Regional conditions shape the food-energy-land nexus of low-carbon indoor farming

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Editor's summary

Greenhouses and vertical farming enable food production in cities, but their energy and energy-related land demands may affect their overall sustainability in specific regions. Through geospatial and mathematical modelling, this study compares open-field and two indoor farming methods for vegetable production in nine city-regions around the world.

Abstract

Modern greenhouses and vertical farming projects promise increased food output per unit area relative to open-field farming. However, their high energy consumption calls for a low-carbon power supply such as solar photovoltaic and wind, which adds to cost and overall land footprint. Here, we use geospatial and mathematical modelling to compare open-field and two indoor farming methods for vegetable production in nine city-regions chosen globally with varying land availability, climatic conditions, and population density. We find that renewable electricity supply is more costly for greenhouses per unit energy demand satisfied, which is due to the greater fluctuation in their energy demand profile. However, greenhouses have a lower energy demand per unit food output, which makes them the least land-intensive option in most of the analysed regions. Our results challenge the land-savings claims of vertical farming compared with open-field production. We also show that regionalising vegetable supply is feasible in most regions and give recommendations based on the regional context.

Main

Food security in highly globalised supply chains was under pressure in the recent pandemic[1], and further shocks due to extreme climate events are expected in the future [2,3]. Calls for increased supply chain resilience[4] and higher demand for regional and fresh produce[5] lead to a trend of increasing the regionalisation of food production[6,7]. The fastest growing sector in industrialised countries addressing this development is controlled-environment agriculture (CEA), in particular greenhouses with supplemental lighting and vertical indoor farming (VF) for vegetable production [8,9]. Such high-tech growing methods promise improvements on a host of sustainability metrics[10] but perform poorly on energy intensity[11–13]. The prospect is that renewable energy will mitigate potentially high carbon emissions associated with energy supply[10,13,14]. However, this potentially contradicts claims by the sector related to land savings[8,15] since most new renewable energy projects are based on solar photovoltaic (PV) or onshore wind energy[16], both of which require large amounts of land[17]. A limiting factor in a low-carbon economy will be land[18], with competing uses between biodiversity/conservation[19], carbon sequestration[20], biofuels[21,22], food[23] and energy[24,25]. These trade-offs will have to be evaluated on a sub-national level to distribute benefits and impacts[26] and reduce import dependencies of food and energy[27,28]. Thus, the direct and indirect land use implications of food production will be of major importance. The resource inter-dependencies and competitions between energy and food supply have received considerable attention in recent years, generally within the framework of "nexus"[29]. However, there is currently a lack of rigorous quantification of the implication of emerging food production methods to energy supply and land use at the regional level, which hampers our understanding of the potential of regional CEA upscaling. Generally, for the regionalisation of food production, localising the supply of fresh produce seems to be more desirable[30,31] and feasible[32] compared with non-perishable staples or animal products[33], with recommendations to convert farmland to fruit and vegetable production[30,33] from its current use. CEA facilities often grow fresh produce for local demand[9], while advances in electrified transport create opportunities for low-carbon peri-urban field production[34].

This work investigates the sub-national food-energy-land nexus implications of localised vegetable supply in nine city-regions, selected for their existing interest in VF and their differing climatic and geographical conditions. The satisfaction of daily nutrient requirements via a selection of typically consumed vegetables is chosen for comparison of different production options. Best practices of three growing strategies are compared (Figure 1): plant factories (PF), ventilated greenhouses (GH) with supplemental lighting and advanced climate control[9] optimised for the lowest specific energy consumption (kWh kg^{-1})[35], and low-input open-field production constrained only by the local climate and soil conditions (but not by poor practice). The open-field option has considered the requirement for food preservation (and the associated losses of micronutrients[36,37]), since in most latitudes it is not possible to produce vegetables year-round. We optimised the climate control systems of the two CEA systems to determine energy consumption patterns, and then modelled renewable energy supply systems to cover this need. The energy was assumed to be supplied regionally (rather than spatially separated from food production) to reflect the growing interests in distributed energy systems and regional or local energy independence[38]. Applying this assumption to all studied locations also allows to highlight potential tensions in the regional food-energy-land nexus and avoid complications of land-use burden shifting from one region to another. In our model, each system has a minimum interaction with the larger grid[14,39] and minimises its cost by the best combination of wind and solar PV[40,41] and the balance between overcapacity and energy storage[42,43] to tackle intermittency[42,44].

Add Figure 1 here (see caption at the end of this doc)The aim of this work is thus to assess a) the regional characteristics of the renewable energy system required for CEA facilities, b) the combined land use of growing and energy provision, and c) the relative land use against the regional land availability for agriculture and renewable energy generation (Figure 1).

