Title: Comparing the environmental sustainability of vertical and conventional wheat farming using Life Cycle Assessment

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Abstract:

Main purposes and research question: Wheat is the second largest grain crop by tonnage in the world and the largest in Denmark. Given the observed, adverse impacts on wheat yields of climate change and the importance of wheat in the human diet, the purpose of this study was to use life cycle assessment to compare conventional wheat farming with indoor vertical farming using hydroponics.

Methods: Life Cycle Assessment was used to assess the base case systems up to the “farm gate” for 1 tonne of wheat grain. The processes contributing most of the impacts were identified, and scenarios were assessed to determine how much the impacts could be reduced.

Results: The conventional system outperformed the base case vertical system in every impact category, due to the electricity consumption in the lighting system. The scenarios included increasing the efficiency of the LED lighting and using 100% wind energy, but the conventional system still outperformed the vertical system by significant margins in all impact categories. This was due to the low photosynthetic conversion efficiency and the high energy density of wheat.

Conclusions: Until significant improvements are made to lighting efficiency, the photosynthesis conversion efficiency of wheat, new wheat variants designed for vertical gardens and the sustainability of electricity supply, conventional wheat production will be environmentally preferable and vertical gardens would be advised to focus on food products with low energy densities.

Keywords (6-8): Life Cycle Assessment; Urban agriculture; wheat; controlled environment agriculture, vertical garden

1. Introduction

Wheat is the second largest grain crop in the world after maize, accounting for approximately 24% of world cereal production (FAO, 2021), and the major crop grown in Denmark, accounting for nearly 50% of all Danish grain production (Statistics Denmark, 2021). The adverse impacts of climate change, such as heat stress and drought (Benke and Tomkins, 2017) have already been observed as decreased yields in wheat and other cereal production (FAO, 2021), leading to concerns about the robustness of current wheat production (González-Esteban, 2017; Le Gouis et al., 2020).

One way to protect against the adverse impacts of climate change on wheat production would be to use a controlled-environment agriculture (CEA) system. CEA is currently used to produce leafy greens, herbs and some other food crops in facilities with multiple floors and there are a range of different technologies available. CEA can allow the close monitoring of production conditions such as lighting level, temperature, water, nutrients, pests and diseases, to optimise yield and production efficiencies and minimise losses in the production stage (Asseng et al., 2020; Benke and Tomkins, 2017; Goldstein et al., 2016; Ramírez-Arias et al., 2018; Romeo et al., 2018).

Current (2021) average electricity production in Denmark is sourced from renewables (24% onshore wind, 9% offshore wind, 8% solar, 8% biomass and 1% biogas), energy-from-waste (25% CHP plants, 1% waste) and most of the residual from fossil fuels (9% natural gas, 7% coal and 3% oil) (Energistyrelsen, 2020). In June 2020, Denmark passed legislation which commits Denmark to reducing it's greenhouse gas emissions by 70% by 2030 compared to 1990 emissions (Danish Energy Agency, 2020). This will include a range of measure, including the phase-out of coal use in electricity production, an increasing share of wind, biogas, biomass and solar photovoltaics and the replacement of oil and gas fired boilers used for heating with electric heat pumps. The combined impact of these measures will be that 2030 energy production in Denmark will have a low greenhouse gas emissions intensity, potentially making it suitable for CEA applications from a carbon footprint perspective.

2. Material and Methods

2.1. System boundaries and functional unit

This study assessed a cradle-to-farm gate system (preparation, growth and harvest) for wheat production in Denmark, comparing conventional field-based farming (CF) with an indoor vertical farming system (VF) as shown in Figure 1. The functional unit for the study was one tonne of wheat grain, and the corresponding reference flows were 0.137 hectares of land and one season for the CF, and 0.027 hectares of land and 70 days for the VF, although the growth area for both systems was 0.137 hectares of land. It was assumed that the same variety of wheat was used in both systems, so that the yield and growth characteristics (such as the harvest index (edible grain/total biomass)) and chemical and physical properties (such as texture, size, nutritional value, taste) were the same in both systems. The VF system uses soil as the passive growth media, a hydroponic system to provide water and nutrients, and full spectrum LED lighting with production spread over 5 vertical floors. While the CF includes pesticide use, the VF does not, and as both systems extended only to the farm gate, they did not include the packaging, transport, processing, wholesale/retail, use or end-of-life life cycle stages, as these aspects of the production system are not controlled by producers and were assumed to be the same in both systems.

