UNIVERSITY OF STAVANGER

An economic and environmental analysis of greenhouse tomato production in Norway using a model-based technique

by

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Abstract

The growing global population levels and the resulting increasing demands for food has put a lot of pressure on the food production systems and made the agricultural sector highly energy-intensive. The intensification in global food production has led to the need to adapt production systems according to the local climatic conditions, making food production possible in areas where it was difficult before and also making the production process environmentally sustainable. One way to adapt food production systems is through protected cultivation techniques, such as greenhouses, that enable controlled indoor climate, crop protection from extreme climate conditions, pests and diseases and the possibility to extend production seasons for certain crops. Yet these techniques affect the investments, economic performance, used resources and have certain environmental consequences. Norway, for instance, is one such region in which one of the biggest challenges associated with protected cultivation systems is the issue of low availability of natural light and heat, especially during the cold winter months. Production in such regions requires high levels of energy, yet some of these regions also have significant availability of renewable energy resources. The challenge of low light and heat can be overcome by bringing about changes in the production techniques, including greenhouse design elements, production seasons and energy sources. However, this also in turn raises the issue of environmental impact of greenhouse vegetable production in high latitude regions and especially from the use of renewable energy that is present in significant amounts in many regions with considerable greenhouse vegetable production.

While there exist several studies on the different aspects of greenhouse vegetable production in various regions, and their resulting environmental effects, works related to the use of renewable energy sources, especially in high latitude regions such as Norway are limited. Moreover, studies regarding the environmental impact of greenhouse production of vegetables often show that there is a trade-off between the economic performance and the environmental impact. Local climate and light variability call for regionally adapted greenhouse production techniques. Moreover, the impact of a certain greenhouse design on the economic performance may not always be correlated to the environmental impact. Thus, there is a need to evaluate the impact of various production strategies on the economic potential,

resource use and the environment in instances where the traditional fossil fuel is supplemented and/or replaced by energy from renewable resources.

In the present work, an attempt has been made to provide a broad picture of greenhouse tomato production at high latitude regions as a result of adapting production strategies in line with the local climates in Norway, with a particular emphasis on renewable energy sources in order to evaluate the environmental impact of locally produced tomatoes that are also economically profitable. The study has been divided into three stages. In the first part, an economic evaluation of seasonal (mid-March to mid-October) greenhouse tomato production in southestern, southwestern, central and northern Norway was performed. In the second part, an economic evaluation and energy use of extended season (from 20th January to 20th November) and year-round production of greenhouse tomatoes in the selected locations in Norway was performed. Sets of plausible design elements, greenhouse climate management, different artificial lighting strategies were assessed to evaluate the impact of the greenhouse design on the Net Financial Return (NFR), energy use and CO_2 emissions of the production process. In the third part, a life cycle impact assessment was conducted for a selected number of designs from the first two stages that yielded high NFR or was associated with low energy use in order to assess whether the designs that performed well economically are also environmentally sustainable.

The study found clear region-dependent differences in the NFR, its underlying elements, energy use and the resulting environmental impact of different greenhouse designs with differing energy-saving and internal climate control equipment. Our results show that economic profitability can be combined with a low environmental impact under certain regions and production techniques. It was found that Kise (southeastern) was the most favorable location for seasonal greenhouse tomato production in Norway, while Orre (southwestern) was the most favorable location in terms of the economic performance and environmental impact during the extended and year-round production seasons. Moreover, our results show that night energy screens, electric heat pumps and light sources had the most impacts of the elements that were investigated on the NFR and the resulting environmental impact across the three production seasons and need to be considered while constructing greenhouses for tomato production in regions having similar climate

as that of Norway. The results of this study provide interesting insights on works related to the greenhouse vegetable production and energy resources in high latitude regions with considerable supplies of renewable energy. The findings can enable local producers across Norway to design greenhouses keeping in mind the local climate, the economic profitability and the environmental sustainability and can help policymakers in devising policies that encourage local growers to adapt production strategies aimed at increasing local production that is both economically profitable and environmentally sustainable.

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To all these brilliant people, I dedicate my work!

Muhammad Naseer

List of Publications

(i) Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., & Verheul, M. J. (2021). **Bio-economic evaluation of greenhouse designs for seasonal tomato production in Norway**. *Biosystems Engineering,* 212, 413-430.

(ii) Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., Ruoff, P., & Verheul, M. J. (2022). **Bioeconomic evaluation of extended season and year-round tomato production in Norway using supplemental light**. *Agricultural Systems,* 198, 103391.

(iii) Naseer, M., Persson, T., Hjelkrem, A. G. R., Ruoff, P., & Verheul, M. J. (2022). **Life cycle assessment of tomato production for different production strategies in Norway**. *Journal of Cleaner Production,* 133659.

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Abbreviations

ACO	Ant colony optimization
Artificial lighting	Greenhouse lighting
CO_2	Carbon dioxide
DOY	Day of the year
E	Eastern
ES	Extended season
FU	Functional unit
GA	Genetic algorithm
GHG	Greenhouse gas emissions
GPS	Grønt Produsentenes Samarbeidsråd
Grow-pipes	Greenhouse heating pipes
GSA	Global sensitivity analysis
GWP	Global warming potential
$H_{boilpipe}$	Energy transfer from the greenhouse boiler to the heating pipes
HPS	High-pressure sodium
I_{glob}	Global solar radiation
IS	Iterative search
I_{sky}	Horizontal infrared radiation from the sky
K	Potassium
kg	Kilogram
kWh	Kilowatt hour
LCA	Life cycle assessment
LED	Light emitting diodes
LMT	Landbruksmeteorologisk Tjeneste

Mg	Magnesium
MW	Midwestern
N	Nitrogen
NFR	Net financial return
NIBIO	Norwegian Institute of Bioeconomy Research
NOK	Norwegian krone
NDSL	Night, day energy screen with lighting greenhouse design
NDSFML	Night, day energy screen, fogging, mechanical heating with lighting greenhouse design
NS	Greenhouse design with night screen
NSL	Greenhouse design with night screen and lighting
N	Northern
P	Phosphorus
PPFD	Photosynthetic photon flux densities
PAR	Photosynthetically active radiation
$\mathbf{RH}_{out}$	Outdoor relative humidity
RRMSE	Relative root mean squared error
SW	Southwestern
$\mathbf{T}_{out}$	Outdoor temperature
$\mathbf{T}_{sky}$	Sky temperature
Top lighting	Greenhouse lighting placed above the canopy
T	Temperature
YR	Year round

To my family

Chapter 1

Introduction

The ever-increasing global population and the growing demand for food have put massive pressures on our food systems, which has resulted in the agricultural sector being one of the most energy intensive systems in the world [1]. The intensification in the world's food system has on the one hand led to significant environmental impact including soil degradation, groundwater depletion, rise in greenhouse gas emissions etc. [2–5] and on the other led to the need to adapt food production systems to suit the needs of specific climates and locations and to make food production possible in areas where it had hitherto been difficult to do so. Norway is one such country, where issues of low light, heat and short day lengths, particularly in the cold winter months, make fresh vegetable production extremely difficult.

One way to mitigate the effects on the environment and for extending the production season is by using protected cultivation, which allows one to control and manage the indoor climate, nutrition, and other biotic and cultural management variables, thus ensuring crop growth and development and allowing one to optimize resources and levels at different points of crop growth [6, 7]. Protected cultivation systems on the one hand protect the crop from unfavorable weather conditions and on the other hand help in increasing the yield, optimizing resource use and improving food production [8, 9]. Among such methods, greenhouses are a popular way to safeguard crops from unfavorable outdoor conditions and to make production of fresh vegetables possible in areas with climates that otherwise hinders production.

This study is a part of a larger project, 'Bioeconomic production of fresh greenhouse vegetables in Norway (BioFresh) (2016-2021)', which focuses on the sustainable greenhouse vegetable production in (semi-) closed greenhouses. The present study, in particular, focuses on the greenhouse tomato production under local Norwegian conditions ensuring the efficient use of resources and the production process that is not only economically profitable but also environmentally friendly. Thus, the study has conducted an economic and environmental analysis of seasonal, extended season and year-round production seasons under a range of different production techniques in order to identify suitable greenhouse designs.

The present chapter, thus, begins with the overall aims and objectives of the study, followed by a brief discussion on the protected cultivation techniques in use and their relevance to Norwegian conditions. In the subsequent section, a review of literature is presented in order to situate this work in the broader field of greenhouse vegetable production, followed by the significance of the study. The chapter ends with a brief description of the organization of the study.

1.1 Aims and objectives of the study

The aim of the study was to evaluate greenhouse tomato production for a range of different production techniques in high latitude regions in order to increase the profitability and reduce the environmental impact of greenhouse vegetable production.

The first two parts of the study were based on the greenhouse production model by Vanthoor (2011) [10], by adjusting the design elements according to the local climate conditions and later added different artificial lighting strategies according to the modifications done by Righini et al. (2020)[11] in order to determine the impact of greenhouse design on the Net Financial Return (NFR), energy use and environmental impacts. The primary focus was to evaluate a number of different greenhouse designs in order to assess the design that yielded maximum returns, as represented by Net financial returns (NFR) and lowest fossil fuel use for three production cycles: 1. seasonal production (mid-March to mid-October); 2. extended season (20th January to 20th November); and 3. year-round production for different locations across Norway. The study was divided in three parts by conducting an economic analysis of different greenhouse designs for seasonal production during the first stage and for extended and year-round production seasons in the second stage. Once specific designs were identified that yielded the most NFR or had the lowest energy use in each production cycle, a life cycle analysis (LCA) was performed on the selected designs in order to assess their environmental impact and the possible consequences of replacing imported tomatoes with locally produced ones.

1.2 Protected cultivation techniques

Greenhouses protect crops from among other things wind, rain and sun as well as allowing heating, cooling, humidity control, CO_2-enrichment, lighting and irrigation, depending on the individual requirements of specific crops. With the expansion of the use and development of greenhouse technology and climate systems, protected cultivation systems around the world have evolved significantly. Local climate conditions dictate the necessary use of certain technologies and design elements and therefore the type, structure and technological range of protected cultivation systems depend to a large extent on the local climate. Ranging from low-cost, low-tech, plastic tunnels in certain areas in Spain to expensive, high-tech greenhouses in use in much of the US, Canada and western Europe, greenhouses vary in size, shape and materials used in their construction. For instance, in some parts of the world, single span structures made of plastic are used, while in others, multi-span greenhouses with glass roofs are in use [12]. A large variation in climate systems also exists, depending on the requirements of the local climate. Unheated greenhouses having natural ventilation may, for example, be better suited in the mild, temperate regions of Spain while in colder regions, high-tech, closed greenhouses with computer-controlled heating, cooling, artificial light, humidification and de-humidification and CO_2 supply are in use.

Protected production systems can also help to increase the yield, optimize the resource use, improve food production and extend the growing season [13]. Another benefit of such systems is that they enable increased efficiency and variation of resources based on individual crop requirements, for example, related to artificial light, heating, cooling, and supply of CO_2 [14]. The economic performance and the environmental consequences of the production process are significantly influenced by the outdoor weather conditions and types of greenhouse designs [12, 15]. From the time of sowing the seed to the ripening of fruit elements such as temperature, light intensity, light spectrum and day length, humidity, CO_2-concentration and fertigation can be adapted under controlled environmental conditions to increase the biomass production [16, 17].

Artificial light, in particular, is especially relevant for high latitude countries such as Norway since it has shown to extend the production season to fall, winter and early spring season when natural light limits production [18, 19]. In fact, an annual increase in yield of about 100 kg $m^{-2}year^{-1}$ (from 40 to 140 kg) was observed for greenhouse tomatoes in 59th parallel north using supplemental lighting [18, 20]. In general, the productivity of greenhouse crops can be increased, and production season can be extended to make it year-round by using artificial lights, which has been conducted successfully in the present study.

1.3 Present state of Norwegian horticulture

Norway has a wide variety of climates across different regions, with some having cold, dark and often harsh climates, especially in the winter months, and others having mild climates, such as in the coastal areas. It is in these latter regions that there is great potential for local production of vegetables. This is complemented by a significant demand for locally produced vegetables [21]. Moreover, several studies have shown that the mild climates in several parts of Norway make it an ideal place for producing vegetables such as tomatoes and cucumbers and that if produced in greenhouses under controlled conditions, it can result in the highest yields of greenhouse vegetables worldwide [22]. Figure 1.1 shows the differences in outdoor temperature and light across different locations in Norway, pointing towards the need for adoption of artificial light and heat sources in order for the production to be made possible year-round.

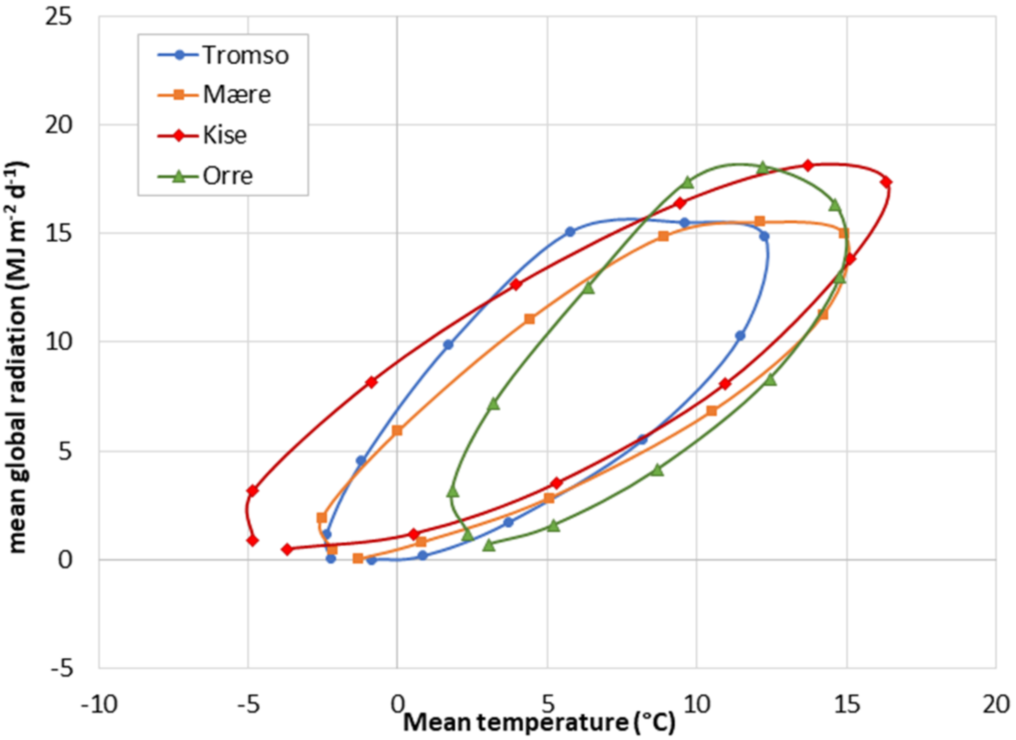

Figure 1.1: The mean air temperature and global radiation (iglob) recorded in the four locations during the last 30 years (from 1989 to 2019). Months are shown clockwise from January to December.

Moreover, only about 3% of mainland Norway is arable land of which only around 15.5% land is used for horticulture production [23]. In 2018, there were 309 agricultural holdings with greenhouses with a total area of 1709 acres and a total sales value of NOK 1.12 billion from vegetables grown in greenhouses (https://www.ssb.no/jord-skog-jakt-og-fiskeri/jordbruk/statistikk/landbruksundersokinga). A brief explanation of trends of various horticultural crops by yield and area in recent years is presented in Table 1.1.

The growing season and the area for agricultural production in the field are short with an average temperature of 5 - 6 °C and low outdoor light conditions. Most of the production takes place during the summer season which is from May to October and little with some artificial lighting in the months from February to November. In a few parts, year-round production also takes place using high capacities of supplemental lighting and heating. Heating in greenhouses is primarily obtained from boilers by burning gas and supplied through pipes because of colder climates. Two main types of supplemental lighting are used in greenhouses, which use electricity: i. High Pressure Sodium (HPS) and, ii. Light Emitting Diodes

Yield and area, by contents, horticultural crop and year						
Area (decares)	2015	2016	2017	2018	2019	2020
Cucumber in greenhouse	227	237	277	229	249	260
Tomato in greenhouse	331	345	328	379	404	390
Rapid lettuce in greenhouse	4	2				
Head lettuce in greenhouse	55	60	86	81	83	88
Other lettuce in greenhouse	5	7	4	7		
(Average Yield in kg m^{-2}.)						
Cucumber in greenhouse	67	68	56	69	68	75
Tomato in greenhouse	35	32	32	34	32	36
Rapid lettuce in greenhouse	28	37	:	:	:	:
Head lettuce in greenhouse	21	29	23	23	25	26
Other lettuce in greenhouse	14	22	7	15	:	:
Yield (tonnes)						
Cucumber in greenhouse	15154	15791	15382	15725	17047	19600
Tomato in greenhouse	11512	11141	10574	12801	12761	14239
Rapid lettuce in greenhouse	113	61	:	:	:	:
Head lettuce in greenhouse	1323	1730	1980	1903	2061	2287
Other lettuce in greenhouse	63	158	32	99	:	:

Table 1.1: Norwegian trends of various horticultural crops by yield and area in recent years.

(LED). Moreover, the need for supplemental lighting arises mostly during day time and for heating during night time. This makes agriculture in colder regions such as Norway highly energy intensive.

As mentioned previously, Norway has the highest share of electricity produced from renewable sources, mainly hydropower, in Europe. To be precise, almost 98% of Norway's electricity comes from renewable sources [24]. This is important since around 95% of CO_2 emissions for greenhouse production for tomato and cucumber come from fuel usage [25]. Thus, adapting greenhouse production techniques in order to increase locally produced vegetables will result in lower environmental impact and lower dependence on imports. With respect to tomato production in Norway, most of the production takes place in Rogaland region during the summer season. A close look at the trends of the previous few years suggests that the share of locally produced tomatoes is around 30-35%, with the bigger share of imported tomatoes [21]. According to GrøntProdusentenes Samarbeidsråd (GPS) (https://www.grontprodusentene.no), however, there was an almost 5 % increase in the production of greenhouse tomatoes in 2020, which meant an increase of almost 2% in the market share of Norwegian tomatoes. In July alone of the same year, the share of sales of Norwegian tomatoes accounted for about 75%. (https://www.nationen.no/landbruk/norsk-tomatproduksjon-okte-i-fjor/).

	Netherlands NOK m^{-2}	Norway NOK m^{-2}
Plant material	30.88	44.39
Fertilizers, incl. water	9.65	25.09
Crop protection	3.86	19.3
Other crops assets	19.3	30
Energy	156.33	550.05 (gas + electricity)
Tangible Assets	75.28	
Labour	90.71	472.85
Contracts	18.33	
Interests	29.92	49.65
General costs	21.23	75.27
Others	30.88	19.3
Total costs	486.40	1275.20

Table 1.2: A comparison of some of the production costs in Netherlands and Norway. The costs for Netherlands was obtained from Cantliffe & Vansickle (2017)[26] and for Norway from consultations with advisors at NIBIO. The costs from Netherlands have been converted from Euros to NOK for easy comparison and according to exchange rate at xe.com in 2018.

Despite the great potential of producing vegetables throughout the year and the high demand of local produce, greenhouse production in Norway is more expensive as compared to other countries such as Netherlands. Around 80% of the total production cost in Norway is related to energy and labor costs. A brief comparison of production costs in Norway and Netherlands is presented in Table 1.2. The most important factors affecting production costs are expenses related to the depreciation of the structure and equipment, labour, energy and variable costs such as plant material, substrate and fertilizer. About 44% of production costs of tomato in Norway are for energy use [27], as shown in Table 1.2. Another unique feature of vegetable production in Norway is the difference between the seasonal and off-season tomato prices whereby seasonal tomato prices are higher as compared to off-seasonal tomato prices when the production is even more energy-intensive and therefore more costly. This is due to the seasonal variation in import duties for tomatoes [28]. For instance, from week 19 to week 41 during the year 2019 the tariff rate for tomatoes ranged from 10.21 NOK kg^{-1} and 6.86 NOK kg^{-1}, while for the rest of the year the tariff rate was zero NOK [29].

1.4 Literature review

There are different ways in which the economic performance of greenhouse production can be improved along with reducing the negative impact on the environment for individual growers as well as for the horticultural sector as a whole. These can include adapting greenhouse designs that reduce the usage of energy and that can be combined with supplemental lighting [27]. Such designs include modified greenhouse construction types as well as different energy sources and production seasons. Another way to increase the profitability of greenhouse production is by either increasing the production value or reducing costs for inputs such as water, CO_2, labour or energy [30]. For high latitude regions that require high amounts of lighting and heating, production costs can become especially great. For instance energy costs, including heating and lighting, account for a major share of total production costs in Norwegian greenhouse vegetable production and is often much higher as compared to production in other countries [31]. Nevertheless, adapting different greenhouse designs for insulation and shading equipment, heating and cooling system, artificial lighting and system for CO_2 supply can improve the efficiency of the use of gas, electricity and other inputs and, as a result, their costs [32].

The effect of different conditions on crop production can be evaluated using process-based simulation models. Different studies focus on different aspects of the production process, such as prediction of crop yield, optimization of light strategies in greenhouses for different crops using a variation in artificial light, including High-Pressure Sodium (HPS) and Light Emitting Diodes (LED), CO_2 enrichment, and heating and cooling. For instance, TOMGRO [33–35] and TOMSIM [36, 37] simulate the impact of light, temperature and CO_2 on tomato production. Similarly, a model has been developed by Slager, Sapounas, van Henten & Hemming (2014)[38] in order to evaluate the economic feasibility and productivity of greenhouse tomato and algae production under Dutch conditions without using supplemental lighting. Likewise, several other models simulate greenhouse production for different locations and design elements [39–42]. Still, other studies have integrated several optimization techniques by using algorithms, including the iterative search (IS) and genetic algorithm (GA), ant colony optimization (ACO), to ascertain optimum values for supplemental lighting and energy usage of lamps for greenhouse production [43, 44]. Likewise, the GroIMP modelling platform uses a 3D light model in conjunction with a 3D tomato model in order to evaluate different light strategies with the aim of reducing the usage of energy [45].

Vanthoor et al.(2011a and 2011b)[46, 47] have developed a model, whose design elements are adjustable according to specific climatic conditions, in order to simulate greenhouse tomato production. The model has been used along with an economic module [48] to evaluate the effect of different greenhouse construction types on the overall economic performance of the production based on its annual net financial return (NFR). The NFR in this combined greenhouse design and economic module, therefore, is a function of yield, variable costs, construction costs, depreciation and costs for maintenance of equipment that is used in greenhouse production. Vanthoor et al. (2012a)[48] previously applied this model in order to identify appropriate greenhouse construction types for warmer climates and low latitude regions including Netherlands, Spain etc. Similarly, Righini et al. (2020)[11] validated the model for higher latitude regions by incorporating supplemental lighting and heat harvesting to the greenhouse production model by Vanthoor et al. (2011a, 2011b)[46, 47].

The growing interest and shift in trends of literature focusing on ways to adapt horticultural production to make it more sustainable as well as profitable notwithstanding, literature regarding mapping the effects of greenhouse production, particularly that of tomato production in high latitude countries, on the environment is still limited. There is also a significant difference in the studied variables in the existing literature i.e., from the production techniques to locations, the system boundaries, and the selection of impact categories. Most of the literature deals with calculating the environmental impact of indoor tomato production in unheated greenhouses [32, 49–57]. Some studies also focus on heating systems and the resultant effect they have on the environment [56, 58–62]. While some studies compare effects of different production strategies and production cycles on the environmental impact of greenhouse vegetable production in specific locations [55, 58–60, 63]. Many of these studies have shown that high-tech, soil-less heated greenhouse production resulted in higher environmental impacts in most impact categories that were studied than unheated tunnels and greenhouses[55, 58–60, 64, 65].

Likewise, numerous studies exist that evaluate the effects of pesticide and fertilizer management on the environment. For example, Hayashi and Kawashima (2004)[66] in their study of the effects of management practices for greenhouse tomato production compare two different greenhouse production systems, i.e. a conventional system, and a drip fertigation system, with the aim of examining the management of pesticides and fertilizers. Their study reveals that combining fertilization and irrigation through a drip irrigation system reduces the direct environmental impacts [66]. Likewise, Martinez-Blanco et al. (2011)[67] in their impact assessment study of horticultural tomato production under Spanish conditions in both open-fields and greenhouses showed that using compost from municipal organic waste as fertilization had lower emissions and caused lesser environmental degradation and pollution as compared to mineral fertilizers.

Several studies have been conducted on the utilization of various technologies for greenhouse production including the type of structure. For instance, Torrellas et al. (2008)[68] showed that for sub-tropical regions such as that of Canary Islands, the focus of their study, simpler greenhouse structures were better environmentally. Similarly, studies on greenhouse production under Italian conditions showed that a greenhouse roof structure made of wood with plastic film covering is more environmentally compatible, with a 50% recycling rate notwithstanding, as compared to a structure in zinc-coated steel with glass covering due to the utilized quantity and the production process of the material [64].

With regards to the management systems of waste from the greenhouse tomato production, Munoz et al. (2003)[69] in their study related to the comparison of different strategies for waste management of plastic waste and biodegradable matter in southern Europe showed that compost of biodegradable matter was the most environmentally sustainable method of managing the waste. On the other hand, an environmental assessment of the energy costs and requirements related to greenhouse tomato production in high altitude tropic regions revealed that improving tomato yield, efficiency of water use and technological advancement can significantly reduce the environmental impact of greenhouse tomato production

[70].

However, European case studies, especially related to horticulture production in heated greenhouses, Boulard et al. (2011)[58] and Torrellas et al. (2012)[65, 71] are especially worth mentioning. The former conducted the environmental assessment for seasonal greenhouse tomato production in France in plastic polytunnel and compared it with results from year-round greenhouse tomato production in Northern France in heated plastic/glass greenhouses. They determined that the type of structure notwithstanding, it was the heating requirements that led to the most impact on the environment, which was around 4.5 times more than the production in polytunnel [58]. Likewise, Torrellas et al. (2012)[65, 71] showed that of the different European greenhouse production scenarios studied, the environmental impact from the climate control system were highest in the Netherlands and Hungary while most of the environmental burdens in Spain resulted from the greenhouse structure and fertilizer management process [72]. These results are reflected in several other studies, whereby in cold climates, the climate control system, specifically the heating requirements, has the greatest environmental burden for greenhouse tomato production in heated greenhouses [25, 73–77]. Verheul and Thorsen (2010) [25] have shown that particularly for greenhouse tomato production under Norwegian conditions, it is the total CO_2 emissions that are by far the most polluting factor. Furthermore, CO_2 emissions from the structure and variable materials, including growth medium and fertilizer, is only about 0.150.20 kg CO_2 per kilo tomato, while CO_2 emissions from fossil fuel is around 4 kg CO_2 per kilo tomato [25].

Despite the vast array of literature on the various aspects of greenhouse vegetable production in different regions and their environmental impact, studies related to the use of renewable energy are limited especially for high latitude regions. Many of the studies related to the evaluation of the environmental impact of greenhouse vegetable production show that there is a trade-off between the economic performance and the environmental impact. However, there is considerable variation in terms of the climate and light conditions among different regions and therefore a variation in techniques in greenhouse production is required, which can lead to a variation in the results. Moreover, many of the high latitude regions, such as Norway, have a significant production of renewable energy, especially in relation to other regions that have considerable greenhouse vegetable production (IRENA, 2021)[78]. Moreover, there are large variations in the geographic and outdoor climate condition between different regions in Norway, that could possibly affect the production process and the subsequent profitability, resource use and resultant environmental impact. The differences in the climate conditions, could also necessitate a variation in the greenhouse production strategies, including artificial lights, energy-saving equipment, thermal screens etc. It is also worth noting that the influence of a specific greenhouse design on the economic performance may not always correlate to the environmental impact. Therefore, there is a need to study effects of different production strategies on the economic performance, resource use and the environment in cases where the traditional fossil energy sources are supplemented by renewable energy resources.

This study has attempted to provide a comprehensive picture of greenhouse tomato production in high latitude regions by adapting different design elements according to the local climate in Norway, by paying special attention to the considerable amounts of renewable energy sources present in these regions in order to assess the environmental impact of locally grown tomatoes that are also economically profitable.

1.5 Significance of the study

Despite unfavorable weather conditions in Norway, there is a significant demand of fresh vegetables, especially tomatoes and cucumber, in the Norwegian market, which is met through a combination of local seasonal production and import of foreign produced vegetables. This is problematic since on the one hand, the current production takes place mostly during the summer and some during autumn with heating and artificial lighting, making it not only energy intensive but also costly. Coupled with the transportation and storage related activities, the availability of fresh tomatoes in Norwegian markets leaves huge carbon footprints. Therefore, there is a need for ways to not only mitigate the environmental impacts of fresh vegetable production but also to encourage local production by making use of greenhouse technology resulting in the production process that is both economically efficient and environmentally friendly.

On the other hand, the Norwegian case is interesting with respect to the country's drive towards a climate friendly economy and the abundant supply of renewable resources. Norway has considerable amounts of renewable energy as compared to other regions having significant greenhouse production (IRENA, 2021)[78]. The production of electricity from renewable sources, mainly hydropower, is the largest in Norway across Europe and the country has one of the lowest carbon emissions from the power sector (Ministry of Petroleum and Energy, 2020)[24]. On the other hand, there is a growing interest within the state and society in promoting sustainable practices in different sectors, with around 69.4 per cent of Norwegians' view being that human activity is affecting the climate [79] and that efforst need to be made in order to mitigate them. This resonates with the government's plan to reduce carbon emissions by at least 40% by 2030 (Norwegian Ministry of Climate and Environment, 2019) under the targets set by the Paris Agreement and other national goals such as 'Klimakur 2030' (lit. climate cure 2030) (Miljødirektoratet, 2020)[80]. The existing will in the Norwegian state and society to combat climate change, the substantial amounts of renewable energy and the possibility of replacing fossil energy in the greenhouse sector with renewable energy make studying greenhouse production of fresh vegetable in Norway highly significant.

The present study, therefore, is important since it attempts to contribute to research on greenhouse tomato production by examining the effects of different design elements and lighting strategies on the profitability of production and its effects on the environment. The study is beneficial for both local tomato growers who either intend to build new greenhouses or adapt already existing units and in policy formulation related to providing incentives for certain greenhouse technologies with an environmental consideration and/or focusing on increasing local tomato production. The results of the study are useful since they can assist in designing and adapting greenhouses for increased economic performance and reduced carbon emissions from the use of fossil fuel under diverse climatic conditions in high latitude regions.

1.6 Organization of the study

The present study comprises of five sections including the introduction and conclusion.

The second chapter consists of the materials and methods section, which forms the basis of this work. It deals with a detailed explanation of the greenhouse design model by Vanthoor et al. (2011)[10] that has been adapted to meet the local climate conditions and is followed by an explanation of the selected greenhouse design elements and the process in which they have been utilized in the first stage of our study, followed by a detailed description of the life cycle assessment carried out using SimaPro software and the related data inventory and system boundary description.

The next chapter contains a detailed description of our results from the simulation of greenhouse tomato production under local Norwegian conditions including their respective impact on the environment and discussion on the results, their implications and limitations along with their relevance with existing literature.

In the fourth chapter, we have presented a general discussion on our findings by placing our study in the broader literature related to greenhouse tomato production, its economic analysis, resource use and the subsequent environmental impact, including a discussion on the limitations and the contributions of this study on further research.

This section is followed by the conclusion, in which the main findings and implications of our work have once again been presented. The publications, as a corresponding author, have been presented as part of appendices.

Chapter 2

Materials and Methods

This chapter entails a detailed description of the methods we have adopted in our study in order to reach our research objective. In the first stage we have simulated the effects of different greenhouse design elements by using a greenhouse design model by Vanthoor (2011)[10] in order to predict an optimal greenhouse design that accrues the highest net financial return (NFR) and lowest fossil fuel use for the seasonal tomato production in four different locations across Norway. In the second stage, a modified version of the greenhouse model is adopted in order to calculate the NFR and energy use for extended season and year-round tomato production in the four locations in Norway, followed by a life cycle assessment in the final stage of the best designs in the three production seasons in order to assess whether the greenhouse designs that are profitable for seasonal and extended and year-round are also environmentally friendly.

2.1 Selected locations

The prospect of greenhouse tomato production and its subsequent environmental impact was conducted for three production seasons: seasonal production (mid-March to mid-October), extended season (20th January to 20th November) and year-round production. This was done by evaluating different greenhouse designs in four different locations across Norway, having differing climates and a combination of different inland and coastal regions, as shown in figure 2.1. The selected locations included: Orre in southwestern (SW) Norway (lat. 58.71, long. 5.56, alt.

18 m a.s.l.), Kise in eastern (E) Norway (lat. 60.46, long. 10.48, alt. 130 m a.s.l.), Mære in mid (M) Norway (lat. 63.43, long. 10.40, alt. 18 m a.s.l.), and Tromsø in northern (N) Norway (lat. 69.65, long. 18.96, alt. 60 m a.s.l.). The reason for the variation in selected regions is either due to the already existing tomato production in these areas or the potential of future greenhouse tomato production in these areas following local demands. Differences in the outdoor climate of each location are shown in figure 1.1.

Figure 2.1: The four locations in Norway, representing coastal and inland climates, for which the greenhouse designs were evaluated.

Before proceeding with the evaluations, a verification of the model's ability to predict the indoor temperature, CO_2 concentration and the fresh weight of tomato crop was conducted against observed data for one of the selected greenhouse designs at Orre for seasonal production and year-round production with HPS as supplemental top light and at Mære for extended season. It should be noted that extended seasonal production in the existing greenhouse at Mære takes place using both HPS and LED as top light; however, in our successive designs for extended season simulation, we have only considered LED as inter-lighting. The data related to the external weather including air temperature, wind speed, global radiation (iglob) and relative humidity needed for the greenhouse climate module were acquired from the LandbruksMeteorologisk Tjeneste (LMT) (lit. Agricultural Meteorological Service) (https://lmt.nibio.no/) of Norwegian Institute of Bioeconomy Research (NIBIO) for each location.

2.2 Greenhouse design

The evaluated greenhouses in all locations consisted of a Venlo type greenhouse [81] which is the most common type of greenhouse structure in use in cold climate regions, having standard glass roofs and natural ventilation that comprised of roof vents on each side equaling approximately 15% of the overall floor area. The material usage for these kinds of greenhouses is taken to be about 17.3 tons of concrete, 7.1 tons of steel (which includes 4.6 tons for construction and 2.5 tons for heating pipes and boiler) and 1.7 tons of aluminum per decare [73]. The side walls had no ventilation. The greenhouses were rectangular in shape (90 x 64 m) and had an overall surface area of about 5760 m^2 and side cover height of 6 m. The floor of the greenhouse was of concrete and had a support structure with rail and grow-heating pipes and a steel boiler. The lifespan of the greenhouse structure was presumed to be 20 years. The material of the roof consists of 4 mm thick glass sheets with a specific gravity of 2.23 g/cm^3. The material used was successively calculated to be 12 tons of glass per decare. These values were based on Williams et al. (2006), Antón et al. (2012) and Verheul & Thorsen (2010) [25, 73, 82]. The light transmissivity of the greenhouse was set to 64%. Plants were grown in regular Rockwool slabs, which were irrigated by a drip irrigation system and bumblebees were used within the greenhouse for pollination throughout the growing season. The marketable yield, that is 1st class fruits, was considered to be above 95% of the total fresh weight predicted yield and at light red ripening stage.

The greenhouse equipment used during the production consisted of trolleys, cultivation gutters, shade systems and growing lights. The material used for a trolley with steel support was determined to be 11.77 kg steel, 0.77 kg aluminum and 0.93

kg of nylon per m^2. The cultivation gutter was assumed to contain galvanized steel with polyurethane coating and un-laden weight of 6.99 kg m^2 (www.formflex.nl). It was assumed that 1 m^2 of cultivation area was required for 1.12 m^2 of gutter. Tying hooks consisting of both nylon and steel were assumed to be 14 cm long and weighed 18.6g, and the amount of nylon rope on the hook was 12 m (10.2 grams). Tomato clips (nylon) were also used in production, and were assumed to weigh 1.4 g per clip. For cultivation tables, cultivation gutters, shade curtains and fixture, a service life of 10 years was assumed.

There were two heating systems using steel rail and grow pipes used for primary and secondary pipe heating, and filled with hot water: a boiler heating system that used fossil fuel energy with a capacity of 1.12 MW and a heat pump that used electricity with a capacity of 25 Wm^{-2}. The excess heat produced during the day or when supplemental lighting are turned on in the greenhouse can be stored by the heat pump in a cold buffer and can be used afterwards through the hot buffer.

It is noteworthy that electricity is predominantly generated by water in Norway and is therefore considered a green resource since CO_2 emissions for electricity use is significantly lower than that of natural gas. Both night and day screens were used in the evaluation, with the night screen comprising of 50% Polyethylene and 50% Aluminum (Alu) with a weight of 0.12 kg m^{-2} and the day screen consisting of 100 % Polyethylene (PE) and a weight of 0.19 kg m^{-2} (www.tradgardsteknik.se/). Moreover, two types of supplemental lighting, i.e. HPS and LED, were used for the extended and year-round production seasons. It was assumed that the growth light comprises of a light bulb (600 W-HPS) along with a fixture comprising of 0.54 kg aluminum and a 1.5m cord, while the fitting parst, housing, brackets and aluminium blocks for LED lights consisted of 8465 g aluminium and 42g copper for wiring along with 25g LED diodes and 127g glass [83–85]. The environmental impact of light bulbs was assessed based on previous analyses [86] and it was assumed that light bulbs have a service life of 2 years. CO_2 was delivered to the greenhouse either through the boiler (mainly during the day) as a result of burning natural gas or from a tank (when the boiler was turned off) as pure CO_2. The greenhouse climate set points that were used throughout all the four locations, greenhouse designs and the three production seasons are presented in table 2.1.

