fossil fuel use is estimated at four million people per year [1]. The economic costs of this air pollution were estimated at USD 2.9 trillion, or over three percent of global GDP in 2018 [2].

Discussion of the relationship between climate change and health is increasing, most recently as the COVID-19 pandemic has highlighted improvements in air quality from reductions in human activity. Addressing this issue more permanently is a challenge; however, it is not a wicked problem as solutions can be mutually beneficial. Tackling the climate emergency goes hand-in-hand with improving public health outcomes by reducing harmful air pollution and developing a circular economy based on renewable energy ecosystems. Hakovirta and Denuwara now suggest ‘sustainability’ be redefined as “the intersection of the economy, environment, society and human health” [3]. The link to health represents an opportunity to accelerate the transition to renewable energy, not least because the health system itself is in a unique position to lead.

Doctors have had considerable success framing this health-related sustainability challenge, raising awareness of the considerable price that humanity pays for an energy ecosystem that relies on fossil fuels [4]. The Sustainable Development Unit of the UK National Health Service (NHS) was established in 2008, and the NHS has since reduced its carbon footprint by 19 percent over the 10 year period to 2018 [5]. Analysis of these efforts was published in *The British Medical Journal* [6]. Other prestigious medical journals have been amplifying calls to action, with editorials published in *The Lancet* [7], *The New England Journal of Medicine* [8] and *The Medical Journal of Australia* [9].

These efforts are critical because the health sector has a significant environmental footprint. In Australia, health care represented seven percent of Australia’s carbon dioxide (CO<sub>2</sub>) emissions in 2014–2015, with over one third of that attributable to public hospitals [10]. Leadership here can have a more pervasive impact since public perception of technology and its safety is important for its acceptance and deployment [11,12]. Doctors and scientists are the two most trusted professions [13], and so have a vital role to play in driving the innovative and creative thinking that will move past just efficiency and recycling to deliver whole system sustainable health services [14].

Systems thinking research supports the concepts of industrial ecology and social ecology that acknowledge connections between organizations and society and the importance of this for driving long-term change [15]. Collective visions of promising techno-scientific futures can legitimize investments and transcend uncertainty [16]. Public energy installations and community energy services are already being used for community interaction with new energy technologies [17,18]. Communities have shown a willingness to invest directly in renewable energy installations and there is interest and receptivity of these installations specifically in the hospital context [19].

Hospitals, as critical and major piece of publicly funded infrastructure, are an excellent case study for energy ecosystems. A hospital is not simply an energy user, it is a community and industry hub. Hospitals are regarded as safe havens, resilient facilities for disaster and emergencies [20]. Large numbers of staff and public use them daily and on-site parking is necessary for patients, staff and for ambulances, as well as commercial delivery vehicles. The hospital facility itself requires extremely secure sources of heat and power, oxygen and water.

Using data from the NHS, heat and power accounted for only 17 percent of the carbon footprint of UK hospitals in 2017 [21]. Supply chain and services accounted for 54 percent, while travel and transport, including staff commuting, accounted for 16 percent. Manufactured fuels, chemicals and gases represented another four percent. This presents an opportunity to consider this power and resource demand holistically.

In Australia, backup power supply for hospitals has been identified as a government priority for projects to drive innovation and demonstrate capability [22]. Renewable technologies can do more than provide backup power, however—they can play a critical role in reimagining a sustainable energy ecosystem. Integrating production and storage solutions in distributed systems presents an opportunity to optimize hybrid systems including the use of hydrogen and batteries [23].

The following multi-generation design concept shows how we envision that sustainable energy technologies can transform a hospital from a resource sink to the centerpiece of a new reliable and healthy energy ecosystem. We assess relevant technologies and integrate them for a hypothetical hospital in New South Wales (NSW), Australia. This located approach provides some grounding for

the design and discussion, though we note the same approach is widely applicable and we aim to inspire similar developments elsewhere.

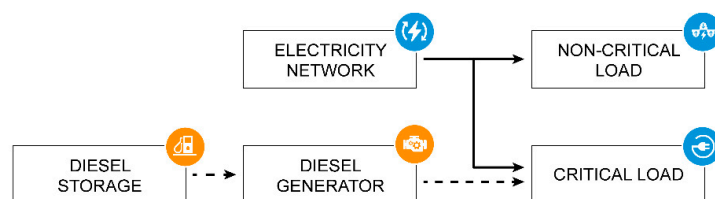
## 2. Materials and Methods: Technology Assessment and Design Approach

There are a range of technologies available to fulfill the multitude of resource requirements of a hospital. Presented here is a selection of technologies available to supply reliable power and the other associated needs for this healthcare system. We frame the design research to revolve around three key atoms: hydrogen, oxygen and carbon. The strengths, weaknesses and potential co-benefits of the individual technologies are discussed and summarized. This assessment is then used to develop sustainable hospital power system concepts through multidisciplinary design that simultaneously responds to carbon emissions, health impacts and material sustainability.