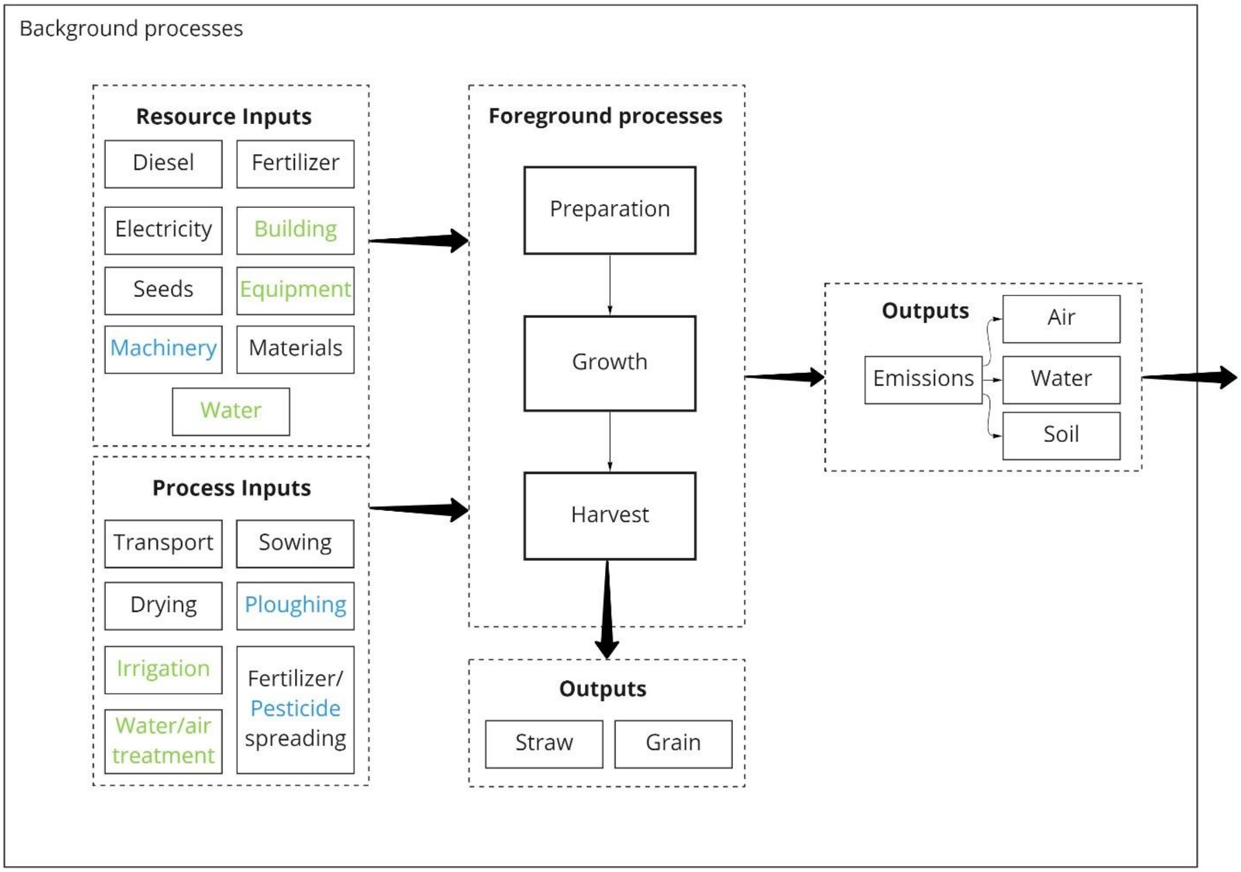

Figure 1: System Boundaries for the LCA of wheat production in a conventional vs vertical farm

2.2. Inventory data

Data for the CF was taken from a recent Danish study (Mogensen et al., 2018), and it was assumed that all micro nutrients and a small portion of the macro nutrients were provided by the soil and wet/dry deposition, the remaining nutrients required were added, the system was 100% rain-fed (no irrigation), and there was 1km from the farm to the field.

