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EDITORIAL

Synergy between vertical farming and the hydrogen economy

Ahmed I. Osman[1] · David Redpath[1] · Eric Lichtfouse[2] · David W. Rooney[1]

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By 2050, the world population will rise to 9.7 billion, and two-thirds of the world's inhabitants will reside in urban areas, according to a forecast by the United Nations (UN 2022). This calls for innovative farming because history shows that without the green revolution techniques of the 1960s, an additional area of 1761 million hectares megahectares would have been required to attain the same agricultural output, and thus these techniques have avoided the emission of 590 gigatonnes of equivalent carbon dioxide (Burney et al. 2010). Unfortunately, the classical techniques of industrial agriculture are actually inducing massive environmental degradation, such as soil erosion, habitat destruction, loss of biodiversity, water pollution and greenhouse gas emissions. Paradoxically, the promising solution to these issues, vertical farming, is also intensive though it is also ecological in many aspects (Fig. 1, Kozai and Niu 2016a). Here, we discuss the potential synergies of vertical farming and wind, solar and hydrogen fuels.

A circular plant factory

The well-insulated airtight opaque building enables internal conditions to be controlled. Also, existing buildings can be retrofitted without altering their exterior appearance. The internal growth area with a multi-tiered hydroponic system increases the area available for plant growth; each tier being equipped with artificial light-emitting diode lighting to supply the light required for plant growth. The plants grow in a hydroponic medium, and there is a heating, ventilation and air conditioning system with circulating fans for space conditioning and air circulation. The carbon dioxide supply system is used for increasing the concentration of carbon dioxide to improve plant growth and sequester carbon. The nutrient supply system supplies the required fertilisers for plant growth. These nutrients can be artificial or organic nutrients derived from anaerobic digestates or via aquaponics. The water transpired by plants is captured in the condenser of the air conditioning systems, then returned to the nutrient supply system, thus minimising water usage.

98% less water usage

Vertical farming was developed during the early 1970s for long-distance space exploration because area is limited on spacecrafts (Zabel et al. 2016). Essentially, vertical farming can be located anywhere, provided there is a plentiful supply of energy, water, nutrients and a suitable structure to contain the multilevel hydroponic growth system. Water usage is reduced by 98% compared to open-field agriculture because 95% of the water from the evapotranspiration of plants can be collected by the air conditioning system and reused (Avgoustaki and Xydis 2020b). When combined with aquaponics, which integrates aquaculture with hydroponics into a system where the input of plant nutrients is provided via the food supplied to the fish, the requirement for artificial fertilisers and pesticides is minimal (Kozai 2013). Switching from conventional open arable farming to enclosed vertical farming reduces the total amount of land required for crop production, negates the requirement for imports of out-of-season produce, and reduces food miles and associated carbon footprints (Despoina Avgoustaki and Xydis 2020). In the United States of America, it was estimated that, on the average, the distance food is transported to retail outlets is 2000 kms (Smit and Nasr 1992). The increased deployment of vertical farms would lead to reduced food waste, as fresher produce lasts longer.

✉ Ahmed I. Osman
aosmanahmed01@qub.ac.uk

Eric Lichtfouse
eric.lichtfouse@icloud.com

[1] School of Chemistry and Chemical Engineering, Queen's University Belfast, Belfast BT9 5AG, Northern Ireland, UK

[2] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, Shaanxi, People's Republic of China