Greenhouse climate management	Extended season	Year-round	Unit	Explanation
Tair_vent_on	23	23	(C)	The indoor greenhouse temperature above which the greenhouse is ventilated during the daytime
RHair_vent_on	90	90	(%)	The indoor greenhouse relative air humidity above which the greenhouse is ventilated
Tair_heat_on (night/day)	17/19	17/20	(C)	The heat is turned on below this temperature for night and day respectively
Tair_fog_on	24	24	(C)	The indoor temperature above which fogging is used
Tair_heat pump_on	21	22	(C)	The heat pump is turned on if the indoor air temperature reaches above these points
Tout_ThScr_on	12	14	(C)	Night thermal screen is used below this outdoor temperature
Tout_Day_EnScr_on	10	10	(C)	Day thermal screen is used below this outdoor temperature
iglob_Day_EnScr_on	150	150	(Wm-2)	Day thermal screen is used below this global radiation
CO$_2$Air_Min	410	410	(ppm)	The CO$_2$ concentration below which CO$_2$ is added
CO$_2$Air_Max	1200	1200	(ppm)	Set point for maximum amount of CO$_2$ if all lights are on
Time_Led_on	04:00	04:00		LED's are switched on at this time after 5 weeks' planting in greenhouse
Time_Led_off	22:00	22:00		LED's are switched off at this time
Time_HPS_on	04:00			HPS is used from the first day of planting at this time
Time_HPS_off	22:00			HPS are switched off at this time
iglob_HPS_on	350		(Wm-2)	HPS are switched off if the global radiations are above this value
Crop conditions				
LAI_start (Initial)	0.3	0.3	(-)	Initial leaf area index
LAI_max	3	3	(-)	Maximum leaf area index
Seasonal Production				
Start growing period		March 10th	(-)	
End growing period		October 15th	(-)	
Extended season duration				
Start growing period		January 20th	(-)	
End growing period		November 20th	(-)	
Year-round Production				
Start growing period		October 1st	(-)	
End growing period		September 31st	(-)	

TABLE 2.1: A description of greenhouse internal climate set-points.

2.3 Stage I & II: Evaluation of suitable greenhouse designs for greenhouse tomato production during seasonal, extended and year-round production

2.3.1 Model overview

In the first stage, the study is based on the greenhouse design model by Vanthoor, Stanghellini, de Visser and Van Henten (2011a and 2011b)[46, 47] in order to simulate the production of tomatoes for seasonal production and to assess the effect of different greenhouse designs on the economic performance and resource efficiency, as determined by its annual net financial return (NFR) and energy used, by adjusting design elements according to the local climate conditions in Norway. The model entails three inter-related modules: a greenhouse climate module, crop yield module and an economic module. Therefore, in this integrated greenhouse design and economic module, the NFR is determined by yield, variable costs, construction costs, depreciation, and costs for maintenance of equipment that is used in greenhouse production while the environmental impact is determined by the CO_2 emissions as a result of the electricity and fossil fuel used.

The greenhouse climate module depicts the impact of the outdoor climate, internal set points for temperature, CO_2-concentation, humidity and greenhouse design elements on the indoor climate of the greenhouse and its resource use. The crop yield module determines the yield based on the indoor climate data of the greenhouse. The economic module determines the NFR of the production, which is based on the resource use and the crop yield. A detailed presentation of the components of the economic module as obtained from Vanthoor et al. (2012a)[87] is presented in section 2.3.1.

The model was previously used to identify appropriate greenhouse designs for various warmer climates and lower latitude regions [87]. The model has thus been adopted to suit the local climatic conditions of Norway since the designs that were considered profitable for tomato production in the initial selected locations cannot necessarily yield the same results in regions having differing climate and light conditions. The same applies to greenhouse designs among different locations in Norway that have varied temperature and climate, and is also applicable to other high latitude regions with varying climates. Likewise, the profitability of certain greenhouse designs may not always be correlated with the environmental impact.

In the second stage, we used the modified version by Righini et al. (2020)[11] of the above-described model, who added artificial lighting and heat harvesting to validate the model for northern climatic conditions. The modified version (Figure 2.2.) has been used in this stage in order to evaluate different artificial lighting strategies, including light types (LED, HPS) and photosynthetic photon flux densities (PPFD) gradients, together with design elements to assess the effect of different greenhouse designs on the NFR, energy use and CO_2 emissions for extended season (ES) and year-round (YR) tomato production in several different climate conditions in Norway, and thus identifying suitable greenhouse designs. The work has also taken into consideration the seasonal tomato price variations.

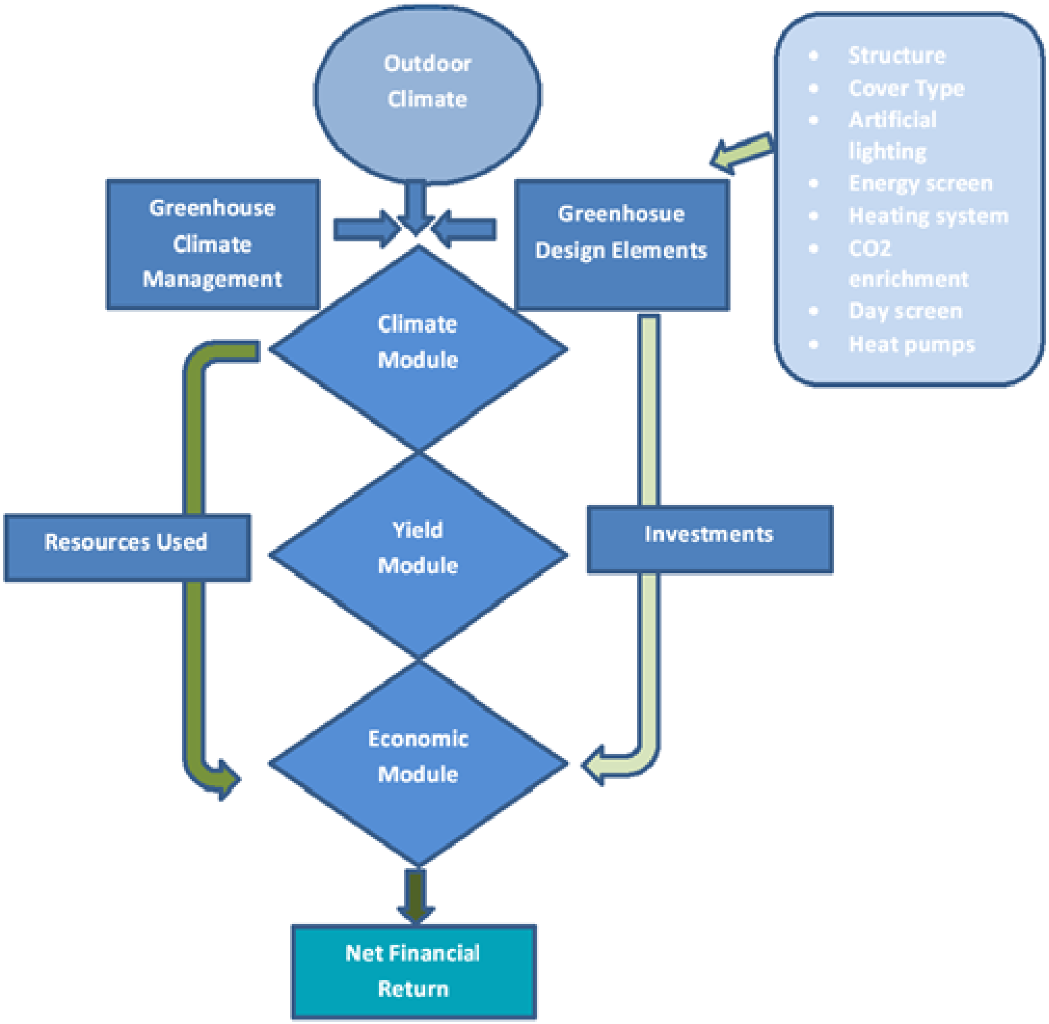

FIGURE 2.2: An overview of the model-based greenhouse design method.

2.3.1.1 Economic tomato yield module

The yearly net financial return P_{NFR} (NOK m^{-2} $year^{-1}$) is calculated according to:

$$P_{NFR}(t_f) = -C_{fixed} + \int_{t=t_0}^{t=t_f} \dot{Q}_{CropYield} - \dot{C}_{Var} \ (NOK m^{-2} year^{-1}) \tag{2.1}$$

where t_0 and t_f are the start and the end time of the growing seasons, C_{fixed} (NOK m^{-2} $year^{-1}$) are the fixed costs for the tangible assets (greenhouse structure, climate computer, cooling system, heating system and structure), C_{Var} (NOK m^{-2}

$year^{-1}$) are the variable costs, and $Q_{CropYield}$ (NOK m^{-2} $year^{-1}$) is the economic value of the crop yield.

The economic tomato yield $\dot{Q}_{CropYield}$ is defined by:

$$\dot{Q}_{CropYield} = \eta_{FMmarketable}\eta_{DMFM}q_{tomat}(t)\dot{D}M_{Har}(t) \ \ (NOKm^{-2}h^{-1}) \tag{2.2}$$

where $\eta_{FMmarketable}$ (-) is the marketable fraction of the harvested yield and η_{DMFM} is the conversion factor from dry matter to fresh matter (kgFM mgDM^{-1}), q_{tomat} (NOK kg^{-1}), is the price for first class tomatoes and DM$_{H}ar$ (mgDMm^{-2} h^{-1}) is the tomato dry matter harvest rate, which is obtained from the yield model. To calculate the cost associated with the collected amount of tomatoes, the crop yield is defined as:

$$Yi\dot{e}ld = \eta_{DMFM}\dot{D}M_{Har}(t) \ \ (kgFMm^{-2}h^{-1}) \tag{2.3}$$

2.3.1.2 Fixed costs

The yearly fixed costs, C$_{fixed}$ (NOK m^{-2} $year^{-1}$),which include maintenance and depreciations, are defined as:

$$C_{fixed} = C_{interest} + \sum_{i=1}^{N} C_{construction,i} + C_{Rem} \ \ (NOKm^{-2}year^{-1}) \tag{2.4}$$

where C$_{interest}$ (NOK m^{-2} $year^{-1}$) are the interest costs of the total investments. Here, i denotes the construction elements and N is the total number of greenhouse design elements used in selected greenhouses construction. C$_{construction}$ (NOK m^{-2} $year^{-1}$) are the costs for depreciation and maintenance and C$_{Rem}$ (NOK m^{-2} $year^{-1}$) are the remaining costs of construction and equipment.

The yearly average interest costs $C_{interest}$ (NOK m^{-2} $year^{-1}$) are calculated as linear depreciation of construction elements till the end of the lifespan of the greenhouse.

$$C_{Interest} = \frac{\eta_{interest}}{100A_{floor}} \sum_{i=1}^{i=N} \frac{C_{invest,i}}{2} \ (NOKm^{-2}year^{-1}) \tag{2.5}$$

where $\eta_{Interest}$ (% $year^{-1}$) is the interest rate, A_{floor} (m^2) is the greenhouse floor area, and $C_{invest,i}$ (NOK) is the initial investment of the construction element i.

The annual costs for depreciation and maintenance of the structure elements $C_{construction,i}$ are defined by:

$$C_{Interest} = \frac{\eta_{maintenance,i} + \eta_{depreciation,i}}{100A_{floor}} \times C_{invest,i} \ (NOKm^{-2}year^{-1}) \tag{2.6}$$

where $\eta_{maintenance,i}$ (% $year^{-1}$) are the annual maintenance fraction of construction element i, $\eta_{depreciation,i}$ (% $year^{-1}$) determines the annual depreciation of construction element i. The remaining costs C_{Rem} related to the greenhouse equipment are defined by:

$$C_{fixed} = \eta_{remaining} \sum_{i=1}^{N} C_{construction,i} \ (NOKm^{-2}year^{-1}) \tag{2.7}$$

where $\eta_{remaining}$ (% $year^{-1}$) is the cost for the unaccounted fraction of the total greenhouse construction costs, costs for disinfection material, internal transport, and sorting. In view of the huge variability among conditions, costs related to the rent or purchase of the greenhouse area, are not taken into account here and are set to be zero.

2.3.1.3 Variable costs

The variable costs $\dot{C}_{var}$ are defined as:

Design element Fixed costs	e_j	Investment NOK m^{-2}	Investment NOK $unit^{-1}$	Depreciation (% year^{-1})	Maintenance (% year^{-1})	Construction (NOK m^{-2} year^{-1})	Source
Structure							Vermeulen (2016) [88] +E^*
Venlo 5760 m^2		519.0		5.0	0.5	28.5	
Covers							[89]
Glass		93.5		5.0	0.5	5.1	
Screens							Dansk Gartneri [89]
No screens	1	0	0	0	0	0	
Day screen	2	35.5		25	0	8.7	
Night screen	3	100		15.0	5	15.5	
Structure energy screens		130		7.0	5	10.5	
Boiler							Vermeulen (2016) [88]+ E*
Boiler: 0.75 MW	1		620530	7.0	1	9.9	
Boiler: 1.16 MW	2		660000	7.0	1	10.6	
Heating pipes		65		5.0	0.5	3.6	
Mechanical Heating							Vermeulen (2016) [88]+ E*
No	1	0	0	0		0	
Mechanical heat and cool: 50 W m^{-2}	2		2688000	7.0	2	37.0	
Cooling systems							Vermeulen (2016) [88]+ E*
No	1	0	0	0	0	0	
Fogging: 200 g h^{-1} m^{-2}	2	65		7.0	5	5	
CO_2 supply							Vermeulen (2016)[88] + E*
Pure CO_2: 130 kg ha^{-1} h^{-1}	1		48763	10.0	0	0.9	
CO_2: from boiler	2		31700	10	5	2.4	
CO_2 distribution system	5		10.0	5	0.7		
Artificial lighting							Growers
HPS NOK/W			0.3	36*106h	1		
HPS structure NOK/W			2.13	15	1		
HPS cable NOK/W			0.25	10	1		
LED NOK/W			12.9	126*106h	0.5		
LED cable NOK/W			0.25	10	1		
Remaining costs for irrigation, crop protection, internal transport							Growers
All selected locations		500		10.0	5	75	

TABLE 2.2: The fixed costs associated with the greenhouse design elements and element alternatives. e_j in the second column represent the number for each design element option. E^* = around 10 % extra costs for transportation expenses and exchange rate (7th Column). *Growers*= The data was obtained from interviews with commercial tomato growers, whose production is representative for Norway, by advisors at NIBIO.

$$\dot{C}_{Var} = \dot{C}_{plant} + \dot{C}_{water} + \dot{C}_{CO_2} + \dot{C}_{fossilfuel} + \dot{C}_{electricity} \ (NOKm^{-2}h^{-1}) \qquad (2.8)$$

where $\dot{C}_{plant}$ (NOK $m^{-2}h^{-1}$) are the costs associated with the crop and are time dependent (such as bumblebees for pollination, fertilizers and crop protection),

$\dot{C}_{water}$ (NOK $m^{-2}h^{-1}$) are costs for water used and $\dot{C}_{CO_2}$ (NOK $m^{-2}h^{-1}$) are the costs for carbon dioxide used as a resource, $\dot{C}_{fossilfuel}$ (NOK $m^{-2}h^{-1}$) are costs for the fossil fuel and $\dot{C}_{felectricity}$ (NOK $m^{-2}h^{-1}$) are the electricity costs used for heating and cooling, in seasonal production. The variable costs C_{var} (t_0) that do not depend on the crop yield are defined as:

$$C_{Var}(t_0) = C_{plant}(t_0)\ (NOKm^{-2}year^{-1}) \tag{2.9}$$

where $C_{plant}(t_0)$ are the plant costs that do not depend on the crop yield and thus are not time dependent, i.e. growth medium, nursery plants. Other plant costs that depend on the crop yield i.e. labor and transport are defined as:

$$\dot{C}_{plant} = C_{labour}(\frac{\zeta_{labour}}{kg}\dot{Yield} + \frac{\zeta_{labour}}{m^2} + \zeta_{transport}\eta_{FMmarketable}\dot{(Yield)})\ (NOKm^{-2}year^{-1}) \tag{2.10}$$

where C_{labour} (NOK h^{-1}) is the labor costs, $\frac{\zeta_{labour}}{kg}$ $(hkg^{-1}$FM) is the labor cost factor that describes the impact of the production level on labor cost, $\frac{\zeta_{labour}}{m^{-}2}$ (hm^{-2}) is the labor cost coefficient that describes the impact of plant related labor (no harvest) on labor cost, $\zeta_{transport}$ (NOK kg^{-1}) represents the transport cost per amount of tomatoes. The variable costs for water $\dot{C}_{water}$, CO_2 $\dot{C}_{CO_2}$ and electricity $\dot{C}_{G.energy}$ are calculated according to:

$$\dot{C}_{water} = 10^{-3}C_{water}(1 + \frac{\eta_{drain}}{100})MV_{canapyair} + MV_{fog.air}\ (NOKm^{-2}year^{-1}) \tag{2.11}$$

$$\dot{C}_{CO_2} = 10^{-6}C_{CO_2}MC_{extr.air}\ (NOKm^{-2}h^{-1}) \tag{2.12}$$

$$\dot{C}_{fuel} = \frac{c_{fuel}}{\eta_{fuel}}(H_{BoilPipe})\ (NOKm^{-2}year^{-1}) \tag{2.13}$$

where c_{water} (NOK m^{-3}) is the water price, η_{drain} (%) is a fraction of drainage to ensure sufficient crop transpiration. $MV_{canapyair}$ (kg $m^{-2}h^{-1}$) is the transpiration

rate of the crop, $MV_{fog.air}$ (kg $m^{-2}h^{-1}$) is the fogging rate, c_{CO_2} (NOK kg^{-1}) is the CO_2 price. $MC_{extr.air}$ (mg $m^{-2}h^{-1}$) is the CO_2 enrichment rate, c_{fuel} (NOK m^{-3}) is the fuel price, η_{fuel} (J m^{-3}) is the energy efficiency of the fuel, $H_{BoilPipe}$ (W m^{-2}) is the heat supply to the heating pipes.
The total investment (NOK m^{-2}) for the greenhouse is defined as:

$$C_{investment} = \sum_{i=1}^{i=N} C_{investment,i} \ (NOKm^{-2}year^{-1}) \tag{2.14}$$

Resource	Amount	Unit price (NOK)	Unit	NOK m^{-2}	Source
Area	5760		m2		
Plants	2.6	25.0	Plant	65	Hovland, 2018 [90]
Growth medium	2.5	10.4	Slab	26	Hovland, 2018 [90]
Fertilizer	1.0	30.0	m2	30.0	Hovland, 2018 [90]
Pollination	1.0	12.0	m2	12.0	Hovland, 2018 [90]
Pesticides	1.0	5.0	m2	5.0	Growers*
Packaging	6.7	3.0	Box	20	Growers
Energy gas		0.39	kWh		http://www.ngfenergi.no/ukens_priser
Energy light		0.39	kWh		ttp://www.ngfenergi.no/ukens_priser
Marketing	1.0	3.0			Growers
Interest	1.0	5.0			Growers
Water		8	m3		Growers
Operating assets	1.0	15.0	m2	15.0	Growers
Other	1.0	10.0	m2	10.0	Growers
Labor costs	1.2	180.0/hour	m2		Growers
Insurance / other	1	15.0	m2	15.0	Growers

TABLE 2.3: Variable costs that were used in the simulations. *= The data was obtained from interviews with commercial tomato growers whose production is representative for Norway.

2.3.2 Economic settings

The tomato price trajectory for the years 2016 (for seasonal production evaluation) and 2019 (for extended and year-round production seasons evaluation) were obtained from Grøntprodusentenes Samarbeidsråd (lit. the Green Growers' Cooperative Marked Council) (https://www.grontprodusentene.no/prisinformasjon-alle-kulturer/) and were applied throughout the four locations and across designs. Moreover, the fixed and variable costs per input unit associated with Norwegian construction and production conditions were kept the same throughout all the designs and locations. These costs were acquired from our review of literature and from interviews conducted by advisors at NIBIO with tomato growers across the country.

2.3.3 Evaluation of the prediction accuracy

The model's ability to accurately predict data such as the internal relative humidity, CO_2 concentration and fresh tomato weight yield was evaluated using the relative root mean squared error (RRMSE):

$$RRMSE = \frac{100}{y_{data}} \sqrt{\frac{1}{n} \sum_{i=1}^{N} (y_{Mod,i} - y_{Data,i})} \qquad (2.15)$$

where y_{data} represents the average of calculated data over the whole growing period, n represents the number of measurements, $y_{Mod,i}$ denotes the simulated yield at time instant i and $y_{data,i}$ represents the measured value at time instant i.

2.3.4 Price sensitivity

The economic productivity of a specific case is influenced by the price of the product, i.e., tomato, and the costs of energy during the production seasons, and these factors in particularly have the greatest effect on the NFR for the extended and year-round production season. We have, therefore, varied the tomato prices and the electricity prices in order to perform a global sensitivity analysis (GSA) in order to capture the relationship between different input variables [91, 92]. Moreover, there is a substantial difference in the whole-sale seasonal and off-seasonal price of tomatoes due the seasonal difference in import duties for tomatoes (Import tariffs for agricultural products, 2016). From week 19 to week 41 during the year 2019 the tariff rate for tomatoes ranged from 10.21 NOK kg^{-1} and 6.86 NOK kg^{-1}, while for the rest of the year the tariff rate was zero NOK [29]. The range of tomato prices that have been used across all designs and locations has been obtained from Grøntprodusentenes Samarbeidsråd [29].

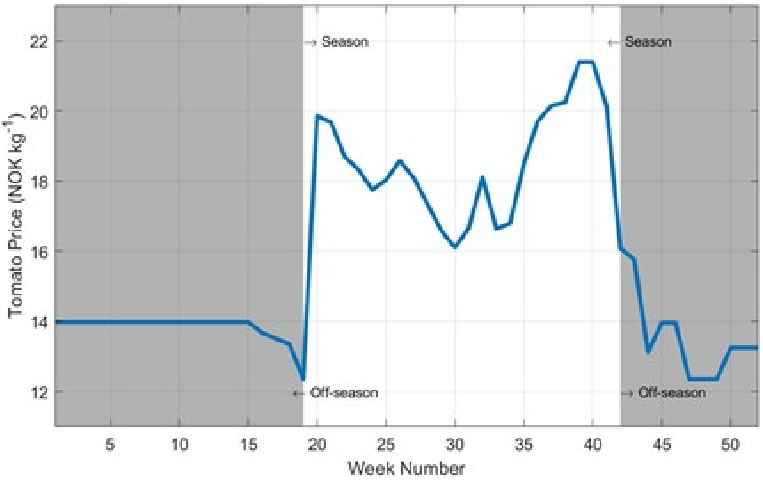

FIGURE 2.3: Tomato price used for season and off-season production period. The dark area depicts the off-season tomato price while the light area depicts the seasonal tomato price.

2.3.5 Description of evaluated greenhouse designs

The different greenhouse designs that were evaluated for different production cycles were considered based on the discussion with advisors at NIBIO and a thorough review of literature [18, 93–97]. In Norway, seasonal production mostly takes place without additional lighting during the months of March to October. Artificial light is supplemented in order to extend the production season and increase the yield, without which production is quite difficult. In our present study, only LED was supplemented as inter-lighting for both the extended and year-round production seasons with a fixed capacity of 125 µmol. For year-round production season, both HPS and LED were used as top-lighting with their capacities varying from 150 µ mol and 350 µmol. Top lighting was not used during the extended season. The capacities of supplemental lighting have been varied in order to find the best combination of top and inter-lighting within the greenhouses that yield best results.

For seasonal production, a greenhouse consisting of a gas boiler having a capacity of 1.16 MW used for heating was considered to be the standard design. The design had no indoor day or night energy screens, and no artificial cooling or fogging system was used. When a night thermal screen made up of 50% aluminum and 50% polyethylene was added in order to save energy whenever the temperature reached below 14 at night (See Table 2.1 for an explanation about how day and night settings were initiated), the design became the same as the existing greenhouse in Orre, for which the climate and yield modules have been validated. Subsequently, different design elements were varied in these designs to form successive greenhouse designs for seasonal production.

For the extended and year-round production season, the greenhouse design consisting of HPS lighting, one thermal screen, boiler pipe for heating and CO_2 from two sources (i.e., from boiler and pure from tank) was considered to be our basic design and is similar to the existing greenhouse in Orre and Mære. In order to validate the model outputs, HPS lights were supplemented by LED inter-lighting in Mære. For the rest of the designs for the two production seasons, the design elements including the number of thermal screens, heating sources (i.e., boiler an electric heat pump) and types, capacities and positioning of artificial lighting were varied. An overview of the greenhouse designs evaluated for the three production cycles and four locations in Norway are presented in Tables 2.4, 2.5, 2.6.

Greenhouse designs evaluated for seasonal tomato production					
	0S	NS	DNS	DNSF	DNSFM
Boiler	Yes	Yes	Yes	Yes	No
Mechanical heating	No	No	No	No	Yes
Screens	No	Yes	Yes	Yes	Yes
CO_2 supply	Yes	Yes	Yes	Yes	Yes
Cooling systems	No	No	No	No	Yes

Table 2.4: The different greenhouse technological design packages for seasonal production. The NS represents the greenhouse in SW Norway (Orre), for which the indoor climate and tomato yield prediction accuracy was evaluated. 0S refers to the Standard greenhouse (without additions), NS is Night energy screen, DNS is Day and night energy screens, DNSF is Day and night energy screens with fogging for cooling, and DNSFM refers to Day and night energy screens with fogging and mechanical cooling and heating. Prices used for the design elements are explained in Table 2.2.

Each of the designs in the three production seasons, as presented in table 2.4, 2.5, 2.6 were evaluated in the first two stages in order to obtain the design that yielded the highest NFR or had the lowest energy use. Subsequently, an LCA was conducted on these selected designs in order to evaluated whether the design having better economic performance can also be considered environmentally friendly,

Greenhouse designs evaluated for extended season tomato production				
Design Elements	Type/Capacity	NSL *LED*	NDSL *LED*	NDSFML *LED*
Light type and capacity		LED (inter) 125 µmol	LED (inter) 125 µmol	LED (inter) 125 µmol
Boiler- Pipe	Boiler	Yes	Yes	Yes
Screen	Indoor Day Screen (100% PE)	No	Yes	Yes
Screen	Thermal Screen (50% PE+50% Alu)	Yes	Yes	Yes
CO_2	Boiler (if on during the day)	Yes	Yes	Yes
CO_2	Pure (130 kg $ha^{-1}hour^{-1}$)	Yes	Yes	Yes
Fogging		No	No	Yes
Heat pump	(25 W m^{-2})	No	No	Yes

Table 2.5: The different greenhouse technological design packages for extended production season. NSL refers to Night energy screen with light, NDSL to Night and day thermal screens + light, and NDSFML refers to Night and day thermal screens + fogging + mechanical heating + lights. Prices used for the design elements are explained in Table 2.2.

Greenhouse designs evaluated for year-round tomato production									
Design Elements	NSL *HPS*	NSL *HPS+LED*	NSL *LED+LED*	NDSL *HPS*	NDSL *HPS+LED*	NDSL *LED+LED*	NDSFML *HPS*	NDSFML *HPS+LED*	NDSFML *LED+LED*
Light	HPS 350 µmol	(HPS 150 to 350 + LED 125) µmol	(LED 150 to 350 + LED 125) µmol	HPS 350 µmol	(HPS 150 to 350 + LED 125) µmol	(LED 150 to 350 + LED 125) µmol	HPS 350 µmol	(HPS 150 to 350 + LED 125) µmol	(LED 150 to 350 + LED 125) µmol
Boiler	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Day Screen (100%PE)	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Night Screen	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CO_2(Boiler)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pure(CO_2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fogging	No	No	No	No	No	No	Yes	Yes	Yes
Heat pump (25Wm^{-2})	No	No	No	No	No	No	Yes	Yes	Yes

Table 2.6: The different greenhouse technological design packages for year-round production season. NSL refers to Night energy screen with light, NDSL to Night and day thermal screens + light, and NDSFML refers to Night and day thermal screens + fogging + mechanical heating + lights. Prices used for the design elements are explained in Table 2.2.

especially with reference to the carbon footprint of imported tomatoes. The selected designs from each production season on which an LCA was performed are as follows: NS, NDSFM for seasonal production; NDSL, NDSFML for extended season; and NDSFML for year- round production. It should be noted that for the year-round production only one design was evaluated by varying the type and capacities of supplemental lighting since this design resulted in both the highest profit and lowest energy use across all selected locations. Moreover, results for only two locations i.e., Kise, associated with a high NFR and low energy use, and Mære, associated with a low NFR and high energy use have been presented in the following chapter. For results related to the selected designs in the other two locations i.e., Orre and Tromsø, see the appendix C paper III.

2.4 Stage III: Life cycle assessment of greenhouse tomato production in Norway during seasonal, extended and year-round production

2.4.1 Scope and system boundaries

In the third part, the environmental impact of Norwegian greenhouse tomato production was evaluated focusing on the designs that performed relatively better economically out of the selected designs from seasonal, extended season and year-round production seasons. All stages of the products life cycle from raw material extraction to the farm gate was set as the system boundary, as shown in figure 2.4 while the transportation to the wholesaler and the store was excluded. The reference unit for expressing environmental effects, as represented by the functional unit (FU), was related to the yield measurements and denoted by 1 kg tomatoes per year kgy^{-1}

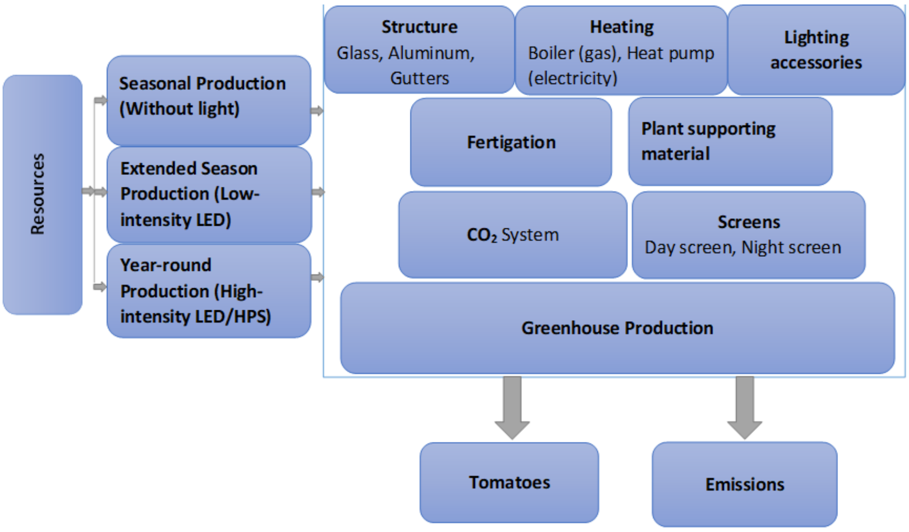

FIGURE 2.4: The system boundaries and process flow chart.

2.4.2 Data inventory

Several studies show that in greenhouse tomato production, the greatest polluting aspect is the total CO_2 emissions. Moreover, the CO_2 emissions from the use of fossil fuel is about 4 kg CO_2 per kilo tomato while from the structural and variable materials, including growth medium, fertilizer, the CO_2 emissions account for only 0.15-0.20 kg CO_2 per kilo tomato [25]. Accordingly, data values relating to greenhouse structure and building, fertilizer, culture medium, packaging, other production material, and waste management have been taken from Verheul and Thorsen (2010) [25] as base values, while data related to the usage of fossil fuel and electricity, CO_2 and yield have been drawn from model-based evaluation of greenhouse designs and production carried out in the first two stages of this study.

Likewise, the production system, as described in the sections above, has been organised in various stages, i.e., greenhouse structure, greenhouse equipment, climate control systems, fertilizers and waste, to enable inventory analysis and the resultant interpretation of results. Tables 2.7, 2.9, 2.9 provide an overview of resources used for different designs, locations, and production seasons.

Input data used in selected greenhouse designs for seasonal tomato production				
	Kise		Mære	
	NS	NDSFM	NS	NDSFM
Crop Yield (kg m^{-2}) (Fresh weight)	41.7	40.3	37.8	36.4
Natural gas (kWh m^{-2})	273.1	137.4	321.8	174.6
Electricity (kWh m^{-2})	0.0	22.1	0.0	22.3
Plant fertilizers				
Nitrate Nitrogen (kgm^{-2})	0.5	0.4	0.4	0.4
Phosphorus (kg m^{-2})	0.1	0.1	0.1	0.1
Potassium (kg m^{-2})	0.8	0.7	0.7	0.7
Magnesium (kg m^{-2})	0.1	0.1	0.1	0.1
Calcium (kg m^{-2})	0.4	0.4	0.3	0.3

TABLE 2.7: Overview of the resources used for the selected greenhouse designs elements for the two regions in Norway for the period Jan-2016 to December-2016. For an explanation of the design names, see section 2.3.5

The data related to the overall amounts of nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) was obtained from advisors at NIBIO. The emissions arising from the production and transport of these fertilizer products were evaluated by SimaPro. The present study does not consider biological plant protection along with the various chemicals the pesticides are comprised of, which are in use by most manufacturers since according to previous studies, CO_2 emissions from the production of pesticides used in Norwegian Greenhouse production is probably minor as compared to the total CO_2 emissions [25]. As far as the waste management is concerned, it was assumed that metal and glass, having a lifespan of 20

Input data used in selected greenhouse designs for extended seasonal tomato production				
	Kise		Mære	
	NDSL	NDSFML	NDSL	NDSFML
Crop Yield (kg m^{-2}) (Fresh weight)	79.5	79.7	76.3	76.6
Natural gas (kWh m^{-2})	536.4	262.3	581.7	295.8
Electricity (kWh m^{-2})	196.8	270.1	212.7	286.0
Plant fertilizers				
Nitrate Nitrogen (kg m^{-2})	0.9	0.9	0.8	0.8
Phosphorus (kg m^{-2})	0.2	0.2	0.2	0.2
Potassium (kg m^{-2})	1.5	1.5	1.4	1.4
Magnesium (kg m^{-2})	0.2	0.2	0.2	0.2
Calcium (kg m^{-2})	0.7	0.7	0.7	0.7

Table 2.8: Overview of the resources used for the selected greenhouse designs elements for the two regions in Norway for the extended seasonal production.

Input factors used in selected greenhouse designs for year-round tomato production				
	Kise		Mære	
	NDSFML *HPS+LED*	NDSFML *LED+LED*	NDSFML *HPS+LED*	NDSFML *LED+LED*
Energy use for HPS 250 µmol				
Natural gas(kWh m^{-2})	138.3	137.1	142.8	142.3
Electricity(kWh m^{-2})	1269.0	948.9	1338	997
Crop Yield (kg m^{-2}) (Fresh weight)	126.9	127.2	127.5	127.8
Energy use for HPS 200 µmol				
Natural gas use	148.3	146.7	154	152.5
Electricity use	1107.0	851.2	1166	893
Crop Yield (kg m^{-2}) (Fresh weight)	120.7	121.2	119.7	121.4
Plant fertilizers used				
Nitrate Nitrogen (kg m^{-2})	1.4	1.4	1.4	1.4
Phosphorus (kg m^{-2})	0.3	0.3	0.3	0.3
Potassium (kg m^{-2})	2.3	2.3	2.3	2.3
Magnesium (kg m^{-2})	0.4	0.4	0.4	0.4
Calcium (kg m^{-2})	1.2	1.2	1.2	1.2

Table 2.9: Overview of the resources used for the selected greenhouse designs elements for the two regions in Norway for the for the Year-round production.

years, were fully recycled while concrete, with a lifespan of 20 years, was recycled 50% and plastics were 50% recycled and 50% incinerated. Emissions included in the study were related to incinerating and emissions due to landfill and incineration. The estimated life span of thermal screens was 4- 5 years and 1 year for Rockwool.

2.4.3 Impact assessment

Different database systems are used to evaluate the environmental impact of various processes and that contain comprehensive data associated with the environmental impact during the production, transport and consumption of various input factors. In the present work, however, SimaPro 9 software (www.simapro.com) has been used to evaluate the life cycle assessment (LCA) of model-based greenhouse tomato production in Norway. This software is a globally recognized tool providing the largest LCA databases in Europe with complete background information. The data associated with the background system, including the production of fertilizers and pesticides, electricity, constructions, etc. was obtained from the Ecoinvent v.3 database and the different impact categories 2.10 related to the environmental impact were calculated using the ReCiPe 2016 Midpoint (H) V1.04 method [98].

Impact category	Abbreviation	Unit
Global warming	GW	g CO_2-eq
Ozone formation, Human health	OzHH	g NOX-eq
Ozone formation, Terrestrial ecosystems	OzTE	g NOX-eq
Terrestrial acidification	TA	g SO2-eq
Freshwater eutrophication	FwEu	g P-eq
Marine eutrophication	Meu	g N-eq
Terrestrial ecotoxicity	TEco	g 1,4-DCB
Freshwater ecotoxicity	FwEco	g 1,4-DCB
Marine ecotoxicity	MEco	g 1,4-DCB
Land use	LU	m2a crop-eq
Mineral resource scarcity	MiRes	g Cu-eq
Fossil resource scarcity	FRes	g oil-eq

Table 2.10: Selected impact categories, their abbreviations, and the measurement units.

Chapter 3

Results and discussion

3.1 Results from the model evaluation

The prediction of air temperature and yield for the three production seasons was fairly accurate as simulated by the model, however, the model performed relatively better when artificial lights were introduced. The relative root mean squared error (RRMSE) for fresh weight tomato yield, temperature and CO_2-concentration was less than 10%. To be precise, despite generally accurate temperature predictions for seasonal production, the measured temperature was under-predicted by the model for the beginning of the production season (20th March to 26th March (day of year 80-86)) as shown in figure 3.1, while for the rest of the season, the temperature was sometimes over predicted. On the other hand, for CO_2-concentration, the predictions were overall higher during the day and lower during the night than the measured values, while values for the temperature were over-predicted during the end of the season (as shown in figure 2 for the days of year 260 to 268) (Figure 3.2).

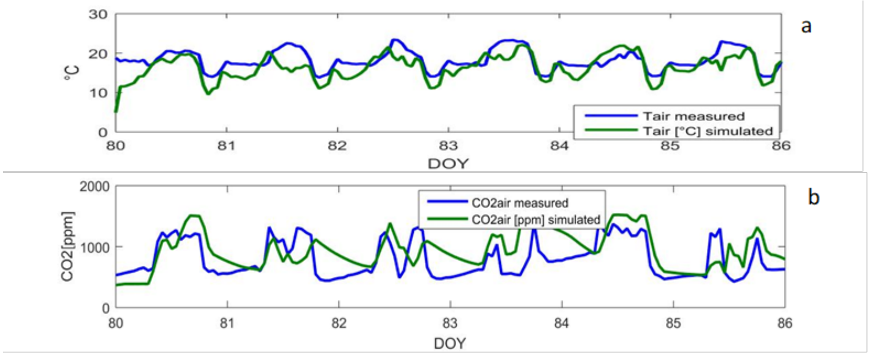

Figure 3.1: Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the start of the growing period. DOY: Day of the Year.