Data for the VF base case was taken from a recent Masters project at DTU on the vertical farming of lettuce, which sourced primary data relating to equipment from the Nordic Harvest operations in Copenhagen (Lenschau, 2019). Secondary data was taken from literature for wheat yields and growth requirements (Asseng et al., 2020), and macro and micro nutrient requirements (Yara UK, 2021). It was necessary to add the total required nutrient demand for wheat in the VF system, as the soil and dry/wet deposition provided none. Assumptions were made about equipment used in the VF system such as the sowing and harvesting systems, as there are no full scale indoor wheat production systems currently operating. The VF system uses 20 hours of lighting a day, which is equivalent to 50 MJ/day per square meter. This creates a growing cycle of 70 days, which allows five harvests per year. It was assumed that emissions related to the nutrients are reduced by 70% in the VF, as the water is recycled, and water use was estimated to be the water uptake in the grain and straw plus an additional 10% for losses not recovered in the air conditioning filtration system. The building area required for the VF was calculated from the reference flow, and 50% was added for infrastructure.

Both systems assumed that there was 30km transport of seeds to the farm, grain needed to be dried to 15% water content and there was no grain loss.

To reflect the difference in data quality between the CF and VF systems, a data quality check using the pedigree matrix approach was completed for each process and a data quality rating (DQR) was calculated for each production stage. A DQR close to 1 represents a data quality level (DQL) of high quality data, numbers from 1.6-3 representing a DQL of "basic quality" data and numbers above 3 indicating a poorer quality DQL of "data estimate" (Weidema and Wesnæs, 1996).

2.3. Life Cycle Impact Assessment – methods and modelling

The guidelines from the International Life Cycle Data system (EC-JRC, 2010) and European Union Product Environmental Footprint (European Commission, 2017) were used, using system expansion to handle by-products and co-products. The system was modelled using SimaPro software (v9.1), and the consequential datasets from Ecoinvent v3.6, as they use system expansion to handle by/co-products. The dataset for electricity production in Denmark was modified to reflect data from the Danish Energy Agency (Energistyrelsen, 2020) for 2021 and 2030. The life cycle impact assessment method used was Environmental Footprint 3.0 (EF 3.0), which includes 16 midpoint impact categories. This paper reports on the 7 most important impact categories for urban agriculture (Goldstein et al., 2016), namely climate change (CC), fossil resource use (FRU), freshwater ecotoxicity (FT), freshwater and marine eutrophication (FE, ME), land use (LU) and water use (WU). It was assumed that the same amount of straw was produced in each system, and that the use of the straw was the same, so it was eliminated from the assessment.

For each system, a hot spot analysis was undertaken to identify the main processes and life cycle stages contributing to the impacts, to assist with identifying where potential improvements could be made, particularly for the VF system. A sensitivity analysis was conducted on the processes with the highest impact in each system, with a relative sensitivity coefficient of over 5% indicating that the process was sensitive to uncertainty (Hauschild et al., 2017).

Midpoint characterised results and internal normalisation were used to compare the CF and VF systems.

2.4. VF system scenarios

Once the hot spots were identified in the VF base case system, improvements in their performance were modelled individually and then together, to assess the best case scenario for the VF system.

3. Results and Discussion

3.1. Life Cycle Inventory data and data quality

The life cycle inventory data for the CF and VF base case is presented in Table 1 and highlights the difference in energy consumption, consumables, infrastructure and production data between the two systems.

Table 1: Life Cycle Inventory data for Conventional (CF) vs Vertical base case (VF) Wheat Farm (Sørensen, 2021)