Results

Renewable energy systems for CEA facilities

The nine regions assessed in this work feature diverse climate conditions, population sizes and availability of renewable energy sources (Figure 2 and Supplementary Table 3), which determine the energy demand and supply for CEA facilities. The energy intensity, shown in Figure 3a, was determined in our previous work[45] via detailed modelling of climate control systems, inside and outside conditions, and plant response, while optimising the hourly climate control strategy for the lowest specific energy consumption (energy input per kg crops output). GHs would require more energy in very cold (with less sunshine and more light supplementation) and very hot months (increased cooling), and annual energy intensity was particularly low for regions with comparatively sunny winters and cloudy or not too hot summers, such as Tokyo and Johannesburg. PFs tend to have a steadier load profile with some outliers when very hot weather makes air-to-air cooling not possible. Further details can be found in SI 1.5 and Supplementary Figure 5. A fully CEA-based regional vegetable supply (with 50% of recommended nutrients derived exclusively from either PFs or GHs) was hypothesised in this work. The projected annual electricity consumption of producing vegetables via GHs and PFs is compared with the current regional electricity consumption in Figure 3b for illustrative purposes. A high percentage indicates that large scale amendments to the current power sector would be required. If the electricity is to be drawn from a grid with limited penetration of low-carbon power generation, this may lead to unacceptable carbon footprints for produce (Supplementary Table 11), calling for renewable energy supply. Regional self-sufficiency in renewable electricity generation for CEA facilities, a proposition of this work, implied minimal interactions with the national grid and thus a need for energy storage. Increasing the installed capacity and factoring in curtailment of overgeneration reduces energy storage needs (at the cost of increased land use). Thus, an economic optimum based on load and renewable resource profiles was found for each region via optimisation in Homer Pro, which determined a) the ratio between wind and solar PV capacity (Supplementary Tables 4 and 5) and b) the balance between energy storage and overgeneration.

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The production split between wind and solar PV and the overgeneration factor are shown in Figure 3d. The steadier load of PFs, contrasting with the seasonally and hourly fluctuating loads of GHs, necessitated less overgeneration. Some regional peculiarities were observed for GHs: (1) sub-optimal wind conditions and strongly varying seasonal demand led to the highest overgeneration ratio in Stockholm; (2) in Santiago, supplemental lighting in the morning and evening hours of winter (Supplementary Figure 5) and the otherwise very low energy demand led to the 2nd highest ratio; (3) hot summers led to considerable cooling requirements in Phoenix; and (4) the more seasonally uniform temperature profiles (and hence uniform cooling needs) of Singapore and UAE led to lower overgeneration factors. For PFs, a higher share of solar PV in the energy mix reduced the required overgeneration due to the temporal match with daytime indoor lighting. However, locations heavily relying on solar PV (Singapore and Tokyo) needed increased overgeneration due to the lack of wind turbine use to mitigate the seasonal nature of solar PV. Numerical results for costs, capacity, share of solar PV and other metrics are listed in Supplementary Tables 4 and 5. Indicative projections about the carbon intensity of CEA using renewable energy are listed in Supplementary Table 11.

Potentially, the excess electricity can be used for other applications within the region if it matches temporal demand, thus reducing the levelised cost of energy (LCOE) through sell-back (Supplementary Figures 7 and 8) and the land theoretically allocated to energy generation for CEA production. The LCOE, together with the regional energy intensity (Figure 3a) determines the specific cost of energy for produce (Figure 3c). The latter cost was consistently lower for GHs with the lowest specific cost in less extreme climates. CEA production in PFs is more costly, particularly when only (Singapore) or predominantly (Tokyo) one form of renewable energy is used. A discussion of findings regarding the LCOE and storage needs can be found in SI 2.2. Alternative scenarios and input sensitivities are shown in the SI, including those for night time operations, offshore wind and discount rate (Supplementary Table 6), unconstrained grid interactions and renewable energy provision (Supplementary Tables 7 and 8).

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Land requirements for growing and renewable energy supply

For open-field farming, only direct land requirements for growing were considered. The annual area-based productivity, i.e. yield, of open field farming was simulated on a regional basis, employing monthly temperature, rainfall and soil characteristics. Combined with preservation requirements due to seasonal production, the yield determines the land requirements to supply year-round vegetables to the local population (Figure 4). Excessive rainfall (Singapore) and low rainfall in summer (Santiago, Phoenix, UAE), potentially prohibitive for growing (Supplementary Figure 3), was assumed to be mitigated by good practice (e.g. drainage, drip irrigation) which allowed this analysis to assume feasible open-field production in those otherwise challenging climates (a comparison with FAO yield values is shown in Supplementary Figure 4). A steady harvest quantity throughout the growing season was assumed due to different seasonal preferences of selected crops and incorporation of growing practices such as plastic soil cover colour to help regulate fruiting. The growing season was limited by temperatures below freezing and above 40°C; Reykjavik, Stockholm and Boston had the shortest season (6 months), followed by UAE (7 months), Phoenix (9 months) and Tokyo (11 months), with Santiago, Johannesburg and Singapore having year-round open-field production (Supplementary Table 3). Preservation of nutrient losses required overproduction (up to 49% for the coldest regions) to continuously satisfy daily nutrient needs (Supplementary Table 3). Low yields and oversupply requirements in Reykjavik meant a high per capita land use for open-field farming (Figure 4). Warm and wet climates had the lowest land requirements, with more than a magnitude difference between the Reykjavik region and Singapore.