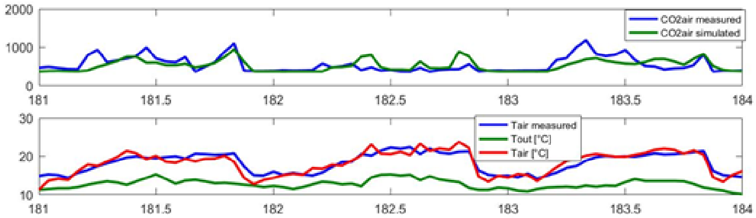

Figure 3.2: Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the mid-production period. DOY: Day of the Year.

When supplemental lights were introduced during the extended and year-round production season, the model gave highly accurate predictions of temperature as compared to during seasonal production. However, during the summer months, a small fluctuation in the model's ability to predict accurate values was seen, which was primarily due to the higher global radiation and external temperatures. The predicted temperature for the extended season for the greenhouse in Mære is presented in Figure 3.3 and the predicted temperature values for the year-round production at the greenhouse in Orre is shown in Figure 3.4 respectively.

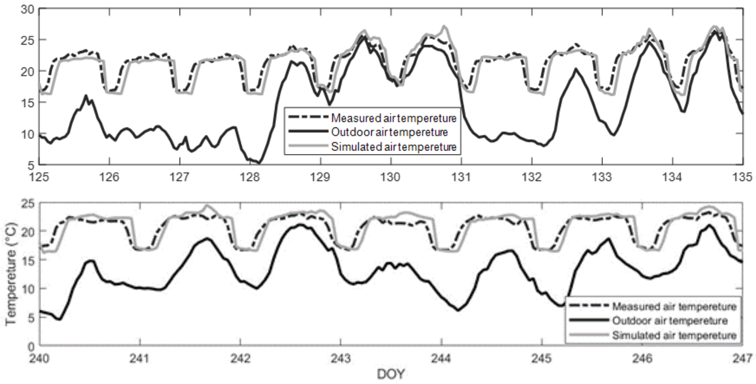

FIGURE 3.3: Prediction of temperature for the commercial greenhouse with HPS top and LED inter-lighting in Mære (mid Norway) at the DOY: 125-135 and DOY: 240-247. DOY= day of the year. The dotted line represents the measured air temperature; the light solid line represents the simulated temperature; while the dark solid line is the outdoor air temperature.

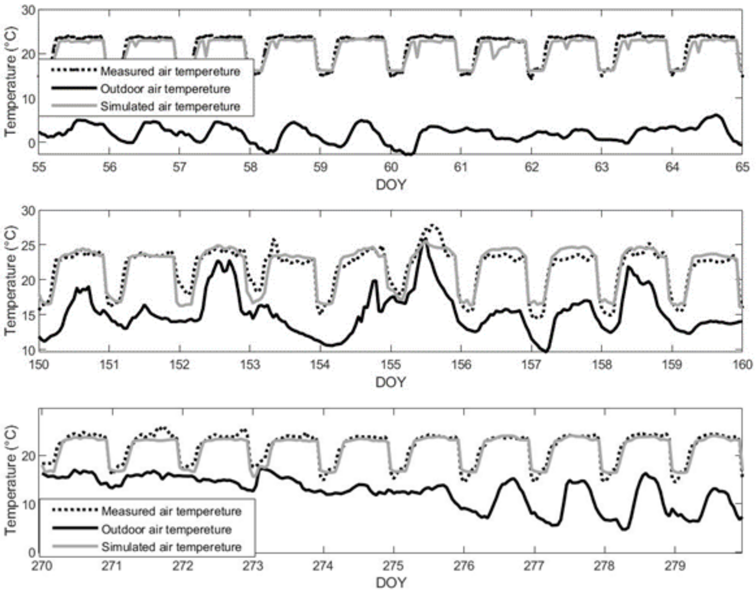

FIGURE 3.4: Prediction of temperature for the commercial greenhouse in Orre (Southwestern Norway) with HPS top light at the beginning of the year (Day of the year (DOY): 55-65), Mid-year (DOY: 150-160) and end of the growing period (DOY: 270-280). The dotted line represents the measured indoor air temperature; the light solid line represents the simulated indoor air temperature while the solid dark line is the measured outdoor temperature.

Generally, the prediction of the yield, especially during the middle of the seasons, during the three seasons was fairly accurate. However, during the beginning of the simulated periods the yield was underpredicted and during the end of the simulated periods the yield was overpredicted. This could be explained due to the lower predicted temperature during the start of the periods and the higher predicted temperatures at the end of the periods. The predicted and measured yield at Orre greenhouse during the year-round production, which is representative of the three production seasons, is presented in figure 3.5.

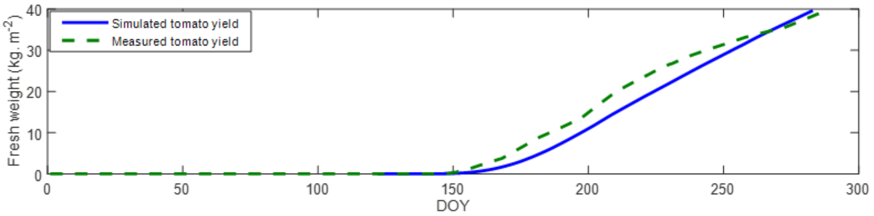

Figure 3.5: Measured (dashed line) and predicted (solid line) yield for southwestern Norway (Orre) greenhouse for the year-round production. The figure presents the measured yield for second crop cycle for the year-round production for the year 2016. DOY: day of the year.

Despite the relatively accurate predictions by the model related to the measured yield and greenhouse climate, certain limitations exist. For instance, the prediction accuracy of the model for indoor temperature, CO_2-concentration, crop growth and yield were evaluated for two commercial greenhouses in Norway. However, the prediction accuracy may possibly be different if other locations and regions having different outdoor climate are considered. Thus, while the simulated NFR and its related components may be more reliable for greenhouse tomato production in southwestern Norway and other regions having similar climate conditions as compared to the other regions included in this study, yet at present, no test data was available for the other locations since there is either little or no existing greenhouse tomato production in these regions. Nonetheless, our simulation study offers a better alternative to evaluate greenhouse vegetable production in Norway and its economic and resource use analysis compared to merely applying the model in its original form with design elements suited to conditions of Netherlands and other milder regions. Secondly, related to the model's sensitivity to CO_2 levels, our results show that there is a need for improvements in the model in order to make it more sensitive to levels of CO_2. For instance, we have observed that in greenhouse designs considered closed, such as NDSFML, despite higher levels of CO_2, there was no significant increase in yield, as has been shown in other studies [99–101]. This observation makes predictions for this particular design slightly uncertain since the lower prediction accuracy of the model, particularly towards CO_2 levels, reduces the accuracy of the outputs from simulations of closed greenhouse designs.

Another issue with closed greenhouse systems, particularly in extended and year-round production cycles, is that the use of high intensity supplemental lighting can contribute to higher levels of humidity within the greenhouse, which in turn can greatly affect the marketable yield along with bringing about changes in the indoor climate of the greenhouse. This was also experienced during the simulations of our present study and led to the opening of the windows, and resultantly, the loss of energy and CO_2. One way to overcome this challenge may be to install an advanced and responsive climate control system responsible for handling the excess humidity and temperature controls similar to the GreenCap solution process technology (https://greencap-solutions.com/), however, there is a need to study how such a system may affect the economic performance and the environment. Likewise, the marketable yield may also be affected by diseases and pests [102], yet such factors have not been considered in our simulations in the present work and need to be explored further.

3.2 Economic performance

The economic performance of the designs varied significantly throughout the locations and production seasons due to the variation in greenhouse design elements. Kise had the highest NFR for seasonal production for the design NS and Orre had the highest NFR for both the extended and year-round production season for the designs NDSL and NDSFML respectively. Furthermore, due to the low global radiations and temperatures resulting in higher energy costs and lower levels of yield, the NFR was negative for all designs in Mære and Tromsø during seasonal production, but with the introduction of artificial lighting, the economic performance improves significantly, as shown in results for the extended and year-round production seasons. The NFR for different designs and locations for the seasonal production are presented in Table 3.1.

	SW Norway (Orre)					MW Norway (Mære)				
	0S	NS	DNS	DNSF	DNSFM	0S	NS	DNS	DNSF	DNSFM
Crop Yield value (NOK $year^{-1}$ m^{-2})	690.6	688.9	670.1	672.1	672.4	634.3	631.6	606.6	608.4	608.7
Fixed costs NOK $year^{-1}$)	125.9	149.9	161.9	165.9	202.6	125.9	149.9	161.9	165.9	202.6
Variable costs (NOK $year^{-1}$ m^{-2})	528.7	501.9	494.6	494.5	467.7	533.9	505.4	498.2	498.1	472.0
Labor costs	199.4	198.9	197.2	197.2	197.2	196.2	195.1	193.7	193.7	193.7
Fossil fuel costs	141.1	114.6	108.7	108.7	61.4	152.9	125.5	110.8	110.8	68.1
Electricity costs	0.0	0.0	0.0	0.0	22.1	0.0	0.0	0.0	0.0	22.3
Cost for pure CO_2	1.3	1.3	1.3	1.3	1.6	1.2	1.2	1.2	1.2	2.2
Variable costs (NOK kg^{-1})	12.7	12.1	12.3	12.3	11.6	14.1	13.4	13.7	13.7	13.0
Potential crop yield (kg m^{-2})	41.6	41.4	40.1	40.2	40.2	38.0	37.8	36.3	36.4	36.4
Net financial result (NOK $year^{-1}$ m^{-2})	35.9	37.1	13.6	11.7	2.1	-25.5	-23.6	-53.5	-55.6	-65.9

	N Norway (Tromsø)					E Norway (Kise)				
	0S	NS	DNS	DNSF	DNSFM	0S	NS	DNS	DNSF	DNSFM
Crop Yield value (NOK $year^{-1}$ m^{-2})	620.8	617.5	592.7	593.5	592.7	693.9	691.8	673.4	675.0	675.0
Fixed costs NOK $year^{-1}$)	125.9	149.9	161.9	165.9	202.6	125.9	149.9	161.9	165.9	202.6
Variable costs (NOK $year^{-1}$ m^{-2})	558.9	527.8	521.4	522.4	485.0	521.8	494.3	489.1	490.1	463.0
Labor costs	197.0	195.8	194.0	194.0	194.0	200.1	199.3	198.0	198.0	198.0
Fossil fuel costs	177.1	148.4	141.8	141.8	85.0	131.1	106.5	101.3	102.3	53.6
Electricity costs	0.0	0.0	0.0	0.0	22.8	0.0	0.0	0.0	0.0	22.1
Cost for pure CO_2	0.6	0.6	0.6	0.6	1.8	3.0	3.1	3.1	3.1	4.2
Variable costs (NOK kg^{-1})	14.9	14.2	14.6	14.7	13.6	12.5	11.9	12.2	12.2	11.5
Potential crop yield (kg m^{-2})	37.4	37.2	35.6	35.6	35.6	41.9	41.7	40.2	40.3	40.3
Net financial result (NOK $year^{-1}$ m^{-2})	-64.0	-60.2	-90.6	-94.8	-94.8	46.2	47.6	22.4	19.0	9.4

TABLE 3.1: Overview of the economic analysis and costs of resources used for the selected greenhouse designs elements for the four regions in Norway for the period Jan-2016 to December-2016. For an explanation of the design abbreviations e.g. 0S, NS etc. see Tables 2.4, 2.5, 2.6.

For seasonal production, the addition of a night screen in the design NS improved the NFR throughout the four locations making it the best deign for seasonal tomato production in Norway. With the addition of a day screen, and further modification of design elements in successive designs, the economic performance is reduced, mainly due to the increase in investment costs and the negative effect, especially of the day screen, on the yield. For the extended season, on the other hand, the design NDSL having a night and day screen with LED as inter-lighting with a capacity of 275 µmol had the best economic performance throughout the locations, with the exception of Tromsø, where NDSFML performed better. Likewise, for the year-round production, the design NDSFML with HPS as top light and LED inter-lighting with respective capacities of 200 µmol and 125 µmol had the best performance. The better performance of NDSFML during year-round production as opposed to the other mentioned designs in the seasonal and extended season is primarily due to the high amounts of energy saved during the most energy-intensive months of December and January, owing to the mechanical heating and cooling. The NFR for the different designs and locations for the extended and year-round seasonal production are shown in figure 3.6.

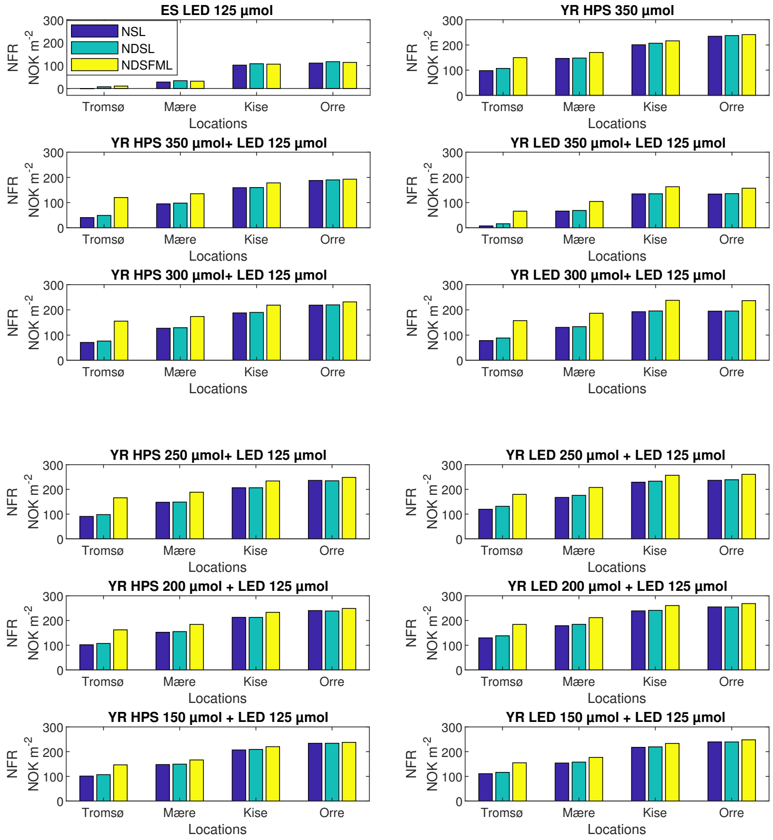

Figure 3.6: Net financial return (NFR) for different designs and locations for the extended seasonal (20th January to 20th November) and year-round tomato production, where ES denotes extended season and YR denotes the year-round. NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump.

To summarise, for seasonal production, Kise had the best economic performance, followed by the simulated designs in Orre. However, it was the opposite case for extended and year-round production, where Orre had the best performing designs followed by Kise. Tromsø, on the other hand, had the lowest NFR regardless of the production season.

3.2.1 Production costs

The production costs, comprising of fixed and variable costs, varied across different designs due to the investments in design elements and energy use for heating and lighting across different locations as shown in Tables 3.2 - 3.3 and Figures

3.7-3.8. For the seasonal production, the variable costs gradually declined across the designs due to the lowered energy costs owing to the introduction of various energy-saving equipment. The same trend continued during the other two production seasons. However, along with the energy-saving elements, the use of particular capacities and types of artificial lighting also affected variable costs during the extended and year-round production. The variable costs were lower for DNSFM than for the other desgns at all locations, and lowest in Kise during seasonal production, while during extended and year-round production, the designs NDSFML$_{LED125\mu mol-ES}$ and NDSFML$_{LED150\mu mol+LED125\mu mol-YR}$ had the lowest variable costs respectively.

On the contrary, fixed costs varied between designs but were constant for a particular design across different locations for seasonal production. On the other hand, for extended and year-round production, fixed costs differed not only across different designs but also throughout the four locations due to the amount of artificial light used. Nonetheless, fixed costs were lowest for the design 0S during seasonal production and for the design NSL$_{LED125\mu mol-ES}$ for the extended season and NSL$_{HPS150\mu mol+LED125\mu mol-YR}$ during year-round production. Fixed costs were highest for the design DNSFM during seasonal production and for designs NDSFML$_{LED125\mu mol-ES}$, and NDSFML$_{LED350\mu mol+LED125\mu mol-YR}$ for extended and year-round production seasons respectively.

Design element Fixed costs	e_j	Investment NOK m^{-2}	Investment NOK $unit^{-1}$	Depreciation (% year^{-1})	Maintenance (% year^{-1})	Construction (NOK m^{-2} year^{-1})	Source
Structure							Vermeulen (2016) +E^*
Venlo 5760 m^2		519.0		5.0	0.5	28.5	
Covers							[89]
Glass		93.5		5.0	0.5	5.1	
Screens							Dansk Gartneri
No screens	1	0	0	0	0	0	
Day screen	2	35.5		25	0	8.7	
Night screen	3	100		15.0	5	15.5	
Structure energy screens		130		7.0	5	10.5	
Boiler							Vermeulen (2016) + E*
Boiler: 0.75 MW	1		620530	7.0	1	9.9	
Boiler: 1.16 MW	2		660000	7.0	1	10.6	
Heating pipes		65		5.0	0.5	3.6	
Mechanical Heating							Vermeulen (2016) + E*
No	1	0	0	0		0	
Mechanical heat and cool: 50 W m^{-2}	2		2688000	7.0	2	37.0	
Cooling systems							Vermeulen (2016) + E*
No	1	0	0	0	0	0	
Fogging: 200 g h^{-1} m^{-2}	2	65		7.0	5	5	
CO_2 supply							Vermeulen (2016) + E*
Pure CO_2: 130 kg ha^{-1} h^{-1}	1		48763	10.0	0	0.9	
CO_2: from boiler	2		31700	10	5	2.4	
CO_2 distribution system	5		10.0	5	0.7		
Remaining costs for irrigation, crop protection, internal transport							Growers
All selected locations		500		10.0	5	75	

Table 3.2: Fixed costs used in the greenhouses. The costs associated with the greenhouse design elements and element alternatives e_j represent the number for each design element option. The depreciation percentage has been derived from the consultations with the local growers. E^* = around 10 % extra for transportation expenses and exchange rate from the Netherlands to Norway.

Resource	Amount	Unit price (NOK)	Unit	NOK m^{-2}	Source
Area	5760		m2		
Plants	2.6	25.0	Plant	65	Hovland, 2018 [90]
Growth medium	2.5	10.4	Slab	26	Hovland, 2018
Fertilizer	1.0	30.0	m2	30.0	Hovland, 2018
Pollination	1.0	12.0	m2	12.0	Hovland, 2018
Pesticides	1.0	5.0	m2	5.0	Growers*
Packaging	6.7	3.0	Box	20	Growers
Energy gas		0.39	kWh		http://www.ngfenergi.no/ukens_priser
Energy light		0.39	kWh		ttp://www.ngfenergi.no/ukens_priser
Marketing etc.	1.0 3.0		Growers		
Operating assets	1.0	15.0	m2	15.0	Growers
Other	1.0	10.0	m2	10.0	Growers
Labor costs	1.2	180.0/hour	m2	Growers	
Insurance / other	1	15.0	m2	15.0	Growers

Table 3.3: Variable costs that were used in the simulations. *= The data was obtained from interviews with commercial tomato growers whose production is representative for Norway.

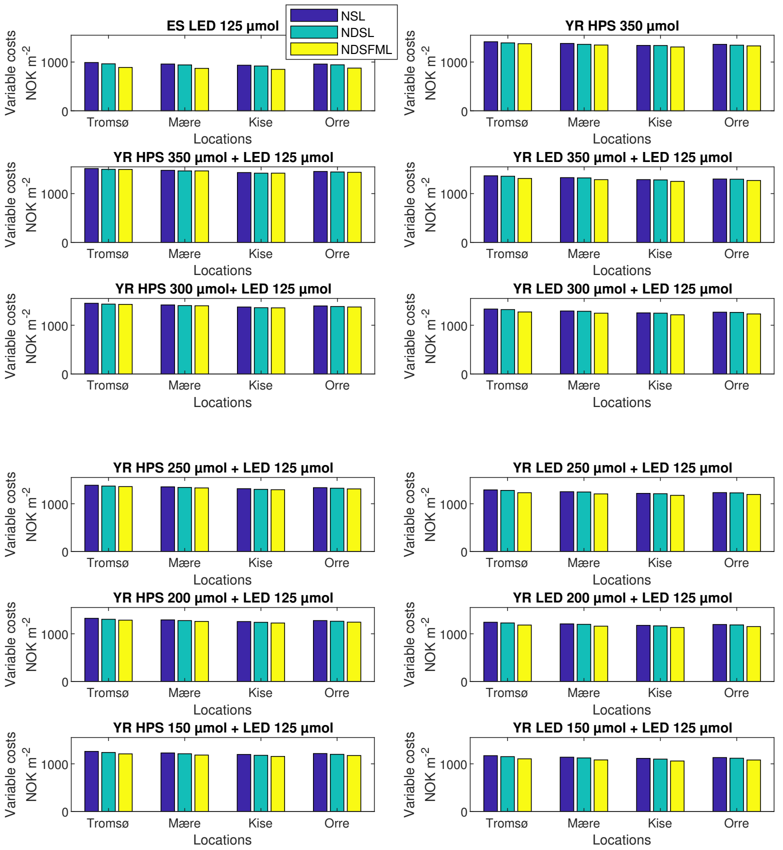

FIGURE 3.7: Total variable costs for the designs and the light strategies for the extended season (20th January to 20th November) and year-round production for the four locations, where ES denotes extended season and YR denotes the year-round. NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump.

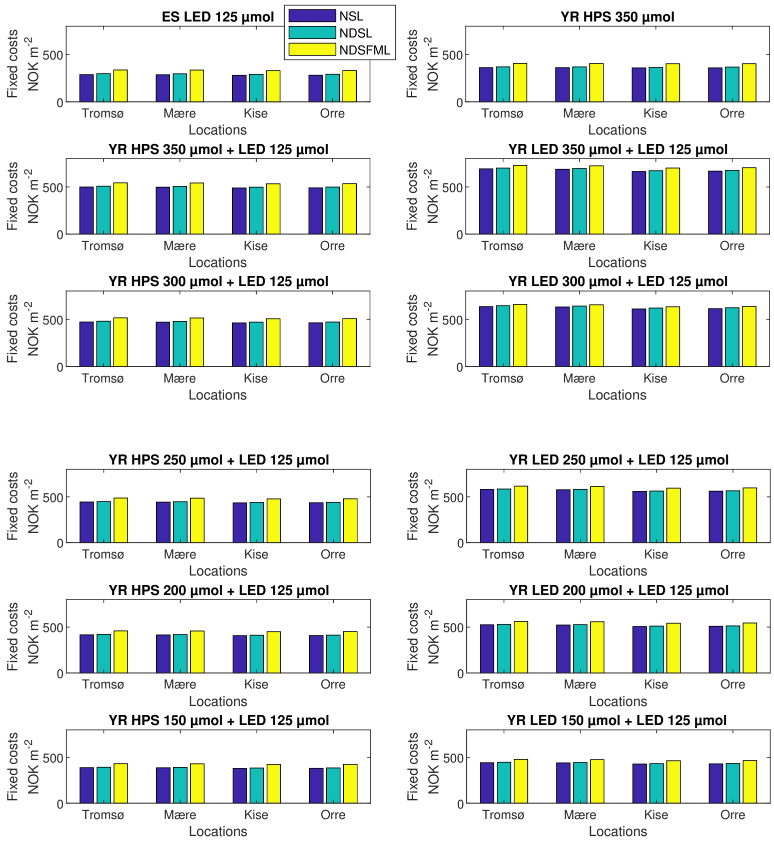

FIGURE 3.8: Total fixed costs for the designs and the light strategies for the extended season (20th January to 20th November) and year-round production for the four locations, where ES denotes extended season and YR denotes the year-round. NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump.

Our results show that across designs and production cycles, the higher energy use, both natural gas and electricity, due to the colder climates, particularly during the winter, make Tromsø, followed by Mære the least favorable locations-both economically and environmentally- for greenhouse tomato production in Norway. For the remaining locations i.e., Orre and Kise, on the other hand, greenhouse tomato production is economically viable for a wide array of greenhouse designs regardless of the production season. Nonetheless, there is a discrepancy between the better performing location and the production season. For instance, during the traditional March to October seasonal greenhouse tomato production, the inland climate conditions in Kise have shown to generate higher NFR and lower energy use while the milder coastal areas such as Orre was the most favorable location during extended and year-round production with supplemental lights. Nonetheless, a conclusion that follows our results is that difference in outdoor conditions in a specific year may result in different outcomes.

Since there is a variation in the energy consumption based on the type of lamps, the type of supplemental lighting used within the greenhouse inevitably affects the overall performance. The results of the study show that during year-round production cycle, LED as top and inter-lighting enhances the economic performance of greenhouses and that it can be improved further by optimizing the capacities of inter-lighting in both extended and year-round production seasons, something that has not been performed in this study. Results indicate that the use of optimum capacities of inter-lighting may result in the reduction of variable costs and an increase in the crop yield and that a suitable capacity of supplemental light is critical to achieving optimum NFR since using either lower capacities or higher capacities than the optimal level, which in this case was found to be 200 µmol for LED top light and 125 µmol for LED inter-lighting, may either result in a reduction in the levels of yield, and NFR or an increase in investment and variable costs and lower level of yield and subsequently lower NFR.

Moreover, the high investment costs of LED lights led to high fixed costs for the designs having LED lights as top and inter-lighting during the year-round production season. However, the low fixed costs in Kise as compared to the other locations for the same designs may be explained due to the relatively lower level of supplemental lighting used due to the high global radiation in the summer season in Kise and the subsequent lower depreciation costs of the lamps. Nonetheless, even though the HPS lamps incurred lower investment costs, the performance of the designs having LED as top and inter-lighting perform far better than those with HPS lamps since LEDs are more efficient and have positive effects on the yield and the overall energy use. This makes LED lights a better choice for supplemental lighting in existing greenhouse production considering their current investments costs. Moreover, considering the downward trend in global prices of LEDs, the choice of LED lighting in greenhouses could prove to be practically feasible in future greenhouse tomato production [103, 104]

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During extended production cycles, however, even though the types of lighting was kept the same throughout the designs, yet the variation in other design elements and their resulting investment costs led to a variation in the NFR and amounts of energy saved. For example, in milder regions such as Orre and Kise, the performance of day and night energy screens was better while in regions with cold climate, i.e., Tromsø, day and night energy screens along with mechanical heating and cooling yielded better results. During year-round production, the design NSL$_{HPS+LED-YR}$ had the highest variable costs across all designs and locations due to the addition of LED and the existing HPS lights and the subsequent use of electricity and natural gas by the combination. Conversely, the design NDSFML$_{LED+LED}$ resulted in the lowest variable costs since LED lights are comparatively more energy efficient and the design used lower amounts of natural gas due to the addition of energy-saving equipment.

3.2.2 Energy use

The addition of energy-saving equipment such as thermal screens and mechanical heating and cooling equipment had a positive effect on energy use across all designs, locations and production seasons, however, with the addition of supplemental lighting in extended and year-round production, it also resulted in profitability of particular greenhouse designs, with the year-round production having the most high-tech design also resulting in the highest profit. During seasonal production, while the designs with energy-saving equipment were able to lower the amounts of energy used, it could not increase the NFR as investment costs far outweighed the amount of energy saved. The same was the case for the colder locations such as Tromsø, in which the high-tech greenhouse designs in all production seasons were able to conserve energy yet it could not be translated into profitability. The fossil fuel use was the lowest in Kise for the design DNSFM during seasonal production while during extended and year-round production, the fossil fuel usage was the lowest for the designs NDSFML$_{LED-ES}$ (in Kise) and NDSFML$_{LED+LED}$ respectively. The total amount of electricity and fossil fuel used for each design and location across the three production season is presented in Table 6 in chapter 2 (section 2.4.3).With regards to the electricity used, the designs NSL$_{LED-ES}$ and NDSL $_{LED-ES}$ had the lowest use of electricity for extended season, with Kise having the lowest amount used and designs NSL$_{LED+LED-YR}$ and NDSL$_{LED+LED-YR}$

had lowest electricity used during year-round production, with the lowest also in Kise.

Our results indicate that in high latitude regions such as Norway, greenhouse designs with high-tech energy saving equipment yield far better results in terms of economic perfprmance and energy use as compared to simple greenhouse designs that do not use energy-saving equipment, especially for year-round production cycle due to the high amounts of energy saved, particularly during winter, thereby resulting in high NFR. Therefore, the significantly better performance of the design NDSFML as compared to other greenhouses, as reflected in the results for the NFR, for the selected locations is in contrast to results for the seasonal production cycle where the considerable increase in fixed costs per m^2 as a result of adding the second energy screen and other energy saving equipment resulted in neither any substantial increase in the yield nor any note-worthy decrease in resources used, and thereby increasing the NFR. Nevertheless, if energy prices increase, the second energy screen may be more beneficial and result in better performance, particularly in colder regions such as Tromsø. However, if energy prices decrease below 0.40 NOK kWh^{-1}, it becomes unprofitable. Similarly, our results found that for seasonal production, fogging could be excluded since its impact on energy-saving and potential crop yield was insignificant. In essence, the overall better economic performance and the lower levels of CO_2 emissions from fossil fuel use in the design NDSFML point towards the benefits of investing in high-tech energy saving equipment in colder regions since they can result in positive environmental effects in addition to being economically efficient.

3.2.3 Price sensitivity analysis

According to our results, a linear relationship exists between the tomato prices and the NFR and as the electricity prices decrease, the NFR increase. Nonetheless, the results reveal that in colder locations, the tomato prices need to be higher in order for the production to be profitable with the same designs and production costs. For seasonal production, an interesting trend was seen whereby Kise saw the most positive effect on NFR following an increase in tomato prices while Tromsø had the most negative effect due to a reduction in tomato prices. The same trend was seen in extended and year-round production seasons, with the exception that the higher tomato prices yielded the most positive effect in Orre. For seasonal production, a price of 19.5 NOK kg^{-1}, or higher, garnered profit for all designs in all locations, which in the case of Kise was 15.5 NOK for the designs 0S and NS (Figure 3.9). For the extended season, a price of 16.5 NOK kg^{-1} yields positive NFR for all designs and locations (Figure 3.10) while during year-round production, tomato price of 14 NOK kg^{-1} or higher will result in positive NFR for all locations and designs, considering the energy prices remain the same (Figure 3.11).

Moreover, results from the GSA show that the designs with the energy-saving elements are more profitable and economically viable and environmental friendly as compared to the standard greenhouse design that are prevalent in Norway.

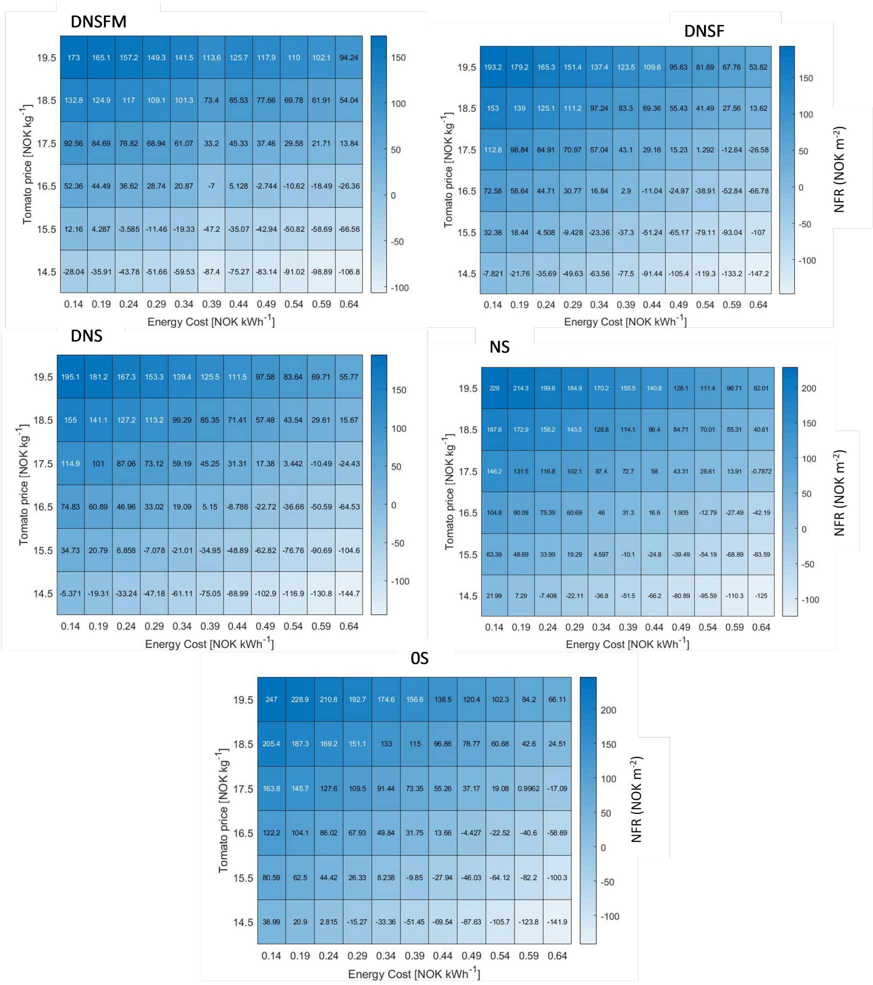

FIGURE 3.9: The effect of tomato price and energy costs on the NFR for the greenhouse in Orre (SW Norway). The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway.

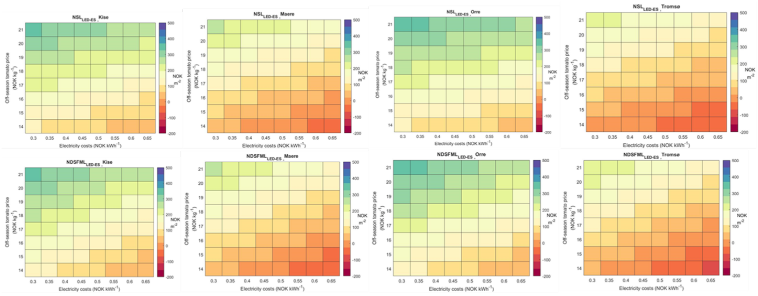

FIGURE 3.10: The effect of tomato price and energy costs on the NFR for the designs NSL and NDSFML for extended seasonal greenhouse production in all four selected locations in Norway. The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway. NSL denotes the design with night screen; NDSFML denotes the design with day and night screens along with fogging and heat pump. The type of light in each design along with the production season is given in subscript.

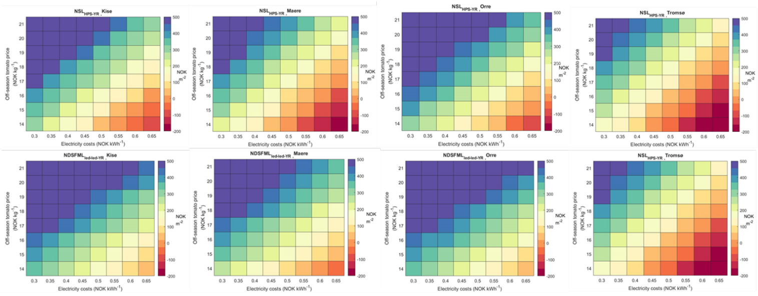

FIGURE 3.11: The effect of tomato price and energy costs on the NFR for the designs NSL and NDSFML for year-round greenhouse production in all four selected locations in Norway. The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway. NSL denotes the design with night screen; NDSFML denotes the design with day and night screens along with fogging and heat pump. The type of light in each design along with the production season is given in subscript.

The variation in greenhouse designs, and production strategies that have been evaluated in this study were considered to be relevant to the Norwegian greenhouse tomato production conditions. The relatively small differences in the sensitivity of NFR to fluctuations in the prices of tomatoes and energy across the different greenhouse designs and regions show that in the Norwegian context, there is a limited possibility of changing the greenhouse designs in order to reduce the risk of exposure to these factors.

Nonetheless, the addition of a sensitivity analysis of the NFR to tomato prices and energy costs adds a sophistication in our study since it allows us to map how the profitability of different greenhouse designs in different locations is affected by fluctuating market prices of the crop and energy. This helps in the decision-making related to the construction of new greenhouses in the future and the feasibility of specific greenhouse designs depending on the energy costs along with any restriction on the fossil fuel use.

3.3 Environmental impact of greenhouse production in Norway

3.3.1 Seasonal production

The results for the seasonal production cycle show that Kise, which was the most profitable location for greenhouse tomato production for the design NS resulted in global warming potential of 2045 g CO_2 eq. for 1 kg tomatoes, while NDSFML, which used the lowest amounts of fossil fuel, resulted in the lowest global warming potential of 1171 g CO_2 eq. for 1 kg tomatoes. On the other hand, the design NS in Mære resulted in a global warming potential of 2620 g CO_2 eq. for 1 kg tomatoes, whereas the design NDSFM for the same location resulted in 1554 g CO_2 eq. for 1 kg tomatoes of global warming potential. The comparatively high global warming potential in Mære was due to the higher use of fossil fuel needed for heating the greenhouse. For results related to the environmental impact of seasonal greenhouse tomato production in Orre and Tromsø see appendix C. Of the different production stages and input categories for the selected designs in the two locations, natural gas use for heating and CO_2 contributed the most towards the different impact categories, followed by structure, fertilizer and electricity. For more details, see Table 3.4 and Figures 3.12.

		Kise		Mære	
Impact category	Unit	NS	NDSFM	NS	NDSFM
Global warming	g CO_2 eq	2045.18	1170.85	2620.62	1553.95
Ozone formation, Human health	g NOx eq	1.68	1.14	2.09	1.43
Ozone formation, Terrestrial ecosystems	g NOx eq	1.75	1.19	2.18	1.49
Terrestrial acidification	g SO2 eq	1.95	1.45	2.40	1.78
Freshwater eutrophication	g P eq	0.13	0.11	0.16	0.14
Marine eutrophication	g N eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	1729.69	1843.24	2017.02	2228.00
Freshwater ecotoxicity	g 1,4-DCB	55.79	69.08	64.31	77.38
Marine ecotoxicity	g 1,4-DCB	71.89	86.69	83.25	97.49
Land use	m2a crop eq	0.01	0.01	0.01	0.01
Mineral resource scarcity	g Cu eq	6.19	6.13	7.03	6.76
Fossil resource scarcity	g oil eq	703.01	391.33	904.53	520.91

Table 3.4: LCA results for seasonal greenhouse tomato production per FU, in Kise and Mære in Norway for NS (Night Screen) and NDSFM (Night and Day Screen with Mechanical Heat Pump and Fogging).