Data type	Processes	CF	Unit	VF base case	Unit
Energy	Drying	1.90E+01	kWh	1.90E+01	kWh
	Lighting	-	-	1.33E+02	kWh
	Irrigation	-	-	3.28E+01	kWh
	Air conditioning	-	-	1.20E+03	kWh
Consumables	N fertiliser	2.05E+01	kg	2.80E+01	kg
	P fertiliser	2.61E+00	kg	5.20E+00	kg
	K fertiliser	9.75E+00	kg	1.80E+01	kg
	Calcium	2.27E+01	kg	4.12E-01	kg
	Other fertiliser	-	-	1.06E+00	kg
	Water	-	-	2.33E+02	kg
	Seeds	2.33E+01	kg	2.33E+01	kg
	Lubricant, oil	1.37E+00	l	-	-
	Pesticide	9.89E-02	kg	-	-
Infrastructure	HDPE (tanks)	-	-	4.98E-02	kg
	PVC (trays)	-	-	3.14E+00	kg
	PVC (pipes)	-	-	1.91E-01	kg
	HDPE (boxes)	-	-	2.37E+00	kg
	Steel	-	-	3.14E+00	kg
	Water pump	-	-	1.66E-01	piece
	Electric motor	-	-	2.00E-01	kg
	Light emitting diode	-	-	1.92E-01	kg
Production data	Building	-	-	1.64E-01	m^2
	Sowing	1.37E-01	ha	6.38E+01	kWh
	Harvesting	1.37E-01	ha	6.38E+01	kWh
	Ploughing	1.37E-01	ha	-	-
	Pesticide spread	1.37E-01	ha	-	-
	Transport	1.70E+00	tkm	7.00E-01	tkm
	Emission filter	-	-	1.00E+00	piece

The DQR is presented in Table 2 and indicates that the CF has less uncertainty relating to it's data, as it is well studied, and that the VF has higher uncertainties, due to the novel nature of the system. This is taken into consideration in the interpretation of the results.

Table 2: Data quality indicator score for CF and VF systems (Sørensen, 2021)

	CF		VF	
Life cycle stage	DQR	DQL	DQR	DQL
Preparation	2.4	Basic quality	3.9	Data estimate
Growth	2.1	Basic quality	3.8	Data estimate
Harvest	3.1	Data estimate	3.5	Data estimate

3.2. LCA results for CF and VF base case

Characterised midpoint results are presented in Table 3 for the CF and VF base case systems, with a factor indicating the difference between the two systems. The differences were 1 or 2 orders of magnitude, with the CF outperforming the VF base case by a minimum factor of 19 for WU and a maximum factor of 227 for LU.

Table 3: Characterised midpoint impact category results for the CF and VF base case (Sørensen, 2021)

Impact category	Unit	CF	VF base case	Factor
Climate change (CC)	kg $CO_{2\ eq}$	5.06E+02	2.84E+04	56
Freshwater eutrophication (FE)	kg P eq	1.42E-01	8.54E+00	60
Marine eutrophication (ME)	kg N eq	9.79E-01	3.34E+01	34
Freshwater ecotoxicity (ET)	CTUe	4.44E+04	8.86E+05	20
Land use (LU)	Pt	7.80E+03	1.77E+06	227
Water use (WU)	m^3 depriv.	1.45E+02	2.74E+03	19
Fossil resource use (FRU)	MJ	3.27E+03	3.31E+05	101

The CC results for the CF system are consistent with other studies of Danish wheat, such as 0.48 kg CO_2-eq per kg of wheat grain (Mogensen et al., 2018), and 0.50 kg CO_2-eq per kg of wheat grain from the CONCITO big climate database (Chrintz and Minter, 2021).

A recent review found that production in single-story greenhouses in warmer climates performed better than conventional agriculture, but production in cooler climates performed worse than conventional agriculture, due to the impact of the electricity used for lighting and heat, ventilation and air conditioning (HVAC) (Goldstein et al., 2016). However, the performance of the VF wheat system relative to the CF wheat system is significantly worse in this study compared to other studies on different food products (Romeo et al., 2018).

Controlled Environment Life Support Systems research as part of a National Aeronautics and Space Administration (NASA) project had identified that the conversion efficiency of photosynthesis (energy in biomass/energy in photosynthetic photons) for wheat ranged from 7-10+%, depending on the photosynthetic photon fluxes (Bugbee and Salisbury, 1988, 1989). The energy content per 100g of food is 1454 kJ for wheat, compared to 64-80 kJ for various lettuce varieties, 68 kJ for baby spinach, 87 kJ for tomato, 191 kJ for kale and 93-201 kJ for various herb varieties (National Food Institute - Technical University of Denmark, 2019). Given the combination of a low photosynthetic conversion efficiency and high energy content, it could be expected that the energy used in lighting to provide the energy for photosynthesis for wheat would be proportionally higher, meaning that the results for wheat would be significantly worse than other food products. Most commercial vertical gardens currently produce fast growing leafy green vegetable, herbs and tomatoes, rather than crops with longer growing periods.