### 2.1. Power Generation

#### 2.1.1. Diesel Combustion

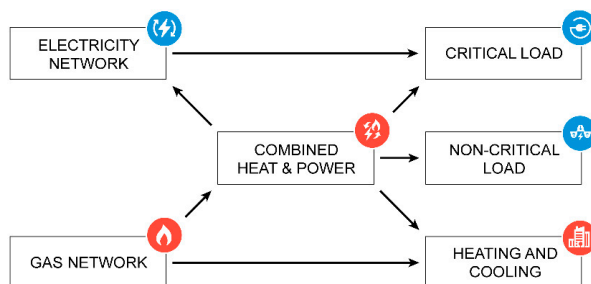
Coal has been the mainstay for the supply of power since the first Industrial Revolution, powering centralized electricity grids. Oil helped power the second Industrial Revolution, and a typical hospital relies on diesel internal combustion engine (ICE) generators for emergency power as shown in Figure 1. These stand-by engines are not designed to run for extended periods and so remain idle for most of their life. When the added burden of maintenance is considered, this is an expensive means of meeting mandated requirements.



**Figure 1.** Conventional system with diesel backup during normal operation.

#### 2.1.2. Gas Combustion

Co-generation or tri-generation captures thermal energy from combustion that would otherwise be wasted and deploys it for heating and cooling using absorption chillers. As hospitals have balanced power requirements and their heat requirements do not typically exceed the temperature for steam sterilization (below 160 °C), they make ideal candidates for using combined heat and power systems (CHP) [24]. This opportunity was identified more than a decade ago [25] and many hospitals have used this opportunity to improve energy efficiency, reduce costs and reduce emissions [26]. Hospital CHP installations use engines or gas turbines burning natural gas from existing networks as shown in Figure 2. This is an improvement on coal-fired power, though these systems still produce air pollution.

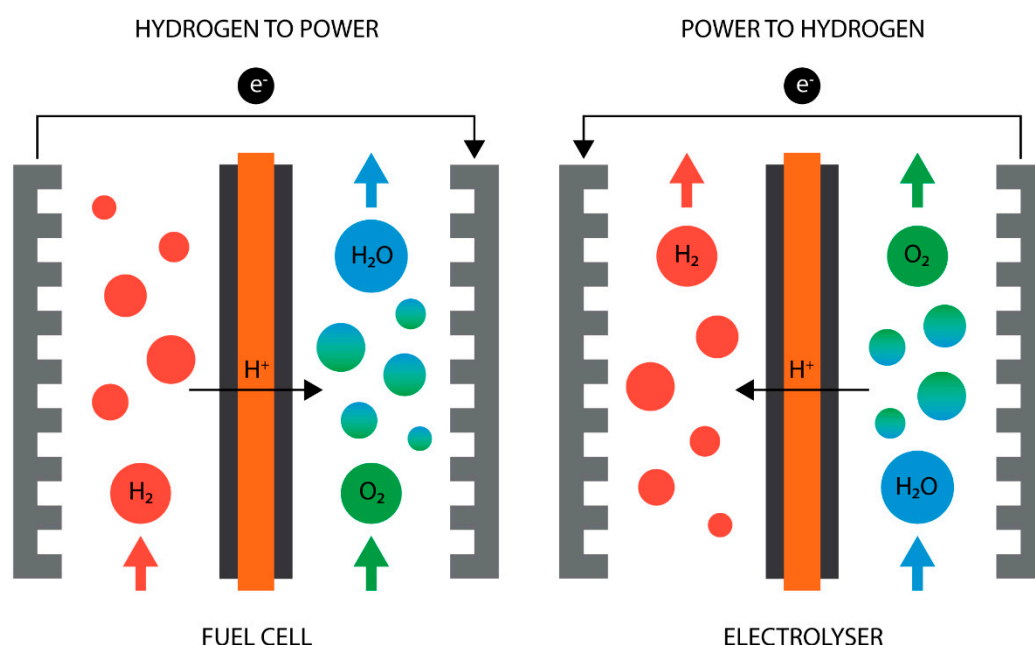


**Figure 2.** Combined heat and power system connected to both gas and electricity networks.

### 2.1.3. Fuel Cells

Commercial solid oxide fuel cell (SOFC) units in operation today generally include integrated steam methane reforming (SMR) equipment to use natural gas as a fuel source, which is broken apart to extract hydrogen. The high operating temperature and water ‘exhaust’ from the hydrogen fuel cell make this combination efficient and well suited for CHP systems. An advantage of this approach compared to simply burning the natural gas in an engine or turbine is the near complete elimination of harmful air pollutants ( $\text{NO}_x$ ,  $\text{SO}_x$  and particulates).

Another fuel cell technology is the proton exchange membrane fuel cell (PEMFC), the twin of a proton exchange membrane (PEM) electrolyzer which applies the same principles but in reverse. The conversion process is shown in Figure 3. In a fuel cell, molecular hydrogen is recombined with oxygen from the air to recover stored potential energy. The only emission from this process is water. The round-trip efficiency of an electrolyzer and fuel cell system is low compared to a battery; however, hydrogen can be transported more readily so is more appropriate for extended duration emergency power.