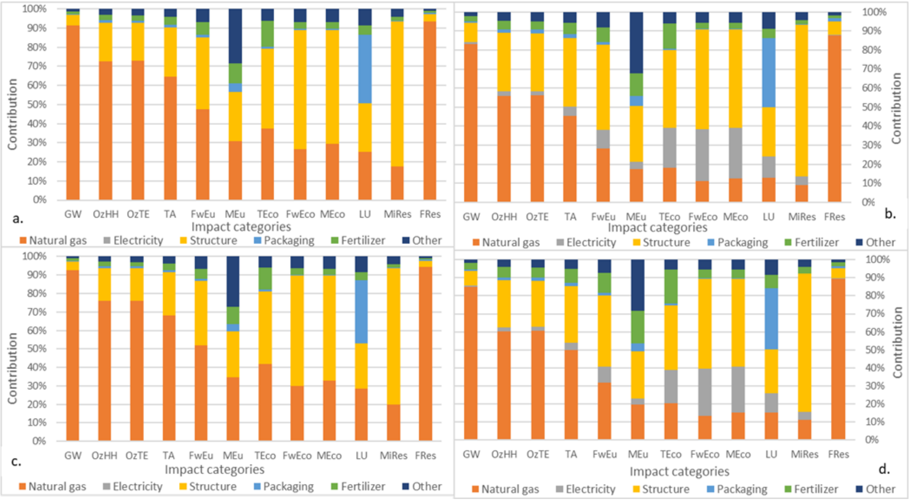

Figure 3.12: Relative contribution to different impact categories for seasonal greenhouse tomato production for NS (Night Screen) (a and c) and NDSFM (Night and Day Screen with Mechanical Heat Pump and Fogging) (b and d), in Kise (a and b) and Mære (c and d). The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

With the addition of an electric heat pump in the greenhouse design NDSFM, the total GW potential decreased to around 1171 g CO_2 eq. in Kise and 1554 g CO_2 eq. in Mære, resulting in a total 43% reduction compared to the NS greenhouse in the two locations. There was also an overall reduction in most of the other impact categories in Kise including in the potential for terrestrial acidification, freshwater eutrophication, marine eutrophication, mineral resource scarcity, fossil resource scarcity and land use. Yet, the potential for terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity were slightly higher in NDSFM than in NS for the same location due to the increased use of electricity. In Mære, on the other hand, the environmental impact was generally higher as compared to Kise, yet, when an electric heat pump was added to the design NDSFM, it resulted in relatively better results for most of the impact categories except terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity due to the use of hydroelectricity, while land use potential remained the same in both designs.

3.3.2 Extended season production

For the extended season production, our results show that the global warming potential for the design NDSL_{LED} in Kise was 2123 g CO_2 eq. for 1 kg tomatoes and was highest for the same design in Mære of about 2384 g CO_2 eq. for 1 kg tomatoes. Global warming potential was lowest for the design NDSFML_{LED} in Kise, which was the most energy efficient design, of about 1173 g CO_2 eq. for 1 kg tomatoes. As compared to the seasonal production, there was a relative increase in most impact categories in extended season in Kise, with the exception of global warming potential and fossil resource scarcity for the design NDSFM, which both decreased during this production cycle. In Mære, however, while there was an increase in most impact categories as compared to the seasonal production, the potentials for global warming, fossil resource scarcity decrease while mineral eutrophication remained the same across the two production seasons. Moreover, results show that as with seasonal production, natural gas had the highest share to the global warming potential, followed by the structure, electricity, used for supplemental lighting, fertilizers and packaging. For results related to the environmental impact of extended season greenhouse tomato production in Orre and Tromsø see appendix C.

According to the LCA results, the higher use of hydroelectricity during the extended season production cycle than druing the seasonal production cycle, therefore resulted in a proportionally greater contribution to the potential for terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and land use. However, the greater use of electricity as compared to natural gas, coupled with the use of LED lights and electric heat pump contributed to the reduction in the overall GW potential between the two designs NDSL and NDSFML for the two locations (from 2123 g CO_2 eq. to 1173 g CO_2 eq. in Kise and from 2384 g CO_2 eq. to 1350 g CO_2 eq. in Mære). Nonetheless, between the two designs across the two locations, the greater use in electricity resulted in an increase in the terrestrial, freshwater and marine ecotoxicity and land use potentials from NDSL to NDSFML. For a full overview of the environmental impact of the extended season production, see Table 3.5 and Figure 3.13.

		Kise		Mære	
Impact category	Unit	NDSL	NDSFML	NDSL	NDSFML
Global warming	g CO_2 eq	2123.26	1172.65	2383.86	1350.30
Ozone formation, Human health	g NOx eq	1.74	1.16	1.93	1.30
Ozone formation, Terrestrial ecosystems	g NOx eq	1.81	1.20	2.01	1.35
Terrestrial acidification	g SO2 eq	2.26	1.74	2.49	1.93
Freshwater eutrophication	g P eq	0.20	0.19	0.21	0.20
Marine eutrophication	g N eq	0.02	0.02	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	4241.62	4620.80	4597.32	4992.20
Freshwater ecotoxicity	g 1,4-DCB	147.04	171.36	161.54	186.25
Marine ecotoxicity	g 1,4-DCB	184.13	212.23	202.27	230.71
Land use	m2a crop eq	0.01	0.01	0.01	0.01
Mineral resource scarcity	g Cu eq	5.90	5.80	6.34	6.21
Fossil resource scarcity	g oil eq	721.64	379.83	812.07	440.14

TABLE 3.5: LCA results for greenhouse tomato production for extended season (20th January to 20th November) per FU in Kise and Mære in Norway for NDSL_{LED} (Night and Day Screens and LED inter-lighting) and NDSFML_{LED} (Night and Day Screens with Mechanical Heat Pump and Fogging and LED inter-lighting) using 125 µmol LED as inter-lighting.

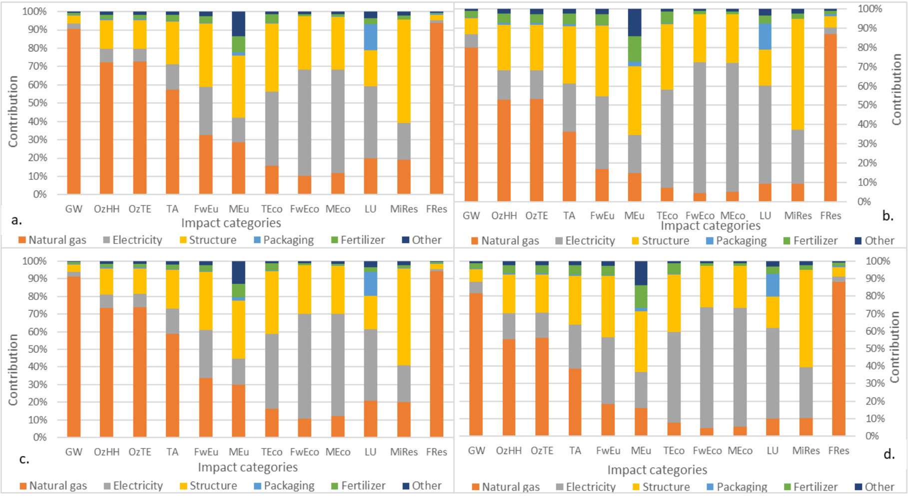

FIGURE 3.13: Relative contribution to different impact categories for extended season greenhouse tomato production for NDSL$_{LED}$ (a and c) and NDSFML$_{LED}$ (b and d), in Kise (a and b) and Mære (c and d). NDSL denotes the design with the Night and Day Screens and LED inter-lighting, NDSFM denotes Night and Day Screens with Mechanical Heat Pump and Fogging and LED inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

3.3.3 Year-round production

For the year-round production cycle, the potential for global warming in Kise for the design NDSFML with 200 µmol HPS top light and 125 µmol inter-lighting capacities was 672 g CO_2 eq. and for NDSFML with 200 µmol LED as top light and 125 µmol inter-lighting capacities it was 600 g CO_2 eq. for 1 kg tomatoes. When lighting capacities and types of lighting were varied for the same location, the lowest global warming potential was seen for the combination 250 µmol LED as top light and 125 µmol LED as inter-lighting, which was the lowest throughout the two locations (593 g CO_2 eq. for 1 kg tomatoes). Of the two locations, the highest global warming potential was observed for the combination HPS as top light with capacity of 200 µmol in Mære (703 g CO_2 eq. for 1 kg tomatoes). For results related to the environmental impact of year-round greenhouse tomato production in Orre and Tromsø see appendix C. Electricity contributed the most to almost all impact categories except the potential for global warming and fossil resource scarcity, to which natural gas contributed the most, whereas the other inputs had relatively lower impact. When LED substituted the HPS as top light, an overall reduction in all impact categories was seen in both locations, regardless of the capacities. For more details, see Tables 3.6 and 3.7 and Figures 3.14 and 3.15.

		Kise		Mære	
Impact category	Unit	NDSFML $_{HPS+LED}$	NDSFML $_{LED+LED}$	NDSFML $_{HPS+LED}$	NDSFML $_{LED+LED}$
Global warming	g CO_2 eq	671.86	599.71	702.96	646.42
Ozone formation, Human health	g NOx eq	0.95	0.82	0.99	0.87
Ozone formation, Terrestrial ecosystems	g NOx eq	0.98	0.85	1.02	0.90
Terrestrial acidification	g SO2 eq	1.89	1.57	1.98	1.66
Freshwater eutrophication	g P eq	0.26	0.21	0.27	0.22
Marine eutrophication	g N eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	7946.16	6250.60	8360.59	6590.33
Freshwater ecotoxicity	g 1,4-DCB	352.91	271.70	372.93	287.50
Marine ecotoxicity	g 1,4-DCB	432.06	332.89	456.49	352.21
Land use	m2a crop eq	0.02	0.02	0.02	0.02
Mineral resource scarcity	g Cu eq	7.10	5.88	7.41	6.16
Fossil resource scarcity	g oil eq	181.92	165.15	190.05	179.28

Table 3.6: LCA results for greenhouse tomato production for year-round production cycle per FU in Kise and Mære in Norway for NDSFML$_{HPS+LED}$ and NDSFML$_{LED+LED}$ with 200 µmol top light and 125 µmol interlighting capacities. NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and interlighting.

		Kise		Mære	
Impact category	Unit	NDSFML $HPS+LED$	NDSFML $LED+LED$	NDSFML $HPS+LED$	NDSFML $LED+LED$
Global warming	g CO_2 eq	647.46	593.11	667.55	633.93
Ozone formation, Human health	g NOx eq	0.96	0.83	0.99	0.86
Ozone formation, Terrestrial ecosystems	g NOx eq	0.98	0.86	1.01	0.88
Terrestrial acidification	g SO2 eq	1.95	1.61	2.02	1.58
Freshwater eutrophication	g P eq	0.27	0.22	0.28	0.21
Marine eutrophication	g N eq	0.02	0.01	0.02	0.01
Terrestrial ecotoxicity	g 1,4-DCB	8439.39	6584.53	8780.12	5949.06
Freshwater ecotoxicity	g 1,4-DCB	379.41	289.26	396.33	252.92
Marine ecotoxicity	g 1,4-DCB	464.22	354.22	484.84	310.22
Land use	m2a crop eq	0.02	0.02	0.03	0.02
Mineral resource scarcity	g Cu eq	7.35	6.07	7.59	5.84
Fossil resource scarcity	g oil eq	169.85	160.58	174.60	189.67

TABLE 3.7: LCA results for greenhouse tomato production for year-round production cycle per FU in Kise and Mære in Norway for NDSFML$_{HPS+LED}$ and NDSFML$_{LED+LED}$ with 250 µmol top light and 125 µmol interlighting capacities. NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and interlighting.

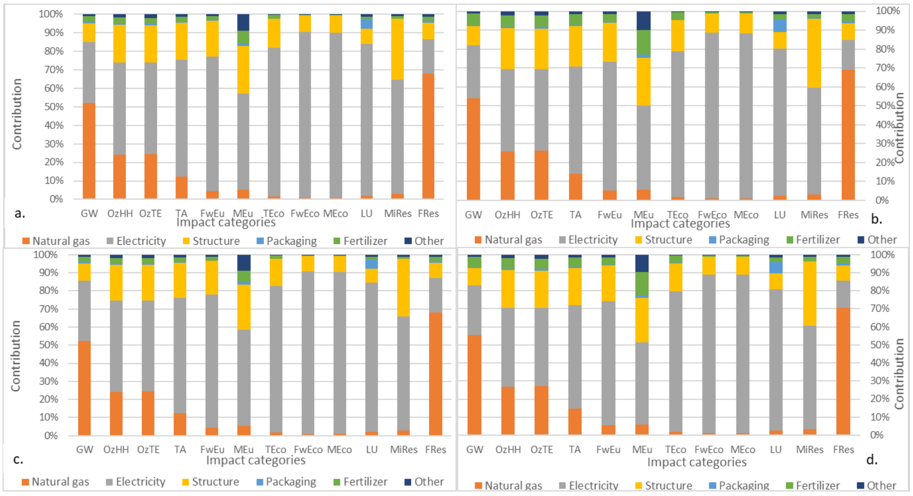

FIGURE 3.14: Relative contribution to different impact categories for year-round greenhouse tomato production for NDSFML$_{HPS+LED}$ (a and c) and NDSFML$_{LED+LED}$ (b and d) respectively with 200 µmol top light and 125 µmol inter-lighting capacities in Kise (a and b) and Mære (c and d). NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

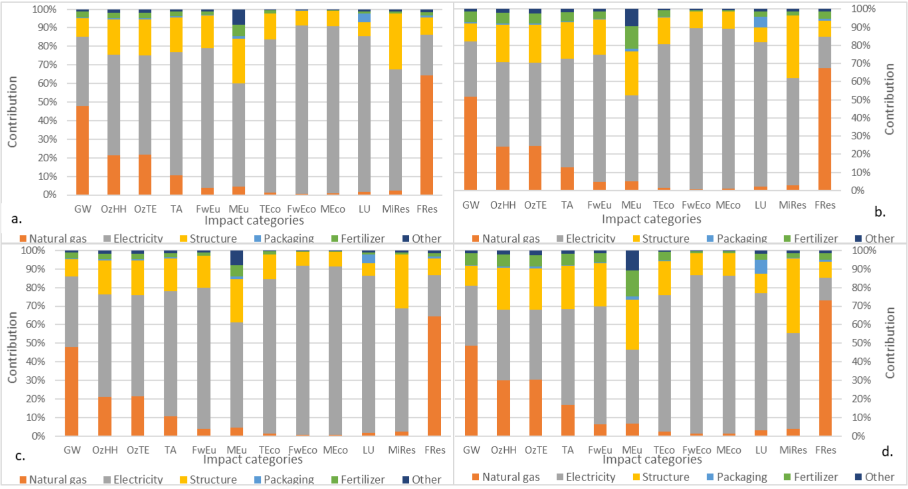

FIGURE 3.15: Relative contribution to different impact categories for year-round greenhouse tomato production for NDSFML$_{HPS+LED}$ (a and c) and NDSFML$_{LED+LED}$ (b and d) respectively with 250 µmol top light and 125 µmol inter-lighting capacities, in Kise (a and b) and Mære (c and d). NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

The results from the life cycle assessment of the environmental impact of greenhouse tomato production in Norway show that unsurprisingly, the greatest environmental impact comes from the use of natural gas that is extensively used under local conditions for heating purposes. Other factors including electricity, greenhouse structure, fertilizers and packaging were also important, however, they were comparatively exceeded by heating in most of the impact categories that were studied. These results are similar to other studies on greenhouse tomato production in high latitude regions [25, 105–109]. Moreover, when natural gas was supplemented by electricity, a considerable reduction in most impact categories could be seen across different designs, locations and production seasons. However, a subsequent increase in the ecotoxicity potential was seen due to the increased use of electricity and for which electricity was the biggest contributor. As shown from the results, this tendency could be observed in both the seasonal and extended season production, yet during year-round production, the trend was reversed moving between the designs NDSFML$_{LED+LED}$ to NDSFML$_{LED+LED}$, and an overall decrease was seen in all impact categories. One possible reason for this variation could be that the use of electricity was gradually increased during the seasonal and extended seasons moving from designs NS to NDSFM and from NDSL$_{LED}$ to

NDSFML$_{LED}$, causing an increase in the terrestrial, freshwater and marine ecotoxicity potential. However, during year-round production cycle, HPS top lights were substituted by LED lights, and this combined with the use of an electric heat pump contributed to the decrease in the electricity use, and subsequently a reduction in the potential for terrestrial, freshwater and marine ecotoxicity. Similar to another study (Milford et al., 2021), the results reinforce the suggestion that under similar climatic conditions to Norway, shifting to year-round production of greenhouse tomatoes will give better results both in terms of economic performance and a lower environmental impact.

Another reason for the relatively lower environmental impact during year-round production may be due to the higher amounts of energy-saved, and consequently lower levels of energy used, due to the incorporation of LEDs and electric heat pump during this season. For instance, in seasonal production cycle, among the different evaluated designs, the design with the night screen resulted in the highest profit due to a higher yield, yet this design consumed greater levels of energy. In extended and year-round production cycles, the design with both a day and night energy screens and an electric heat pump performed better due to higher yield and high amounts of energy saved due to the two screens and the heat pump. Moreover, the use of supplemental lighting and electric heat pump during the two production seasons had two-fold beneficial result: they not only contributed to increasing the levels of yield but also reduced the use of fossil fuel due to the heat produced from the lights.

The above results offer interesting insights into the impact of different design strategies on the environment. However, certain limitations also exist with this. For instance, among the selected locations, currently most of the greenhouse tomato production takes place in Orre in Rogaland region, which primarily uses natural gas as the main energy source and CO_2 supply and HPS lighting during the extended and year-round production seasons. In order for the switch to year-round production to yield positive results, it is assumed that the existing greenhouses will switch to electricity, either through existing power grids, or new ones. Moreover, they will need to substitute the existing HPS lights with LEDs, since they have longer lifespans and use lesser levels of energy despite being more costly, and to incorporate electric heat pumps. Yet, these changes require large financial costs. Therefore, it is essential to keep in mind factors such as an increase in investments associated with improvements in the electric power grid system in the region and the introduction of energy-saving equipment such as electric heat pumps and LED lights.

Chapter 4

General discussion

The objective of the study was to conduct an economic and environmental analysis of greenhouse tomato production in a selected number of greenhouses designed during three production cycles in four different locations across Norway in order to assess whether the designs that are economically profitable can also be environmentally sustainable.

The present study has shown clear region-dependent variations in NFR, its underlying elements, energy use and the successive environmental impact of different greenhouse designs with varying energy-saving and indoor climate control equipment. Moreover, our economic and environmental analysis of greenhouse tomato production in Norway has revealed that the production strategy, together with the use of artificial lighting, type of heating system and the production cycle, has a considerable influence on the economic performance and the environmental impact of the production process, even within the same location. Additionally, our results show that economic profitability can be combined with a low environmental impact, as apparent from the results of certain designs that resulted in high NFR and low environmental impact for the three production cycles across the selected locations.

The results of our study highlight the significance of taking such elements, especially night energy screens, electric heat pumps and LEDs, which had the most positive effects on the NFR and the ensuing environmental impact throughout the three production seasons, in the construction of greenhouses for tomato production in Norway and that can be replicated to the same extent in other regions having similar climates. Previous studies have shown that even in other climatic zones, night screens have significant benefits for greenhouse production [110–112]. Our results show similar effects yet currently according to our knowledge, there are no other published works on such findings for similar climatic zones that we have studied. This may be explained by the fact that currently less than 50% of greenhouse tomato production in Norway is carried out with night thermal screen while the use of day thermal screen is even lower [113].

In this study, we initially applied a previous model [87] in order to simulate greenhouse tomato production for local climatic conditions representing high latitude regions that have a considerable supply of energy from renewable sources. Our results show that a comparison with other studies focusing on the greenhouse energy-yield-economy models under climatic conditions different from what we have studied cannot be drawn with any accuracy. Nonetheless, some sort of comparison can be made with energy-yield-economy analysis studies that consider renewable energy resources, including solar, wind and biomass [114–121]. Many of these studies, to a large extent, focus on year-round production. However, in some cases, either data from existing works was used instead of validating the model against existing climate conditions, or in others, only one or a limited number of days were simulated [110, 122]. While some studies evaluated the economic performance of greenhouse production but considered only one or two aspects of the greenhouse designs while not varying other design elements, such as energy and economic analysis of greenhouse ground insulation design [123], economic analysis of greenhouse energy use [96, 124] and cost and benefit analysis for different greenhouse covers [125]. The present study, on the other hand, has evaluated the effect of different design elements on the NFR, energy use and the resultant environmental impact.

Our study found that Tromsø was the least favorable of the evaluated locations for greenhouse tomato production across the three production seasons, both in terms of the NFR and the high environmental impact due to the greater heating and electricity requirements in colder regions. On the other hand, inland climate conditions were the most favorable during the traditional March to October seasonal greenhouse tomato production in Norway, while the milder coastal regions such as Orre performed better economically and had lower environmental impact. Nonetheless, changes in the external climate in a specific year may result in different conclusions. Moreover, the findings of our study show that while simple greenhouse designs that did not include energy-saving equipment yielded better results during seasonal production cycle, during year-round production designs with high-tech energy-saving equipment resulted in better economic performance since they helped save high amounts of energy, especially during the cold winter months, and led to higher NFR.

In high altitude regions including Norway, low light and heat, especially during winter is a persistent concern for greenhouse vegetable production. Multiple studies have shown that with the addition of artificial lighting the greenhouse tomato yield can be increased considerably [20, 22, 126]. Similarly, Liu et al. (2012)[127], Li et al., (2014)[128], Tian (2016)[129] and Paucek et al. (2020)[130] have shown that the use of artificial LED as inter-lighting can also improve the yield of tomatoes in the Mediterranean region. The findings from our study also show similar benefits of using LED as top and inter-lighting [97, 104], in particular, our results have shown that certain capacities of LED lights as top and inter-lighting help in not only improving the economic performance by lowering their related variable costs but also reducing the fossil fuel use. However, when the LED top and inter-lighting was combined together with an electric heat pump, an improvement in the economic performance was seen along with a lower environmental impact. This was especially prominent for Northern areas such as Tromsø. Therefore, our study notes that in order for year-round greenhouse production in high latitude regions to be both economically profitable and environmentally sustainable, there is a need for relevant economic policies that encourage local vegetable producers to use LEDs and other related energy-saving equipment, including thermal screens and electric heat pumps.

According to the LCA results, when natural gas was replaced by electricity, a considerable reduction in most impact categories could be seen across different designs and production seasons, however, a subsequent increase in the ecotoxicity potential was seen due to the increased use of electricity and for which electricity was the biggest contributor. As shown from the results, this tendency could be observed in both the seasonal and extended season production for Orre and Tromsø. In Kise, however, moving from seasonal to extended season, an overall increase in almost all impact categories was seen, with the exception of mineral resource scarcity potential. While in Mære, between the seasonal and extended production seasons, the potential for global warming decreased while all others increased, and mineral eutrophication remained the same. Yet during year-round production, the trend was reversed moving between the designs $\mathrm{NDSFML}_{HPS+LED}$ to $\mathrm{NDSFML}_{LED+LED}$, and an overall decrease was seen in all impact categories. The differences in the trends observed in the selected locations across the two production seasons can be explained by the fact that during the extended season, there is a greater need for heating and lights in Kise, Tromsø and Mære as compared to the milder climate of Orre. Thus, higher amounts of energy use was seen in these locations, and the resultant higher environmental impact in Kise. Yet in both Tromsø and Mære, the global warming potential was reduced in both designs as compared to the seasonal production. This was due to the positive effects of energy-saving equipment such as the thermal screens that were much more pronounced in colder regions.

One possible reason for the relatively lower environmental impact during year-round production may be due to the higher amounts of energy-saved, and consequently lower levels of energy used, due to the incorporation of LEDs and electric heat pump during this season. For instance, in seasonal production cycle, among the different evaluated designs, the design with the night screen resulted in the highest profit due to a higher yield, yet this design consumed greater levels of energy. In extended and year-round production cycles, the design with both a day and night energy screens and an electric heat pump performed better due to higher yield and high amounts of energy saved due to the two screens and the heat pump. Moreover, the use of supplemental lighting and electric heat pump during the two production seasons had two-fold beneficial result: they not only contributed to increasing the levels of yield but also reduced the use of fossil fuel due to the heat produced from the lights. The decrease in the electricity used therefore also resulted in a reduction in the potential for terrestrial, freshwater and marine ecotoxicity. Similar to another study [113], the results reinforce the suggestion that under climatic conditions similar to Norway, shifting to year-round production of greenhouse tomatoes will give better results both in terms of economic performance and a lower environmental impact.

A review of relevant literature shows that there are multiple works focusing on the environmental impact of locally produced vegetables, including tomatoes, which have found that the higher environmental impact of local production of vegetables due to the higher need for heating greenhouses in cold climate zones, most of which relies on the use of fossil fuels such as oil and natural gas, makes imported tomatoes a better option [131–134]. Although the focus of our study was not to make any sort of comparison with the environmental impact of imported tomatoes, our findings have shown that under local Norwegian conditions, compared to seasonal and extended season production cycles, the year-round production of greenhouse tomatoes has a comparatively lower environmental impact, especially considering the various impact categories such as global warming potential, terrestrial acidification and fossil resource scarcity potentials. Moreover, comparing our findings with other LCA studies of tomato production under similar climate conditions reveals that locally produced tomatoes in high-tech greenhouses, installed with energy-saving equipment, generally have a lower environmental impact than imported ones. This can be explained by the considerable availability of renewable energy sources in Norway and is also shown in a similar study by Nordenström et al. (2010)[135] that studied the environmental impact of imported tomatoes produced in open field in Spain and compared it with locally produced tomatoes in greenhouses heated by bio-fuelled CHP in mid-Norway. The study showed that the bio-fuelled CHP heated greenhouses had lower environmental impact in all impact categories that were studied.

Nonetheless, there were certain limitations associated with our study, related to the economic analysis and the environmental impact assessment. Firstly, during the validation of the model, our study found that there was an inconsistency in the values for temperature and CO_2 between measured and simulated environmental conditions, which can be seen in the measurement of errors. This could be related to the ventilation in the greenhouse. For instance, in Rogaland, local growers generally open the greenhouse windows in the evening in order to allow plants to transition into the night-time mode. This leads to a sudden drop in internal air temperature of the greenhouse and the model then requires a long time to adjust to the change. The presence of a screen also increases the time constant. Other than that, the issue of leakage ventilation, that could also be a relevant factor in the night-time ventilation may only be assumed by any model since it depends to a large extent on the age and quality of each greenhouse. This suggests that the model was not particularly sensitive to CO_2, and lowers the accuracy of outputs from the simulations. However, this merely points towards the inherent limitation of models in general. Nonetheless, this is particularly significant since the quantity, growth and quality of the crop is affected to a large extent by CO_2 enrichment levels[136–139].

A second limitation of our study is related to the system boundaries that we have assumed for the economic evaluation and the LCA. For instance, the marketable tomato yield is a fraction of the total tomato yield and is heavily dependent on the greenhouse design and in turn affects the NFR. In practical experiments, the marketable yield can be affected by diseases and pests [102] along with a high relative humidity within the greenhouse, that leads to the opening of the windows and resulting in a change in the indoor climate of the greenhouse. However, these factors were not considered during our simulations and incorporating them in future works may yield different results. Moreover, while considering the NFR, even though we took into account that the greenhouse and the different equipment used have different lifespans that depends on re-investments etc., yet the pay-back period and return of investment have not been considered in this study. Therefore, adding this aspect in future works may also improve the ability to make relevant decisions since the pay-back period depends largely on the interest on capital and resultantly on the existing conditions.

Related to the LCA of greenhouse tomato production, a system boundary consisting of all processes form raw material extraction to the farm gate was considered, while the transport to the wholesaler and store was not within our boundaries. This can lead to challenges since along with the transport from the farm to the consumer not being included, the related losses that may occur during the transport phase are also not considered. Moreover, the related costs and CO_2 emissions from the transportation phase are also excluded from our analysis. Therefore, the NFR and the environmental impact for, in particular distant Tromsø, would have been comparatively better than the other locations if these aspects had been considered since previous studies have revealed that the environmental impact of transporting fresh fruits and vegetables to long distances can be significant [25]. Moreover, a comparison of the results with other studies also need to consider the system boundaries that are considered in LCA evaluations. For example, a study assessing the environmental burden for year-round tomato production in a multi-tunnel greenhouse in Almeria, Spain considering the raw materials extraction to the farm gate including material disposal as the system boundary found that for Mediterranean conditions the structure, auxiliary equipment and fertilizers contributed the most to the global warming potential for 1 kg tomatoes in the absence of heating requirements for the greenhouse [71]. These findings were similar to other studies on the Mediterranean region [50, 140]. Likewise, when the entire production phase was considered including the processing of input materials to the disposal stage in another LCA study of greenhouse tomato production in Southern Spain, it was found that nearly 77% of its energy requirements and carbon emissions arise due to packaging and transport [141]. Therefore, the choice of the system boundary has a substantial effect on the NFR and the ensuing environmental impact.

Another limitation of our study relates to the finding that with the increased use of electricity, there is not only an improvement in the NFR but also lowers most of the impact categories, especially when LEDs and electric heat pump is included. However, as the results show that the increase in the electricity use leads to the consequent increase in the terrestrial, freshwater and marine ecotoxicity potentials, even though there is a significant reduction in the rest of the impact categories. The trade-off that arises due to the increased use of electricity is challenging for evaluating the environment impact of greenhouse tomato production and is reflected in similar studies that consider renewable energy sources in different climatic conditions. For example, an LCA study of greenhouse tomato production in Hungary considering two alternative heating systems i.e., one using geothermal energy and the other natural gas, showed that although the geothermal energy resulted in lower environmental impact, yet it had higher financial costs and was not feasible on a functional unit basis [65]. Likewise, a recent study on greenhouse production in Ontario, Canada revealed that when wooden biomass replaced the natural gas for heating the greenhouses, a nearly 85% reduction in global warming potential was seen relative to the fossil fuels, however, relative to global warming potential, the use of biomass led to higher impacts in eutrophication and respiratory effects [106, 107]. Thus, some experts suggest that weighting or normalisation is necessary in order to be able to compare different types of impacts with one another since different impact categories cannot be directly compared with one another per functional unit as they have differing effects and naturally occur at different concentrations. Therefore, it may not be possible to explain what the increase in the potentials for terrestrial, freshwater and marine ecotoxicity means in relation to the decrease in the other impact categories [142].

Nonetheless, assessing the effects of different energy sources on the environment is complex and points towards important issues regarding the comparison of impact categories of fresh vegetable production. A previous study comparing the environmental impact of locally produced off-season tomatoes in France with off-season tomatoes grown in unheated greenhouse in Morocco found that there was a trade-off between the usual impact categories, which were mostly energy-related, with freshwater use impacts that the studies had included [134]. The results of the study emphasised the significance of the selection of impact categories and the preference one gives to them. Therefore, it is not merely that a specific production strategy is recommended but also the importance of the impact category one chooses to give preference to. Nonetheless, further research is required on the selection criteria and the trade-off between different impact categories. Similarly, a detailed study comparing the environmental impact of greenhouse tomatoes produced in Norway and in other regions using the same system boundaries for both production types, inventory data and assumptions may yield different or additional results.

The study comprised of an economic and environmental evaluation for several different greenhouse designs within each of three production cycles. The results from our study found that differences in greenhouse management systems, in particularly climate control, has a substantial effect on the environmental burden related to the production of the same crop i.e., tomato and even within the same production region. This point towards the benefits of studying different production strategies in order to reduce the environmental impact of greenhouse tomato production in Norway even further.

Chapter 5

Conclusion

This study has conducted an economic and environmental evaluation of greenhouse tomato production for three production seasons and four selected locations throughout Norway. In the first part, the economic evaluation was conducted of tomato production in (semi-) closed greenhouses that use different forms of energy and utilize differing temperature regulation technologies. This was done by using a model-based greenhouse design comprising a crop growth module, greenhouse indoor climate module and an economic module under Norwegian conditions across the three production seasons. In the second part an LCA was conducted of selected greenhouse designs from each of the three production cycles, that either had the highest NFR or lowest energy use, using SimaPro software and taking into account all processes from raw material extraction to the farm gate.

The results of the study show that for seasonal production, the addition of a night thermal screen led to an increase in the NFR across all evaluated locations, with Kise being the most favorable location for seasonal production of greenhouse tomatoes. For the extended and year-round production, on the other hand, the addition of a night and day thermal screen had the most benefits, with Orre being the most favorable location for the two production cycles. Moreover, it was found that investing in high-tech energy-saving equipment could especially be useful in the colder regions such as Tromsø as they helped in reducing the energy use, even though the economic performance was relatively low in these regions. Likewise, for year-round production, the LED lights were found to be the better choice in the long run since they helped save energy and were more efficient in increasing the yield despite lower investment costs associated with the HPS lights. It was found that the capacities of artificial lights have considerable effect on the NFR and that if an optimization in light capacities is not performed, it may result in a negative NFR even though they are associated with lower investment costs, as was seen during the extended season in which lighting capacities were not optimized. Our results from the sensitivity analysis showed that of the three production cycles, year-round production was the most sensitive to changes in the tomato and energy prices.

Moreover, the study found that from seasonal to extended and finally to year-round production seasons, most impact categories were significantly reduced, and that the year-round production of greenhouse tomato production in the milder location of Orre in southwestern Norway had lower environmental impact than the other three locations. Likewise, the greenhouse's heating requirements arising from the use of natural gas and electricity contributed the most towards most of the impact categories and that even though there was a significant reduction in most impact categories with the increased use of electricity in extended and year-round production, its contribution to the potentials for terrestrial, freshwater and marine ecotoxicity was considerably large.

The findings of our study provide interesting insights into greenhouse vegetable production in cold climate zones having significant supplies of renewable energy. The results can aid local producers in different regions in Norway in designing suitable greenhouses according to the local climate keeping in mind both the economic profitability and environmental sustainability and also help policymakers in formulating policies that encourage the growers to adopt production strategies that increase local production, with the production being economically profitable and environmentally friendly.

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Appendix A

Paper 1

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Research Paper

Bio-economic evaluation of greenhouse designs for seasonal tomato production in Norway

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Greenhouses are complex systems whose size, shape, construction material, and equipment for climate control, lighting and heating can vary largely. The greenhouse design can, together with the outdoor weather conditions, have a large impact on the economic performance and the environmental consequences of the production. The aim of this study was to identify a greenhouse design out of several feasible designs that generated the highest net financial return (NFR) and lowest energy use for seasonal tomato production across Norway. A model-based greenhouse design method, which includes a module for greenhouse indoor climate, a crop growth module for yield prediction, and an economic module, was applied to predict the NFR and energy use. Observed indoor climate and tomato yield were predicted using the climate and growth modules in a commercial greenhouse in southwestern Norway (SW) with rail and grow heating pipes, glass cover, energy screens, and CO_2-enrichment. Subsequently, the NFR and fossil fuel use of five combinations of these elements relevant to Norwegian conditions were determined for four locations: Kise in eastern Norway (E), Mære in midwestern Norway (MW), Orre in southwestern Norway (SW) and Tromsø in northern Norway (N). Across designs and locations, the highest NFR was 47.6 NOK m^{-2} for the greenhouse design with a night energy screen. The greenhouse design with day and night energy screens, fogging and mechanical cooling and heating having the lowest fossil energy used per m^2 in all locations had an NFR of −94.8 NOK m^{-2}. The model can be adapted for different climatic conditions using a variation in the design elements. The study is useful at the practical and policy level since it combines the economic module with the environmental impact to measure CO_2 emissions.

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1. Introduction

The agriculture sector is one of the most energy intensive industries in the world (Diakosavvas, 2017) and can also result in environmental impacts including soil degradation, groundwater depletion and rise in greenhouse gas emissions etc. (Lamb et al., 2016; Longo, Mistretta, Guarino, & Cellura, 2017; Notarnicola et al., 2015; Tamburini, Pedrini, Marchetti, Fano, & Castaldelli, 2015). Expanding food production to high latitude regions, where cold climate, short growing seasons and light conditions limit production, could be one way of alleviating the pressures on global food production. One way to reach such an expansion in food production is to use protected cultivation techniques, which mitigate the effects of unfavourable weather conditions. Such systems can include protection against wind, rain and sun as well as heating, cooling, humidity control, CO_2-enrichment, lighting and irrigation, and can help to increase the yield, optimise the resource use, improve food production and extend the growing season (Tap, 2000). Greenhouses are one of the main methods of protected cultivation that shield crops against unfavourable outdoor conditions. They are complex systems whose size, shape, construction material, and equipment for climate control, lighting and heating can vary greatly. The greenhouse design can, together with the outdoor weather conditions, have a large impact on the economic performance and the environmental consequences of the production process (Hemming, Sapounas, de Zwart, Ruijs, & Maaswinkel, 2010; Sapounas, Hemming, & De Zwart, 2010). From seed to fruit, there are multiple drivers (temperature, light intensity, light spectrum and day length, humidity, CO_2-concentration and fertigation) that can be modified under controlled environmental conditions to increase the biomass production (Incrocci, Stanghellini, & Kempkes, 2008; Moe, Grimstad, & Gislerod, 2005).