3.3. Hot spot analysis for CF and VF base case

The results in Table 4 use the preparation stage in each system as the internal normalisation reference point. This shows that in the CF system, the preparation phase produces the most impacts and the growth phase the least, whereas in the VF base case system it is the growth phase that produces the most impacts and the harvest phase the least. This is consistent with the inventory data in Table 1, and consistent with the CF system being able to harvest "burden free" energy from the sun to grow the wheat.

Table 4: Relative environmental performance for CF and VF base case systems, with preparation stage used as internal normalisation for each system separately (ie value of 1) (red shading indicates the most impacts, green the least). (Sørensen, 2021)

		CF life cycle stages			VF base case life cycle stages		
Impact category	Unit	1. Prep	2. Growth	3. Harvest	1. Prep	2. Growth	3. Harvest
Climate change (CC)	kg $CO_{2\ eq}$	1.00E+00	1.44E-02	5.74E-02	1.00E+00	4.09E+01	2.73E-02
Freshwater eutrophication (FE)	kg P eq	1.00E+00	2.21E-02	4.78E-02	1.00E+00	3.68E+01	3.17E-02
Marine eutrophication (ME)	kg N eq	1.00E+00	1.95E-02	1.23E-01	1.00E+00	3.17E+01	2.13E-02
Freshwater ecotoxicity (ET)	CTUe	1.00E+00	4.23E-03	1.28E-02	1.00E+00	1.23E+01	9.92E-03
Land use (LU)	Pt	1.00E+00	5.53E-03	5.20E-02	1.00E+00	1.98E+02	1.23E-01
Water use (WU)	m^3 depriv.	1.00E+00	1.41E-02	1.17E-02	1.00E+00	1.24E+01	9.15E-03
Fossil resource use (FRU)	MJ	1.00E+00	5.54E-02	1.23E-01	1.00E+00	6.59E+01	4.37E-02

Table 5 compares the life cycle stages for each system, with the equivalent stage for the CF as the internal normalisation reference point. This indicates that in the preparation stage, the VF base case is only slightly worse than the CF, from a factor of 1.19 for ME to 1.78 for FRU. In the growth stage, the VF base case is significantly worse that the CF, by orders of magnitude - 4 for CC and 3 for all other impact categories. In the harvest stage, the VF performs better in CC, ME and FRU, but worse in all other impact categories.

Table 5: Relative environmental performance of CF and VF base case, with the CF preparation stage used as the internal normalisation value (ie 1.0). Numbers in italics indicate that the VF base case performs better than the CF (Sørensen, 2021).

	VF base case life cycle stage compared to CF		
Impact category	1. Preparation	2. Growth	3. Harvest
Climate change (CC)	1.43	4,054	*0.68*
Freshwater eutrophication (FE)	1.71	2,834	1.13
Marine eutrophication (ME)	1.19	1,929	*0.21*
Freshwater ecotoxicity (ET)	1.53	4,433	1.19
Land use (LU)	1.21	43,249	2.86
Water use (WU)	1.45	1,276	1.13
Fossil resource use (FRU)	1.78	2,118	*0.63*

Table 6 indicates which processes contribute the most to impacts in each of the systems. For the CF system, fertiliser is the main contributor in all impact categories except LU, where the seeds are the main contributor. Fertiliser and seeds are ranked first and second most significant impacts in the CF system, similar to the VF base case system where they are second and third in that order. For the VF base case system, electricity use in the lighting system is the main contributor in every category, contributing over 90% of the impacts in all cases, with fertiliser and seeds very distant second and third contributors.

Table 6: Main contributing processes to each impact category for the CF and VF base case systems (Sørensen, 2021)

	CF main processes			VF base case main processes		
Impact category	Fertiliser	Seeds	Harvesting	Lighting	Fertiliser	Seeds
Climate change (CC)	87.2%	2.1%	4.5%	97.0%	1.8%	0.0%
Freshwater eutrophication (FE)	83.8%	7.2%	3.6%	96.9%	1.6%	0.1%
Marine eutrophication (ME)	45.5%	34.7%	10.2%	96.7%	1.5%	1.0%
Freshwater ecotoxicity (FT)	97.1%	0.6%	1.0%	92.1%	7.0%	0.0%
Land use (LU)	16.1%	76.5%	1.6%	99.3%	0.1%	0.3%
Water use (WU)	96.4%	0.3%	0.9%	91.4%	6.0%	0.0%
Fossil resource use (FRU)	74.8%	2.2%	8.9%	97.9%	0.9%	0.0%

Although the 2021 electricity mix in Denmark has a substantial proportion of renewable energy, it still has 3% oil, 7% coal and 9% natural gas, and these are responsible for most of the results in the CC, FE, ME, WU and FRU impact categories. The LU results initially seem surprising, but as 8% of 2021 Danish electricity comes from biomass, the underlying forestry processes which supply the biomass occupy land and contribute to this impact category.