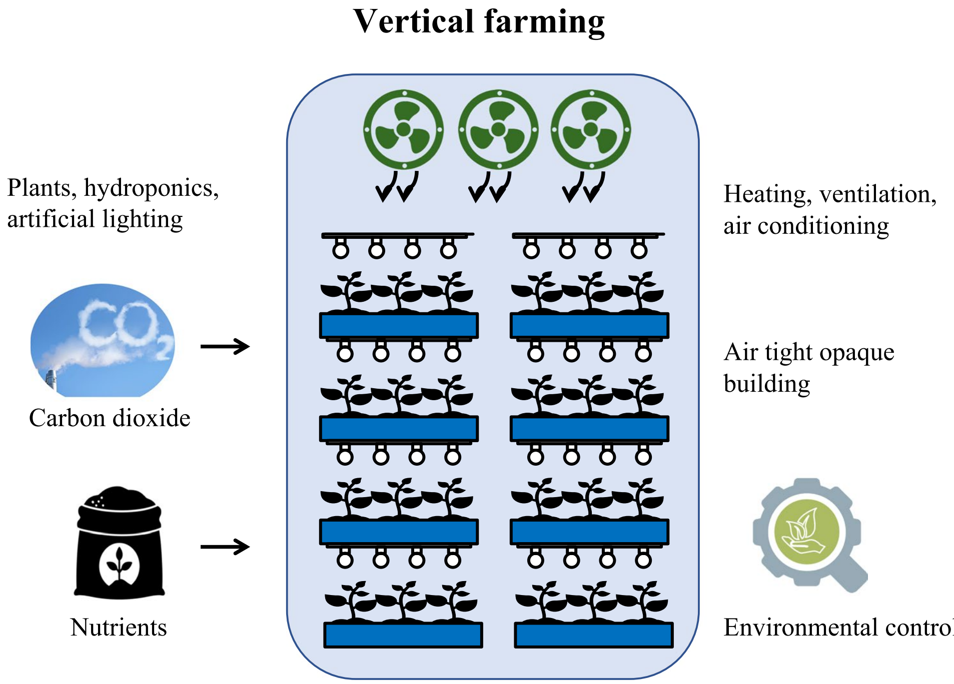

Fig. 1 The main components of a vertical farm: An internal multitiered grow area for plants with hydroponics and artificial lighting; a carbon dioxide supply system; a nutrient supply system; a heating, ventilation and air conditioning system, a well-insulated airtight opaque building, and an environmental control system. Modified from Kozai (2013)

200 times more productive

Typically, a vertical farm with ten tiers has a productivity 100 to 200 times that of conventional open-field agriculture (Kozai 2013); a theoretical investigation estimated a potential increase of 514 times (Banerjee and Adenaeuer 2014). With continuous production, vertical farms offer permanent rather than seasonal employment opportunities in agriculture (Kalantari et al. 2018). Recent research has identified that small tuberous root vegetables are particularly useful for growth enhancement using elevated carbon dioxide concentrations as the roots are effective carbon sinks, so photosynthesis in the leaves is increased using the sieve tubes in the stems, which transport carbohydrates more efficiently (Kozai Toyoki et al. 2020). Previous research reported that increasing the atmospheric concentration in controlled environments, such as from 800 to 1000 parts per million (ppm) in a verticl farm, increased yields of C_3 plants by up to 100% (Poudel and Dunn 2017).

More resources and capital needed

Whilst vertical farms are more resource efficient, they are more resource and capital-intensive than open-field agriculture or greenhouse cultivation (Stein 2021, Plant Factory 2022). It was estimated that the electrical energy required for lighting when cultivating basil all year round was 1030 kWh/m^2/yr, providing an annual yield of 50 kg/m^2 (Avgoustaki and Xydis 2020b). The capital expenditure for a building containing a vertical farm with a 15-tier system, and a vertical separation distance of 50 cm between the tiers, was estimated at \$4000/m^2 (Kozai and Niu 2016b). A vertical farm in Denmark using a six-tiered growing system for producing basil had capital expenditure costs of €1430/m^2 (Avgoustaki and Xydis 2020c).