Add Figure 4 here (see caption at the end of this doc)

The indirect land requirement per person for CEA production is the land required to generate renewable electricity, which depends a) on the regionally required nominal or peak capacity (W_p), determined in Homer Pro and influenced by local capacity factors of wind turbines and solar PV panels and b) their land-use efficiency. Figure 4 visualises land requirements for a land-use efficiency of 76.6 W_p m^{-2} for solar PV and 6 MW_p km^{-2} for wind turbines. Direct land use for growing in PFs is relatively small due to the high ratio of growing area to building footprint assumed (7.2:1). GH production tends to have significantly lower energy intensity than PF and thus requires less land for energy production, despite higher overgeneration requirements. The combined land use of GHs is higher than that of PFs only in Reykjavik and Stockholm, since in these locations the difference between the two growing systems in the specific energy (Figure 3A) is less than that in overgeneration required (Figure 3D). Regions where wind energy is more economical than solar PV, such as Reykjavik and Stockholm, also have a higher combined land use than those where solar PV is more economical. Johannesburg, Santiago, Phoenix and UAE have significant land savings due to a high co-location potential of solar PV and wind farms. The co-location savings are generally higher for PFs as they have a higher share of solar PV, which was the limiting factor for co-location. Figure 4 implies that GH production is the most land efficient in most cases, although PFs may perform better in very cold climates. Santiago is the only region where open-field farming requires a lower land area than GH production with renewable energy provision (not considering co-location savings). This is mainly due to very favourable (open-field) growing conditions and seasonally and hourly fluctuating GH loads which necessitate overgeneration. In Singapore and Tokyo, the combined land use of PFs is relatively low (in comparison with other locations) due to the high land-use efficiency of solar PV. Land used for wind only (not co-located facilities) might also be available for other uses. The factors influencing the differing combined land uses for PFs are highlighted in SI 2.3 and Supplementary Figure 10. Sensitivities for the combined land use, i.e. no constraints on land availability (Supplementary Figure 9), yield increase (Supplementary Figure 11), regional use of excess energy (Supplementary Figure 12) and solar land use efficiency (Supplementary Figure 13) are discussed in SI 2.3. Numerical land use results are listed in Supplementary Table 9.

Regional land-use implications

The combined land requirements need to be put in context with the locally existing land for agriculture and potential energy generation (Figure 2). The land considered for energy generation was separate from farmland, resulting in two land occupation metrics. Figure 5 visualises these metrics and puts the combined land use in a regional context for fully scaled-up CEA. The hypothetical farmland sparing describes the extent to which farmland can be spared by implementing local vegetable production with CEA. It is calculated as the ratio between a) the land savings by using CEA instead of open-field farming for supplying 50% of recommended nutrients to the regional population (i.e. the difference between the land required by open-field farming and the land occupied by CEA facilities for the targeted supply) and b) the currently existing farmland. As such, this ratio can exceed 100% mathematically in certain regions which is not physically achievable (hence the term "hypothetical") and therefore should be treated as an indicative measure. The calculated farmland sparing is high in regions with little existing farmland compared to the population, such as UAE, Boston, and Tokyo. Contrastingly, not much farmland would be spared by switching to CEA in the regions in cluster II (Figure 5a). In regions with abundant land for renewable energy generation, the required solar and wind farms for CEA would leave sufficient land for other uses (Reykjavik, UAE, Phoenix, Santiago, Johannesburg). The regions in cluster I (Figure 5a) had rather limited land available for renewable energy generation and shifting to CEA would require dedicating a substantial share of the available land to this end-use of energy. Insufficient land for energy generation was available to entirely switch to CEA in Singapore and for PFs in Tokyo (Figure 5b). In addition, the land use of PFs alone (without energy generation) already exceeded the available farm land in Singapore (see Supplementary Table 10), necessitating the use of other spaces (e.g. conversion of existing buildings) or more growing layers within a facility. An additional interpretation of the hypothetical farmland sparing can be derived in the case of PFs: Their low direct land requirement means the quantity of land savings achieved by using PFs is approximately the hypothetical amount of farmland required for the targeted supply. Hence, regions in cluster II could fully localise open-field vegetable production using only ~10% of the current farmland in these regions, which suggests a less critical role of CEAs in land saving for vegetable supply compared to other regions.

Add Figure 5 here (see caption at the end of this doc)

The relative importance of farmland sparing to the occupation of land suitable for energy generation is a regional, political choice; the more to the right and top a region sits in Figure 5, the more favourable CEA is, irrespective of the absolute combined land use (bubble size) of any of the three growing techniques. This differing implication between combined and relative land use was particularly striking for Stockholm, where the combined land use would indicate the favourability of CEA, however, the large amount of existing farmland compared with the small amount of land available for energy generation relativises these results. A significant difference between the two CEA practices was observed for Johannesburg as GHs can be run with moderate energy input there. The relative land use for PFs in Singapore and Tokyo, although neither location is feasible for a full scale-up, provides a contrasting message. For Singapore, the ratio between hypothetical farmland sparing and relative land requirements for energy generation (indicated by the inverse of the y coordinates) for PFs is close to 6 (GHs around 14), primarily due to significant potential for rooftop solar PV. This implies that about 6% (or 14%) ground-based farmland savings could be achieved (when switching from open-field to CEA) for every 1% of the available land for solar energy generation allocated to PFs or GHs. Therefore, localising some food production through CEA in Singapore could be sensible. In Tokyo, this ratio is less than 1 for PFs, which makes replacing open-field farming with PFs less justifiable from the land-use perspective, regardless of the level of uptake. Note that these ratios were calculated assuming all farming operations take place only on farmland; the results may change if other spaces (e.g. rooftops) are considered. Numerical results are presented in Supplementary Table 10 and region-specific recommendations are provided in Supplementary Table 12.