3.4. Sensitivity analysis

The sensitivity analysis indicated that in the CF system, the fertiliser process was sensitive in most impact categories, and the LU impact category in the harvesting process was sensitive, as the values were over 5%. For the VF base case, the lighting was sensitive in all impact categories, while the fertiliser and seeds processes were not sensitive.

Table 7: Relative sensitivity coefficient for most contributing processes for CF and VF base case. Italics indicates that the process is sensitive to uncertainty (Sørensen, 2021).

	CF main processes			VF base case main processes		
Impact category	Fertiliser	Seeds	Harvesting	Lighting	Fertiliser	Seeds
Climate change (CC)	*7.93%*	0.41%	0.19%	*8.82%*	0.16%	0.00%
Freshwater eutrophication (FE)	*7.62%*	0.32%	0.66%	*8.81%*	0.14%	0.01%
Marine eutrophication (ME)	4.13%	0.93%	3.16%	*8.79%*	0.14%	0.09%
Freshwater ecotoxicity (FT)	*8.83%*	0.09%	0.05%	*8.37%*	0.64%	0.00%
Land use (LU)	1.46%	0.15%	*6.95%*	*9.03%*	0.01%	0.03%
Water use (WU)	*8.77%*	0.08%	0.03%	*8.31%*	0.54%	0.00%
Fossil resource use (FRU)	*6.80%*	0.81%	0.20%	*8.90%*	0.08%	0.00%

3.5. LCA result for scenarios and VF best case

3.5.1 Electricity mix – Denmark 2021 and 2030

As the main environmental impacts of the VF base case came from the electricity used in lighting, the difference between the 2021 and business-as-usual 2030 scenario for the electricity generation mix was assessed. The generation mix in 2021 and 2030 for Denmark is provided in Table 8, and indicates that there is expected to be a significant increase in renewable energy technologies, namely solar and offshore wind generation technologies, and a corresponding decrease in the proportion of electricity sources from fossil fuels such as coal, natural gas and oil.

Table 8: Danish electricity mix, 2021 and 2030 (Energistyrelsen, 2020; Sørensen, 2021).

	2021 mix		2030 mix		Relative %
Generation Technology	Megawatt	%	Megawatt	%	change vs 2021
CHP plant	4.82E+03	24.7%	3.03E+03	11.8%	-52%
Condensation in CHP plant	8.25E+02	4.22%	8.25E+02	3.21%	-24%
Industrial surplus	2.61E+02	1.33%	2.61E+02	1.01%	-24%
Offshore wind	1.70E+03	8.70%	5.18E+03	20.1%	132%
Onshore wind	4.75E+03	24.3%	6.15E+03	23.9%	-2%
Solar	1.54E+03	7.87%	6.42E+03	24.9%	217%
Hydro	6.79E+00	0.03%	6.79E+00	0.03%	-12%
Coal	1.35E+03	6.93%	1.00E-06	0.00%	-100%
Natural gas	1.83E+03	9.36%	1.44E+03	5.60%	-40%

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	2021 mix		2030 mix		Relative %
Generation Technology	Megawatt	%	Megawatt	%	change vs 2021
Oil	6.76E+02	3.46%	6.58E+02	2.56%	-26%
Waste	2.29E+02	1.17%	2.01E+02	0.78%	-33%
Biogas	7.48E+01	0.38%	7.34E+01	0.29%	-25%
Biomass	1.48E+03	7.56%	1.47E+03	5.72%	-24%
Total	1.95E+04	100%	2.57E+04		

The change in electricity generation mix in 2030 was coupled with the expected 100% increase in LED efficiency (Pattison et al., 2020) and is shown in Figure 3 with the 2021 VF base case used as the internal normalisation reference value, all impact categories improve significantly, with the 2030 values at consistently less than 40% of the 2021 value. Although this is a significant improvement, it still does not bridge the performance gap compared to the factors provided in Table 3. Therefore, each individual renewable generation source in the 2030 Danish electricity grid mix was investigated further, to identify how close combining the potential improvement available from the 100% improvement in LED efficiency to the electricity generation source could come to the performance of CF of wheat.