Recycling green oxygen from hydrogen production

Vertical farming also allows synergies with the green hydrogen economy and the increasing use of renewable power generation. In particular, this can help grid balancing, by using the currently curtailed wind power. It was estimated that, by doing this, the initial capital expenditure of vertical farms could be repaid in 4 to 8 years (Xydis et al. 2021). Green oxygen generated during the electrolysis of water for the production of green hydrogen, which is normally considered as waste, could potentially be supplied to the plant roots via the circulating nutrient solution. Supersaturating the nutrient solution with pure oxygen rather than air doubles the yield of hydroponically grown crops and additionally inhibits fungal growth on roots (Suyantohadi et al. 2010; Chérif et al. 1997).

Securing an indigenous energy and food supply with strategic energy storage levels removes the reliance on any other external sovereign regimes for food and energy, essentially providing complete independence for any nation adopting these technologies. By identifying clearly the agricultural applications and economic advantages of using green oxygen generated from water electrolysis, the higher costs associated with green hydrogen production could be reduced, improving the payback period and stimulating the emerging hydrogen economy.

Grid balancing

Using vertical farms for grid balancing or "flexible connections" also reduces the costs associated with grid reinforcement. From 2020 to 2021, the installed capacity of wind rose by 47.8% from 59 to 113 gigawatts (GW), whereas generation rose by only 17% (IEA 2022). The lack of flexibility associated with transient renewable power generation, such as wind or solar photovoltaics, means that some countries assume a capacity factor of only 10% for wind turbines. (IEA 2020). Lighting provided for vertical farms can be switched off for short periods, allowing these to act as grid balancing services assisting the integration of transient renewable energy generation technologies, and research by Avgoustaki et al. (2021) reported that intermittent lighting increased biomass production by 47%.

Synergy with hydrogen and wind energies

The costs of wind energy curtailment from 2011 to 2021 for the United Kingdom is increasing (Fig. 2, Matson and Knighton 2022). The planned increase in the generation of green hydrogen in the United Kingdom to 5 Gigawatts and the expansion of installed offshore wind energy generation capacity to 50 Gigawatts by 2030 suggests that developing vertical farming technology would simultaneously supply an indigenous hydrogen economy, a sustainable source of energy and secure food supplies. This would also support the transition to net zero by 2050 by increasing the capacity factor of renewable energy generation and reducing greenhouse gas emissions from the agricultural sector. As the quantity of renewable energy generation in the United Kingdom has increased, so has the problem of curtailment along with its associated costs. A 2022 report produced for the DRAX company estimated the cost of wind energy generation curtailment in 2020 and 2021 as £806 million.

Curtailed wind energy could power vertical farms

If the curtailment value of 2021 stayed the same by 2030, assuming that the target of 50 Gigawatts of offshore wind is met, then the quantity of curtailed energy from this expansion in offshore wind capacity would be 4465 Gigawatt hours. Regarding the unit growth area, Avgoustaki and Xydis (2020a) reported that 0.176 kW/m^2 was required for lighting. Kozai and Niu (2016a) reported that for a well-insulated, airtight building, lighting constitutes 80% of the total electrical input, with the cooling systems requiring 16% and the other components 4%. Assuming that the daily photoperiod is 16 h, then the lights would operate for 5840 h annually,