**Figure 3.** Simplified schematics of a proton exchange membrane (PEM) electrolyzer cell and a proton exchange membrane fuel cell (PEMFC) during operation, showing hydrogen and electron flows.

### 2.1.4. Renewable Energy Technologies

Renewable energy technologies integrated with digital grids are the new paradigm for electricity networks. Solar photovoltaic (PV) panels have become ubiquitous around the world and, accompanied by on- and off-shore wind turbines, are driving the transition to distributed non-fossil fuel based energy. Due to their solid-state nature, they require limited maintenance over their 25-year life, and economies of scale have resulted in spectacular cost reductions in recent years, which is continuing for large installations.

Despite the potential for large hospitals, only 13 of the 695 public and 497 private hospitals in Australia have been identified as having installed mid-scale solar PV systems [27]. An industrial 850-kW rooftop solar installation for a hospital in New South Wales (NSW) can be expected to achieve a capacity factor of 17 percent [27]. High-quality large-scale renewable resources in Australia supplied through the grid can increase capacity to 30 percent and 45 percent for solar and wind, respectively [28].

### 2.1.5. Comparison of Technologies

A comparison of renewables and the other power generation technologies discussed above is summarized in Table 1. Fuel cells and renewables present an opportunity to reduce emissions with flexible technology where energy can be stored and the value of co-benefits can be realized.

**Table 1.** Energy generation technologies for healthcare and their strengths, weaknesses and opportunities.

Technology	Strengths	Weakness	Opportunities
Diesel combustion	Well understood and easily refueled	Expensive and polluting	Existing system
Gas combustion	High energy efficiency	Polluting	Existing system
Hydrogen fuel cell	Clean and can be refueled	Expensive for conventional backup	Fuel flexibility
Renewables	Sustainable and scalable	Variable output requires storage	Low marginal cost power

## 2.2. Energy Storage

That you cannot turn on and off variable renewable energy (VRE) generators at will as you can with fossil fuel combustion generation is not always a weakness; the low marginal cost of renewable power is an opportunity to be creatively used in a symbiotic energy ecosystem.

### 2.2.1. Hydrogen

One of the greatest opportunities from low-cost renewable electricity technologies is to produce renewable hydrogen from water. PEM electrolyzers are now emerging as a preferred technology for this opportunity. The key advantage to PEM is their flexibility—PEM electrolyzers can accept partial, dynamic loads and are available from kW to MW scale. The technology functions by applying a current across a cell with two halves separated by a selective polymer that allows only hydrogen to move between the two, as shown in Figure 3. Water is fed into one side and the electrical energy splits the liquid into gaseous oxygen and hydrogen that can be collected and used in a range of applications.

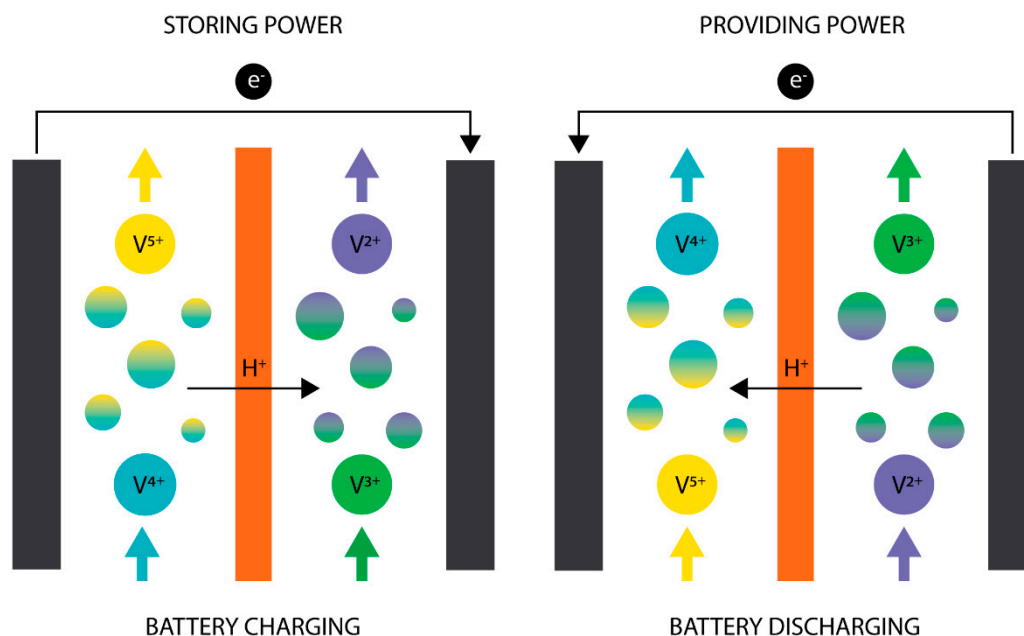
Hydrogen is a good candidate for long-term energy storage to meet emergency requirements and the seasonal variation in energy demand which occurs in hospitals [29] and energy networks. There are many ways to store hydrogen, the most mature forms being as a compressed gas in high-pressure tanks and as a cryogenic liquid in insulated low-pressure vessels. Either of these storage systems can be situated on-site as stationary installations or mounted on truck trailers or rail cars. Solid-state hydrogen storage is an alternative with the potential for much greater energy density and it is now being demonstrated at scale [30]. Hydrogen can also be blended into the natural gas network, which will have a role to play in areas where it currently exists as complete fuel switching from gas to electricity is likely to cost more than rethinking existing infrastructure [31].