Several studies have used modelling techniques to simulate and optimise different subsystems within the greenhouse system to improve the performance of various aspects of production (Joudi & Farhan, 2015; Pakari & Ghani, 2019; Verheul, Grimstad, & Maessen, 2012; Ahamed, Guo, Taylor, & Tanino, 2019; Singh & Tiwari, 2010; Von Elsner et al., 2000). These studies included evaluations of the effect of the shape of greenhouse on energy consumption and thereby optimum productivity (Çakır & Şahin, 2015), and of the effects of greenhouse designs on productivity (Vanthoor et al., 2012a). Kondili and Kaldellis (2006) presented an analytical model to estimate optimal dimensions of a geothermal fluid transportation network, resulting in the minimisation of heat loss and energy consumption within a greenhouse in Greece. Flores-Velázquez et al. (2009) and Flores-Velazquez, Montero, Baeza, and Lopez (2014) studied the effects of greenhouse spans, and ventilation system on the temperature exchange and distribution using computational fluid dynamics. Likewise, Roy, Fatnassi, Boulard, Pouillard, and Grisey (2015) simulated the distribution of temperature and air humidity in a semi-closed greenhouse, measuring around 960 m^2, for tomato production and furnished with several air cooling and dehumidifying ducts. Flores-Velázquez and Vega-García (2019) showed that, in regions with mild summers, the combined use of mechanical and natural ventilation can lower the costs related to temperature regulation and energy use. Dynamic modelling techniques have also been used to simulate the greenhouse indoor climate for different climate conditions, crops and variables (De Zwart, 1996; Impron, Hemming, & Bot, 2007; Luo et al., 2005a, 2005b), including predictions of indoor air temperature in the greenhouse by studying six greenhouse types with different orientations related to energy consumption in the Iranian region of Tabriz (Mobtaker, Ajabshirchi, Ranjbar, & Matloobi, 2016). Vanthoor, Stanghellini, Van Henten, and De Visser (2011a, 2011b) developed and applied a model to simulate tomato production, and its design elements can be adjusted to represent those suitable to different climate conditions. The model has been used in conjugation with an economic module (Vanthoor et al., 2012a) to evaluate the effect of greenhouse construction types on the economic performance of the production as determined by its annual net financial return (NFR). Hence, in this combined greenhouse design and economic module, the NFR is a function of yield, variable costs, construction costs, depreciation and costs for maintenance of equipment that is used in greenhouse production. Previously this model has been applied to identify suitable greenhouse construction types under a range of warm climates and lower latitude countries such as Spain, Netherlands etc. (Vanthoor et al., 2012a). However, previous studies of greenhouses and greenhouse subsystems have mostly excluded high latitude regions. The few studies that did include high latitude or otherwise cold regions did not consider renewable energy (Ahamed, Guo, & Tanino, 2018; Ahamed et al., 2019; Torrellas et al., 2012). The climate and light conditions in these regions differ considerably from those in lower latitude regions. Moreover, overall there is a considerable production of renewable energy in these regions, especially in comparison with other regions with significant greenhouse production (IRENA, 2021). Hence, in total, findings about greenhouse performance, energy use and related environmental impact from previous simulation and optimisation studies cannot be directly extrapolated to these regions.

Norway is suitable as a case for evaluating greenhouse economic and energy performance under high latitude regions. Its greenhouse vegetable production is small compared to the vegetable consumption but nevertheless growing (Rebnes & Angelsen, 2019). The production of tomatoes in Norway, its economically most important greenhouse vegetable, increased by, on average, 3.5% per year from 2009 to 2018. This increase is also in line with great preference for locally produced tomatoes in Norwegian markets over imported ones (Bremnes, Hansen, Slimestad, & Verheul, 2019). The growing season and the area for agricultural production in the field are short with an average temperature of 5–6 °C and low outdoor light conditions. Most of the greenhouse production takes place during the summer season which is from May to October and a little with some artificial lighting in the months from February to November. Heating in greenhouses is primarily obtained from boilers by burning gas and is supplied through pipes. There is potential to further decrease the CO_2 emissions from the greenhouse sector (Verheul & Thorsen, 2010), which is needed to meet national goals to reduce carbon emissions as outlined by ‘Klimakur

2030' (lit. climate cure 2030) (Miljødirektoratet, 2019) towards which attempts are being made by both the agriculture sector and the Norwegian government (Fremstad, 2020). Norway has the highest share of electricity produced from renewable sources, mainly hydropower, in Europe along with the lowest carbon emissions from the power sector (Ministry of Petroleum and Energy, 2020) and the large hydroelectric energy production in Norway provides the possibility to replace fossil energy in the greenhouse sector with renewable energy.

Energy costs, of which heating is a major component and lighting, account for about 44% of total production costs in Norwegian greenhouse vegetable production (Verheul, Maessen, & Grimstad, 2012). This is a high percentage in comparison with production in other countries (Raviv, Lieth, & Bar-Tal, 2019). However, the efficiency of the use of gas, electricity and other inputs and thus their costs may vary between greenhouses with different designs for insulation and shading equipment, heating and cooling system, artificial lighting and system for CO_2 supply (Hatirli, Ozkan, & Fert, 2006). Labour costs, depreciation of the structure and equipment, and costs for plant material, substrate, fertilisers and plant protection agents also have great impact on the total production costs (Moe et al., 2005; Vanthoor et al., 2012a). Production designs, which reduce the use of energy, water or CO_2 emissions per unit of product, could increase the profitability for the grower and the tomato production sector as a whole (Verheul et al., 2012), and hence encourage growers to use environmentally friendly methods. There is a growing understanding that an agreement between the government and the growers is fundamental in order for policy decisions regarding environmentally sustainable production methods to be practised by growers, something that is only possible if they are also economically profitable (www.climplement.no; Pretty, Ball, Xiaoyun, & Ravindranath, 2013; Fremstad, 2020).

Suitable greenhouse designs may also vary considerably between regions in Norway with different climate conditions. Moreover, the effect of the greenhouse design on the profitability may not always be correlated with the environmental impact. The objective of this study was to identify the greenhouse design, out of a number of feasible designs, that generated the highest NFR and the lowest fossil fuel use for seasonal tomato production from mid-March to mid-October in Norway. Therefore, we adjusted and evaluated the greenhouse production model of Vanthoor (2011) against observed climate conditions and seasonal tomato yield in a commercial greenhouse in Norway. Subsequently, tomato production for a set of combinations of outdoor climate and light conditions and greenhouse designs was simulated, and the economic performance and fossil use associated with these combinations were evaluated.

2. Materials and methods

2.1. Model overview

The present study uses the approach presented by Vanthoor (2011) in order to design a greenhouse which maximises the profit, as quantified by the NFR, and minimises energy use for tomato growers in Norway. The design technique consists of a greenhouse climate module, crop yield module and an economic module that are connected to each other as shown in Fig. 1. The model simulates greenhouse climate conditions, crop growth and yield with an hourly time step and provides the yearly NFR as an output.

The greenhouse climate module describes the effect of the outdoor climate, internal set points for temperature, CO_2-concentration, humidity as well as greenhouse design elements on the indoor climate of the greenhouse and its resource consumption. The crop yield module simulates the tomato growth and yield as a function of the indoor climate. The economic module calculates the NFR of the production, which is affected by the resource use and the crop yield. The climate model, extensively described by Vanthoor et al. (2011a), is based on the energy and mass balance of each greenhouse element. Righini et al. (2020) later added heat storage through a heat pump to the model, and the work includes a summary of all the equations, along with an updated scheme of the model. The structure of the yield model, with a common carbohydrate buffer and carbohydrate distribution to plant organs, based on the photosynthesis model of Farquhar, Von Caemmerer, and Berry (2001) is the one generally applied. Vanthoor, Stanghellini, Van Henten, and De Visser (2011b) added two lumped temperature-dependent functions inhibiting re-distribution of carbohydrates and thus growth. Both sub- and supra-optimal temperature inhibit growth, short term deviations having less impact than deviations in daily means. A temperature sum representing the development stage of the crop was modelled to define the timing of first fruit set and the time at which the carbohydrate distribution to the fruits reaches its potential. The temperature functions, which Vanthoor et al. (2011b) derived from an extensive literature survey, have not been changed. A short

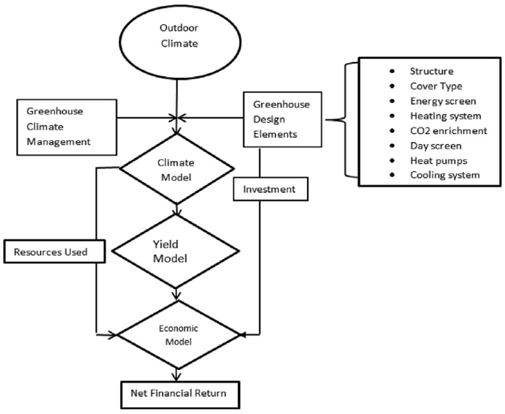


Fig. 1 – An overview of the model-based greenhouse design method used in this study. The climate model predicts the indoor climate of the greenhouse based on the outdoor climate management and design elements. The yield model predicts the fresh-mass harvest based on the climate model. The economic model predicts the NFR based on the used resources and values of the yield. Adapted from Vanthoor et al. (2011b).

presentation of the components of the economic module is given in the following section.

2.1.1. *Economic tomato yield module*

The yearly net financial return P_{NFR} (NOK m^{-2} year^{-1}) is calculated according to:

$$P_{NFR}(t_f) = -C_{fixed} + \int_{t=t_0}^{t=t_f} \dot{Q}_{CropYield} - \dot{C}_{Var} \quad (NOK\, m^{-2}\, Year^{-1}) \tag{1}$$

where t_0 and t_f are the start and the end time of the growing seasons, C_{fixed} $(NOK\, m^{-2}\, Year^{-1})$ are the fixed costs for the tangible assets (greenhouse structure, climate computer, cooling system, heating system and structure), C_{Var} $(NOK\, m^{-2}\, Year^{-1})$ are the variable costs, and $Q_{CropYield}$ $(NOK\, m^{-2}\, Year^{-1})$ is the economic value of the crop yield. Figure 2 presents details of the costs and sub-costs that are included in the economic module.

2.1.1.1. Fixed costs. The yearly fixed costs are calculated based on the interests and the total investments of the construction elements, $C_{fixed}(NOK\, m^{-2}\, Year^{-1})$, which include maintenance and depreciations and are defined as:

$$C_{fixed} = C_{interest} + \sum_{i=1}^{N} C_{construction,i} + C_{Rem} \quad (NOK\, m^{-2} year^{-1}) \tag{2}$$

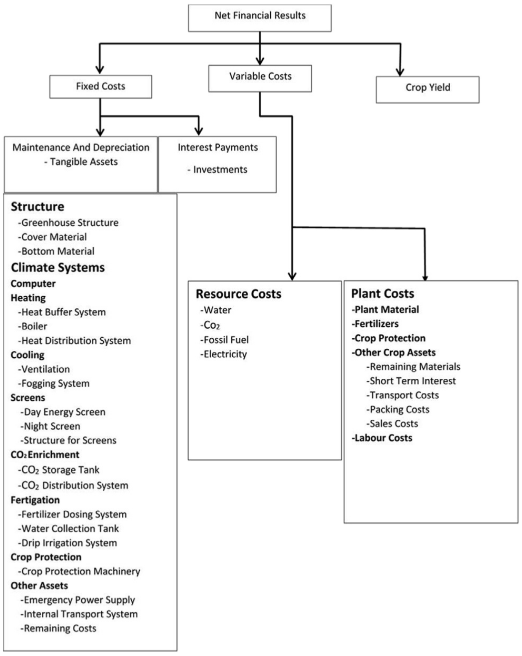


Fig. 2 – An overview of the costs associated with the Net Financial Return (NFR) of the grower. The costs are divided into fixed and variable costs and include the costs occurred as a result of using different design elements. Adapted from Vanthoor et al. (2011b).

where $C_{interest}(NOK\, m^{-2} Year^{-1})$ are the interest costs of the total investments. Here, i denotes the construction elements and N is the total number of greenhouse design elements used in selected greenhouses construction. $C_{construction}(NOK\, m^{-2} Year^{-1})$ are the costs for depreciation and maintenance and C_{Rem} $(NOK\, m^{-2}\, Year^{-1})$ are the remaining costs of construction and equipment. For equations for construction elements, interests and remaining costs see Vanthoor et al. (2012a).

2.1.1.2. Variable costs. The variable costs are the sum of the costs for plant, water used, CO_2, and the two types of energy used: fossil fuel and the electricity. The total variable $\dot{C}_{var}$ are defined as:

$$\dot{C}_{var} = \dot{C}_{plant} + \dot{C}_{Water} + \dot{C}_{CO2} + \dot{C}_{Fossil\ fuel} + \dot{C}_{Electricity} \quad \left(NOK\, m^{-2} h^{-1}\right) \tag{3}$$

where $\dot{C}_{plant}(NOK\, m^{-2}\, h^{-1})$ are the costs associated with the crop and are time dependent (such as bumblebees for pollination, fertilisers and crop protection), $\dot{C}_{Water}(NOK\, m^{-2} h^{-1})$ are costs for water used and $\dot{C}_{CO2}(NOK\, m^{-2} h^{-1})$ are the costs for carbon dioxide used as a resource, $\dot{C}_{Fossil\ fuel}(NOK\, m^{-2} h^{-1})$ are costs for the fossil fuel and are the electricity costs used for heating and cooling in seasonal production. For more information about variable costs equations for plant, water and energy see Vanthoor et al. (2012a).

2.2. *Locations, greenhouse design and evaluated cases*

The present study applied the model described above to identify the greenhouse design that generated the highest NFR and the lowest energy used out of several plausible greenhouse designs for tomato production at four locations (Fig. 3) in Norway. Five combinations of alternative choices of seven greenhouse design elements, as described in the subsequent sections were evaluated.

Fig. 3 – A rough depiction of the four locations in Norway, representing coastal and inland areas, for which the greenhouse designs were evaluated.

2.2.1. *Locations*

First, to evaluate the applicability of greenhouse tomato production model to conditions that represented Norway, we tested its prediction accuracy for indoor temperature, CO_2 concentration and tomato fresh mass that was observed in a greenhouse in southwestern (SW) Norway (Orre (lat. 58.71, long. 5.56, alt. 18 m a.s.l.)) during one seasonal production cycle for one of the selected greenhouse designs (Night screen (NS) as defined in section 2.2.3). Subsequently, the greenhouse designs of the selected combinations as well as its underlying economic components were identified for tomato production from 10th March to 15th October for Orre, Kise (lat. 60.46, long. 10.48, alt 130 m a.s.l.) in eastern (E) Norway, Mære (lat. 63.43, long. 10.40, alt 18 m a.s.l.) in midwestern (MW) Norway and Tromsø (lat. 69.65, long. 18.96, alt 60 m a.s.l.) in northern (N) Norway (Fig. 3). These locations were included because they represent different latitudes and have varying coastal and inland climate conditions in Norway (Fig. 4), and either represent major tomato-producing regions or could, in our opinion, have the potential for greenhouse tomato production due to local demand for tomatoes.

2.2.2. *Greenhouse design*

All the greenhouse designs that were evaluated were Venlo-type greenhouses (Fernandez & Bailey, 1992) as usually used in Norway, covered with standard glass and with natural ventilation (alternate roof vents on both sides that corresponded to about 15% of floor area (Fig. 5)). There was no ventilation in the side wall of the greenhouses. The greenhouses had a rectangular shape of 90 × 64 m, i.e., a floor area of 5760 m^2. The light transmission of the greenhouse cover including structural material (aluminium/steel) was set to 64%. No artificial lighting was used.

Two types of heating systems were evaluated, with one that used fossil fuel energy and the other green energy. More specifically, a boiler heating system, using natural gas, and a heat pump, using electricity generated in a hydropower plant, were applied. The evaluation included the use of night and day energy screens. Both the boiler and heat pump were used for primary and secondary pipe heating. CO_2 was supplied to the greenhouse either by burning of natural gas in the boiler or as pure CO_2 from a tank. The heat distribution system consisted of both rail pipes and grow pipes made of steel, which were filled with hot water. The capacity of the CO_2 enrichment system was 130 kg CO_2 ha^{-1} h^{-1}. Temperature, humidity and CO_2 supply were controlled by settings for global radiation, indoor temperature and window opening (Table 4). Plants were grown in standard Rockwool slabs and irrigated by a drip irrigation system.

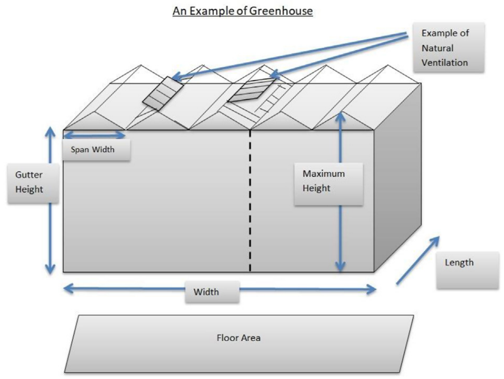


Fig. 5 – The shape and natural ventilation system in Venlo type greenhouses used in Norway.

The tomato price trajectory (Fig. 6) from 2016, obtained from *Grøntprodusentenes Samarbeidsråd* (the Green Growers' Cooperative Marked Council) (https://www.grontprodusentene.no), was applied for all greenhouse designs and locations. Likewise, the fixed and variable costs per input unit that were associated with the Norwegian construction and production conditions presented in Tables 1 and 2 were set the same for all greenhouse designs and locations. These costs were either obtained from literature or from interviews with tomato growers across Norway by advisors at The Norwegian Institute of Bio-economy Research (NIBIO).

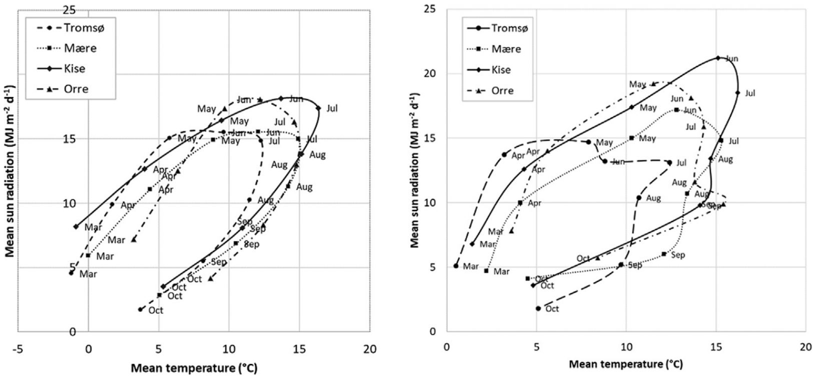


Fig. 4 – The mean temperature and radiation recorded in the four locations during the last 30 years (1989–2019) (left) and for the year 2016 (right).

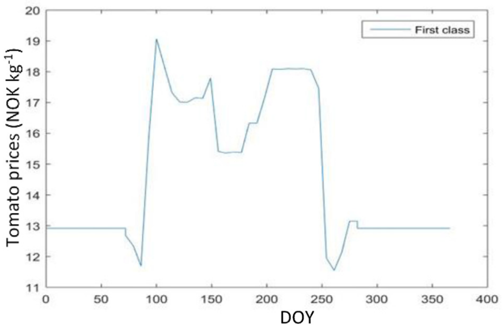


Fig. 6 – Price trajectory used for the tomatoes for year 2016 in Norway. Only the first-class yield is taken into account and so only the first-class yield was registered for this study. DOY: Day of the Year.

2.2.2.1. *Greenhouse climate control*. For all four locations and greenhouse designs, the same greenhouse climate set points were used, as presented in Table 4. However, the period for which day and night energy screens were applied was adjusted according to the local light and temperature conditions and was thus allowed to vary between locations. The strategy for controlling the air temperature is presented in Fig. 7.

2.2.2.2. *Indoor climate and tomato fresh mass predictability*. The model for tomato production was validated for an existing greenhouse in Orre in Norway for seasonal production for the year 2016 without artificial lighting in Orre. The validation was conducted with the following production conditions. Hourly outdoor weather data including average temperature, wind speed, relative humidity and global radiation that were input to the climate module also represented the year 2016 and were obtained from the Særheim station of

Table 1 – Fixed costs used in the greenhouses. The costs associated with the greenhouse design elements and element alternatives e_j represent the number for each design element option. The depreciation percentage has been derived from the consultations with the local growers. E* = around 10% extra for transportation expenses and exchange rate from the Netherlands to Norway.

Design element/Fixed costs	e_j	Investment (NOK m^{-2})	Investment (NOK $unit^{-1}$)	Depreciation (% $year^{-1}$)	Maintenance (% $year^{-1}$)	Construction (NOK m^{-2} $year^{-1}$)	Source
Structure							Vermeulen (2016) +E*
Venlo 5760 m^2		519.0		5.0	0.5	28.5	
Covers							Dansk Gartneri
Glass		93.5		5.0	0.5	5.1	
Screens							*Growers*
No screens	1	0	0	0	0	0	
Day screen	2	35.5		25	0	8.7	
Night screen	3	100		15.0	5	15.5	
Structure energy screens		130		7.0	5	10.5	
Boiler							Vermeulen (2016) + E*
Boiler: 0.75 MW	1		620,530	7.0	1	9.9	
Boiler: 1.16 MW	2		660,000	7.0	1	10.6	
Heating pipes		65		5.0	0.5	3.6	
Mechanical Heating							Vermeulen (2016) + E*
No	1		0	0.0	0	0.0	
Mechanical heat and cool: 50 W/$m^2$$unit^{-1}$	2		2,688,000	7.0	2	37.0	
Cooling systems							Vermeulen (2016) + E*
No	1	0	0	0	0	0	
Fogging: 200 g h^{-1} m^{-2}	2	65		7.0	5	5	
CO_2 supply							Vermeulen (2016) + E*
Pure: 130 kg ha^{-1} h^{-1}	1		48,763	10.0	0	0.9	
CO_2: from boiler	2		31,700	10	5	2.4	
CO_2distribution system		5		10.0	5	0.7	
Remaining costs for irrigation, crop protection, internal transport							*Growers*
All selected locations		500		10.0	5	75	

Table 2 – Variable costs that were used in the simulations. * = The data was obtained from interviews with commercial tomato growers whose production is representative for Norway.

Resource	Amount	Unit price (NOK)	Unit	NOK/m^2	Source
Area	5760		m^2		
Plants	2.6	25.0	Plant	65	Hovland (2018)
Growth medium	2.5	10.4	Slab	26	Hovland (2018)
Fertiliser	1.0	30.0	m^2	30.0	Hovland (2018)
Pollination	1.0	12.0	m^2	12.0	Hovland (2018)
Pesticides	1.0	5.0	m^2	5.0	Growers*
Packaging	6.7	3.0	Box	20	Growers
Energy gas		0.39	kWh		http://www.ngfenergi.no/ukens_priser
Energy light		0.39	kWh		http://www.ngfenergi.no/ukens_priser
Marketing etc.	1.0	3.0	%		Growers
Operating assets	1.0	15.0	m^2	15.0	Growers
Other	1.0	10.0	m^2	10.0	Growers
Labour costs	1.2	180.0/hour	m^2		Growers
Insurance/other	1	15.0	m^2	15.0	Growers

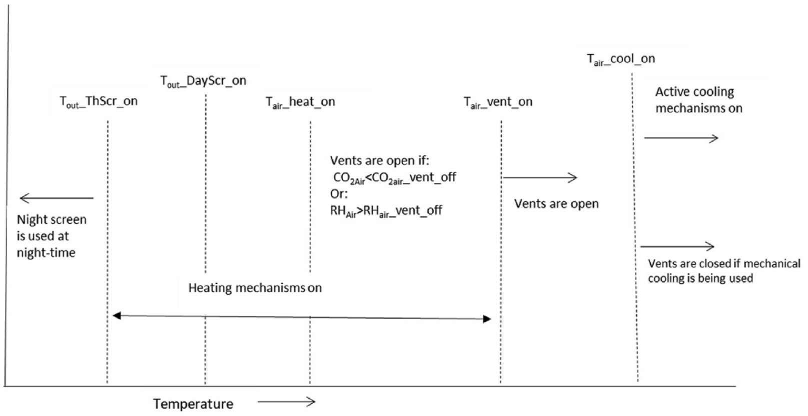


Fig. 7 – Strategy for managing the greenhouse climate. The average set points for climate control are shown in Table 4. Adapted from Vanthoor et al. (2011b).

the Agroclimate Station Network (https://lmt.nibio.no/) of NIBIO. The weather station from which weather data was obtained for simulation at Orre was located 8 km northeast of the greenhouse. Weather input data for 2016 was chosen because the mean monthly outdoor air temperature and global radiation in that year adequately represented monthly mean values of these weather elements over the past 30 years at the four locations (Fig. 4). Global radiation was measured with a Kipp solarimeter, placed outside of the greenhouse. Light transmission of total photosynthetic active radiation (PAR, mol m^{-2} d^{-1}) was estimated based on measurements in the empty greenhouse and the outdoor global radiation. CO_2 of greenhouse air was measured at 5 minute intervals with a gas analyser (Priva CO_2 monitor Guardian +). Air temperature and relative humidity were measured by dry- and wet-bulb thermocouples placed in ventilated boxes that shielded against direct solar radiation and placed in the middle of the canopy. Thermocouples were calibrated before the start and controlled at the end of the experiment. Temperature (°C), relative humidity (%), CO_2 concentration (ppm) and window opening (%) were registered every 5 min using a Priva computer (Priva Connext).

Tomato seeds were sown at the end of January 2016 in a separate greenhouse. Young plants were transplanted in the greenhouse on standard Rockwool slabs with a density of 2.60 plants m^{-2} and a row separation of 1.5 m on 10th March and grown until 15th October. The night, day and ventilation temperature set points were 17, 19, 23 °C respectively. Light transmission of total photosynthetic active radiation (PAR, mol m^{-2} d^{-1}) was estimated based on measurements in the empty greenhouse and the outdoor global radiation. Leaf area was estimated once a week by measuring leaf length and leaf number on 10 representative plants.

CO_2 was applied up to the maximum concentration of 1000 ppm when the temperature and global radiation matched the criteria in Table 4 for CO_{2Air_ExtMax} and the windows were closed, and decreased with decreasing global radiation, decreasing indoor temperature and increasing ventilation rate according to Magán, López, Pérez-Parra, and López (2008) to a minimum value of

390 ppm with 100% window opening. Greenhouse temperature, CO_2 concentration and humidity were measured every five minutes but, in the simulations, the hourly average values were used. For pollination, bumblebees were used in the greenhouse during the whole cultivation period. Fruits were harvested, twice a week, at light red ripening stage and only 1st class fruits (marketable fraction) were taken into account here.

The model prediction accuracy of the indoor air temperature, CO_2-concentration and fresh mass tomato yield was evaluated using the Relative Root Mean Squared Error (RRMSE), Mean Bias Error (MBE) and Mean Absolute Error (MAE) as defined below:

$$RRMSE = \frac{100}{\overline{y_{data}}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(y_{Mod,i} - y_{Data,i}\right)\hat{}2}$$

$$MBE = \frac{1}{n} \sum\nolimits_{i=1}^{n} \left(y_{Mod,i} - y_{Data,i}\right)$$

$$MAE = \frac{1}{n} \sum\nolimits_{i=1}^{n} \left|y_{Mod,i} - y_{Data,i}\right|$$

where y_{data} is the mean of measured data over the total time span, n is the number of measurements, $y_{Mod,i}$ is the simulated output at time instant i and $y_{Data,i}$ is the corresponding measured value at time instant i.

2.2.3. *Evaluated cases*

An overview of the greenhouse designs evaluated for the four locations in Norway is presented in Table 3 and details are explained below.

Standard greenhouse (without additions) (0S): A gas boiler with 1.16 MW capacity was used for heating. There were no indoor day energy screens or night energy screen included in this greenhouse design. Moreover, there was no artificial cooling or fogging system used.

Night energy screen (NS): This greenhouse design is like the existing greenhouse in Orre that was used to validate the climate and yield module. It had the same design elements as **0S** except for the addition of a night energy screen consisting of 50% aluminium and 50% polyethylene, which was used for energy saving purposes whenever the temperature was below 14 °C at night (See Table 4 for an explanation about how day and night settings were initiated.).

Day and night energy screens (DNS): This greenhouse design was the same as the design **NS** except for the use of a day energy screen consisting of 100% polyethylene (PE) during the day when outside global radiation was less than 150 Wm^{-2} and temperature was below 10 °C to save energy while also allowing more light to pass through during the day time as compared to the night energy screen.

Day and night energy screens with fogging for cooling (DNSF): The design **DNSF** was the same as the **DNS** except that a fogging system for cooling and humidification purposes was activated when the air temperature exceeded 24 °C and the relative humidity was below 84%.

Day and night energy screens with fogging and mechanical cooling and heating (DNSFM): This design represents a production system in which the fossil fuel is partly substituted by hydroelectric energy. The design of DNSFM differed from DNSF in the following ways: An electrical heat pump with a coefficient of performance (COP) of 3 was used for heating i.e. 1 kWh energy consumed would provide 3 kWh of output heat. There was an activation of mechanical cooling and heat harvest during the day when the temperature in the greenhouse exceeded 25 °C. In addition, CO_2-enrichment was provided by pure CO_2. All electricity was assumed to be from a hydroelectrical power plant representing the energy supply conditions in Norway (The Norwegian Water Resources and Energy Directorate, 2020). This design can be considered to be a relatively closed design as compared to the others and is expected to have lower fossil fuel use.

2.3. *The effect of tomato price and energy costs on the NFR*

Economic performance of the simulated cases depends on the tomato price and the energy cost in the production seasons. The sensitivity of the economic performance of the evaluated greenhouse designs to the seasonal tomato price was analysed by varying the tomato price and energy costs within the range of 14.5 NOK kg^{-1} to 19.5 NOK kg-1 using a 1 NOK step-size and 0.14 NOK kWh^{-1} to 0.64 NOK kWh^{-1} with a 0.05 NOK step-size from the original energy cost respectively.

Table 3 – The different greenhouse technological design packages. The NS represents the greenhouse in SW Norway (Orre), for which the indoor climate and tomato yield prediction accuracy was evaluated. The greenhouse design with two energy screens was extended with various combinations of CO_2-enrichment and with heat buffer technology. Numbers in table are explained in the e_j column in Table 1. The columns 1–4 represent traditional production using fossil energy, while column 5 represents a production based on hydro-electrical energy.

	Standard greenhouse (without additions) (0S)	Night energy screen (NS)	Day and night energy screens (DNS)	Day and night energy screens with fogging for cooling (DNSF)	Day and night energy screens + fogging and mechanical cooling and heating (DNSFM)
Boiler	2	2	2	2	1
Mechanical heating	1	1	1	1	2
Screens	1	3	2 + 3	2 + 3	2 + 3
CO_2 supply	1 + 2	1 + 2	1 + 2	1 + 2	1
Cooling systems	1	1	1	2	2

Table 4 – Set points for managing the indoor climate of the greenhouse.

Greenhouse climate management	Value	Unit	Explanation
$\text{Tair}_{\text{\_vent\_on}}$	23	(°C)	Temperature set point, measured inside the greenhouse, for opening of roof ventilation during daytime
$\text{RHair}_{\text{\_vent\_on}}$	84	(%)	Relative humidity set point, measured inside the greenhouse, for opening of roof ventilation
$\text{CO}_2\text{air}_{\text{\_vent\_min}}$	390	(ppm)	Set point for CO_2 dosage at maximum ventilation
$\text{Tair}_{\text{\_heat\_on}}$ (night/day)	17/19	(°C)	Temperature set point for turning on the heating system for night and day respectively
$\text{Tair}_{\text{\_fog\_on}}$	24	(°C)	Set point for fogging if the indoor air temperature was above this
$\text{Tout}_{\text{\_NightScr\_on}}$	14	(°C)	Set point for using night screen if temperature is below this
$\text{Tout}_{\text{\_Day\_EnScr\_on}}$	10	(°C)	Set point for using day energy screen if temperature is below this
$\text{Iglob}_{\text{\_Day\_EnScr\_on}}$	150	($W\ m^{-2}$)	Set point for day energy screen if Iglob is below this
$\text{CO}_{\text{2Air\_ExtMin}}$	390	(ppm)	The CO_2 concentration below which the air is enriched with CO_2
$\text{CO}_{\text{2Air\_ExtMax}}$	1000	(ppm)	Maximum CO_2 set point if Iglob $\geq$650 Wm-2 and temperature Tair $\geq$23 °C
Crop conditions			
LAI_start (Initial)	0.3	(–)	The initial leaf area index at planting date
LAI_max	3	(–)	Maximum leaf area index
Planting date	March 10th		
End growing period	October 15th		

3. Results

3.1. *Prediction accuracy of observed indoor greenhouse climate and tomato yield in Orre*

The Relative Root Mean Squared Error (RRMSE), Mean Bias Error (MBE) and Mean Absolute Error (MAE) for temperature, CO_2-concentration and fresh mass tomato yield are shown in Table 5. While the RRMSE for the three variables is less than 10%, pointing towards the model being relatively accurate, the results from MBE show that the model prediction, especially for CO_2, is negatively biased. The MAE results show that the model's prediction of CO_2 values differs on average by 40 ppm from the measured values. This implies that the lower predictions of CO_2 could also have affected the predicted values of yield negatively.

Generally, throughout the production period, the simulated temperature varied from 2 to 3° below the measured values to 1–2° above the measured temperature with lower differences during most of the period (Fig. 8). Notably, the model under-predicted the measured temperature in the beginning of the growing season as exemplified by the period from 20th March to 26th March (day of year 80–86) whereas during mid-production the difference between predicted and measured temperature was lower. During the last period of the growing season, the model tended to over-predict the measured temperature growing season as exemplified in the period from 17th to 25th September (day of year 260–268) in Fig. 10. Also, the accuracy of the predictions of CO_2-concentration varied during the growing season. During the first period of the growing season, as exemplified by period from 20th March to 26th March, the prediction accuracy varied (Fig. 8).

During the mid-season, as exemplified by the period from 30th June to 6th July (day of year 181–187), the prediction accuracy of the CO_2-concentration was lower during the day than during the night (Fig. 9).

At the end of the season, the measured CO_2-concentration was generally over-predicted during the day and under-predicted at night (Fig. 10).

Overall, the simulated yield was close to the measured fresh-mass yield (Fig. 11). The model, however, under-predicted the measured yield at the beginning of the season, which may be due to the lower temperature prediction at the beginning of the growing season (Fig. 8). The over-prediction of the yield at the end of the season may be due to the higher temperature predicted by the model at the end of the season (Fig. 10).

There was a clear decrease in ventilation in the DNSFM greenhouse due to the mechanical heating and cooling. For instance, the percentage ventilation for the DNSFM design decreased by 0.9% as compared to the other four designs not having the mechanical heating and cooling equipment and that had average ventilation for the entire growing season of about 0.24%.

3.2. *Economic performance*

3.2.1. *Net financial return (NFR)*

The present simulation study showed clear region-dependent differences in NFR and its underlying components as well as

Table 5 – Relative Root Mean Square Error (RRMSE), Mean Bias Error (MBE) and Mean Absolute Error (MAE) values for air temperature, CO_2 concentration and yield simulation for the greenhouse in Orre (SW Norway).

Error	Location	T_{air}	CO_2	Yield
RRMSE	Orre	7.6	8.6	0.7
MBE	Orre	0.2	−7.1	0.08
MAE	Orre	1.1	39.9	0.09

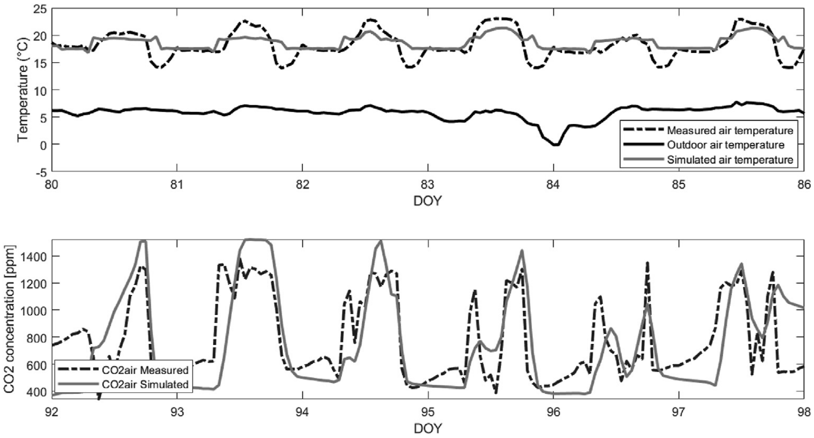


Fig. 8 – Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the start of the growing period. DOY: Day of the Year.

in fossil energy use between greenhouse types with different energy saving and temperature regulation elements. Of the four locations studied, it was found that the NFR was highest for Kise, and lowest for Tromsø for all investigated greenhouse designs. Moreover, for both Mære and Tromsø, the NFR was negative for all designs. This was primarily due to the low temperature and low solar radiation at these locations, which necessitated high costs for energy and resulted in low crop yield. The effect of the greenhouse structure on NFR differed between locations. Applying a night energy screen in the NS design increased the NFR at all locations. When a day energy screen was added (DNS design), the NFR declined compared to the greenhouse with just a night energy screen (NS) at all locations and also compared to the greenhouse with no screen (0S). One possible explanation for this result could be that, while there was no significant increase in energy saving, there was a high increase in the installation costs. This makes 0S the design with the second highest NFR for all locations (Table 6). When mechanical heating and cooling was introduced in the greenhouse design DNSFM, the NFR decreased as compared to all other designs with the lowest NFR for all locations except Tromsø, which had an almost equal NFR for the DNSF and DNSFM designs.

Moreover, the fact that the difference in NFR among regions followed the same pattern for all greenhouses with negative economic performance in Mære and Tromsø, gives a clear indication of the regions of Norway where traditional March to October seasonal greenhouse tomato production is economically viable for a rather wide range of greenhouse constructions. The decrease in energy use associated with the application of a day energy screen and mechanical heating and cooling equipment clearly illustrates that there is a

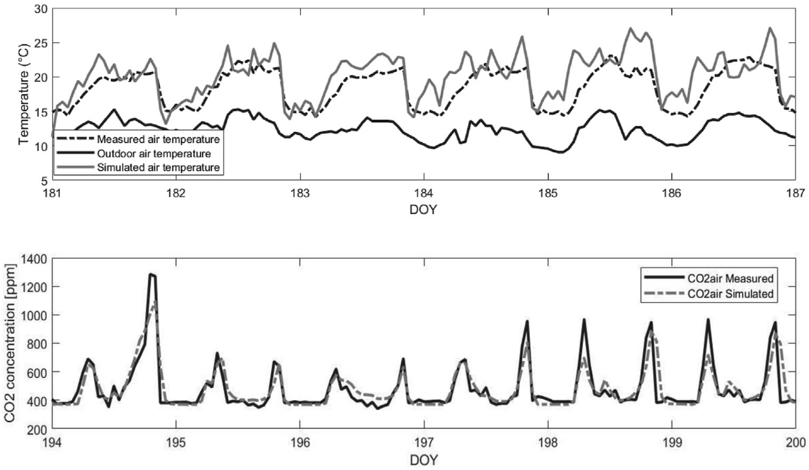


Fig. 9 – Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the mid-production period. DOY: Day of the Year.