The above results have considered the aggregated land use by solar PV and wind energy; their separate contributions to land use (Supplementary Figures 14 and 15) show that the economic optimum of combined wind-solar generation, as adopted in this work, has led to a higher usage of the land available for wind turbines than that for solar panels, except where feasibility constraints on wind exist (Singapore, Tokyo). An alternative scenario could be when farmland is also used for energy production via solar PV panels installed above crops[46] with a low filling ratio (limiting shade throw) and wind turbines placed along the field lines. This practice would allow Tokyo to fully scale up CEA within the land constraints and significantly reduce land requirements for energy production in Boston and Stockholm (Supplementary Figure 16), where the ratio of available farmland to available land for energy generation is high.

Discussion

Notwithstanding the recognition of other advantages of indoor growing by PFs, such as micronutrient content adaptation and freshness[8], we challenged generalised claims about land savings of PFs. We also demonstrate that land for renewable energy production is limited in most regions studied in this work, which – given the host of other potentially more pressing energy end uses – could strongly limit the scale-up potential of PFs in a low-carbon world, particularly within the setting of regional food and energy independence. Furthermore, given the high resource footprint[47] and ecosystem fragmentation impact[17] of solar panels and wind turbines, CEA might be less favourable when open-field farming has a similar total land footprint (e.g. Santiago), even more so when open-field production is done in an ecosystem-friendly way, e.g. by adopting agroecological practices[48]. More broadly, additional considerations related to customer preferences, water availability[12], local customs or political possibilities need to be considered when opting for policy to support any of the growing methods. In terms of land use for energy generation, some countries already produce a major share of their electricity from other low-carbon sources (e.g. hydro and nuclear in Sweden, geothermal in Iceland) or offshore wind energy can be expanded. Thus, they are potentially able to cover the additional load requirements for their main city-regions without significant additional land occupation for energy generation.

We expect that the insights from this work apply to other regions with similar characteristics. Nevertheless, a few limitations present opportunities for further comparisons between CEA practices and open-field vegetable farming. The embedded resources and energy in infrastructure and the criticality of scarce raw materials might be prohibitive for the vast renewable energy systems required for CEA. Operational aspects such as labour intensity, labour availability, and automation potentials likely differ between practices and approaches and could be an important factor in regional decision making. The cost of land was excluded in this assessment and is likely relevant when it is scarce or expensive. For the respective growing practices, some adaptations at the local operational scale deserve further assessment: the feasibility and viability of adjusting LED timings in PFs to intermittent renewable energy resources, utilising waste or geothermal heat in GHs, and employing hoop-houses to save water, extend seasons and increase the yield of open-field vegetable farming. Symbiotic benefits with urban infrastructure can also be realised by utilising rejected heat from LEDs for space and water heating in buildings[49]. The interactions with and proximity to the consumer might have other downstream effects on sustainability[31], which vary between urban and rural hinterland production. Finally, cultural and socio-economic aspects also play a role in regionalising agriculture, on top of the food-energy-land nexus.

Conclusion

Plant factories have been touted by many as the future of agriculture. Current private sector developments in this area typically frame their value around low water and land use as well as market proximity and freshness. Energy is typically underappreciated in these discussions – yet it is clear that their energy use is extensive. This work investigates total land use of vegetable production and the required regional energy production through comparing several systems. We showed that the favourability of a specific production strategy (GH, PF, and open field) differs across regions; no single global recommendation can be given across these systems. Nevertheless, an observed tendency is that GH production with electrified and advanced climate control (as modelled in this work) requires the least amount of land and has lower energy expenses than PF production. We showed that the fluctuating nature of the energy load in GHs requires oversized renewable energy systems, which could benefit from complementary local demand for the excess energy. More generally, CEA seems particularly recommendable for extreme climates with abundant wind or solar energy resources (e.g. Reykjavik, UAE), and to some extent, for highly urbanised regions with little farmland compared to land available for energy generation (e.g. Singapore). To ease the tension in land use, these latter regions could opt for (low-carbon) electricity import to increase their food security, provided that financial, technical and political conditions are conducive.

Methods

Composition and characteristics of the vegetable basket

The six vegetables in the basket were chosen based on their relevance in global consumption patterns[50], the feasibility of growing them indoors (usually hydroponically) and micronutrient composition of fresh and processed forms. Tomato is by far the most produced crop according to the FAO but considering a share of production is for processed use[51], it received a share of 40% in the basket, the other five crops received an equal share of 12%. The satisfaction of 50% of the daily recommended nutrient intake (RNI) was used as a basis and results for the basket in around 376.8 grams of fresh vegetables per person per day (see Supplementary Table 1). This number is consistent with recommendations for a healthy and sustainable diet[52]. Nine relevant micronutrients for human consumption were considered for this work (Ca, Fe, Zn, ascorbic acid, thiamine, riboflavin, niacin, vitamin B-6, folate and vitamin A), and their content in fresh and preserved (frozen or canned) vegetables was obtained from nutrient tables [53] (see Supplementary Table 2).