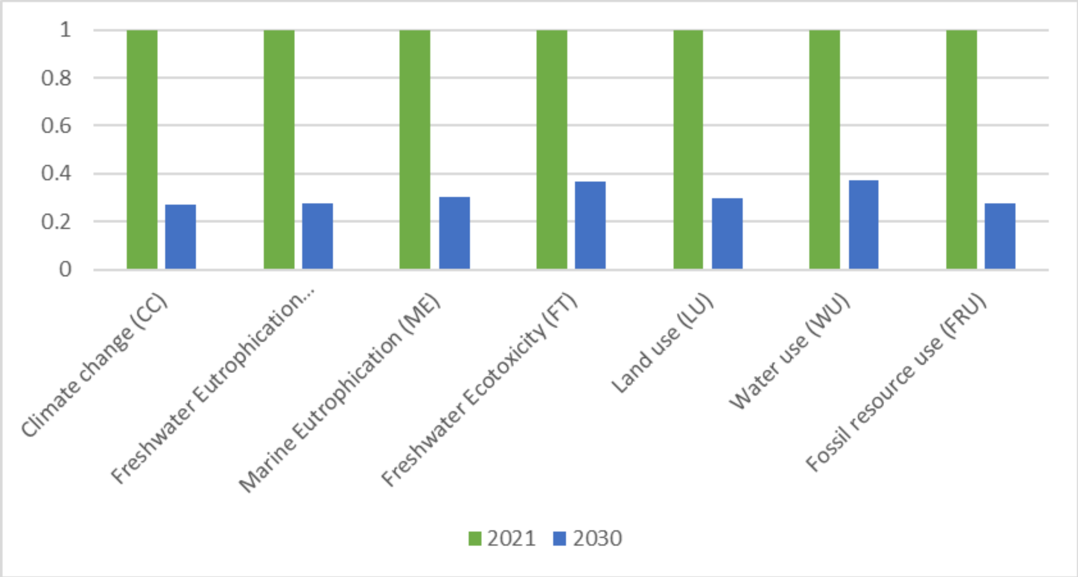

Figure 2: VF base case using average 2021 Danish electricity grid mix compared to VF using average 2030 Danish electricity grid mix and 100% improvement in LED efficiency (Sørensen, 2021).

3.5.2 VF best case – onshore wind and 100% LED improvement

The electricity generation source with the lowest impact was onshore wind generation for all midpoint impact categories except LU, where offshore wind was best, as outlined in Figure 4.

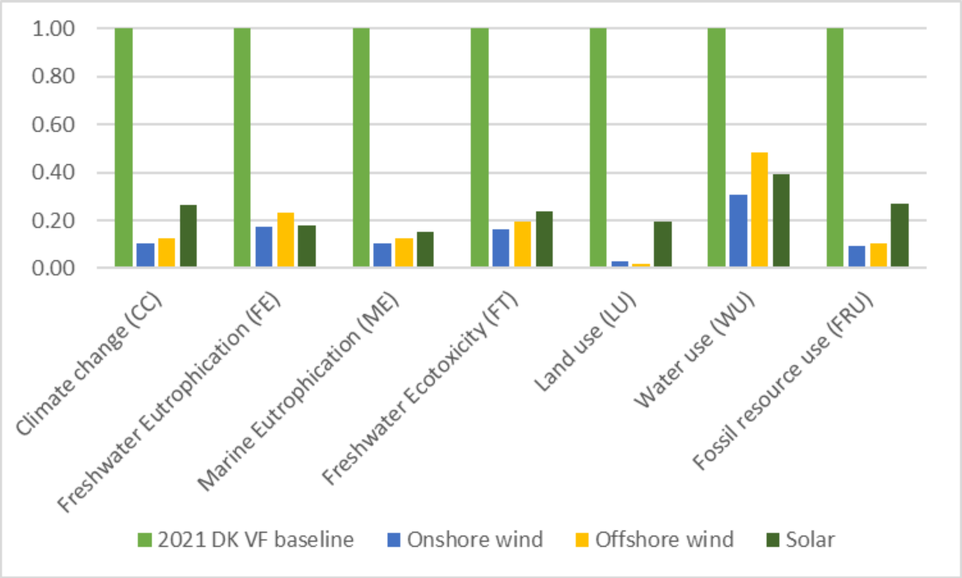

Figure 3: 2021 Danish electricity mix in VF base case compared to other electricity generation mixes (Sørensen, 2021)