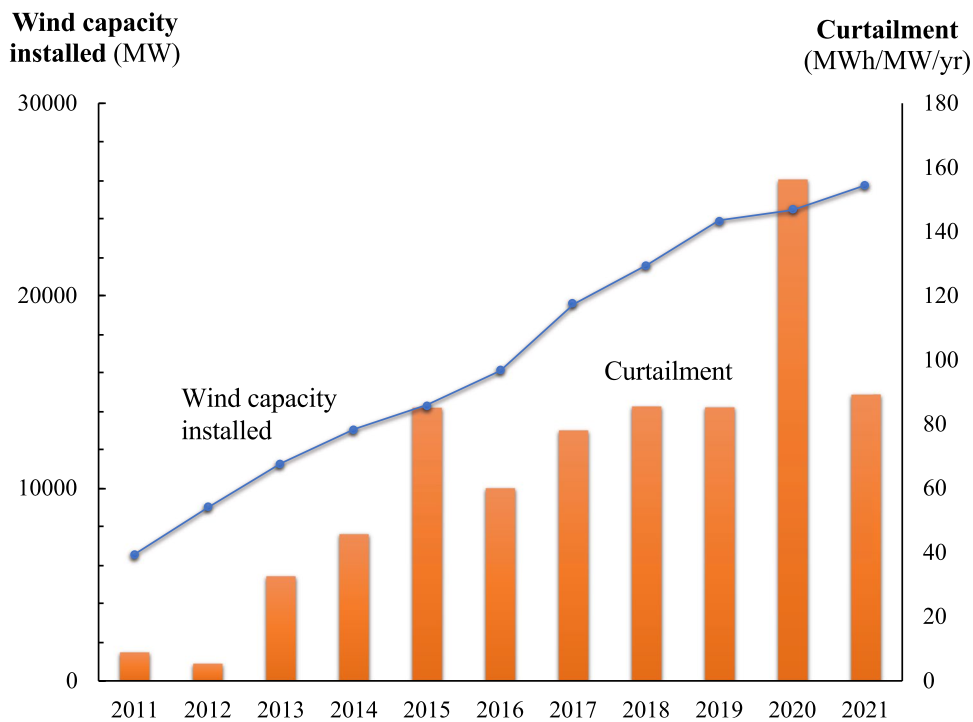

Fig. 2 Installed wind capacity, in megawatt (MW), and wind energy curtailment, in megawatt-hour (MWh)/MW installed capacity, for the United Kingdom from 2011 to 2021

requiring 1028 kWh/m^2/yr, cooling would require 206 kWh/m^2/yr and the other electrical components 51k Wh/m^2/yr, so in total 1.285 MWh/m^2/yr is required to run a vertical farm. The quantity of curtailed United Kingdom wind energy in 2021, 2,299,296 Megawatt hours, could have powered the equivalent of 1.79 million m^2 of vertical farm. If a similar level of curtailment was occurring globally, then the 2021 installed capacity of 113 Gigawatts would indicate a curtailment of 10.1 million Megawatt hours sufficient to power 7.85 million m^2 of vertical farm.

As vertical farms use artificial lighting, curtailed energy generated during periods of low demand could be used to grow food and replace imports of exotic or out-of-season produce as they do not have seasonal variations in output. This would decrease food miles and provide a revenue stream for the currently wasted curtailed electricity (Avgoustaki et al. 2021), potentially providing a market for green oxygen to increase yields and hence annual profits. In 2021, 58% of food consumed in the United Kingdom was of domestic origin; however, the value of food imports at £45,852 million was 56% higher than exports at £20,240 million (DEFRA 2022). Assuming that vertical farms were collocated with the new hydrogen and industrial hubs being developed on the east coast of England, waste carbon dioxide from flue gas emissions or blue hydrogen production would be readily available, which could be used to potentially increase yields by 100% and additionally sequester carbon. Using green oxygen could potentially improve yields by a further 100%. Assuming that curtailed electricity generated from offshore wind was supplied to vertical farms at its 2024/2025 clearing price of £41.61/MWh (UKGOV 2019), it could be determined if vertical farming was an economically cost-effective for the United Kingdom under these conditions and thus indicate if it is a cost-effective solution to curtailment.

A profitable basil vertical farm

To investigate this, the capital expenditure (CAPEX), operational expenditure (OPEX), with the growing conditions for basil and vertical farm building details provided from the previous studies by Kozai and Niu, (2016a) and Avgoustaki and Xydis (2020a) were used, all costs were adjusted to 2023 values and then converted to pounds. The building used to contain the vertical farm was assumed to be similar to that shown in Fig. 1, as described by Kozai and Niu (2016b), with the area available for growing as 900 m^2, including 3 racks with 15 tiers. For growing basil in a vertical farm, the research by Avgoustaki and Xydis (2020a) stated that 10 harvests per year were achievable, resulting in an annual yield of 50 kg/m^2/year. The influence of adding carbon dioxide to the grow chamber was assumed to increase yields to 100 kg/m^2/yr if combined with using green oxygen to 200 kg/m^2/yr. The cost of basil was assumed as £6.36 (TRIDGE 2022).