Selection and characteristics of studied regions

Since this study examines how different geographical, climatic, and societal conditions influence growing practice's favourability over another, a selection of regions was chosen. These are in different continents and climate zones but also a) have an existing or upcoming vertical farming industry, b) have a capital city or otherwise prominent city in their centre, and c) country-level data is available on the FAOSTAT portal[50]. The regional selection was also in line with our previous work, to enable the use of electricity load profiles of CEA farming facilities. The following heuristics determined the extent of a region considered for this analysis. If the prominent city or region of interest was in a sufficiently small country, the whole country was chosen (Singapore, UAE). If the city or region had an established boundary definition for research, business or statistical purposes that included the whole extent of the urban conglomeration (incl. satellite towns) and sufficient rural hinterland, the established boundary was chosen (Greater Tokyo Area[54], Combined Statistical Area of Boston[55], Stockholm-Mälaren region[56]). If there was no established boundary that would satisfy the conditions, all lowest-level administrative areas[57] (usually municipalities) with their centre within 125 km of the centre of the central city were selected using ArcGIS Pro (Reykjavik, Phoenix, Santiago, Johannesburg). The following steps were carried out in ArcGIS Pro for all regions. The regional population[58] was determined through Zonal Statistics. The total regional area was obtained by calculating the geometry attributes. Monthly precipitation, average minimum, and average maximum temperature were obtained from WorldClim[59] and extracted for the regions through Feature To Point and Extract Multivalues to Point. The data set for the land cover types was primarily the Copernicus Global Land Cover[60] (100m resolution), with more detailed information on agricultural land from the Corine Land Cover dataset[61] for Europe and from the USGS[62] for the United States.

Land availability for food production

The existing farmland was used as a basis for assessing the farmland sparing potential of switching from open-field farming to CEA farming practices. Although only a fraction of farmland is typically used for vegetable production[30], this study conceptualises regional self-sufficiency with a dietary preference for vegetables. Thus, all land currently used for agricultural purposes is considered in this work; code 40 in the Copernicus dataset, code 555-557 in the USGS dataset and code 211-224 in the Corine dataset. The geoprocessing sequence was Extract by Mask, Reclassify and Zonal statistics (sum). Due to differences between planar and geodesic measurements, each region’s total number of raster pixels was extracted for each land cover type raster. The number of pixels obtained by assessing the respective land cover type was then divided by the total number of pixels and multiplied by the region's geodesic area, allowing accurate determination of the available area for agricultural and renewable energy generation purposes. For Singapore, a fixed value of 200 ha was chosen according to the Singapore Food Agency[63]. To determine the regional annual yield per unit area as described in a subsequent paragraph, the average regional values for Soil Productivity Index[64] (reclassified to exclude water areas), Moisture Index[65] and Growing Degree Days (derived from WorldClim[59] monthly data according to Ramankutty[66]) raster were obtained by multiplying their source raster with the reclassified agricultural land raster (indicating the location of farmland) and using Zonal statistics (mean). This way, only the on-the-ground conditions at the farmland locations determined those regional values. The direct land use of GHs and PFs was allocated to the farmland and counted as farmland occupancy of CEA. Although greenhouses can also be built on bare land and flat rooftops[67], it was assumed here that primarily it is the experienced farmers who would build them and they would do so on their land. PFs were assumed as single-purpose buildings with a growing area to building footprint ratio of 7.2 (12 growing layers, 60% of floor space for growing). PFs can also be operated underground or in old buildings but such opportunities may play a rather limited role in a fully up-scaled CEA system and therefore were not considered in this study.

Land availability for energy generation

A brief discussion about the selection of land cover types and their availability is described in SI 1.2. This work's philosophy is to be more on the technically feasible side; we treated land in this way to avoid political differences in land use regulations across regions and time. Straightforward land availability values were chosen for the main scenario reported in the figures, with land cover types shrubland, herbaceous vegetation and sparse vegetation allowing 50% of the land area for onshore wind and solar PV. Also, 5% of the urban land area was considered available for solar PV and 50% of the open forest area for wind turbines (with tree cover between 15-70%). The latter reflects the emerging practice to place newer wind turbines in or close to open forests with minimal destruction, since the actual footprint of turbines and access roads is only between 3-6%[68–70] of the considered land and the increased hub height has low detrimental effects on the ecosystem[71]. Land cover types completely excluded were closed forests, wetlands, snow and ice, cultivated land, and water. The existing farmland was also excluded in this work. Although it is likely desirable to develop renewable energy alongside agriculture [46,72], it is currently not common practice and might interfere with mechanised field operations such as ploughing or harvesting. Additionally, any energy generated on open-field farms could either be used for transporting, processing and storing the open-field produce[73]; excluding the potential use of farmland for energy generation thus prevents any double-counting.