### 2.2.2. Flow Batteries

Carbon-free hydrogen gas production is extremely flexible; however, inherent energy losses mean it is not always the most efficient means of providing secure and reliable power from renewable energy technologies [32]. Batteries have a significant role to play, although there are serious sustainability concerns for the widespread adoption of lithium batteries [33,34]. Large-scale deployment of this incumbent technology will face battery materials constraints in a global-scale energy transition [35]. There are other battery technologies suitable for grid-scale energy storage, such as the vanadium redox flow battery (VRB/VRFB).

VRBs are a hybrid between fuel cell and conventional battery technology. Energy is stored in liquid electrolyte tanks for power conversion in cell stacks that operate in a similar manner to a fuel

cell. The power is stored (or recovered) from the change in state of vanadium ions in an aqueous sulfuric acid solution which changes color based on its state of charge. Figure 4 provides a simplified visual explanation of this process. By separating power (kW/MW) from energy storage (kWh/MWh), a VRB system is highly scalable and can readily be configured to suit the needs of the application.



**Figure 4.** Simplified schematics of a vanadium redox flow cell during charge and discharge showing electrolyte color change with hydrogen and electron flows.

The aqueous electrolyte is non-flammable by nature, eliminating the potential fire safety hazard of lithium batteries. The reduced fire risk means these systems are more suitable for enclosed spaces, such as underground car parks. Electrolyte contamination is eliminated because the electrolyte is the same on both sides of the system, giving VRBs a long lifetime (>25 years) with low capacity fade. All-vanadium batteries' tolerance for practically unlimited charge–discharge cycles over their lifetime makes the technology ideal for high-use applications, such as supporting renewables and electric vehicles. The valuable vanadium in the electrolyte can be easily recovered for use in a new battery system or other applications. The balance of material is predominately carbon, metals and polymers that can also be recovered and recycled at end of life [36].

### 2.2.3. Hybrid Batteries

The ubiquitous lead-acid battery (LAB) has no moving parts and is the standard for uninterruptible power supplies (UPS). The conventional format of this technology, however, is not well suited to new power demands. Hybrid battery installations are being used to take advantage of the strengths of different technologies [37]. Pairing battery components with integrated supercapacitors creates new opportunities for mature LAB technology by improving its peak power capacity.

This hybrid technology was invented by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) and commercially acquired in 2010. It has since been deployed for a range of kW- and MW-scale storage applications. Similar to vanadium-sulfuric acid electrolyte flow batteries, hybrid lead-sulfuric acid batteries are almost completely recyclable. The Environmental Protection Agency in the United States found that lead-acid batteries are consistently one of the most recycled products [38]. This and the other energy storage technologies discussed above are summarized in Table 2 below.



**Table 2.** Storage technologies for healthcare and their key strengths, weaknesses, and opportunities.

Technology	Strengths	Weakness	Opportunities
Hydrogen electrolysis	Sustainable and flexible	Expensive when considered alone	Oxygen supply and demand management
Lithium-ion battery	High power density	Sustainability concerns and limited storage	Electricity network support
Lead-acid hybrid battery	Readily recyclable and high peak power	Limited storage capacity	Electricity network support
Vanadium flow battery	Recyclable, stable and non-flammable	Low power and energy density	Electricity network and electric vehicle support

### 2.3. Related Technologies and Resource Considerations

In addition to being a facility with heat and power demands, healthcare requires disinfectant and oxygen, and a hospital precinct is also a transport hub. Technologies related to energy generation and storage can help meet these additional sustainability challenges and realize the associated opportunities.

#### 2.3.1. Transport

Society is transitioning away from fossil-fueled passenger cars and commercial vehicles to the use of electric vehicles (EVs). If managed poorly, charging battery electric vehicles (BEVs) could strain electricity grids [39]. Smart charging can reduce this impact by creating a large demand response capability. One step further is vehicle-to-grid (VtG/V2G) technology which allows BEVs or fuel cell electric vehicles (FCEVs) with hydrogen to act as networked energy storage devices [40]. In this way, an EV fleet can become a virtual power plant (VPP) that is profitable to owners and beneficial for power networks [41]. The potential to support system security [42] is driving trials with government fleets [43]. Fleet operators are one of the main stakeholders driving the electric vehicle market [44] which is an opportunity for health services looking to reduce air pollution with more environmentally friendly vehicles [45].

#### 2.3.2. Oxygen

Non-energetic gas demands are an important component of energy transitions [46,47]. Oxygen is critical for health care and has been in short supply in some regions during the coronavirus pandemic in 2020 [48]. Hospitals commonly procure oxygen in bulk from suppliers as a compressed gas or as a cryogenic liquid, which is produced on a commercial scale through liquefaction and distillation. Oxygen is sold at a premium to the health sector, so generating it locally could save costs [49]. On-site production using compressed air with pressure swing adsorption (PSA) oxygen concentrators (OCs) has been found to reduce costs for hospitals [50]. High-quality medical grade 99.5% purity oxygen can be supplied from water as a by-product of producing hydrogen with electrolysis. Using this oxygen stream from renewable hydrogen in a multi-generation system can help support a new hydrogen economy.