The use of 100% onshore wind generation of electricity was combined with a 100% improvement in the efficiency of LEDs, with all other parameters unchanged and the results are presented in Table 9. This shows a significant improvement in the VF results, by two orders of magnitude for the LU and FRU impact categories, which reflects the use of only onshore wind power, rather than the average Danish mix that includes biomass and fossil fuels respectively. Other impact categories improve by one order of magnitude, but are still 2.3 – 6 times higher than the CF system.

Table 9: Relative environmental performance of CF compared to VF base case and VF best case, with CF presented as the internal normalised value (1.0) (Sørensen, 2021).

Impact category	CF	VF	
		Base case	Best case Onshore wind
Climate change (CC)	1.0	56	3.7
Freshwater eutrophication (FE)	1.0	60	6.0
Marine eutrophication (ME)	1.0	34	2.3
Freshwater ecotoxicity (ET)	1.0	20	2.4
Land use (LU)	1.0	227	4.1
Water use (WU)	1.0	19	3.7
Fossil resource use (FRU)	1.0	101	5.6

3.6. Limitations and possible further research

As indicated by the data quality matrix, a lot of assumptions were used in the VF case, although the infrastructure did not have a significant environmental impact compared to the electricity consumed in the lighting system.

Research has been conducted on the spectral characteristics of the radiation, optimisation of lighting location and orientation of lighting to minimise loss and reflection, which then may reduce the energy required in CEA and potentially improve wheat (Pattison et al., 2018), but it is unclear about the extent of improvement possible.

Similarly, using a wheat variant that is suited to CEA, with optimisation of water, nutrients, loss rates and carbon dioxide levels may reduce wheat plant stress and the use of incident radiation for non-productive uses such as respiration. In turn, this may improve production metrics such as increasing the wheat growth rate, reducing the number of days/light hours required until physiological maturity, optimising the leaf area ratio and increasing the harvest index (edible grain/total biomass eg reduce root dry mass), thus increasing the grain yield per unit of light provided (Bugbee, 1995, 1992; Volk et al., 1995). One example is the wheat cultivar 'USU-Super Dwarf', which is a hard red spring wheat that was specifically developed by the Utah Agricultural Experiment Station in co-operation with the National Aeronautics and Space Administration (NASA) for spaceflight and controlled environment applications where volume for growth is limited (Goins et al., 1997). Similarly, there has been some research about changing the type of light provided to improve wheat grain characteristics, such as the milling quality of flour via modification of strength and the extensibility of the dough and solubility of proteins including the gluten content (Monostori et al., 2018). However, the research on CEA for applications such as the international space station now focus on the production of supplemental perishable foods such as lettuce, spinach, radish and Swiss chard, which are comparatively more difficult to transport (Kim et al., 2005; Wheeler et al., 2003).

Of the current CEA operations, most of them are currently growing fast growing leafy greens, herbs and some other products such as tomatoes and strawberries. These have short growing cycles and correspondingly low energy levels per mass unit (National Food Institute - Technical University of Denmark, 2019) and it may be useful to conduct an LCA of them or other low energy content foods using electricity supply from renewables.

4. Conclusions

Based on the results found in this study, it appears that with current yields and photosynthetic conversion efficiencies of wheat, vertical farming is not environmentally preferable to conventional wheat production, even when using electricity generated from the most sustainable sources.

VF of wheat may be suitable in locations that are not suited to conventional wheat production (due to a very short growing season, land availability, severe water constraints or environmental pollution), where a low burden source of electricity is available and where food security is of paramount importance, so cost is not so much of a consideration. However, the global market for wheat is likely to provide a more economic and environmentally friendly source of wheat in the foreseeable future.

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