Additional constraints for installing solar PV were a maximum slope of 5 degrees (assuming a 2.5 percent slope[74] for all directions and a third of slopes facing SW, S or SE with up to 20 percent[75,76]) and for wind a maximum slope of 15 degrees (26.8%)[75,77]. Both were constrained by a relative altitude of 1000 m above the city level[74] (due to considerations of difficulties in access and maintenance). Finally, the following were used as constraints for wind turbine siting: 500 m buffer zones around urban areas; land cover by water, snow, and ice[78]; and insufficient wind speeds for a wind turbine's economic operation[76] (wind speeds at 50 meters below 5 m s^{-1}). The described heuristics result in some land being potentially available for both technologies. In this case, it was assumed that co-located hybrid plants would be possible and economically preferred[28,76,79], since they save land and the effects due to shade and access restrictions are limited and less than the benefits derived from co-location[80]. For those locations, a conservative turbine footprint of 5% (in which no solar PV panels can be placed) was used to describe the dual-use of land[17]. An alternative scenario assumed 100% availability of the non-forest land cover types mentioned for solar PV and wind, 10% for solar PV in urban areas and 100% of the open forest areas. These percentage figures mean that the region-specific results reported in this work can be linearly and proportionally adapted to differing land availability assumptions.

Productivity and land use requirement of open-field farming

Reported yield figures by the FAO[50] were insufficient for this work as they are influenced by high-yield greenhouse-based production and are only available at the country (as opposed to regional/local) level. Another issue is the varying level of current agricultural development and intensity between countries; this work intends to compare best practices based on geophysical constraints, rather than social, economic, or political constraints. A hypothetical yield model was thus established to estimate the impact of monthly deviation from the optimum conditions leading to maximum vegetable yields. Three local peculiarities were used in this hypothetical yield model: monthly temperature, monthly precipitation and soil characteristics. A discussion about the influence of temperature and precipitation can be found in SI 1.3. For daytime temperature, the PGDD (photo growing degree days) method described by Aslam[81] was used as a basis, incorporating a modest influence from the length of the photoperiod and a minimum (5 °C), optimum (27.7°C) and maximum (40 °C) growing temperature for the vegetable basket[82]. The yield response to temperature for a given month was then the curve's daytime temperature deviation from the optimum in per cent. The region's photoperiod was correlated to its latitude via polynomials as described in our previous work[45]. The effect of night-time temperature is a linear curve[83] with optimum growth above 19.7 °C and halting of growth at 0° C. Daytime and night-time correlations are shown in Supplementary Figure 1. The effect of solar radiation on plant growth (relating daily global horizontal irradiation values to photosynthesis) was excluded; we found that adding its effects to that of the temperature-yield response led to a minimum difference and was thus considered negligible.

Besides temperature, the amount of seasonal precipitation affects yields[84,85], but irrigation and drainage reduce negative influences of low or excessive precipitation[86] and stretches optimality conditions. A fair comparison with high-tech indoor growing techniques assumes such practices. This work combines the principles discussed in SI 1.3 to a yield response curve relating potentially sub-optimal monthly precipitation conditions to their yield impact (Supplementary Figure 2). A sensitivity analysis for the precipitation response was carried out and results are shown in Supplementary Figure 3.

The last influential variable was the soil characteristics; previous studies considered soil carbon density and soil pH[66] or soil depth and nitrogen content[87]. A fair comparison with indoor farming assumes optimum plant care to supply nutrients (fertilisation) and compost application for soil depth. The productivity of the soil (describing carbon content and pH) was accounted for with a soil productivity index[64] (SPI). It can take seven different values (0-6), ranging from prime to bare land[22] and is linearly correlated to yield[88] according to the equation below with a minimum value of 0.5.

$$Yield\ soil\ factor\ = \begin{cases} \frac{SPI-1}{10} + 0.5 & if\ SPI > 1 \\ 0.5 & if\ SPI \leq 1 \end{cases}$$

The monthly temperature and precipitation response factors were multiplied and finally correlated to the maximum achievable yield to determine the local yield (in kg m^{-2} $year^{-1}$) as shown below.

$$Monthly\ yield\ response = yield\ response\ to\ temperature * yield\ response\ to\ precipitation$$

$$Local\ annual\ yield\ factor = \frac{\sum_{1}^{12} Monthly\ yield\ response}{12} * yield\ soil\ factor$$

$$Local\ annual\ yield = \frac{Local\ annual\ yield\ factor}{SF} * maximum\ reported\ yield$$

The maximum yield was determined using the highest reported figures[50,89] (discounting for high-yield greenhouse production) listed in Supplementary Table 1, its average for the basket is 8.3 kg m^{-2} $year^{-1}$. A scaling factor (SF) was introduced to account for the fact that year-round perfect conditions do not exist, even for the locations which reported highest yields for a specific vegetable. Its value (0.74) was the maximum local annual yield factor determined for 25 locations in different climate zones and continents. The results of the hypothetical yield model are compared in Supplementary Figure 4 with a) the reported yield values from the FAO[50] for the selected vegetables, and b) with conventional GDD and moisture index as used by Ramankutty[66] with the values of curve parameters determined by linear regression using the FAO yield data for the 16 smaller countries mentioned above. The effects of extreme anomalies (with yield losses of up to 20%[90]) and the potential change to growing conditions due to climate change were out of the scope of this study. Nevertheless, a yearly average of 5% yield loss due to extreme anomalies was accounted for and is also visualised in Supplementary Figure 4.