#### 2.3.3. Water

Water use is one of the more significant aspects of sustainability management considered by the health sector, so it is important that water use issues are not exacerbated when designing a sustainable energy ecosystem [51]. To close the hydrogen water cycle loop, it is necessary to consider the water supply for electrolysis. This is commonly expected to be obtained through the desalination of seawater, which will thus be an important component of renewable energy networks [47]. Alternatively, water can be drawn from the air using an atmospheric water generator (AWG). These adsorption-based devices can utilize thermal energy from solar or waste heat even in arid climates [52]. The other advantage is that the water they produce is of high purity, reducing the need for purification for electrolysis [53].

#### 2.3.4. Disinfectant

Hydrogen peroxide is widely used in hospitals for disinfection and has been in particularly high demand during the COVID-19 pandemic [54,55]. The majority of hydrogen peroxide is produced using the industrial anthraquinone process, which is only viable at a large scale. Issues relating to highly concentrated solutions and concerns about this process from a green chemistry perspective have led to considerable interest in alternative means of supplying hydrogen peroxide [56]. Local production of dilute hydrogen peroxide reduces waste products and the risks associated with transporting and storing high concentrations in bulk [57].

Processes have been developed for direct production of hydrogen peroxide from hydrogen and oxygen [58] or from water and oxygen [59]. Convergent PEM electrochemical synthesis uses water and oxygen as inputs to a fuel cell and produces dilute hydrogen peroxide. This approach is particularly promising in a hospital context if oxygen is made readily available using on-site production for medical use. Other electrochemical synthesis processes are under development for on-site production of hydrogen peroxide along with other useful products, such as ozone [60], hydrogen [61,62] and oxygen [63].

#### 2.4. Design Approach

A full engineering design study would be necessary for any specific site; however, it is informative to explore system-level constraints and capabilities, which is the approach we have taken in this conceptual research.

##### 2.4.1. Regulation Constraints

Regulations relating to hospital power have been considered in our conceptual scenario of a multi-generation health precinct. Standards vary at the intra- and inter-national scale. For example, in the US, the updated code NFPA 99 allows for fuel cell systems as alternate sources of power since 2015 [64]. The code also now allows for oxygen concentrators as central supply sources for hospital medical oxygen systems, which could be integrated to support on-site production from electrolysis. Returning to the Australian context, the relevant standard for emergency power supplies in hospitals from 1998 (AS/NZS 3009:1998) states the power source may be provided by central battery systems, provided they are of a type specifically designed for continuous float charging conditions [65]. Lead-acid batteries meet this criterion but others do not, despite alternative battery technologies and contemporary digital battery management systems.

The  $N + 1$  supply configuration is a commonly accepted practice that shapes the design of emergency power systems, including those for hospitals [66] in NSW [20], to ensure enough redundancy is built in to ensure a highly resilient system. This means building in one additional piece of key equipment than is strictly required, so that one sub-system can fail and operations can continue. Providing capacity modularity to meet an  $N + 1$  guideline is straightforward with battery packs and fuel cells stacks; the most critical point of failure would relate to the inverter. The need for multiple inverters can be seen as a prohibitive cost or as an opportunity to install valuable assets able to provide ancillary services to electricity networks [67]. Demonstrations of the ability to replace the mechanical inertia of conventional power plants with battery-powered digital inertia are underway [68].

##### 2.4.2. Specification Constraints

The ongoing trend towards modularity facilitated by batteries and other clean technology in the energy sector brings flexibility to concept design which can be readily adjusted for specific requirements and translated to different sites. To provide an accessible example, we present a design concept for a hypothetical 550-bed hospital for a small city such as Newcastle, NSW, Australia.

We consider average energy demand, assumed to be 41 MWh per day based on an annual average of 27 MWh per bed [69]. Total energy use consists of electrical and thermal demands which will vary



based on climate and facilities. Using an average value from previous studies, it is assumed here that 49 percent of the total energy use is electrical demand and the remainder is thermal [24,29,69,70]. There are analytical data available for medical oxygen in hospitals [49] and the demand for this scale is assumed to be 708 kg per day.

### 2.4.3. Design Goals

The key constraints discussed above are:

- 41 MWh per day total average energy demand.
- 49 percent of total demand is electrical energy.
- 708 kg per day of medical oxygen.
- Uninterruptible power supply with  $N + 1$  redundancy.
- Battery systems designed for continuous float charging.