Annually the cash flow for this theoretical vertical farm was calculated as £286,200; if carbon dioxide augmentation improved yields by 100%, this would rise to £572,400 with a 50% increase over the standard configuration and by using green oxygen it would be £1,144,800, which is 75% greater than the standard configuration. These figures were used for an initial estimate of the impact that vertical farming could have on the United Kingdom. The adjusted CAPEX and OPEX expenditure values collected from the two studies are shown below. The payback period in years for each scenario is shown in Fig. 3; this calculation assumed that half of the CAPEX was borrowed and repaid at a discount rate of 10% over ten years, that electricity costs were £41.61/MWh and that the plant lifespan was 20. The information in Fig. 3 shows that vertical farms could be an economically cost-effective investment as well as provide a solution to currently wasted curtailed wind energy. A standard configuration is repaid in 6.1 years, and this reduces to 2.9 and 1.8 years if carbon dioxide and combined carbon dioxide and oxygen can be successfully integrated, respectively.

The synergies between vertical farming, biogenic carbon sequestration, curtailed renewable energy generation and using currently wasted green oxygen from the emerging green hydrogen sector are shown by Fig. 4. Vertical farming can be used by any country to transform curtailed renewable energy into a revenue stream, make use of green oxygen and

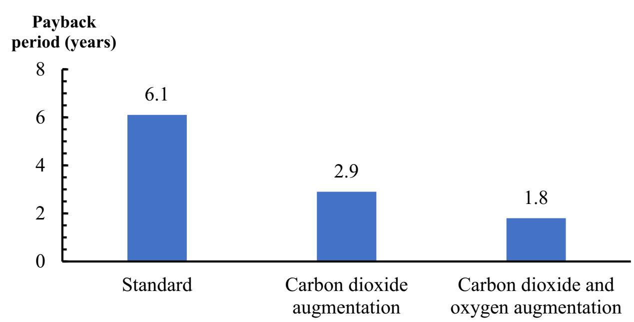

Fig. 3 The payback period for a standard vertical farm, carbon dioxide-augmented vertical farm and combination of carbon dioxide, and oxygen-augmented vertical farm, at a discount rate of 10%, a growing area of 900 m^2, 50% of the CAPEX is borrowed, and the loan is repaid over 10 years. The CAPEX and OPEX for a vertical farm with a growing area of 900 m^2; the values shown were derived from research by (Avgoustaki and Xydis 2020a) and Kozai and Niu, (2016b) and used to determine the economic cost-effectiveness of vertical farms making use of currently curtailed energy assuming that electricity was supplied at the cost of £41.61/MWh. MWh refers to megawatt-hour. In vertical farming, the CAPEX required for setting up the facility amounts to £588,140. Regarding OPEX, the breakdown is as follows: £48,122 is allocated for electricity, £1,466 for real estate lease, £182 for water, £119 for nutrients, £1,454 for seeds, £531 for packaging and £110,025 for labour. This leads to a total operational expense of £113,777