Since this study takes the satisfaction of daily nutrient requirements as basis, the reduced nutrient content of preserved food needs to be accounted for by producing more fresh crops during the growing season. Besides the initial nutrient loss from preservation (e.g. blanching or shock freezing, around 24% as an average for the vegetable basket), the subsequent storage loss in freezers or cans was determined as 0.1% per day as an average of reported figures from Drew and Khee[36] and Rickmann et al.[91]. The total nutrient storage loss, and thus the need to overproduce, was dependent on the length of the growing period (LGP). The LGP (days per year) was determined in monthly intervals; the average minimum temperature had to be above 0 C° and the average maximum temperature below 40 °C[82]. The months in between were assumed to be productive with a harvestable fraction of the vegetable basket (due to different harvesting periods for the chosen crops), except the first month. An overproduction factor (OP) was defined for these considerations and is further described in SI 1.4.

Besides yield and overproduction, the land use is affected by an additional footprint of paths and other infrastructure, resulting in a land coverage of growing beds of 82%, equal to greenhouses[92]. This was combined with the yield, the overproduction factor and the daily requirements described earlier to obtain the open-field farming land use per person (in m^2 $person^{-1}$) as shown below.

$$Land\ use\ per\ person = \frac{1}{local\ annual\ yield\ * \frac{1}{OP} * 82\%} * 0.3768 \frac{kg}{day} * 365\ days$$

Electricity demand for CEA facilities

The hourly electricity demands (i.e. load) to produce vegetables in the CEA facilities are needed to reliably estimate the extent and cost of the renewable energy infrastructure required. This demand was modelled by combining established principles and sub-models employed in the literature of plant factory and greenhouse modelling, while incorporating several newly developed methods for climate regulation and yield-energy optimisation (detailed in Weidner et al.[45]). The optimisation determined the minimum electricity input per kilogram of produce for plant factories and open (ventilated) greenhouses with electrified humidity and temperature regulation, including particularly heat pump based heating which would be preferable compared to conventional natural gas based heating in a future world of low-carbon electricity. The modelling method consists of an hourly optimisation algorithm regulating the climate control system, taking into account material and heat exchange with the environment, hourly external climate conditions, the efficiency of various technical components, and climate-dependent plant growth and evapotranspiration characteristics. The calculated hourly loads and yields were calculated for a typical facility size. To estimate the regional energy requirements, those values were extrapolated based on the annual facility yields, the number of inhabitants of each region, and the required vegetable production to satisfy 50% of daily RNI.

Land use for renewable electricity supply

The land required for renewable energy facilities depends on the required installed capacity of solar PV and onshore wind and their respective land-use efficiencies (i.e. square metres per Watt capacity). The required capacity depends, apart from the load profile, on the local capacity or loading factor, the amount of energy storage available (in equivalent storage days) and the interactions with the existing electricity grid. A brief discussion about the assumptions and trade-offs is provided in SI 1.6.

The CEA facilities act as quasi-independent prosumers. Therefore, the maximum interactions with the regional grid are set to 10% of the annual load (assuming access to dispatchable low-carbon energy), while the economic trade-off between storage and overcapacity is evaluated with the Homer Pro[93] software, using near-term projected equipment costs. Homer Pro is a grid simulation software for renewable energy applications initially developed by the National Renewable Energy Laboratory in the US and is used to evaluate the set-up and cost of microgrids[40,41,94]. Homer Pro determined the local capacity factor of wind turbines and solar panels based on the monthly sunshine and wind speed profiles, adjusted by a scaling factor. Considering plant factories, the annual dispatchable energy restriction resulted in storage days and overcapacity similar to the results from the studies mentioned in SI 1.6. The standard grid purchase price is set at 0.10 USD kWh^{-1}, inflation and discount rate are set at 2% and 6%, respectively, and sell-back to the grid was not permitted to avoid sizing a facility more towards a renewable energy investment project instead of one for powering CAE. The potential revenue from grid sales as an alternative scenario was calculated for visualisation. The wind speed values were scaled according to the regional average for suitable locations described in the land availability section. If an initial analysis of combined land use resulted in exceeding land available for wind while occupying only a small share of the land available for solar PV, another optimisation was carried out in which a maximum wind capacity was set (Boston and Tokyo). Wind energy was fully disregarded in the optimisation if there was no suitable land for wind turbines (Singapore). Other project settings and equipment efficiencies are described in SI 1.7. A sensitivity analysis encompassing alternative grid interactions, zero-cost storage, night-time operations, and a single energy source (offshore wind and solar PV) was also carried out to assess their impact on the required power generation capacity.