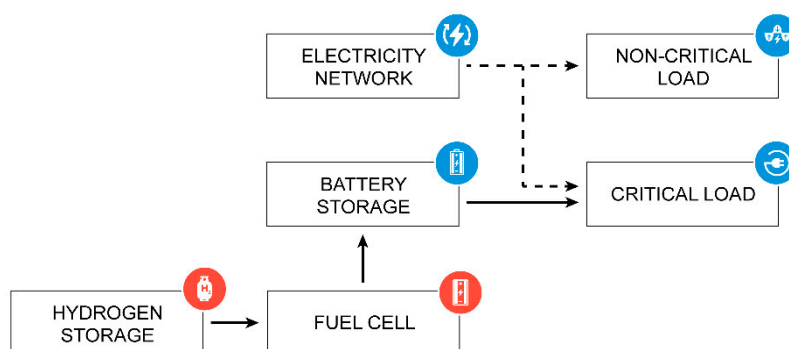
Meeting hospital demands sustainably within these constraints is the goal of our design work presented below. Re-imagining a healthcare precinct as a renewable energy hub in this way uses public infrastructure to build resilience, improve public health and accelerate the energy transition.

## 3. Results and Discussion: Design Specification for Hospital Renewable Energy Ecosystem

We re-imagined a multi-generation energy system for a sustainable hospital precinct that integrates renewable hydrogen and battery energy technologies to reduce harmful emissions while supporting reliable operations. To present the integrated systems, we break down the concept design into two sections. The first replaces fossil fuel combustion with fuel cells and batteries for reliable power with redundancy. The second broadens the scope, presenting a networked multi-generation system to sustainably provide other resources in addition to heat and power for deep decarbonization.

### 3.1. Replacing Engines and Turbines

In this case, we consider only the requirement for electrical power. The conventional generator setup could be replaced by a hydrogen fuel cell with storage to meet the set number of hours for the given location. This would take the form of a hybrid energy storage system with a battery, as shown in Figure 5.



**Figure 5.** Electrical backup system with hydrogen fuel cells during emergency operation.

This energy storage system for emergency power could consist of 1.5 h in lead to comply with AS/NZS 3009 and 24 h in hydrogen. If the system is configured with a suitable amount of spare capacity, this secondary power supply need not be reserved solely for emergencies. The hybrid supercapacitor technology broadens the usefulness of the lead-acid battery cells, and additional flexible capacity can be added with VRBs.

Starting with the fuel cell backup, six containerized 200-kW units [71] would provide 1.2 MW of power to meet the N + 1 redundancy guideline for an additional unit. 24 h storage would require 850 kg of hydrogen, which could be replenished by a high capacity 300-bar truck trailer. This could be stored on site at 165 bar in approximately 40 tubes with mature technology, or two of the type of containerized solid state 17-MWh units planned for demonstration in Australia [30].

Three commercially available containerized hybrid lead-acid battery units would provide 2.5 MW of peak power with 1.5 MWh of storage [72] to meet a 1.5-h specification for tertiary power supply. An emergency capacity of 2.4 MWh exceeds this by almost 90 percent, meeting the AS/NZS required margin of 1.33 times minimum capacity at install. This also meets the N + 1 redundancy guideline, as two of three units could meet the demand if required.

A vanadium battery secondary supply could consist of four containerized 250-kW units, with a range of capacity options [73]. In a three-hour configuration, this would translate to 3 MWh of capacity and 1 MW of nominal power. This could provide a limited secondary power supply alone, whilst together it could contribute to electricity system security and reliability. For BEVs, this could support up to 100 vehicles with 10-kW vehicle-to-grid connections.

An alternative to this setup is a CHP installation which is typically matched to the heat demand. Two containerized SOFC units would deliver 880 kW of power and 900 kW of heat [74]. Heat pumps, boilers and chillers would support the tri-generation system to reliably meet the variable thermal demands of the facility. In this scenario, a gas-fueled CHP system can be the normal supply, and the electricity grid the backup.

Batteries and stored hydrogen are still desirable for a system like this, connected to both gas and electricity networks, providing greater redundancy whilst making a larger contribution to network security and reliability. Twenty four hours of storage is suitable for VRE penetration of 90 percent [75] and building this in to provide reserves will help deliver fast-responding power assets in the grid that are missing incentives [76]. To achieve the full potential of this approach, though, hydrogen should be enabled to act as a two-way resource as with the battery system.

### 3.2. Multi-Generation for Coupled Power and Resources

Smart energy networks (SNE) integrate electricity, gas and heat under common Information and Communications Technology (ICT) with power-to-gas technology (PtG) [77]. An 850-kW rooftop solar installation generating 3.5 MWh per day for an electrolyzer system of five 30-Nm<sup>3</sup>/h units would be expected to produce 54 kg of hydrogen per day [78]. Two tonnes of adsorption material (sorbent) in an AWG system could be used to capture the approximately 500 L per day of water required for this electrolysis [52].