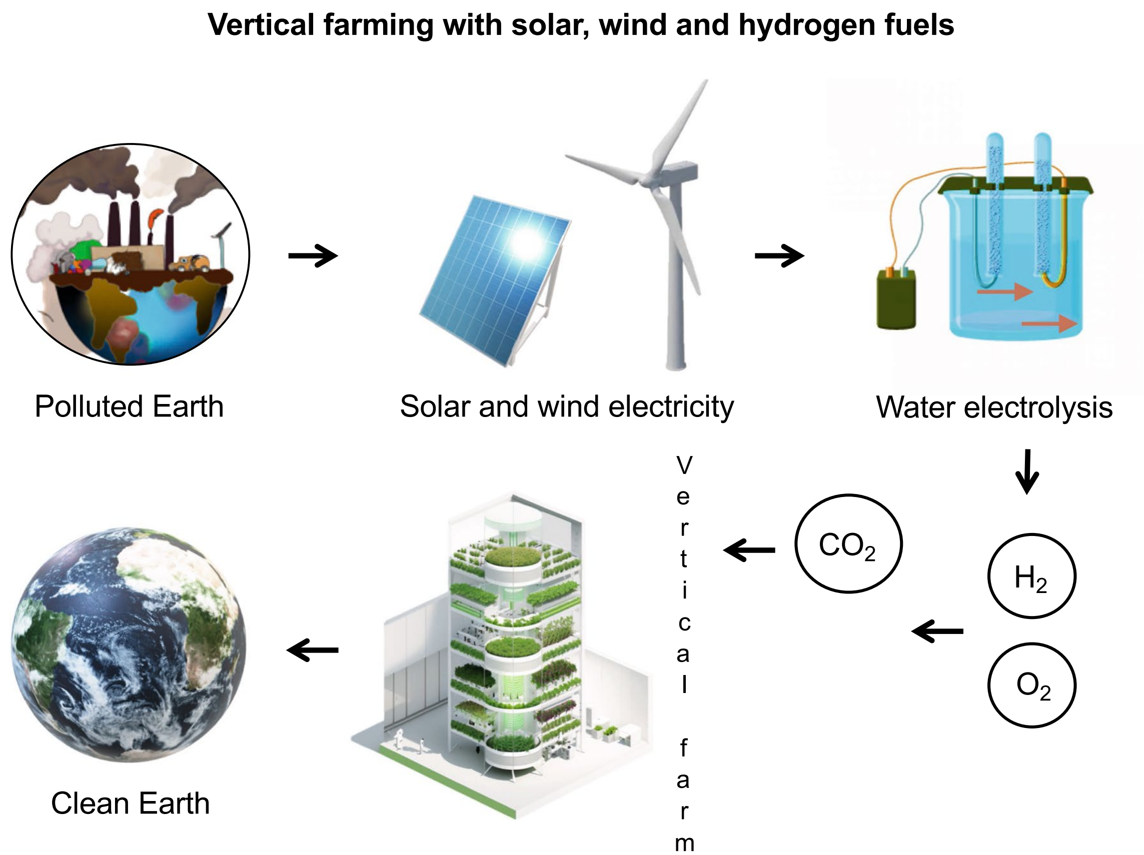

Fig. 4 Actual industrial agriculture could be transformed using a combination of currently curtailed renewable energy, green oxygen and vertical farming to reduce the global impacts of agriculture and improve the capacity factor of renewable energy generation. CO_2, H_2 and O_2 refer to carbon dioxide, hydrogen and oxygen, respectively

develop an indigenous food supply. Adding additional carbon dioxide and green oxygen can reduce payback periods to under 2 years. Vertical farms are secure from the extreme climatic events expected from climate change. Compared to conventional open-field agriculture, vertical farms clearly have many advantages; new crop varieties are being developed, with vertical farms now producing pharmaceutical products from plants, orchids, roses, paprika, maize, strawberries and tomatoes (Bosman van Zaal 2023).

In conclusion, vertical farming has the potential to provide a sustainable solution to reducing curtailed renewable energy, reducing the environmental impact of food production and converting currently wasted curtailed energy and green oxygen into a revenue stream. Governments, businesses and investors should support research and development in vertical farming, creating a sustainable and resilient food system for future generations. The policy should be developed to encourage developers of wind farms to supply curtailed energy at its clearing price to vertical farms to encourage their further deployment. Globally in 2021, curtailed wind energy was sufficient to power 7.85 million m^2 of the vertical farm described by this research.

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