The second factor determining the required land is the ratio of nominal or peak capacity to land (or land-use efficiency). A brief discussion is provided in the SI 1.6; this study assumes 6 MW_p km^{-2} for onshore wind energy and 76.6 MW_p km^{-2} for solar PV. As described above for co-located plants, 5% is added on top of the solar PV land use to account for wind turbine footprint and other interactions. The corresponding equations for the per person and relative land use are further detailed in SI 1.8.

Data availability

The majority of the data that are important to interpret, verify and/or extend this work have been included either directly in the main text or detailed in Supplementary Tables 2 and 3. Further primary data is available at *https://doi.org/10.6084/m9.figshare.14778804.v1*[95] and include the energy demand curves, vegetable basket and yield factor data, and the output from Homer Pro and ArcGIS

Pro. Publicly available third-party datasets are described in Methods and are listed in the References[58–62,64].

Code availability

All computations are fully described in Methods and in the Supplementary Information. Homer Pro files and Excel files to generate the figures can be obtained from the corresponding author on reasonable request.

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Contributions

TW has developed the methodology, conducted the analysis and wrote the original draft. AY has aided in the conceptualisation and development of the methodology, supervised TW, validated the model and calculations and reviewed and edited the draft. FF has validated parts of the methodology and the model and reviewed and edited the draft. MH has conceptualised the work, validated the methodology and reviewed and edited the draft.

Ethics declaration - Competing interests

The authors declare no competing interests.

Supplementary information

Supplementary Information (including Supplementary Tables 1-12 and Supplementary Figures 1-16) is available for this paper at [DOI to be inserted during production]

Primary data is available for this paper at *https://doi.org/10.6084/m9.figshare.14778804.v1*

Source Data File Figure 2

Source Data File Figure 3

Source Data File Figure 4

Source Data File Figure 5

Figure captions

Figure 1: Overview of the land-use comparison approach for open-field farming and two CEA farming practices. The optimised electricity consumption profiles of plant factories and greenhouses and the corresponding yields were derived from Weidner et al. 2021[44]. The renewable energy system diagram (lower right) is a screenshot of HomerPro[93] simulation. Icon credit: Flaticon.com.

Figure 2: Spatial analysis results and regional characteristics. Top: Location of farmland (green) and land suitable for renewable energy generation via PV solar (yellow and orange), onshore wind (pink) and co-located wind and solar (blue) within the 9 regions, on top of a satellite image. Maps were created in ArcGIS Pro[96]. Bottom: Characteristics of the studied regions. The windspeed at 50 m is the average of all locations considered suitable for onshore wind energy generation. The order of countries is according to their average annual temperature (ascending).

Figure 3: Renewable energy system indicators. Top left (a): Annual specific energy consumption, describing the annual electricity consumption for either type of a growing facility divided by the annual production of produce. Top middle (b): The hypothetical electric demand (i.e. load) of scaled-up CEA farming compared with the current regional demand for either of the two CEA systems, derived from national figures and population adjusted. A higher share of CEA-farming makes it more challenging to utilise the overgeneration indicated in the bottom graph. Top right (c): The specific energy cost per unit mass of produced vegetable. It is the product of the specific energy consumption (A) and the levelised cost of energy (Supplementary Figures 7 and 8), not considering grid sell-back. Bottom (d): The ratio of generated electricity to electricity utilised in the respective CEA types. This ratio describes how much overgeneration is required to cover the annual electricity requirements under the project constraints (grid supply limited to 10% of the annual demand, economic trade-off between overgeneration and storage). It is influenced by local solar and wind energy generation potential and the mismatch with the utilisation profile. Singapore had no and Tokyo limited land availability for wind, thus the share of solar PV is higher in those cases. Depending on the local context, this overgeneration could be used for other industrial and residential purposes, improving the values indicated in this figure.

Figure 4: Combined land use requirements for both growing and renewable energy supply. Co-location of PV solar and wind facilities is included and preferred, if feasible. The savings due to co-location are shown in the translucent bar and the value indicates the land use without the savings. If the land available for co-location was restricted, land was allocated exclusively to the suitable renewable energy option. Singapore had no and Tokyo limited land availability for wind, thus solar PV is predominantly used in those cases. This figure only considers the direct and indirect land required to satisfy nutrient requirements for one person (at 50% of RNI), without accounting for limitations due to regional land availability. The value for open field farming in Iceland is 303.6 m^2 $capita^{-1}$.

Figure 5: Regional land use requirements of CEA practices. Calculations are based on the hypothetical sparing of farmland by avoiding open-field vegetable farming in relation to the total farmland available (x-axis, a higher value is better), and the ratio of total land available for renewable generation versus that which would need to be used to supply the CEA farming technique (y-axis, logarithmic in 5a, a higher value is better). Farmland sparing values are hypothetical as values above

100% indicate the reduction in farmland requirement through meeting the specified demand by CAE is greater than the area of existing farmland in the region. The bubble size depicts the net land use per person subtracted with savings of co-locating solar PV and wind. The dashed-line circle is for greenhouses and the solid-line circle is for plant factories. The characteristics of the regions in cluster I and II are described in the text. 5a only shows regions and CEA practices for which sufficient land would be available to generate the energy required for fully scaled-up CEA. 5b shows the cases in which insufficient land is available to upscale CEA.

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