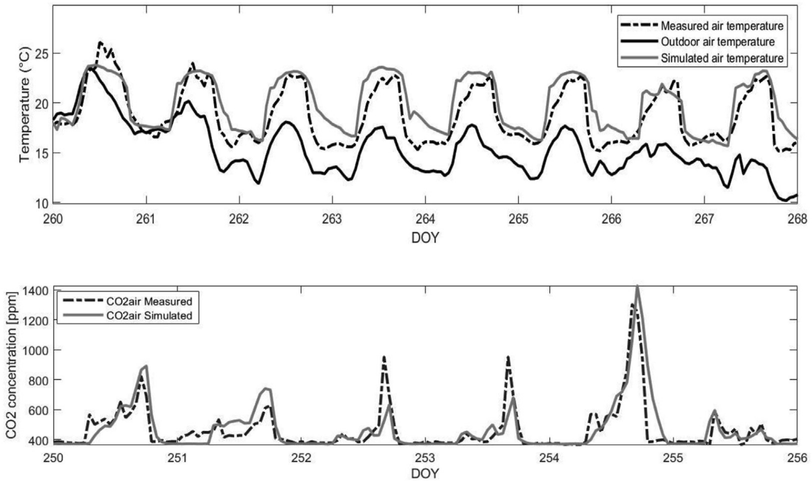


Fig. 10 – Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the end of the growing period. DOY: Day of the Year.

discrepancy between the effect of greenhouse design on economic performance and resource use efficiency under the investigated conditions.

3.2.2. *Fixed and variable cost analysis*

With the increase in energy saving equipment across the greenhouse designs from the one with no screen (0S) to the one with mechanical heating and cooling (DNSFM), there was a gradual decline in the energy costs resulting in decreased variable costs for all locations. The decrease in variable costs ranged from 58.8 (in Kise) to 74.0 (in Tromsø) NOK m^{-2} $year^{-1}$ in all locations for DNSFM as compared to the greenhouse with no energy screen (0S). By using energy screens and mechanical heating and cooling, less heating was required and thus a smaller sized boiler was needed. Using a boiler with smaller capacity, i.e. 0.75 MW, also reduced fixed costs (Table 6). However, the overall fixed costs increased with the increase in investments in equipment for regulation of temperature and energy use for all locations. The results show that energy-saving equipment, with the exception of the night screen, is not particularly profitable for seasonal production due to the differences between their associated costs per m^2 and the increase in yield or decrease in energy use as compared to the design with the night screen. Likewise, it was found that fogging can be omitted under the investigated production regimes, since it had negligible impact on energy saving and potential crop yield.

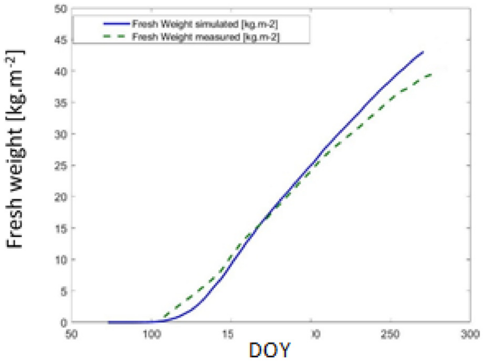


Fig. 11 – Measured (dashed line) and predicted (solid line) yield for SW Norway (Orre) greenhouse during the growing period from mid-March to mid-October in the Orre greenhouse. DOY: day of the year.

3.3. *Prediction of crop yield*

There was a slight decrease in the simulated yield for all locations when going from 0S to NS, which can be explained by the shading effect of the structure added for the night energy screen. There was a further decline in the potential crop yield when going from NS to DNS in all locations, which might be explained by the shading effect of the day energy screen. At all locations, adding mechanical heating and cooling equipment (DNSFM) had a slightly positive effect on the crop yield value (Table 6). These results indicate that a more closed system with less variability in the indoor climate is positive for the tomato growth and production. This can be explained by the observation that a closed greenhouse design prevents heat loss and CO_2 loss, which in turn has a positive effect on the photosynthesis process during the day.

3.4. *Effects on energy and CO_2 use*

The changes in the profit notwithstanding, the increase in investments in energy screens and mechanical heating and cooling equipment had the added benefit of lowering the use of fossil energy. These results are linked to the lower

Table 6 – Overview of the economic analysis and costs of resources used for the selected greenhouse designs elements for the four regions in Norway for the period Jan-2016 to December-2016. For an explanation of the design abbreviations e.g. 0S, NS etc. see Table 3.

	SW Norway (Orre)					MW Norway (Mære)				
	0S	NS	DNS	DNSF	DNSFM	0S	NS	DNS	DNSF	DNSFM
Crop Yield value (NOK year^{-1} m^{-2})	690.6	688.9	670.1	672.1	672.4	634.3	631.6	606.6	608.4	608.7
Fixed costs (NOK year^{-1})	125.9	149.9	161.9	165.9	202.6	125.9	149.9	161.9	165.9	202.6
Variable costs (NOK year^{-1} m^{-2})	528.7	501.9	494.6	494.5	467.7	533.9	505.4	498.2	498.1	472.0
Labor costs	199.4	198.9	197.2	197.2	197.2	196.2	195.1	193.7	193.7	193.7
Fossil fuel costs	141.1	114.6	108.7	108.7	61.4	152.9	125.5	110.8	110.8	68.1
Electricity costs	0.0	0.0	0.0	0.0	22.1	0.0	0.0	0.0	0.0	22.3
Cost for pure CO_2	1.3	1.3	1.3	1.3	1.6	1.2	1.2	1.2	1.2	2.2
Variable costs (NOK kg^{-1})	12.7	12.1	12.3	12.3	11.6	14.1	13.4	13.7	13.7	13.0
Potential crop yield (kg m^{-2})	41.6	41.4	40.1	40.2	40.2	38.0	37.8	36.3	36.4	36.4
Net financial result (NOK year^{-1} m^{-2})	35.9	37.1	13.6	11.7	2.1	−25.5	−23.6	−53.5	−55.6	−65.9

	N Norway (Tromsø)					E Norway (Kise)				
	0S	NS	DNS	DNSF	DNSFM	0S	NS	DNS	DNSF	DNSFM
Crop Yield value (NOK year^{-1} m^{-2})	620.8	617.5	592.7	593.5	592.7	693.9	691.8	673.4	675.0	675.0
Fixed costs (NOK year^{-1})	125.9	149.9	161.9	165.9	202.6	125.9	149.9	161.9	165.9	202.6
Variable costs (NOK year^{-1} m^{-2})	558.9	527.8	521.4	522.4	485.0	521.8	494.3	489.1	490.1	463.0
Labor costs	197.0	195.8	194.0	194.0	194.0	200.1	199.3	198.0	198.0	198.0
Fossil fuel costs	177.1	148.4	141.8	141.8	85.0	131.1	106.5	101.3	102.3	53.6
Electricity costs	0.0	0.0	0.0	0.0	22.8	0.0	0.0	0.0	0.0	22.1
Cost for pure CO_2	0.6	0.6	0.6	0.6	1.8	3.0	3.1	3.1	3.1	4.2
Variable costs (NOK kg^{-1})	14.9	14.2	14.6	14.7	13.6	12.5	11.9	12.2	12.2	11.5
Potential crop yield (kg m^{-2})	37.4	37.2	35.6	35.6	35.6	41.9	41.7	40.2	40.3	40.3
Net financial result (NOK year^{-1} m^{-2})	−64.0	−60.2	−90.6	−94.8	−94.8	46.2	47.6	22.4	19.0	9.4

ventilation in the greenhouses with a more advanced design than in those without mechanical heating and cooling, curtailing energy losses and water losses through transpiration. For instance, as shown in Table 7, for Kise, the fossil fuel consumption decreased with the investment in energy screen and adding mechanical heating and cooling (DNSFM) by 198.6 kWh m^{-2} as compared to the design with no screen (0S). The same tendency for reduced energy use can be seen for the other locations, with the highest decrease in fossil fuel use recorded in Tromsø (236.2 kWh m^{-2}).

Likewise, the DNSFM design had a lower CO_2 use due to shorter periods with open windows. Nonetheless, the model predicted an increase in the use of pure CO_2 of about 1.2 kg m^{-2} from 0S to DNSFM for all locations, with the highest pure CO_2 use in Kise. The reason for the highest usage in Kise was the low fossil fuel use as compared to the other locations. The total CO_2 use is shown in Table 7, which includes pure CO_2 and CO_2 from gas. The CO_2 from gas decreases with the increase of investments in energy screens, fogging and mechanical heating and cooling equipment.

3.5. *Effect of tomato price and energy costs on NFR*

The results showed that there is a linear relationship between tomato prices and the NFR, and that with an increase in tomato prices, NFR also increases. Likewise, a tomato price of 14.5 NOK or lower resulted in net losses for all greenhouse designs across all locations. On the contrary, a price of 19.5 NOK or higher increased profit for all designs in all locations. For Kise, however, the minimum price out of the selected range of tomato price for a positive NFR for the designs 0S and NS was calculated to be 15.5 NOK. For all other locations, the same price resulted in negative NFR for all designs. On the other hand, in Tromsø the minimum price required for a positive NFR for any design was 17.5 NOK.

Another trend observed from the analysis was the variation in the effects of tomato prices on NFR in different locations (Fig. 12). For instance, Kise witnessed the most positive change in NFR following a price increase, while Tromsø faced the most negative effect in NFR with a decrease in tomato prices. The main reason for this trend is the difference in potential crop yield and energy used (Fig. 13).

However, when tomato prices are considered along with the energy costs, the results show that the designs with the energy-saving elements become more profitable and economically viable and environmental friendly as compared to the standard greenhouse design prevalent in Norway.

4. Discussion

The results of our study emphasise the importance of considering energy-saving design elements, notably night energy screens, which had the most positive effects on the NFR, in greenhouse construction for tomato production in Norway and can be equally relevant for other countries with similar climatic conditions. The benefits of night thermal screen are similar to findings under other climate conditions (Gupta & Chandra, 2002; Shukla, Tiwari, & Sodha, 2006; Mobtaker, Ajabshirchi, Ranjbar, & Matloobi, 2016). However, there are, to our knowledge, no published scientific findings for the conditions we have studied here. That the beneficial

Table 7 – Overview of the resources used for the selected greenhouse designs elements for the four regions in Norway for the period Jan-2016 to December-2016. For an explanation of the design abbreviations e.g. 0S, NS etc. see Table 3.

	SW Norway (Orre)					MW Norway (Mære)				
	0S	NS	DNS	DNSF	DNSFM	0S	NS	DNS	DNSF	DNSFM
Energy use gas (kWh m^{-2})	371.3	293.9	278.7	278.7	157.4	391.9	321.8	284.1	284.1	174.6
Energy use gas (kWh kg^{-1})	8.9	7.1	7.1	7.1	4.0	10.3	8.5	8.0	8.0	4.9
Electricity use (kWh m^{-2})	0.0	0.0	0.0	0.0	22.1	0.0	0.0	0.0	0.0	22.3
CO_2 total (kg m^{-2})	27.4	22.0	20.9	20.9	12.7	28.8	23.9	21.2	21.2	14.5
Pure CO_2 (kg m^{-2})	1.3	1.3	1.3	1.3	1.6	1.2	1.2	1.2	1.2	2.2
CO_2 from gas used (kg m^{-2})	26.1	20.7	19.6	19.6	11.1	27.6	22.7	20.0	20.0	12.3
	N Norway (Tromsø)					E Norway (Kise)				
	0S	NS	DNS	DNSF	DNSFM	0S	NS	DNS	DNSF	DNSFM
Energy use gas (kWh m^{-2})	454.1	380.5	363.6	363.6	217.9	336.0	273.1	259.8	262.3	137.4
Energy use gas (kWh kg^{-1})	12.1	10.2	10.2	10.2	6.1	8.0	6.6	6.6	6.7	3.5
Electricity use (kWh m^{-2})	0.0	0.0	0.0	0.0	22.8	0.0	0.0	0.0	0.0	22.1
CO_2 total (kg m^{-2})	32.6	27.4	26.2	26.2	17.1	26.7	22.3	21.4	21.6	13.9
Pure CO_2 (kg m^{-2})	0.6	0.6	0.6	0.6	1.8	3.0	3.1	3.1	3.1	4.2
CO_2 from gas used (kg m^{-2})	32.0	26.8	25.6	25.6	15.3	23.7	19.2	18.3	18.5	9.7

effects of night screen under these conditions are not established knowledge is further underlined by the fact that most greenhouse tomatoes in Norway are produced without this equipment (Milford, Verheul, Sivertsen, & Kaufmann, 2021).

Our application of a model (Vanthoor et al., 2012a) to simulate greenhouse tomato production for cold-temperate conditions with a large potential supply of renewable energy for heating has revealed results that cannot be drawn with any precision from similar studies related to greenhouse energy-yield-economy modelling and which have been applied to other climate conditions. A previous application of the same model showed that a Parral, a greenhouse with a single bay, whitewash and fogging, had a higher NFR than a Parral with whitewash and heating, and a multi-tunnel design with whitewash, for economic and climate conditions in Spain using other design elements, which contrasts with the lack of effect of fogging on NFR that we found for conditions representing Norway.

Other energy-yield-economy analyses of greenhouses have largely focused on other sources of renewable energy such as wind, solar and biomass, and primarily to study year-round production (Acosta-Silva et al., 2019; Bartzanas, Tchamitchian, & Kittas, 2005; Çakır & Şahin, 2015; Mussard, 2017; Fuller, Aye, Zahnd, & Thakuri, 2009; Campiotti et al., 2010; Henshaw, 2017; Aş;chilean, Răsoi, Raboaca, Filote & Culcer, 2018). In some studies, the model used was not validated against existing conditions and instead used data from

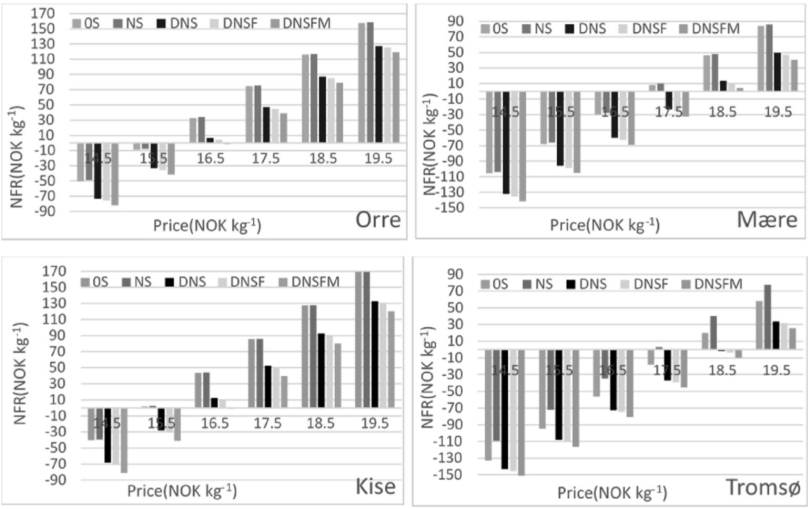
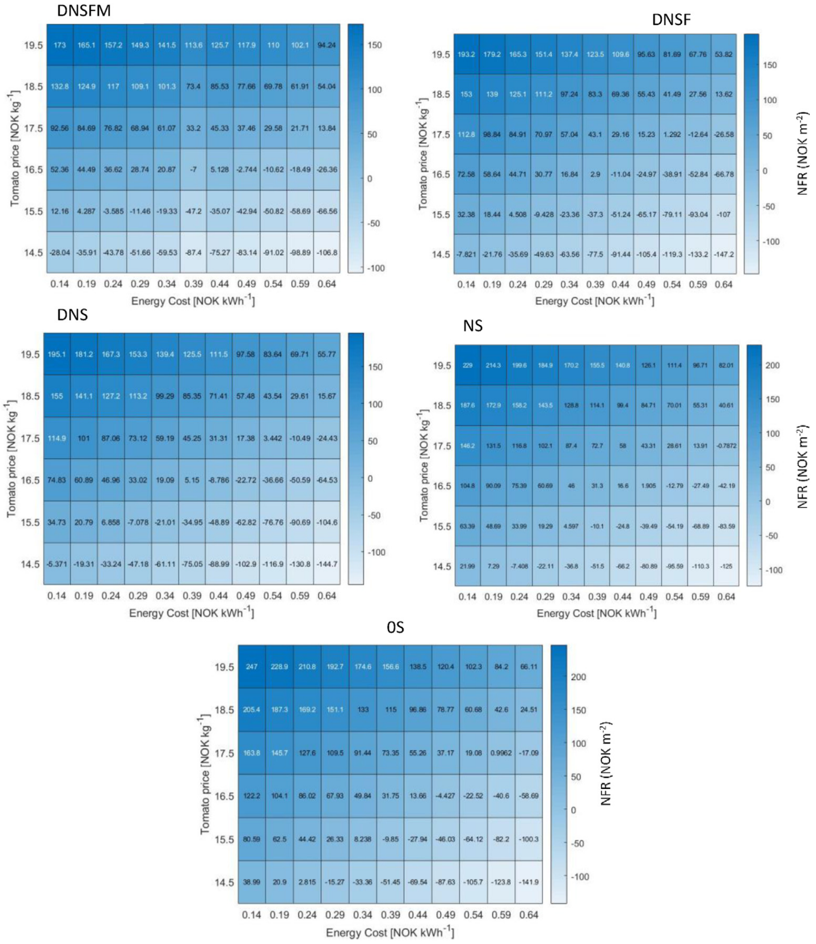


Fig. 12 – The relationship between NFR and tomato price trajectory for the four locations. This figure shows the prices which may yield an economically viable greenhouse design at each of the selected locations.



DNSFM

	0.14	0.19	0.24	0.29	0.34	0.39	0.44	0.49	0.54	0.59	0.64
19.5	173	165.1	157.2	149.3	141.5	113.6	125.7	117.9	110	102.1	94.24
18.5	132.8	124.9	117	109.1	101.3	73.4	85.53	77.66	69.78	61.91	54.04
17.5	92.56	84.69	76.82	68.94	61.07	33.2	45.33	37.46	29.58	21.71	13.84
16.5	52.36	44.49	36.62	28.74	20.87	-7	5.128	-2.744	-10.62	-18.49	-26.36
15.5	12.16	4.287	-3.585	-11.46	-19.33	-47.2	-35.07	-42.94	-50.82	-58.69	-66.56
14.5	-28.04	-35.91	-43.78	-51.66	-59.53	-87.4	-75.27	-83.14	-91.02	-98.89	-106.8

DNSF

	0.14	0.19	0.24	0.29	0.34	0.39	0.44	0.49	0.54	0.59	0.64
19.5	193.2	179.2	165.3	151.4	137.4	123.5	109.6	95.63	81.69	67.76	53.82
18.5	153	139	125.1	111.2	97.24	83.3	69.36	55.43	41.49	27.56	13.62
17.5	112.8	98.84	84.91	70.97	57.04	43.1	29.16	15.23	1.292	-12.64	-26.58
16.5	72.58	58.64	44.71	30.77	16.84	2.9	-11.04	-24.97	-38.91	-52.84	-66.78
15.5	32.38	18.44	4.508	-9.428	-23.36	-37.3	-51.24	-65.17	-79.11	-93.04	-107
14.5	-7.821	-21.76	-35.69	-49.63	-63.56	-77.5	-91.44	-105.4	-119.3	-133.2	-147.2

DNS

	0.14	0.19	0.24	0.29	0.34	0.39	0.44	0.49	0.54	0.59	0.64
19.5	195.1	181.2	167.3	153.3	139.4	125.5	111.5	97.58	83.64	69.71	55.77
18.5	155	141.1	127.2	113.2	99.29	85.35	71.41	57.48	43.54	29.61	15.67
17.5	114.9	101	87.06	73.12	59.19	45.25	31.31	17.38	3.442	-10.49	-24.43
16.5	74.83	60.89	46.96	33.02	19.09	5.15	-8.786	-22.72	-36.66	-50.59	-64.53
15.5	34.73	20.79	6.858	-7.078	-21.01	-34.95	-48.89	-62.82	-76.76	-90.69	-104.6
14.5	-5.371	-19.31	-33.24	-47.18	-61.11	-75.05	-88.99	-102.9	-116.9	-130.8	-144.7

NS

	0.14	0.19	0.24	0.29	0.34	0.39	0.44	0.49	0.54	0.59	0.64
19.5	229	214.3	199.6	184.9	170.2	155.5	140.8	126.1	111.4	96.71	82.01
18.5	187.6	172.9	158.2	143.5	128.8	114.1	99.4	84.71	70.01	55.31	40.61
17.5	146.2	131.5	116.8	102.1	87.4	72.7	58	43.31	28.61	13.91	-0.7872
16.5	104.8	90.09	75.39	60.69	46	31.3	16.6	1.905	-12.79	-27.49	-42.19
15.5	63.39	48.69	33.99	19.29	4.597	-10.1	-24.8	-39.49	-54.19	-68.89	-83.59
14.5	21.99	7.29	-7.408	-22.11	-36.8	-51.5	-66.2	-80.89	-95.59	-110.3	-125

OS

	0.14	0.19	0.24	0.29	0.34	0.39	0.44	0.49	0.54	0.59	0.64
19.5	247	228.9	210.8	192.7	174.6	156.6	138.5	120.4	102.3	84.2	66.11
18.5	205.4	187.3	169.2	151.1	133	115	96.86	78.77	60.68	42.6	24.51
17.5	163.8	145.7	127.6	109.5	91.44	73.35	55.26	37.17	19.08	0.9962	-17.09
16.5	122.2	104.1	86.02	67.93	49.84	31.75	13.66	-4.427	-22.52	-40.6	-58.69
15.5	80.59	62.5	44.42	26.33	8.238	-9.85	-27.94	-46.03	-64.12	-82.2	-100.3
14.5	38.99	20.9	2.815	-15.27	-33.36	-51.45	-69.54	-87.63	-105.7	-123.8	-141.9

Fig. 13 – The effect of tomato price and energy costs on the NFR for the greenhouse in Orre (SW Norway). The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway.

previous models, while other studies have used the model to simulate just one day or a limited number of days (Gupta & Chandra, 2002; Su & Xu, 2015). The results of our evaluation of the effect of several design elements together on NFR and on the use of fossil fuel also differ from and arguably add to the results from other greenhouse design studies that have analysed economic performance but dealt with one or two aspects of the greenhouse design but not varied other design elements, for instance energy and economic analysis for greenhouse ground insulation design (Bambara & Athienitis, 2018), cost and benefit analysis for different greenhouse covers (Lopez-Marin, Rodriguez, Del Amor, Galvez, & Brotons-Martinez, 2019), economic analysis of greenhouse energy use (Ahamed et al., 2019; Mohammadi & Omid, 2010).

There are, however, some uncertainties and shortcomings associated with our study which deserve further discussion. First, the reliability of the simulations is arguably higher for the greenhouse Night energy screen (NS) type against which the model was validated at Orre than when using the model to evaluate the other combinations of locations and greenhouses for which there was no validation data. The accuracy of the predictions of indoor temperature and CO_2-concentration as well as tomato growth and yield could possibly have been different in other regions with different outdoor climate conditions and for other designs. Hence the simulated NFR and its underlying components are probably more reliable for greenhouse seasonal production in southwestern Norway and regions with similar climate conditions. Additional validation against data from greenhouses with artificial light in Orre and Mære (Naseer et al., submitted) have indicated that the model can produce accurate results for a wider range of conditions.

Secondly, the results show a discrepancy in temperature and CO_2 values between the measured and simulated environmental conditions, as shown in the measurement of errors, which may be related to the ventilation. Generally, growers in Rogaland region tend to open the windows in the evening so that there is a sudden drop of greenhouse air temperature. This is done so as to allow the plants to transition into the night-time mode. In addition, the model requires a long time to adapt to such a change, and the presence of a screen lengthens the time constant. Moreover, it has to be said that leakage ventilation, which may be a relevant fraction of night-time ventilation, is something that is only “guessed” at by any model, as it is heavily dependent on the quality, and age, of each greenhouse. This implies that the model is not particularly sensitive to CO_2, which lowers the accuracy of outputs from the simulations, pointing towards an inherent limitation of models. This is especially important since the growth, quantity and quality of the yield is greatly affected by levels of CO_2 enrichment (Karim et al., 2020; Kläring, Hauschild, Heißner, & Bar-yosef, 2007; Lanoue, 2020; Singh, Poudel, Dunn, Fontanier, & Kakani, 2020).

Thirdly, the fraction of total tomato yield that is marketable depends on the greenhouse design and has a big impact on the NFR. In practical experiments, the marketable yield can decline due to diseases and pests (Gázquez et al., 2007) and can also be affected by a high relative humidity in the air inside the greenhouse, which necessitates the opening of the windows, thereby changing the indoor climate of the greenhouse. These factors, however, have not been taken into account in our simulations and may be incorporated in future modifications of the model.

Fourthly, although the considerations of NFR include the fact that the greenhouse and the equipment used in the production process have different lifespans, also depending upon re-investments etc., the return of investment and the payback period has not been considered in the present work. The pay-back period is heavily dependent on interest on capital and thus on prevailing conditions. Adding this aspect in the future works can help in an improved ability to make relevant decisions. The results of our study, which are based on the reproduction of the physics of a complex system, are probably of more general value than could be achieved in an experiment based on a few greenhouse compartments where results may be affected by issues such as crop health, greenhouse leakages, etc. Nonetheless, this simulation study arguably provides a good indication of the economic performance and energy use of greenhouses throughout Norway using design elements and existing market conditions that make the simulations close to the actual values. The alternative of obtaining such information solely from experimental studies would be very costly and therefore would not be realistic to conduct given the number of locations and greenhouse combinations that we have included in our study.

The design alternatives, outdoor conditions and economic settings that were evaluated here represent those that were considered relevant for current greenhouse tomato production in Norway. The rather small difference in NFR sensitivity to changes in energy and tomato prices between greenhouse designs and locations indicates that the possibility to reduce the risk exposure to these factors by changing the greenhouse design is limited under Norwegian production conditions. Previous studies have revealed that there is a considerable impact of climate set-points on NFR under other climate and production conditions, which will have impact on the optimal design as well (Vanthoor, Stanghellini, van Henten, & De Visser, 2008). The next step could include an analysis of NFR for different climate set-points as well as greenhouse sizes and weather conditions at the four locations. To compare the impact of greenhouse structure and climate modification techniques on NFR, costs related to the irrigation system, climate computer, emergency power and internal transport and harvesting systems were assumed to be identical for all greenhouse designs. Since these costs vary between greenhouses, notably due to greenhouse size, it could be useful to vary them in further profitability analyses. Moreover, to improve the greenhouse design for Nordic countries, where light is often the limiting factor, other climate modification techniques such as artificial lighting (light-emitting diode (LED), high pressure sodium (HPS)), an active heat buffer and a heat pump might be integrated in a model for year-round production and evaluated for different production conditions.

The results of our study show that the evaluation of feasible greenhouse types, with a special focus on energy-saving elements, could be useful for local tomato growers in decisions related to construction of new greenhouses or renovation of existing ones. The combination of NFR with reduced use of fossil energy, an important indicator of environmental impact, could prove beneficial for policy-makers regarding facilitation of measures geared towards stimulating greenhouse production and the reduction of CO_2 emissions in a country.

5. Conclusion

This study has used a model-based greenhouse design comprising a crop growth module, greenhouse indoor climate module and an economic module to determine the economic performance of tomato production in (semi-) closed greenhouses that use different forms of energy and utilise different temperature regulation technology under Norwegian seasonal production conditions. The results reveal that, for seasonal tomato production, adding a night energy screen, the use of which is at present limited in Norway, increased the NFR at all evaluated locations, with the highest NFR of 47.6 NOK m^{-2} in Kise in Eastern Norway. On the other hand, investing in high-tech energy saving equipment could be beneficial in the colder regions since they reduced the energy use, despite comparatively lower economic performance. The lowest fossil fuel use was seen in Kise that of 137.4 kWh m^{-2}, for the design having both a day and night energy screen, fogging equipment, cooling and heat harvest equipment. The results from our sensitivity analysis show that Tromsø was the most sensitive to variations in tomato and energy prices due to the difference in potential crop yield and energy used.

The study offers interesting insights into studies related to greenhouse vegetable production in high latitude regions with large potential supplies of renewable energy and can assist growers at different locations in Norway to select suitable greenhouse designs and pave the way for further development to take advantage of greenhouse technology in an economically and environmentally sound way. The results can also assist authorities in encouraging growers to increase local tomato production and design environmentally friendly policies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B

Paper 2

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Bioeconomic evaluation of extended season and year-round tomato production in Norway using supplemental light

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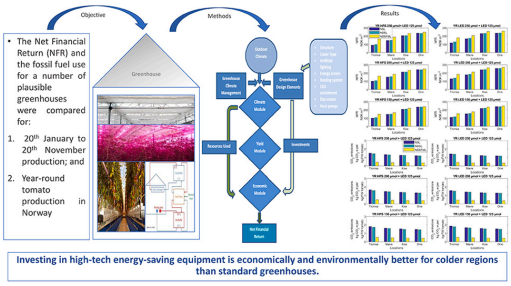
HIGHLIGHTS

- A simulation model was applied to evaluate greenhouse design elements with artificial light in Norway;
- The economic and environmental performance of extended season and year round tomato production was determined;
- Observed temperature, CO_2-concentration and yield were predicted fairly accurately;
- For year-round, the design with day and night thermal screens, heat pump and top and inter-lighting LED had the highest NFR;
- High-tech energy saving equipment has better results for greenhouse tomato production in colder regions than standard designs.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: For high latitude countries like Norway, one of the biggest challenges associated with greenhouse production is the limited availability of natural light and heat, particularly in winters. This can be addressed by changes in greenhouse design elements including energy saving equipment and supplemental lighting, which, however, also can have a huge impact on investments, economic performance, resources used and environmental consequences of the production.

OBJECTIVE: The study aimed at identifying a greenhouse design from a number of feasible designs that generated highest Net Financial Return (NFR) and lowest fossil fuel use for extended seasonal (20th January to 20th November) and year-round tomato production in Norway using different capacities of supplemental light sources as High Pressure Sodium (HPS) and Light Emitting Diodes (LED), heating from fossil fuel and electricity sources and thermal screens by implementing a recently developed model for greenhouse climate, tomato growth and economic performance.

METHODS: The model was first validated against indoor climate and tomato yield data from two commercial greenhouses and then applied to predict the NFR and fossil fuel use for four locations: Kise in eastern Norway,

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Møre in mid Norway, Orre in southwestern Norway and Tromsø in northern Norway. The CO_2 emissions for natural gas used for heating the greenhouse and electricity used for lighting were calculated per year, unit fruit yield and per unit of cultivated area. A local sensitivity analysis (LSA) and a global sensitivity analysis (GSA) were performed by simultaneously varying the energy and tomato prices.

RESULTS AND CONCLUSIONS: Across designs and locations, the highest NFR for both production cycles was observed in Orre (116.9 NOK m^{-2} for extended season and 268.5 NOK m^{-2} for year-round production). Fossil fuel was reduced significantly when greenhouse design included a heat pump and when extended season production was replaced by a year-round production.

SIGNIFICANCE: The results show that the model is useful in designing greenhouses for improved economic performance and reduced CO_2 emissions from fossil fuel use under different climate conditions in high latitude countries. The study aims at contributing to research on greenhouse vegetable production by studying the effects of various designs elements and artificial lighting and is useful for local tomato growers who either plan to build new greenhouses or adapt existing ones and in policy formulation regarding incentivizing certain greenhouse technologies with an environmental consideration or with a focus on increasing local tomato production.

1. Introduction

Efficient use of energy, effects on the environment and competitiveness of the production process are inherent challenges for the agriculture sector (Pinho et al., 2012). The use of fossil fuel continues to rise at the global level in this sector and has numerous environmental and social consequences, notably significant greenhouse gas emissions (GHG) (Lamb et al., 2016). A recent report by The Food and Agriculture Organization of the United Nations (FAO) (2020) states that in 2017, the percentage contribution of agriculture to world CO_2eq emissions from all human activities was 20%. The anthropogenic pressures along with an increase in the demand for food require energy intensive methods that between 1989 and 2009 have led to the decrease in energy use efficiency (Martinho, 2016). The high dependence of the agricultural sector on energy resources can also make it vulnerable to the fluctuating global energy prices (Taki et al., 2018). Thus, efficient use of energy in food production systems could at the same time reduce their negative environmental impact and increase their economic viability (Rohani et al., 2018). Such positive effects from increased energy use efficiency could be particularly significant for greenhouse production in northern latitude countries whose climatic conditions often necessitate the use of energy intensive methods due to the shortage of light and heat during the winter season. Norway is one of those countries in which short growing seasons and low availability of light and heat, particularly in the winter months, limit the ability to produce fresh greenhouse vegetables and fruits. According to the data from Statistics Norway, the tomato production decreased from 13,763 t in 2014 to 10,574 t in 2017 (Statistics Norway, 2021). Nonetheless, there is high demand and preference for locally produced fruits and vegetables in the Norwegian market (Bremnes et al., 2019) highlighting the need to make local production efficient.

Protected cultivation in greenhouses, as a means to increase the production per area and extend the production period, can include the use of artificial lighting, heating, cooling and CO_2-enrichment in addition to wind and rain protection, depending on the type of crop and its needs (Gupta and Agarwal, 2017; Tap, 2000). An added benefit of protected cultivation is that it enables increased efficiency and variation of resources according to the specific crop needs. This includes efficient use of technologies related to artificial light, heating, cooling, and supply of CO_2 (Hemming, 2009). Artificial light has been used in greenhouses since the early twentieth century, primarily to extend the production season of vegetable and fruit production (Pinho and Halonen, 2017; Pan et al., 2019). Such an extension of the production season by artificial light to fall, winter and early spring season when natural light limits production is especially relevant in high latitude regions (Verheul et al., 2012; Pinho and Halonen, 2017). Annual yield increase of 100 kg m^{-2} $year^{-1}$ (from 40 to 140 kg) with artificial light has been reported for tomato greenhouse production at the 59th parallel north (Verheul et al., 2012; Paponov et al., 2020). Still, only limited production takes place during the winter season from November to March, with a partial or total dependence on artificial light (Verheul et al., 2012).

The use of supplemental light in greenhouses ensures that electric energy is converted into light and convective heat. For the most part, high pressure sodium (HPS) lamps and light emitting diode (LED) lamps are in use within greenhouses. The efficiency, which is expressed as photosynthetic active radiation (PAR) output per unit of input electric energy, is higher for the latter lamp type (Persoon & Hogewoning, 2014). Moreover, HPS lamps exchange more infra-red, thermal radiation, causing higher temperatures on plants and in the greenhouse air, while LED lamps facilitate cooling and thus loose comparatively more heat through convection. Owing to the high temperatures that the HPS lamps can attain, they are used as top lights i.e., well above the canopy, while the LEDs can be used as both top and between the canopy as inter-lighting.

The capacity of greenhouse lamps can be evaluated by the photosynthetic photon flux densities (PPFD) (μmol m^{-2} s^{-1}) that they emit, and which can be used by the plants. Previous studies on greenhouse production in high latitude regions recommend lighting capacities of up to 300 μmol m^{-2} s^{-1} (Moe et al., 2005), whereas currently, capacities of up to 322 μmol m^{-2} s^{-1} are in use as top lights in the Norwegian greenhouses (Righini et al., 2020) as measured below the lamps and above the plants' heights.

Nonetheless, despite the ability to regulate inputs such as light, heat and CO_2 to specific crop demand in greenhouse production, such production still requires large amounts of energy. Greenhouses are energy intensive, with energy as a pre-requisite component that is used throughout the production process, from seed plantation to crop harvesting, and is heavily dependent on fossil fuels (Woods et al., 2010). An increase in artificial light use from current level would further increase the energy use in the greenhouse sector should there be no significant increase in the energy use efficiency. Production designs of greenhouses, which increase the energy use efficiency and can be combined with artificial light, could potentially increase the profitability for individual growers as well as for the horticultural sector in Norway as a whole, while at the same time decrease the negative environmental impact (Verheul et al., 2012). Such production designs could include altered greenhouse construction types as well as different energy sources and production seasons.

Different studies focus on different aspects of the production process, such as prediction of crop yield, optimization of light strategies in greenhouses for different crops using a variation in artificial light, including High-Pressure Sodium (HPS) and Light Emitting Diodes (LED), CO_2 enrichment, and heating and cooling. Slager et al. (2014) developed a model to evaluate the productivity and economic feasibility of greenhouse production of tomato crop and algae with a focus on Dutch conditions without the use of artificial lighting. Some studies have incorporated various optimization techniques using algorithms (the iterative search (IS) and genetic algorithm (GA), ant colony optimization (ACO)) in order to determine the optimum values for artificial light and the energy used for lamps for greenhouse production (Mahdavian and Wattanapongsakorn, 2017; Xin et al., 2019). Likewise, the GroIMP modelling platform has been used for evaluating different light strategies to reduce the energy use by using a 3D light model in conjunction with a 3D tomato model (de Visser et al., 2014). Likewise, Righini et al. (2020) added artificial lighting and heat harvesting to a greenhouse production model by Vanthoor et al. (2011a, 2011b) in order to validate the model for northern climatic conditions. Naseer et al. (2021) applied the model by Vanthoor et al. (2011a, 2011b, 2012) and adapted different design elements with respect to local climatic conditions to provide an economic and environmental analysis of greenhouse seasonal (from mid-March to mid-October) tomato production for northern climates such as Norway. Another recent study on the optimisation of supplemental light against the net financial return (NFR) in greenhouse production in the Norwegian conditions has found the optimum capacities of supplemental lighting to be in the range of 256 to 341 μmol m^{-2} s^{-1} (Wacker et al., 2022).

Currently most of the greenhouse tomato production in Norway takes place in the south-eastern part of the country (Statsforvalteren i Rogaland, 2019) but other greenhouse vegetables such as cucumbers are to a larger extent produced in other regions of the country (https://www.hridir.org/countries/norway/index.htm). The conditions for greenhouse production with additional light vary considerably between regions within Norway. Firstly, there are large geographic differences in the outdoor climate, which potentially can have large effect on both the profitability of the production, and the use of energy and emissions of greenhouse gases. These climatic differences could also mean that the suitability of different greenhouses varies between regions. Moreover, the price of electricity, which in Norway is mostly generated from hydropower plants, can vary considerably within the country (Hofstad et al., 2021; Norwell, 2021). To understand the advantages and disadvantages of different greenhouses, production regimes and locations in Norway and hence the prospects of a geographic differentiation of the artificial light-based tomato greenhouse production in Norway, there is a need for further analyses about how the variation in climate and electricity price affects greenhouse tomato production with artificial light.

In our present study, we evaluated different artificial lighting strategies along with design elements in order to determine the impact of the greenhouse design on the Net Financial Return (NFR), energy use and CO_2 emissions for extended season (ES) (from 20th January to 20th November) and year-round (YR) tomato production in several different climate conditions including 4 locations in Norway, thereby identifying suitable greenhouse designs. The study was performed by applying the model by Vanthoor et al. (2011a, 2011b) as modified by Righini et al. (2020) comparing different sets of plausible design elements, greenhouse climate management, light types (LED, HPS) and PPFD gradients. The study also took into account seasonal tomato price differences.