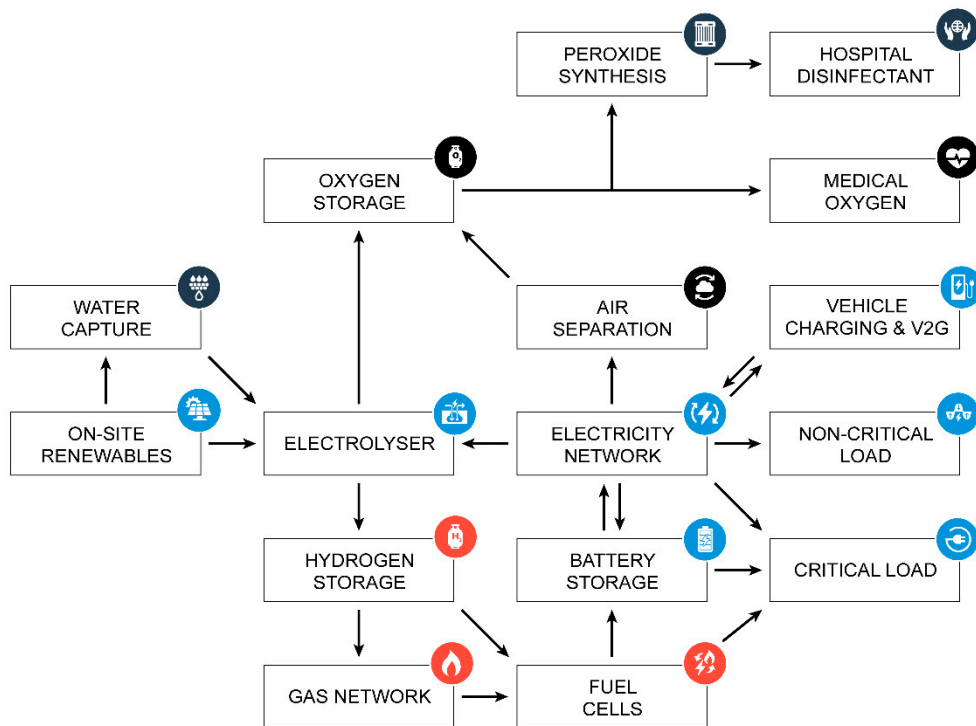
Theoretically, this size system could also produce 427 kg of oxygen per day, enough for approximately 45 medium-concentration oxygen therapy devices or 60 percent of the anticipated demand. Low-cost energy from grid connected solar or wind during periods of excess supply could power additional electrolysis to increase this to 80 or 120 percent of the demand. Efficient on-site oxygen concentrators could fill any supply gaps with cylinder backup [50]. Excess oxygen can feed hydrogen peroxide synthesis for disinfectant supply, as discussed in Section 2.

Excess hydrogen surplus to the hospital's energy storage requirements could be fed into the gas network. Existing methane infrastructure could accept up to 10 or 20 percent hydrogen [79,80], or more as synthetic methane after being combined with carbon dioxide extracted from the atmosphere [81]. Hydrogen could, alternatively, replace natural gas altogether. In addition to its use as fuel for electricity generation, hydrogen can be used in industry as a chemical feedstock and to supplement thermal energy primarily provided by heat pumps.

Hydrogen could also be used for vehicles, either in its pure molecular form for cars and commercial vehicles or as a feedstock for synthetic fuel [82] to support aeromedical services. A hospital campus of this size may have thousands of parking spaces [83]. Just 50 medium size EVs represent over 3 MWh of

energy storage and at least 500 kW of two-way power with vehicle-to-grid connections. Covering the car park with solar PVs could provide a much larger on-site solar precinct.

Figure 6 shows how all these systems interact to meet hospital requirements. In addition to redundancy, all these systems would be backed up independently from an infrastructure network and/or by road transport.



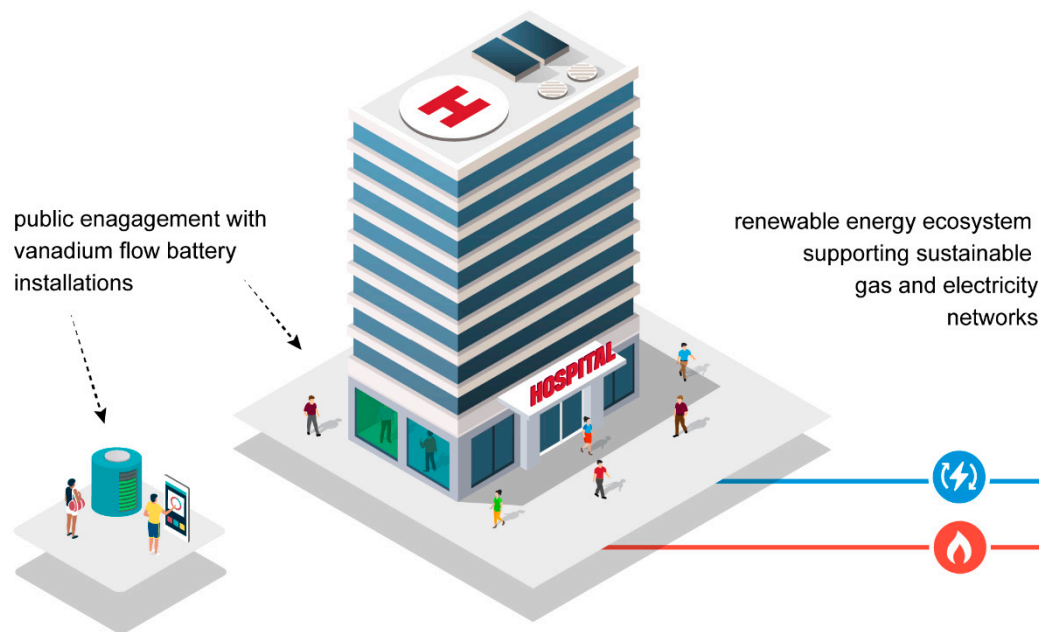
**Figure 6.** Multi-generation hospital precinct energy system concept diagram, with energy and resource flows for coupled energy and resource demands.

This high-level system design meets the goals outlined in Section 2.4 of this article, namely ‘sustainably provisioning for reliable on-site power requirements to improve outcomes for the community’. Future work would need to examine specific site requirements in more detail. This would include techno-economic optimization of system components and could also explore other opportunities, such as wastewater treatment and mobile installations for field hospitals. Detailed engineering design would consider other applicable standards and regulation, including the location of gas storage. Hydrogen is not inherently more hazardous than conventional fuels but it must be managed appropriately [84–86]. The positioning of technology in this hybrid clean energy system presents an opportunity to engage the public with the vision presented here, particularly with less well known vanadium systems.

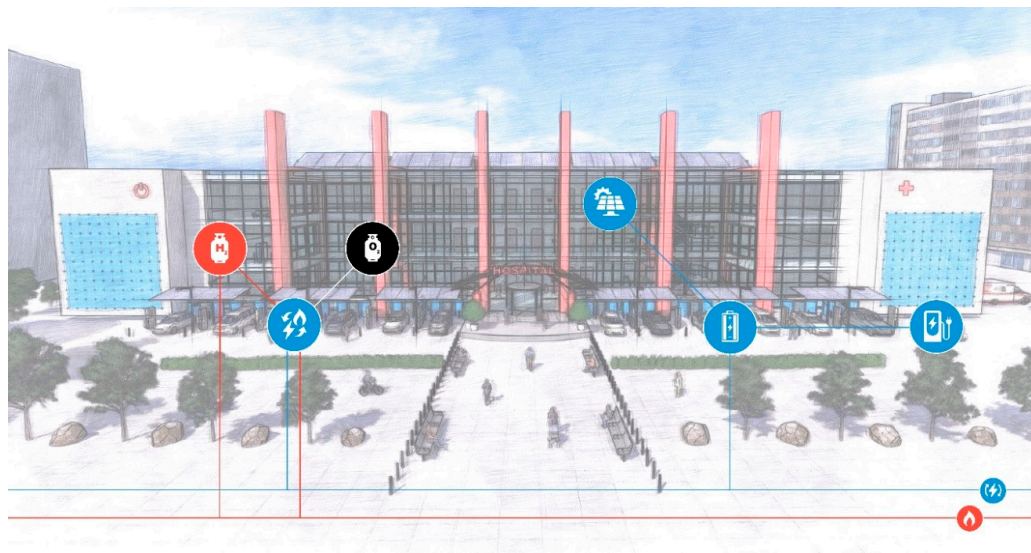
### 3.3. Illustration of Multi-Generation Hospital Precinct Energy System

Systems in plant equipment rooms and back-of-house containerized solutions provide large energy solutions; however, there is something to be gained from visible systems. A public installation could provide science education and potentially a useful distraction and on-site exhibition to the hospital patients and visitors. A dilute vanadium electrolyte solution or another water-based system with lighting would display the state of the energy system. Air or an inert gas, such as nitrogen, bubbled through the solution would simultaneously represent hydrogen and oxygen gas production from electrolysis. Battery modules, in a design suggestive of common household batteries [87], installed in locations such as car parks where solar PV panels are visible [88] would highlight the

benefits of EV-to-grid technology for the hospital and the public. Figures 7 and 8 illustrate this design concept.



**Figure 7.** Illustration of hospital concept with on-site generation and storage connected to gas (red) and electricity (blue) networks. Color-changing vanadium flow battery installations are used to engage the public with the energy systems, shown here in the green and blue of  $V^{3+}$  and  $V^{4+}$ .



**Figure 8.** Model rendering of concept hospital powered by coupled on-site renewable multi-generation and storage connected to gas (red) and electricity (blue) networks. Electrolysis produces hydrogen for fuel cells and oxygen for medical demands while batteries support electric vehicles and provide uninterrupted power for critical loads.

#### 4. Conclusions: A New Energy Ecosystem

We have re-imagined healthcare precincts and presented a design concept for a hospital as a flagship community energy hub where sustainable networks are coupled with medical requirements.



This design shows how versatile and scalable exchange membrane cell systems, including flow batteries and fuel cells, replace combustion to meet emergency power requirements and improve resource security. Battery inverters help manage grid power quality while solar powered electrolysis supports medical oxygen requirements and feeds hydrogen into decarbonized gas pipelines. Fleet, staff and public transport become an asset with electric vehicle-to-grid integration. Visible vanadium electrolyte and modular battery systems are also used to engage the community with this energy system to help drive the energy transition. Together, this provides a vision for healthy power to help redefine sustainability.

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