2. Material and methods

2.1. Model overview

The study was based on the model by Vanthoor (2011), and later modified by Righini et al. (2020), in order to identify a greenhouse that generates the maximum profit while reducing the energy use for the production of tomatoes under Norwegian climatic conditions. The applied model comprises of three inter-connected modules including a greenhouse climate module, a crop yield module and an economic module and reproduces the hourly indoor climate conditions of the greenhouse, growth and yield of the tomato crop, and the greenhouse resources used. As a result, it calculates the yearly NFR. The original model as developed by Vanthoor (2011) and its parameter settings have been validated for different climatic conditions including mild and extreme temperature conditions as well as non-optimal and long-term diurnal temperature variations, including indoor temperature and CO_2 and tomato yield data from a greenhouse in southwestern Norway (Naseer et al., 2021). The adaptation to greenhouses with artificial light and heat pumps were developed and validated for Norwegian conditions by Righini et al. (2020). See Vanthoor (2011), Righini et al. (2020) and Naseer et al. (2021) for further details about model developments and validations. We considered the validated parameter settings representative of the conditions included here and hence did not perform any additional model validations.

The indoor climate of the greenhouse and the resource usage are determined by the climate module based on the effects of the outdoor climate, indoor temperature set-points, CO_2-concentration, humidity, and the greenhouse design elements and calculated in the greenhouse climate module. While the crop yield module determines the growth and yield of the tomato crop based on the indoor climate, the economic module predicts the NFR of the production, which is influenced by the resources used and the yield of the crop. For a more detailed explanation see Vanthoor et al. (2012). Equations for artificial light were obtained from Righini et al. (2020).

2.1.1. Economic module

The following equation is used to calculate the yearly net financial return P_{NFR} (NOK m^{-2} $year^{-1}$):

$$P_{NFR}(t_f) = -C_{fixed} + \int_{t=t_0}^{t=t_f} \dot{Q}_{CropYield} - \dot{C}_{Var} \; \left(NOKm^{-2}\;Year^{-1} \right) \tag{1}$$

where t_0 and t_f denote the beginning and the end of the production season respectively, C_{fixed} ($NOKm^{-2}Year^{-1}$) represents the fixed costs for investments for greenhouse structure, artificial lights ((LED, HPS), which includes bulbs, fixtures and cables), climate computer, cooling system, heating system and structure (i.e. construction elements) and maintenance and interest costs, C_{Var} ($NOKm^{-2}Year^{-1}$) denotes the variable costs including costs for the resources used, labor costs and other production related costs (plant material, slabs, crop protection equipment), while $Q_{CropYield}$ ($NOKm^{-2}Year^{-1}$) represents the economic value of the crop yield.

2.1.1.1. Fixed costs.

The annual fixed costs are determined on the basis of the entire investments of the construction elements and the interests, C_{fixed}($NOKm^{-2}Year^{-1}$), which also include costs for maintenance and depreciation. Moreover, the costs for the artificial lights depend on the kind of light used (LED or HPS) and their depreciation costs depend on how much they are used. Fixed costs are calculated by:

$$C_{fixed} = C_{interest} + \sum_{i=1}^{N} C_{construction,i} + C_{Rem} \; \left(\text{NOK}\; m^{-2} year^{-1}\right) \tag{2}$$

where $C_{interest}$ ($NOKm^{-2}Year^{-1}$) denotes the interest costs of the entire investments, i stands for the construction elements, and N denotes the overall set of design elements used in the construction of the greenhouse. $C_{construction}$($NOKm^{-2}Year^{-1}$) represents the depreciation and maintenance costs and C_{Rem} ($NOKm^{-2}Year^{-1}$) represents the remaining costs of construction and equipment. For a detailed explanation of how the interests, costs of construction elements and remaining costs are calculated, see Vanthoor et al. (2012). The fixed costs associated with the design elements used in our study are shown in Table 1.

2.1.1.2. Variable costs.

The variable costs are the costs for the plants and plant materials (including slabs, fertigation), water usage, CO_2, the types of energy used (fossil fuel and electricity) and are denoted by:

$$\dot{C}_{var} = \dot{C}_{plant} + \dot{C}_{Water} + \dot{C}_{CO2} + \dot{C}_{Fossil\ fuel} + \dot{C}_{Electricity} \; \left(NOKm^{-2}h^{-1}\right) \tag{3}$$

where $\dot{C}_{plant}$ $\left(NOKm^{-2}h^{-1}\right)$ represents the costs related to the production (labour, packaging, sales, bumblebees for pollination and the protection of crops), $\dot{C}_{Water}$ $\left(NOKm^{-2}h^{-1}\right)$ represents the costs for the usage

Table 1

The fixed costs associated with the greenhouse design elements and element alternatives. e_j in the second column represent the number for each design element option. E* = 10% extra costs for transportation expenses and exchange rate (7th Column). Growers** = The data was obtained from interviews with commercial tomato growers, whose production is representative for Norway, by advisors at NIBIO.

Design element/Fixed costs	e_j	Investment (NOK m^{-2})	Investment (NOK $unit^{-1}$)	Depreciation (% $year^{-1}$)	Maintenance (% $year^{-1}$)	Construction (NOK m^{-2} $year^{-1}$)	Source
Structure							Vermeulen (2016) +E*
Venlo 5760 m2		519.0		5.0	0.5	28.5	
Covers							*Growers***
Glass		93.5		5.0	0.5	5.1	
Day screen	2	35.5		25	0	8.7	
Night screen	3	100		15	5	15.5	
Structure screens		130		7.0	5	10.5	
Boiler							Vermeulen (2016) + E*
Boiler: 0.5 MW	1		620,530	7.0	1	9.0	
Boiler: 1.12 MW	2		660,000	7.0	1	9.3	
Heating pipes		65		5.0	0.5	3.8	
Grow pipe		45		5.0	0.5	2.5	
Mechanical Heating							Vermeulen (2016) + E*
No	1		0	0.0	0	0.0	
Mechanical heat and cool: 25 W/m^2unit^{-1}	2		2,688,000	7.0	2	37.0	
Cooling systems							Vermeulen (2016) + E*
No	1	0	0	0	0	0	
Fogging: 200 g h^{-1} m^{-2}	2	65		7.0	5	5	
CO_2 supply							Vermeulen (2016) + E*
Pure: 130 kg ha^{-1} h^{-1}	1		48,763	10.0	0	0.9	
CO_2: from boiler	2		31,700	10	5	0.6	
CO_2distribution system		5		10.0	5	0.7	
Remaining costs for irrigation, crop protection, internal transport							Growers
Crop protection			50,000	10.0	5	1.3	
Packaging and sorting			150,000	5	5	3.1	
Emergency power supply			80,000	7	7	2.2	
Water collection tank			250,000	7	5	5.2	
Fertilizer system			150,000	7	5	3.1	
Gutters		70		7	1	5.6	
Artificial lighting							*Growers*
HPS bulbs NOK/W			0.3	$36*10^6$h	1		
HPS fixture NOK/W			2.13	15	1		
HPS cable NOK/W			0.25	10	1		
LED fixture NOK/W			12.9	$126*10^6$h	0.5		
LED cable NOK/W			0.25	10	1		

of water and $\dot{C}_{CO2}\left(NOKm^{-2}h^{-1}\right)$ denotes the costs for pure CO_2, $\dot{C}_{Fossil\ fuel}\left(NOKm^{-2}h^{-1}\right)$ denotes the costs for the natural gas used and $\dot{C}_{Electricity}\left(NOKm^{-2}h^{-1}\right)$ represents the costs for electricity used in heating, cooling and artificial lighting in the greenhouse. The variable costs used for our study are shown in Table 2. For details about how the equations for the variable costs are calculated, see Vanthoor et al. (2012).

2.2. *Selected locations, description of evaluated greenhouses and greenhouse climate controls*

In order to determine the greenhouse design that accrued the highest NFR and the lowest use of energy, we used the model summarized in the previous section for two scenarios: 1. Extended seasonal production (from 20th January to 20th November), and three combinations of design elements with the addition of LED inter-lighting, and 2. Year-round production and three combinations of greenhouse design elements with multiple light strategies including HPS and LED with various power capacities. Two inter-plantings of tomato production were considered for year-round production, however, for the simulation the leaf area index (LAI) of 3 was kept constant, and the initial crop stages were adjusted accordingly. Information about the locations, greenhouse structure and settings, and economic settings are explained in the following sections along with a detailed explanation of the different design elements.

2.2.1. *Selected locations*

The suitability for extended season and year round greenhouse production of tomatoes under conditions representing Norway was evaluated against the NFR, energy use and CO_2 emissions from fossil fuel for four locations across the country that included Orre in southwestern (SW) Norway (lat. 58.71, long. 5.56, alt. 18 m a.s.l.), Kise in eastern (E) Norway (lat. 60.46, long. 10.48, alt. 130 m a.s.l.), Mære in mid (M) Norway (lat. 63.43, long. 10.40, alt. 18 m a.s.l.), and Tromsø in northern (N) Norway (lat. 69.65, long. 18.96, alt. 60 m a.s.l.) (Fig. 1.). These locations represent different light conditions and coastal and inland climates (Fig. 2.). Moreover, the regions around these locations have existing tomato production or may have the possibility of greenhouse

Table 2

Variable costs used in our simulations. * = The data was obtained from interviews with commercial tomato growers, whose production is representative for Norway, by advisors at NIBIO.

Resource	Value	Unit price (NOK)	Unit	NOK /m2	Source
Area	5760		m^2		
Plants	2	25.0	Plant	50	Hovland, 2018
Growth medium	2.5	10.4	Slab	26	Hovland, 2018
Fertilizer	1.0	30.0	m^2	30.0	Hovland, 2018
Pollination	1.0	12.0	m^2	12.0	Hovland, 2018
Pesticides	1.0	10.0	m^2	10.0	Growers*
Packaging	6.7	3.0	Box	20	Growers
Natural gas		0.39	kWh		Norsk Gartnerforbund, 2016
Light		0.39	kWh		Norsk Gartnerforbund, 2016
Marketing	1.0	3.0	%		Growers
Interest		5.0	%		Growers
Operating assets	1.0	15.0	m^2	15.0	Growers
Water		8	m^3		Growers
Other	1.0	20.0	m^2	20.0	Growers
Labor costs	1.2	180.0	m^2h		Growers
Insurance	1	15.0	m^2	15.0	Growers

Fig. 1. The four locations in Norway, representing coastal and inland climates, for which the greenhouse designs were evaluated.

tomato production based on the local market demands. Before these evaluations, the model's ability to predict the internal temperature, CO_2 concentration and the fresh weight of tomato was verified against observations under extended season and year-round production and with artificial HPS and LED light in the two greenhouses: the first in Orre, and the second in Mære. (See section 2.3 for details about the design of these two greenhouses). The external weather data (air temperature, wind speed, global radiation (iglob) and relative humidity) that were input to the greenhouse climate module were obtained from the *LandbruksMeteorologisk Tjeneste (LMT)* (lit. Agricultural Meteorological Service) of Norwegian Institute of Bioeconomy Research (NIBIO) (https://lmt.nibio.no/) for each of the four locations.

2.2.2. *Description of evaluated greenhouses*

The greenhouse construction that was assessed in all locations was a Venlo type greenhouse (Fernandez and Bailey, 1992) that is commonly in use in cold-temperate climates, with standard glass roofs and natural ventilation. Natural ventilation comprised of different roof vents on both sides that equalled to around 15% of the total floor area. The side wall of the greenhouses did not have any ventilation. The total floor area of the greenhouse was around 5760 m^2 and the greenhouses were rectangular in shape (90 × 64 m). Standard Rockwool slabs irrigated by a drip irrigation system were used to grow plants. Bumblebees were used in the greenhouse for pollination during the entire growing season. Above 95% of the total fresh weight predicted yield was considered to be the marketable yield, i.e., 1st class fruits, and at light red ripening stage.

Two types of artificial lights were introduced within the greenhouses i.e., HPS and LED. Likewise, two kinds of heating systems were assessed, both using steel rail and grow pipes, filled with hot water. One system comprised a boiler heating that utilized natural gas and the other system comprised a heat pump that utilized electricity that was generated in a hydropower plant. It is worth mentioning at this point that electricity is primarily generated by water in Norway and is considered a green resource since CO_2 emissions for the use of electricity is much lower than that of natural gas. The supply of CO_2 to the greenhouse was ensured through the boiler, by burning natural gas, or as pure CO_2 from a tank. CO_2 was supplied primarily from the boiler during the day and when the boiler was off, pure CO_2 was supplied from the tank. The pure CO_2 distribution system had a capacity of 130 kg CO_2 ha^{-1} h^{-1}, however, CO_2 supplied from the boiler to the greenhouse was not registered by the grower. The supplied amounts of CO_2, heating and moisture were influenced by the global radiation, indoor greenhouse temperature and ventilation along with the artificial light.

2.2.3. *Greenhouse climate control for the two production periods*

The study used the same set points for the indoor greenhouse climate across all designs and all four locations (Table 3).

The transmission of light through the rooftop and above and below the HPS lamps in the greenhouse was 68% and 63%, respectively based on measurements in the existing greenhouse in Orre, where measurements were taken simultaneously by one sensor inside the greenhouse for measuring the indoor global radiation and one outside the greenhouse for measuring the external global radiation. In order to ensure correct measurements, we first calibrated the two sensors by placing them outside the greenhouse and taking the difference in account afterwards. The global radiation was measured with a Kipp solarimeter, which was placed outside of the greenhouse. Light transmission of total photosynthetic active radiation (PAR, mol m^{-2} d^{-1}) was calculated based on measurements in the empty greenhouse and the outdoor global radiation. CO_2 of greenhouse air was measured at 5 min interval with a gas analyzer (Priva CO_2 monitor Guardian +). Measurements of the air temperature and relative humidity were recorded by dry- and wet-bulb thermocouples placed in ventilated boxes that shielded against direct solar radiation and placed in the middle of the canopy. Thermocouples were calibrated before the start and controlled at the end of the experiment. Temperature (oC), relative humidity (%), CO_2 concentration (ppm) and window opening (%) were registered using a Priva computer (Priva Connext). The maximum concentration of the CO_2 applied was 1200 ppm if the temperature and global radiation corresponded to the criteria for CO_{2Air_ExtMax} as given in Table 3, and the windows were closed. It decreased linearly if the global radiation decreased, internal temperature decreased and the rate of ventilation increased to the lowest value of 410 ppm with 100% window opening (Magán et al., 2008). The measurements for the greenhouse temperature, CO_2 concentration and humidity were taken every five minutes, although only the hourly average values were used in the simulations.

2.2.4. *Economic settings*

We acquired the tomato price history for the year 2019 from

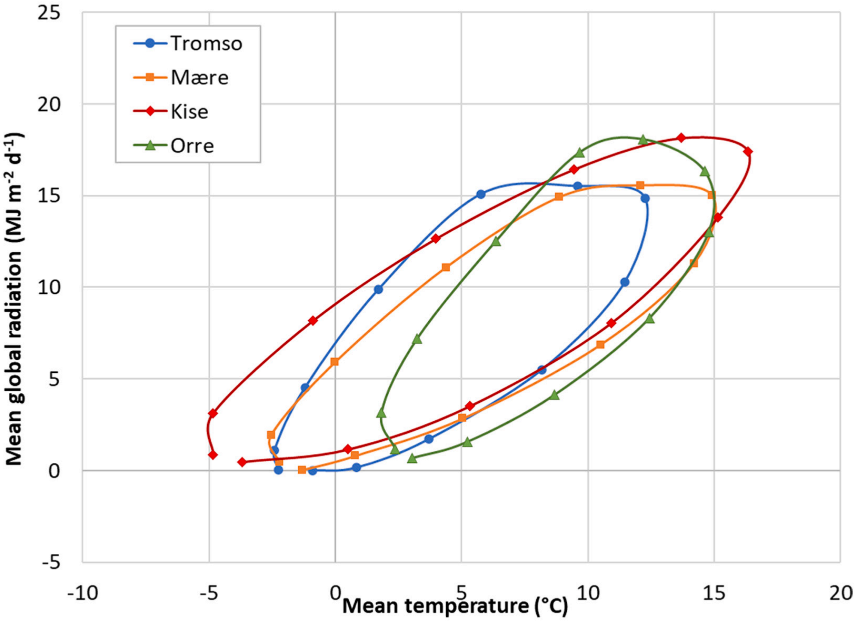

Fig. 2. The mean air temperature and global radiation (iglob) recorded in the four locations during the last 30 years (from 1989 to 2019). Months are shown clockwise from January to December.

Grøntprodusentenes Samarbeidsråd (lit. The Green Growers' Cooperative Marked Council) (Markeds- og prisinformasjon, 2019) and applied it for all the greenhouse designs and locations. Similarly, we set the same fixed and variable costs per unit related to the construction and production conditions in Norway throughout the four locations and greenhouse designs as obtained from literature and from interviews with tomato growers across the country conducted by advisors at NIBIO (Table 1 and Table 2).

2.3. Description of the evaluated design elements and greenhouses

Greenhouse designs for the extended season and year-round production that were evaluated for the four locations in Norway with different design elements are presented in Table 4 and Table 5. These designs were considered as a result of our discussions with advisors at NIBIO and a review of literature (Verheul et al., 2012; Ahamed et al., 2019; Singh and Tiwari, 2010; Zhang et al., 1996; Von Elsner et al., 2000; Verheul et al., 2022). We considered the design with HPS lighting, one thermal screen, boiler pipe for heating and CO_2 from two sources (from boiler and pure from tank) as our basic design. This is the design of the existing greenhouses in Orre and Mære. In Mære HPS lighting was supplemented by LED inter-lighting for which model outputs were verified. For the subsequent designs, for extended season and year-round production, we used a variation in design elements including type and capacities of light and their positioning, number of thermal screens and source of heating (heat pump and boiler) as shown in Tables 4 and 5.

The growing season for unlighted tomato production in Norway is from March to October and in order to extend the growing season artificial is necessary. For the extended season, only low intensity LED inter-lighting was used with an installed amount of 125 μmol (43.7 Wm^{-2}). For the year-round production season, a variation of HPS and LED was used as top lights with only LED as inter-lighting. In designs where HPS was used as top light in combination with LED inter-lighting, its capacity varied between 150 μmol (87 Wm^{-2}) and 350 μmol (203.5Wm^{-2}). In designs where LED was used both as top-light and inter-lighting, its capacity as top-light ranged from 150 μmol (52 Wm^{-2}) to 350 μmol (122.8 Wm^{-2}) while the capacity of LED inter-lighting was kept the same, i.e., 125 μmol (43.7 Wm^{-2}). The capacities of top lights have been varied in designs containing both HPS and LED in order to find the best combination of top and inter-lighting within the greenhouses that yield best results.

We used two types of thermal screens: i. 100% Polyethylene (PE) and, ii. 50% Polyethylene and 50% Aluminium (Alu). The former was considered as a day screen since it has high light transmission and the latter as night screen since it has high energy saving power. Heat was provided to the greenhouse by a natural gas-powered boiler with a capacity of 1.12 $MWunit^{-1}$ and by an electric-powered heat pump with a capacity of 25 Wm^{-2} and having a cold and hot water buffer of volumes 0.02 m^3m^{-2}. The heat pump can store excess heat produced during the day or when the artificial lights are on in the greenhouse in a cold buffer to be used later through a hot buffer.

2.4. Prediction accuracy evaluation

The prediction accuracy of the internal relative humidity, concentration of CO_2 and fresh tomato weight yield was evaluated by the relative root mean squared error (RRMSE):

$$RRMSE = \frac{100}{\overline{y}_{data}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(y_{Mod,i} - y_{Data,i}\right)}$$

where y_{data} denotes the average of calculated data over the entire growing period, n denotes the number of measurements, $y_{Mod,i}$ represents the simulated yield at time instant i and $y_{Data,i}$ represents the measured value at time instant i.

2.5. CO_2 emissions

The CO_2 emissions for two main input variables i.e., natural gas used

Table 3
A description of internal climate set-points for the two production seasons.

Greenhouse climate management	Production seasons		Unit	Explanation
	Extended season	Year-round		
$\text{Tair}_{\text{vent\_on}}$	23	23	(°C)	The indoor greenhouse temperature above which the greenhouse is ventilated during the daytime
$\text{RHair}_{\text{vent\_on}}$	90	90	(%)	The indoor greenhouse relative air humidity above which the greenhouse is ventilated
$\text{Tair}_{\text{heat\_on}}$ (night/day)	17/19	17/20	(°C)	The heat is turned on below this temperature for night and day respectively
$\text{Tair}_{\text{fog\_on}}$	24	24	(°C)	The indoor temperature above which fogging is used
$\text{Tair}_{\text{heat pump\_on}}$	21	22	(°C)	The heat pump is turned on if the indoor air temperature reaches above these points
$\text{Tout}_{\text{ThScr\_on}}$	12	14	(°C)	Night thermal screen is used below this outdoor temperature
$\text{Tout}_{\text{Day\_EnScr\_on}}$	10	10	(°C)	Day thermal screen is used below this outdoor temperature
$\text{iglob}_{\text{Day\_EnScr\_on}}$	150	150	(Wm^{-2})	Day thermal screen is used below this global radiation
$\text{CO}_{2\text{Air\_Min}}$	410	410	(ppm)	The CO_2 concentration below which CO_2 is added
$\text{CO}_{2\text{Air\_Max}}$	1200	1200	(ppm)	Set point for maximum amount of CO_2 if all lights are on
Time_Led_on	04:00	04:00		LED's are switched on at this time after 5 weeks' planting in greenhouse
Time_Led_off	22:00	22:00		LED's are switched off at this time
$\text{Time}_{\text{HPS\_on}}$		04:00		HPS is used from the first day of planting at this time.
$\text{Time}_{\text{HPS\_off}}$		22:00		HPS are switched off at this time
iglob_HPS_on		350	(Wm^{-2})	HPS are switched off if the global radiations are above this value
Crop conditions				
LAI_start (Initial)	0.3	0.3	(–)	Initial leaf area index
LAI_max	3	3	(–)	Maximum leaf area index
Year-round Production				
Start growing period		October 1st		
End growing period		September 31st		
Extended season duration				
Start growing period	January 20th		(–)	
End growing period	November 20th		(–)	

for heating the greenhouse and electricity used for lighting, were calculated per year, unit fruit yield and per unit of cultivated area. Previous studies (Verheul and Thorsen, 2010) have shown that the environmental impact of greenhouse production is mainly related to the global warming potential due to the use of fossil fuel. Other environmental impacts, like Ozone depletion, acidification, eutrophication, depletion of resources, toxicity and pollution and land use, in greenhouse production are very low compared to other agricultural production systems. This also applies to the production of elements like greenhouses, screens and lamps and is mainly due to the high yields in greenhouse production. For this reason, we have only taken in to account the CO_2 emissions from heating and lighting. The total natural gas and electricity used were simulated by using the greenhouse climate module. The CO_2 emission as a result of burning the natural gas and electricity per m^2, as predicted by the climate module, was calculated per kg of fresh weight tomato yield.

2.6. *Sensitivity analysis*

With regards to the economic value of the crop yield, the temporal electricity, natural gas and tomato price variation were taken into account. These are the variables that have the most impact on the NFR for extended and year-round production. In Norway there is a significant difference in off-season and seasonal tomato whole-sale price mainly due to seasonal variation in import duties for tomatoes (Import tariffs for agricultural products, 2016). From week 19 to week 41 during the year 2019 the tariff rate for tomatoes ranged from 10.21 NOK kg^{-1} and 6.86 NOK kg^{-1}, while for the rest of the year the tariff rate was zero NOK (Markeds- og prisinformasjon, 2019). The range of tomato prices (Fig. 3.) that was applied throughout the greenhouse designs and locations was acquired from *Grøntprodusentenes Samarbeidsråd* (Markeds- og prisinformasjon, 2019).

We carried out a local sensitivity analysis (LSA) (Tian, 2013) in order to analyse the effect of tomato prices on the NFR. Since the LSA does not take into account the relationship between the various input variables, we also carried out global sensitivity analysis (GSA) (Tian, 2013; Ahamed et al., 2018) by simultaneously varying the electricity, natural gas and tomato prices. To be precise, we varied the electricity and natural gas prices from 0.3 NOK kWh^{-1} to 0.65 NOK kWh^{-1}, with a step size of 0.05 NOK kWh^{-1} and the tomato prices from 14 NOK kg^{-1} to 21 NOK kg^{-1}, with a step size of 1 NOK kg^{-1}.

3. Results

3.1. *Results from the Model evaluation*

The model predicted air temperature and yield with fair accuracy. The relative root mean squared error (RRMSE) for temperature, CO_2-concentration and fresh weight tomato yield was less than 10%. The predicted and measured indoor air temperature for the commercial greenhouses in Orre and Mære are shown in Fig. 4a and b respectively,

Table 4
The different greenhouse designs for the extended seasonal (ES) production. The greenhouse design with one thermal screen was extended with various combinations of thermal screens, CO_2 enrichment (i.e., from the boiler and pure) and with heat pump. PE refers to Polyethylene Screen; Alu stands for Aluminium; inter stands for inter-lighting. Costs for the design elements are given in Table 1.

Greenhouse designs evaluated for extended season tomato production				
Design Elements	Type/Capacity	NSL$_{\text{LED\_ES}}$	NDSL$_{\text{LED\_ES}}$	NDSFML$_{\text{LED\_ES}}$
Light type and capacity		LED (inter) 125 µmol (43.7 Wm^{-2})	LED (inter) 125 µmol (43.7 Wm^{-2})	LED (inter) 125 µmol (43.7 Wm^{-2})
Boiler- Pipe	Boiler	Yes	Yes	Yes
Screen	Indoor Day Screen (100% PE)	No	Yes	Yes
	Thermal Screen (50% PE+50% Alu)	Yes	Yes	Yes
CO_2	Boiler (if on during the day)	Yes	Yes	Yes
	Pure (130 $kg\,ha^{-1}\,h^{-1}$)	Yes	Yes	Yes
Humidification/ Dehumidification	Fogging	No	No	Yes
	Heat pump (25 Wm^{-2})	No	No	Yes

and Fig. 5 shows the predicted and measured yield at Orre and Mære. At the start of the production season (from February 24th to March 5th) and the end of the production season (from September 26th to October 6th) for the year-round production season, the model predicted the temperature with high accuracy. However, in the middle of the production season, when the outdoor global radiation and the temperature were high, the prediction was less accurate than at the start and end of the season.

3.2. NFR for different designs and locations

The results showed clear differences for the NFR and CO_2 emissions between the designs and locations (Figs. 6-11). Of the four locations, the greenhouse in Orre, in SW Norway, resulted in the highest yield and NFR with the production process having the lowest CO_2 emissions from natural gas and electricity use throughout all the selected designs and lighting strategies. Tromsø, in N Norway, had the lowest NFR, yield and the highest energy use and the maximum impact on the environment regardless of the selected designs and lighting strategies. These results were also consistent across the two production seasons, extended season, and year-round production.

Orre had the highest yield: 81.9 $kg\,m^{-2}$ for extended season in the design NDSFML$_{\text{LED\_ES}}$ and 136.8 $kg\,m^{-2}$ for year-round production in the design NDSFML$_{\text{\_HPS+LED\_YR}}$ (Fig. 6.), and NFR: 116.9 NOK m^{-2} for extended season and 268.5 NOK m^{-2} for year-round production (Fig. 7.). Meanwhile, Tromsø had the lowest yield and NFR for both production seasons (74.8 $kg\,m^{-2}$ in extended season and 102 $kg\,m^{-2}$ in year-round production and − 1.2 NOK m^{-2} for the extended season and 7.5 NOK m^{-2} for the year-round production) (Fig. 7). Moreover, the designs with LED as top lighting with capacities 300 µmol or lower (105.26 Wm^{-2} or lower) resulted in higher NFR than the designs with HPS as top lighting having same capacities. On the contrary when the capacities of LED as a top light were increased, it did not result in significant yield increase and in fact led to a decrease in the economic performance due to high investment costs and higher energy use.

With the exception of the design NSL$_{\text{\_LED\_ES}}$ in Tromsø, all other designs across all locations resulted in positive NFR for extended seasonal production. NFR for year-round production was higher compared to NFR for extended seasonal production. The design NDSFML$_{\text{\_LED200µmol+LED125µmol\_YR}}$ had the highest NFR for all locations (Fig. 7).

3.3. Fixed and variable costs

The fixed and variable costs varied across different designs, with the variable costs also varying among locations (Fig. 8). The fixed costs were highest for the design NDSFML$_{\text{LED125µmol\_ES}}$, (336 NOK m^{-2}) for extended season, and for NDSFML$_{\text{LED350µmol+LED125µmol\_YR}}$ (728 NOK m^{-2}) for year-round production in Tromsø due to the high investment costs in LED lights and heat pump. Fixed costs were the lowest in the design NSL$_{\text{LED125µmol\_ES}}$ (280 NOK m^{-2}) for extended season and for NSL$_{\text{\_HPS150µmol+LED125µmol\_YR}}$ (around 388 NOK m^{-2}) for year-round production in Kise because of the low investment costs of lighting. This was due to the lower light capacities used in these designs as compared to the other designs along with the lesser energy-saving equipment used. Meanwhile the variable costs were the lowest for the design NDSFML$_{\text{LED125µmol\_ES}}$ for extended season and for NDSFML$_{\text{LED150µmol+LED125µmol\_YR}}$ because of the lowest energy use in this particular design, and highest for the design NSL$_{\text{\_LED125µmol\_ES}}$ during the extended season and for NSL$_{\text{\_HPS350µmol+LED125µmol\_YR}}$ during year-round due to the high fuel usage.

3.4. Energy use

For the extended season, the design NDSFML$_{\text{LED\_ES}}$ used the lowest amount of natural gas across all locations, with the lowest in Kise (262 $kWh\,m^{-2}$) (Fig. 9.). Regarding electricity used, the designs NSL$_{\text{LED\_ES}}$ and NDSL$_{\text{LED\_ES}}$ used the lowest amount of electricity for the extended season, with the lowest in Kise (197 $kWh\,m^{-2}$), while for the year-round production, the designs NSL$_{\text{LED+LED\_YR}}$ and NDSL$_{\text{LED+LED\_YR}}$ had the lowest electricity use, with the lowest in Kise (485 $kWh\,m^{-2}$) (Fig. 10.).

3.5. CO_2 emissions

CO_2 emissions from natural gas and electricity varied between the production seasons, designs and the types of lights used (Fig. 11). The emissions were highest for the design NSL$_{\text{LED125µmol\_ES}}$ at Tromsø, (2.4 kg CO_2eq kg^{-1} fresh weight), and lowest in Orre and Kise for the design NDSFML$_{\text{LED125µmol\_ES}}$, (0.9 kg CO_2 eq kg^{-1} fresh weight), in extended seasonal production. For the year-round production kg CO_2 emissions were highest in Tromsø for the design NSL$_{\text{\_HPS350µmol\_YR}}$ (1.8 kg CO_2 eq kg^{-1} fresh weight), and the lowest in NDSFML$_{\text{HPS150µmol+LED125µmol\_YR}}$ in Orre (0.6 kg CO_2 eq kg^{-1} fresh weight).

3.6. Sensitivity analysis

The study showed a linear relationship between the tomato prices and the NFR, and that the lower the electricity prices and the higher the tomato prices, the higher the NFR. For the extended season, for Tromsø the minimum off-season tomato price needed for the NFR to be positive for all designs was 16.5 NOK kg^{-1} assuming an electricity price 0.4 NOK kWh^{-1}. This is the same price of electricity that we have used for our simulations for both production seasons (Fig. 12.). A price of 17 NOK kg^{-1}, or higher, garnered profit for all designs in all locations, with the same energy prices. Likewise, price of 13 NOK kg^{-1} or lower resulted in net losses for all greenhouse designs across all locations. For the year-round production, off-season tomato price of 14 NOK kg^{-1} or higher will result in positive NFR for all locations and designs, considering the

Table 5
The different greenhouse designs for year-round (YR) production season. The greenhouse design with one thermal screen was extended with various combinations of thermal screens, CO_2 enrichment (i.e., from the boiler and pure) and with heat pump. PE refers to Polyethylene Screen; Alu stands for Aluminium; inter stands for inter-lighting. Prices used for the design elements are explained in Table 1.

Greenhouse designs evaluated for year-round tomato production										
Design Elements	Type/ Capacity	NSL$_{\_HPS\_YR}$	NSL$_{\_HPS+LED\_YR}$	NSL$_{\_LED+LED\_YR}$	NDSL$_{\_HPS\_YR}$	NDSL$_{\_HPS+LED\_YR}$	NDSL$_{\_LED+LED\_YR}$	NDSFML$_{\_HPS\_YR}$	NDSFML $_{\_HPS+LED\_YR}$	NDSFML $_{\_LED+LED\_YR}$
Light		HPS (top 350 µmol (203.5Wm^{-2}))	HPS (top 150 µmol (87 Wm^{-2}) to 350 µmol (203.5Wm^{-2})) + LED (inter 125 µmol (43.7 Wm^{-2}))	LED (top 150 µmol (52 Wm^{-2}) to 350 µmol (122.8 Wm^{-2})) + LED (inter 125 µmol (43.7 Wm^{-2}))	HPS (top 350 µmol (203.5Wm^{-2}))	HPS (top 150 µmol (87 Wm^{-2}) to 350 µmol (203.5Wm^{-2})) + LED (inter 125 µmol (43.7 Wm^{-2}))	LED (top 150 µmol (52 Wm^{-2}) to 350 µmol (122.8 Wm^{-2})) + LED (inter 125 µmol (43.7 Wm^{-2}))	HPS (top 350 µmol (203.5Wm^{-2}))	HPS (top 150 µmol (87 Wm^{-2}) to 350 µmol (203.5Wm^{-2})) + LED (inter 125 µmol (43.7 Wm^{-2}))	LED (top 150 µmol (52 Wm^{-2}) to 350 µmol (122.8 Wm^{-2})) + LED (inter 125 µmol (43.7 Wm^{-2}))
Boiler- Pipe	Boiler	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Thermal Screens	Day Screen (100% PE)	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
	Night Screen (50%PE+50% Alu.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CO_2	Boiler (if on during the day)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Pure (130 kg ha^{-1} h^{-1})	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Humidification/ Dehumidification	Fogging	No	No	No	No	No	No	Yes	Yes	Yes
	Heat pump (25 Wm^{-2})	No	No	No	No	No	No	Yes	Yes	Yes

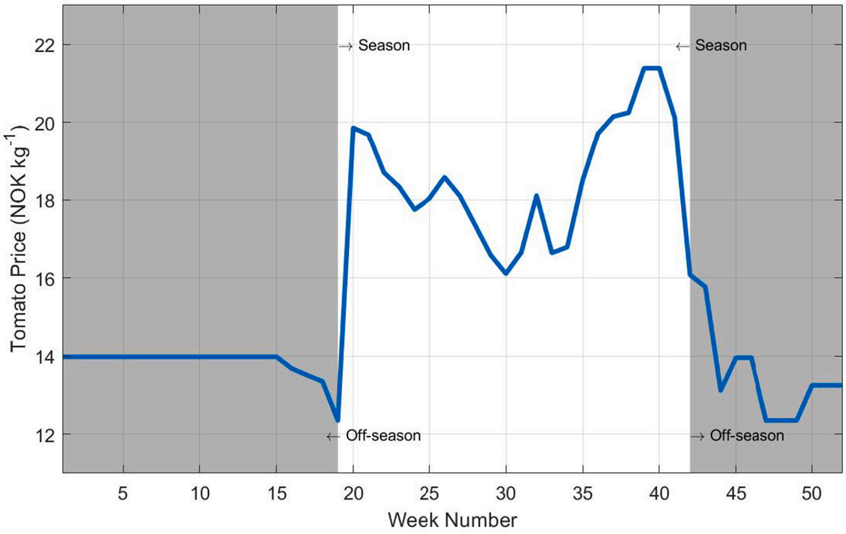

Fig. 3. Tomato prices used for season and off-season production period. The dark area depicts the off-season tomato price while the light area depicts the seasonal tomato price.

energy prices remain the same (Fig. 13.). Likewise, the NFR remained negative for all locations and designs if the tomato prices were 12 NOK kg^{-1} or lower, with the same energy prices. Moreover, it was found that if the energy prices increased the design with energy-saving elements resulted in higher NFR as compared to the design NSL.

For greenhouse tomato production in Norway, the biggest costs of production are due to energy and labour while other costs such as pesticides, fertilizers and pollination etc. have a negligible effect, for the year-round production. Since labour costs were outside the scope of our study, we have only conducted a sensitivity analysis on energy prices. Furthermore, the biggest impact on the NFR in year-round production is of the electricity prices and tomatoes prices. The reason being that in year-round production, electricity is primarily used for the supplemental lighting along with energy-saving equipment such as heat pump, while the use of natural gas is lower as compared to the overall use of electricity within the greenhouse. With regards to natural gas prices, it was found that of the four locations, Tromsø was the most sensitive to any variations in the natural gas prices for the year-round production. For instance, for the design NSL in Tromsø, a minimum tomato price of 15 NOK kg^{-1} or higher with the natural gas price of 0.4 NOK kWh^{-1} was needed for the NFR to be positive. Moreover, it was found that the design without the heat pump i.e., NSL was the most sensitive to variations in natural gas prices, as shown in Fig. 14.

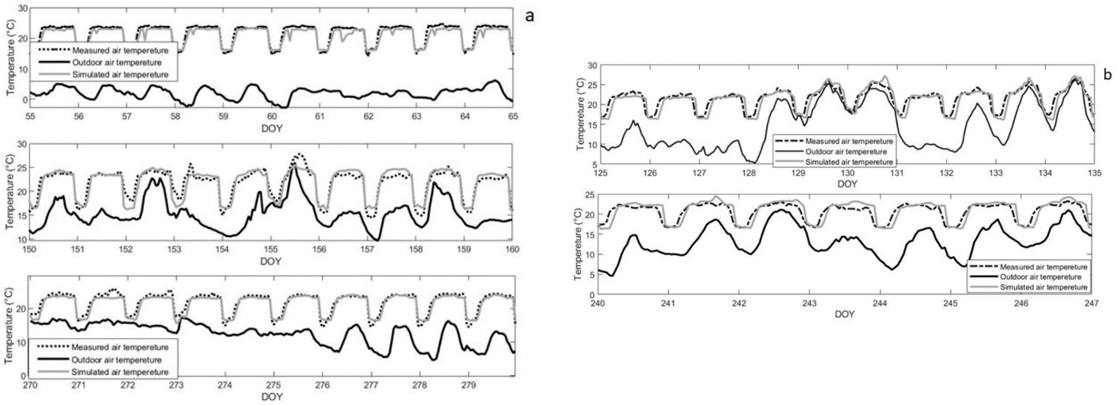

Fig. 4. Prediction of temperature for the commercial greenhouse in Orre (Southwestern Norway) with HPS top light at the beginning of the year (Day of the year (DOY): 55–65), Mid-year (DOY: 150–160) and end of the growing period (DOY: 270–280). The dotted line represents the measured indoor air temperature; the light solid line represents the simulated indoor air temperature while the solid dark line is the measured outdoor temperature (figure a). Figure b represents prediction of temperature for the commercial greenhouse with HPS top and LED inter-lighting in Mære (mid Norway) at the DOY: 125–135 and DOY: 240–247. DOY = day of the year. The dotted line represents the measured air temperature; the light solid line represents the simulated temperature, while the dark solid line is the outdoor air temperature.

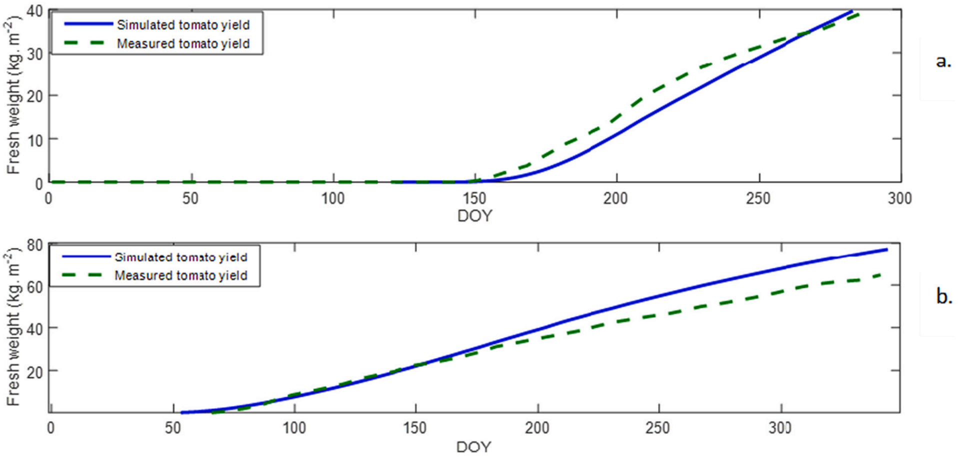

Fig. 5. Measured (dashed line) and predicted (solid line) yield for southwestern Norway (Orre) greenhouse for the year-round production (figure a.). The figure presents the measured yield for second crop cycle for the year-round production for the year 2016. Measured and predicted yield for Mære (mid Norway) greenhouse for the extended season production (figure b.). DOY: day of the year

4. Discussion

The effects of different design elements, especially the thermal screens, heat pump and the type of light, on NFR that were found, highlight the need to take into account these elements, input costs and tomato prices when designing greenhouses for tomato production in Norway and other regions having similar climate. The NFR sensitivity to the electricity price, which was higher in the year-round production than in the extended season production, indicates that energy saving equipment including day thermal screen and mechanical heating and cooling would become more useful should the fuel and electricity prices increase.

The greater need for heating and electricity in colder climates makes Tromsø the least favourable location -both economically and environmentally- for greenhouse tomato production, while the milder coastal areas such as Orre being the most favourable location for both extended season and year-round production. This is in contrast to greenhouse summer season production from March to October in Norway, which has been shown to generate higher NRF and lower energy use under inland climate conditions than under coastal climate conditions (Naseer et al., 2021). It goes without saying, of course, that changes in the outdoor conditions in a particular year could yield different results.

Our results show that for year-round production in higher latitude countries such as Norway, greenhouses with high-tech energy saving equipment yield far better results than simple greenhouse designs without energy-saving equipment due to the high amount of energy saved especially during winter, which results in positive NFR. For instance, the significantly better performance of the NDSFML greenhouse as compared to other designs, as reflected in the NFR across all locations is in contrast to the studies on the summer season tomato production in Norway (Naseer et al., 2021). In total, the better economic performance and the lower CO_2-emissions from fossil fuel use in the NDSFML design greenhouse than in the other greenhouses indicate that in colder climates investing in high-tech energy saving equipment can have positive environmental effects while also being economically efficient.

The type of lighting used within the greenhouse affects its performance since different types of lamps consume different levels of energy. Our study notes that LED as top and inter-lighting improves the economic performance of greenhouses in the year-round production and that the performance can be improved further through performing the optimization of inter-lighting capacities in both production seasons since it reduces the variable costs and increases the crop yield. It was found that an appropriate level of light is crucial in order to achieve optimal NFR and that both lower capacities and higher capacities than that, which in this case was found to be about 200 μmol (70.2 Wm^{-2}) for LED top light and 125 μmol (43.7 Wm^{-2}) for LED inter-lighting, can either result in lower levels of yield, and lower NFR or higher investment and variable costs and not enough yield, and thereby lower NFR. While we kept capacities for inter-lighting the same for both seasons in our present study, our simulations showed (data not shown) that for the extended season, the inter-lighting capacities can also be varied in order to achieve better results.

The high fixed costs in the designs containing LED lights at the top and inter-lighting for year-round production are due to the high investment costs associated with the LED lights. One possible reason for the relatively lower fixed costs in Kise as compared to other locations for these designs is the low artificial light use due to the high global radiation during summer and the resultant low depreciation costs of the lamps in Kise. The lower investment costs associated with the HPS notwithstanding, the designs with LED top and inter-lighting perform better since they are more efficient than HPS and affect the yield positively along with reducing the energy use, making it a better choice for lighting in existing greenhouse production keeping in mind the current investment costs of LEDs. Moreover, with the global prices of LEDs decreasing steadily, the option of LEDs could prove to be more practical in the future greenhouse tomato production (Van Iersel, 2017).

During the extended season, despite the use of same lighting throughout all designs, there was a variation in NFR due to different design elements that require different investment costs, and variations in amounts of energy saved. For instance, day and night energy screens performed better in milder regions while night and day screens along with mechanical heating and cooling performed better in colder climate (Tromsø). For the year-round production, across the four locations and the selected designs, the design $NSL_{HPS+LED\_YR}$ had the highest variable costs due to the addition of LED along with the existing HPS lights and the resultant electricity and natural gas used by the combination. On the other hand, the design $NDSFML_{LED+LED}$ had the lowest variable costs due to the LEDs being more energy efficient and lower amounts of natural gas used due to the addition of energy saving equipment.

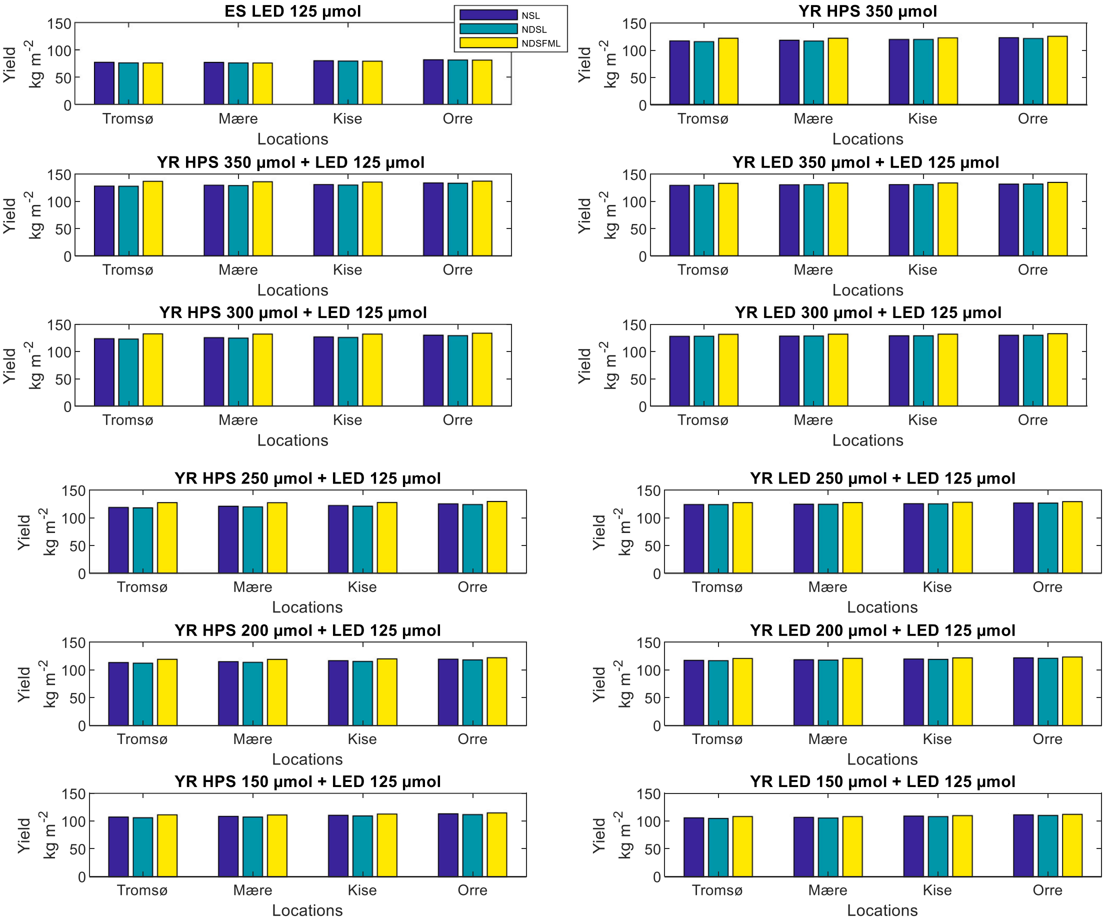

Fig. 6. Predicted marketable yield for greenhouse designs with different light strategies for extended season (20th January to 20th November) and year-round production, where ES denotes extended season and YR denotes the year-round. NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The availability of light and heat during the cold winter months in high latitude countries such as Norway is a persistent concern for greenhouse production. Verheul et al. (2020), Paponov et al. (2018) and Paponov et al. (2020) have shown that by adding supplemental lighting in greenhouse production, the yield of tomatoes grown in Norway can be increased significantly. Likewise, Paucek et al. (2020), Li et al. (2014), Tian (2016) and Liu et al. (2012) have shown that supplemental LED inter-lighting also enhance tomato yield in the Mediterranean region. Likewise, our study noted that certain combinations of capacities of LEDs as top and inter-lighting not only reduce fuel use, increase the yield but also are an economically viable option for existing greenhouse tomato production due to the lower variable costs associated with them, which is also reflected in other studies (Verheul et al. (2022); Van Iersel and Gianino, 2017). Moreover, combining LED top and inter-lighting with a heat pump can be even more economically and environmentally feasible especially for Northern areas such as Tromsø. Therefore, in order for the year-round greenhouse production in northern latitude countries to be both economically efficient and environmentally friendly, our study highlights the importance of designing relevant economic policies that enable and encourage the local growers to use LEDs and other energy-saving equipment, such as thermal screens and heat pumps.

4.1. Limitations

The study attempted to analyse the economic viability and CO_2 emissions of greenhouse tomato production in colder climates such as that of Norway for both the extended season and year-round production. Our results indicate that achieving economic efficiency along with the production being environmentally friendly is a difficult task since the climatic conditions in high latitude regions dictate energy intensive production systems, requiring both light and heat, particularly in the cold winter months, and likewise high investment costs in order to install energy-saving equipment.

Previous studies have shown that in closed greenhouses, higher levels of CO_2 can result in great increase in yield (De Gelder et al., 2012;

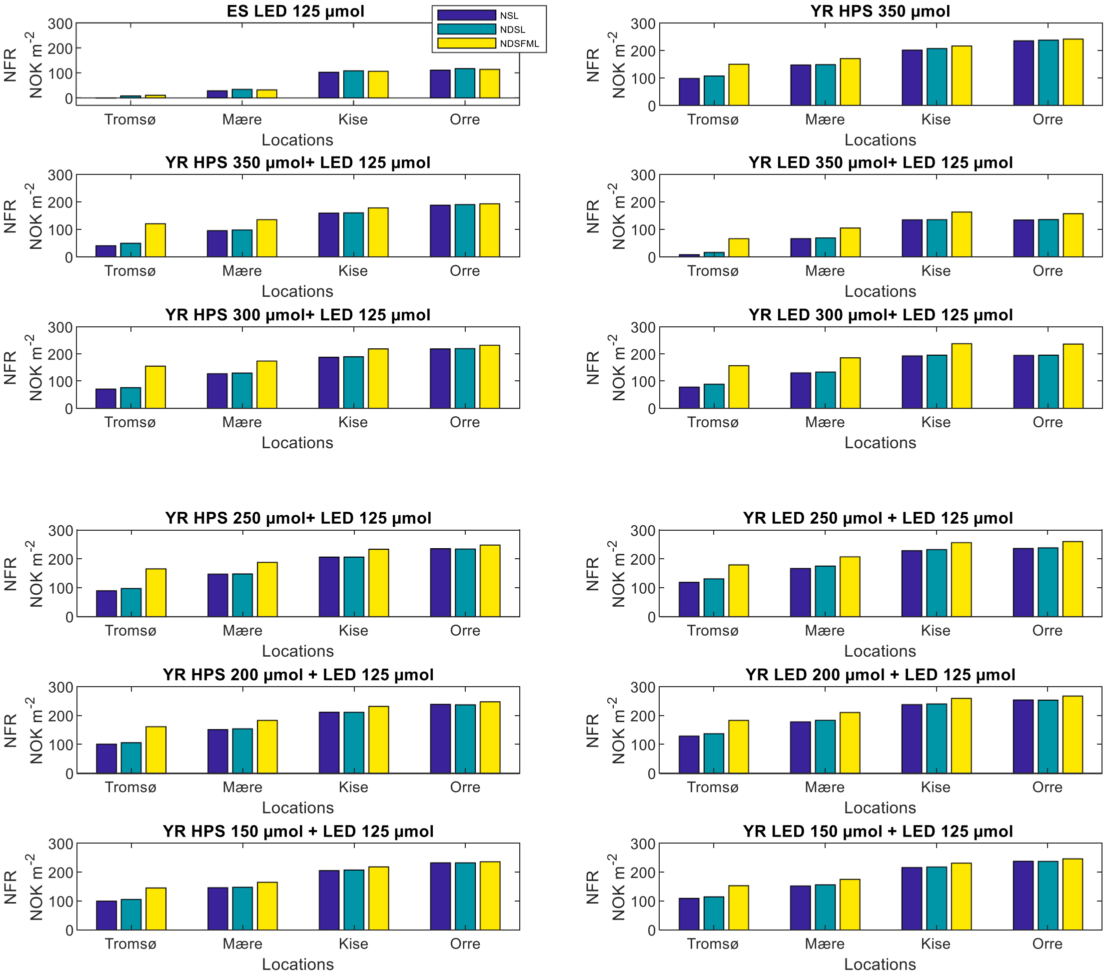

Fig. 7. Net financial return (NFR) for different designs and locations for the extended seasonal (20th January to 20th November) and year-round tomato production, where ES denotes extended season and YR denotes the year-round. NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

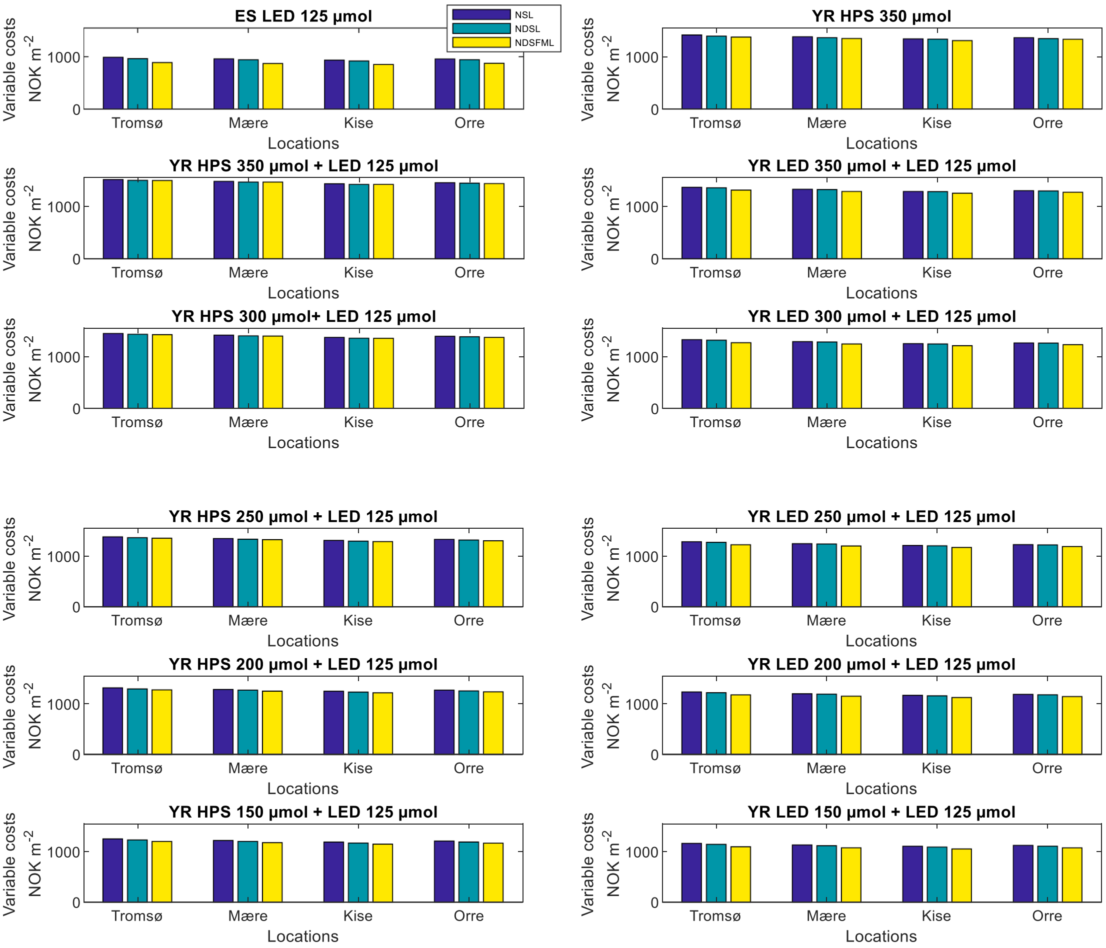

Fig. 8. Total variable costs for the designs and the light strategies for the extended season (20th January to 20th November) and year-round production for the four locations, where ES denotes extended season and YR denotes the year-round. NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

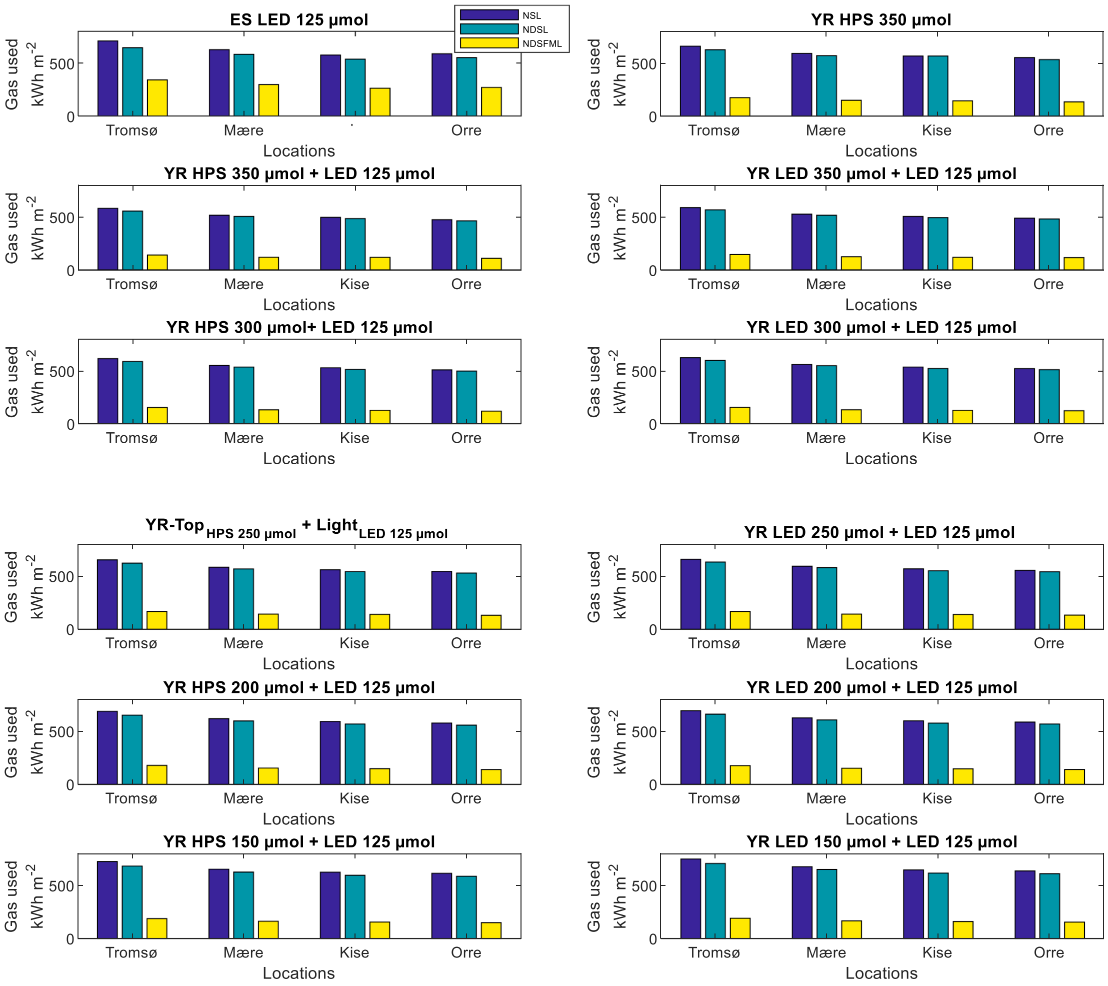

Fig. 9. Natural gas used for the different designs, light strategies, and locations for extended season (20th January to 20th November) and year-round production. ES denotes extended season and YR denotes the year-round; NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

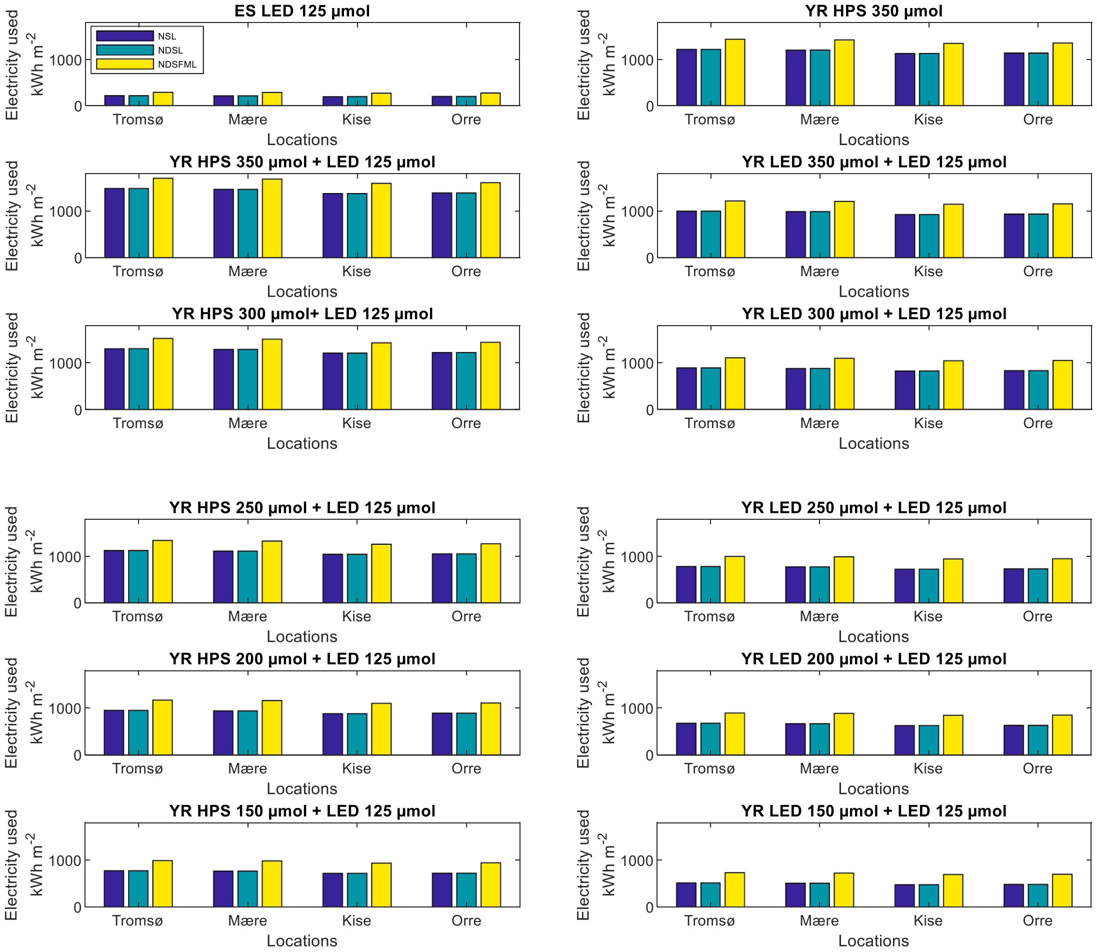

Fig. 10. Electricity used for the different designs, light strategies, and locations for extended season (20th January to 20th November) and year-round production.ES denotes extended season and YR denotes the year-round; NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

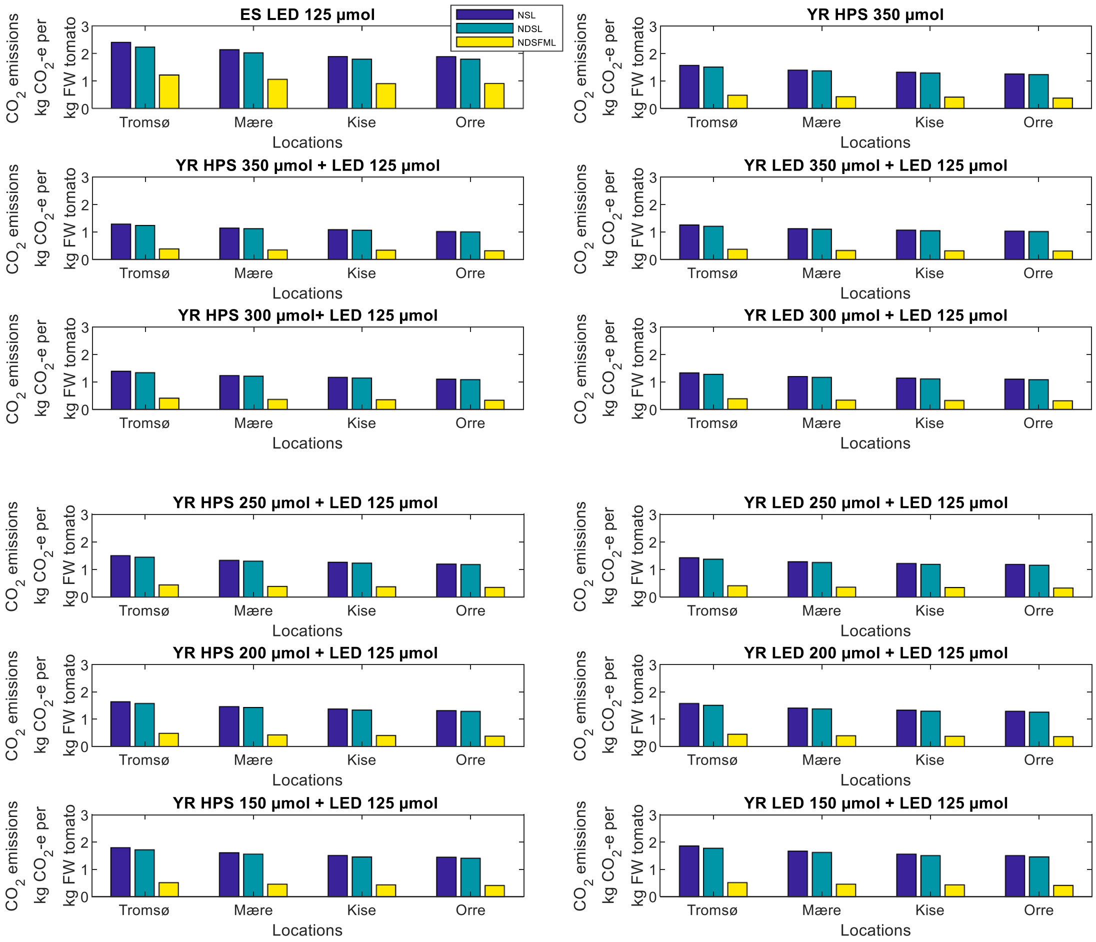

Fig. 11. CO_2 emissions for different designs, light strategies, and locations for extended season (20th January to 20th November) and year-round production. ES denotes extended season and YR denotes the year-round; NSL (blue bar) denotes the design with night screen; NDSL (green bar) denotes the design with day and night screens; NDSFML (yellow bar) denotes the design with day and night screens along with fogging and heat pump. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Huber et al., 2021; Sánchez-Guerrero et al., 2005). However, during our simulations, levels of yield did not increase to the extent as expected in the closed greenhouse design NDSFML, making the prediction for this design somewhat uncertain. This is because the model used is not particularly sensitive to CO_2, which lowers the accuracy of outputs from simulations of closed greenhouse designs, pointing toward the need for further modifications in the model. Another challenge with closed greenhouse systems is that the levels of humidity within the greenhouse can increase due to the high intensity of artificial lighting. This can substantially affect the marketable yield, which was seen during our simulations, while also bringing about changes within the indoor climate of the greenhouse. Thus, windows must be opened, which in turn lead to the energy and CO_2 losses. One possible solution can be the introduction of an advanced and responsive climate control system to handle excess humidity, and temperature control such as the GreenCap Solution process technology (https://greencap-solutions.com/), but its possible impact on the economic performance and the environment needs to be studied further.

Another limitation with our study is that it excludes costs and CO_2 emissions related to transportation. Previous studies show that environmental burden of transporting fresh vegetables long distances can be considerable (Verheul and Thorsen, 2010). Hence, should such transportation aspects have been taken into account, especially the NFR and CO_2-emissions for the distant Tromsø location may have been relatively better compared to the other locations.

4.2. Practical implications

Of the regions in Norway having existing facilities for seasonal tomato production, our study found that southwestern Norway seems to be the best region for greenhouse tomato production in both the extended and year-round production given the current tomato and energy prices, with it being the location that had greenhouses with the highest NFR in both production seasons. The fact that NDSFML in Tromsø resulted in a much higher NFR as compared to other designs, is an interesting finding since it points to the possibility of using energy saving equipment such as energy screens and heat pumps under conditions that are similar to this. Nonetheless, regarding the CO_2 emissions

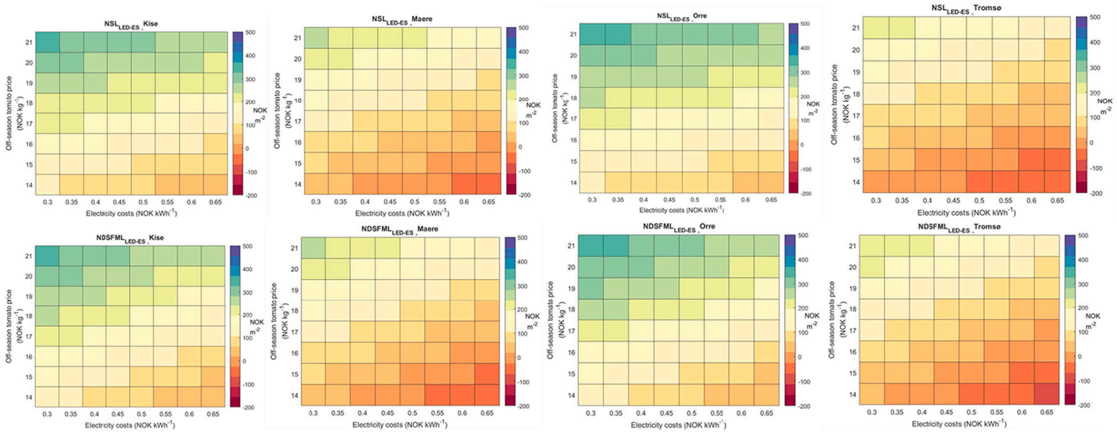

Fig. 12. The effect of tomato price and energy costs on the NFR for the designs NSL and NDSFML for extended seasonal greenhouse production in all four selected locations in Norway. The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway. NSL denotes the design with night screen; NDSFML denotes the design with day and night screens along with fogging and heat pump. The type of light in each design along with the production season is given in subscript.

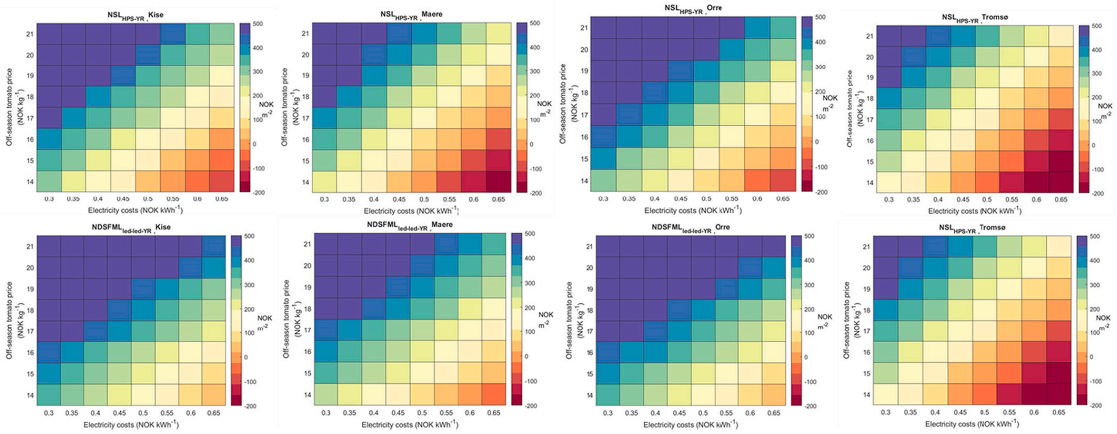

Fig. 13. The effect of tomato price and energy costs on the NFR for the designs NSL and NDSFML for year-round greenhouse production in all four selected locations in Norway. The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway. NSL denotes the design with night screen; NDSFML denotes the design with day and night screens along with fogging and heat pump. The type of light in each design along with the production season is given in subscript.

from natural gas and electricity, and keeping in mind the current costs of different types of supplemental lighting, our study recommends the design NDSFML$_{LED+LED\_YR}$ in high latitude countries such as Norway for the year-round tomato production.

Our study aimed at identifying a design out of several possible designs that gives the highest NFR and lowest energy use for extended season and year-round greenhouse tomato production. The findings of our study point toward the need for governments to formulate relevant policies, such as the regulation of electricity prices and investment costs of LED lighting and heat pump.

4.3. Way forward

The particular emphasis on energy saving design elements along with a consideration of increased profitability would be beneficial for not only the governments by promoting sustainable greenhouse production but also prove to be valuable in terms of opening up new directions for further research related to the off-season greenhouse production. With regards to the CO_2 emissions, the combination of LED as top and inter-lighting with heat pump and the resulted lower CO_2 emissions, due to a low energy use as compared to other light strategies, implies the need for the formulation of relevant policies that provide incentives to growers in order to encourage them to use LED lighting with energy saving equipment in greenhouses which would make the production process not only economically viable but also environmentally friendly.

Nonetheless, further work may be conducted to vary the indoor climate set-points, amend the model used in this study to make it more sensitive to variables such as CO_2 and relative humidity in order to achieve further accuracy in simulated scenarios and on optimizing

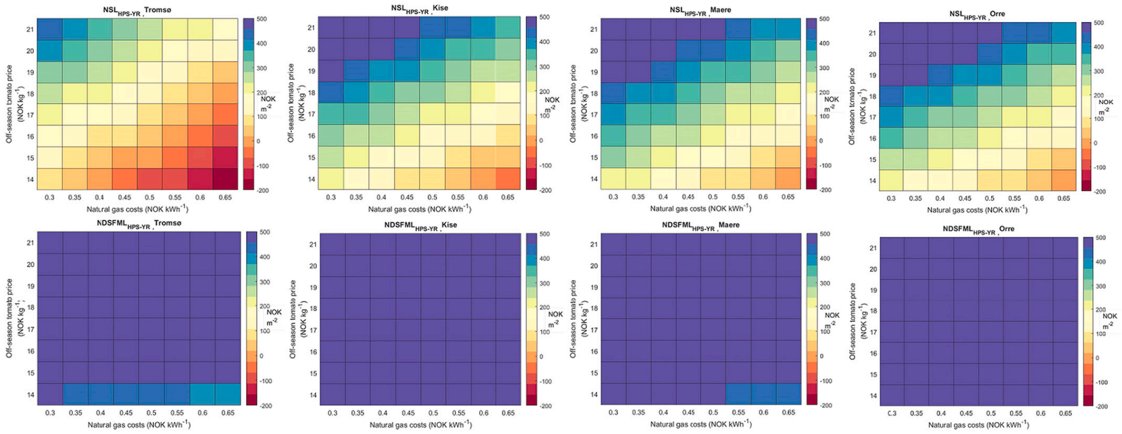

Fig. 14. The effect of tomato price and natural gas costs on the NFR for the designs NSL and NDSFML for year-round greenhouse production in all four selected locations in Norway. The figure shows that if the natural gas prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway. NSL denotes the design with night screen; NDSFML denotes the design with day and night screens along with fogging and heat pump. The type of light in each design along with the production season is given in subscript.

capacities of inter-lighting along with top-light for different production seasons. To further understand the prospects of greenhouse tomato production in different regions, aspects such as the economic cost and environmental burden of transporting the tomato from the production sites to the consumers also need to be taken into account.

5. Conclusions

The study showed that for year-round production even though the HPS lamps had lower investment costs, in the long run the LED lamps are still the better choice since it not only saved energy significantly but also were more efficient in yield increase. Moreover, the study noted that the capacities of supplemental lighting have a significant impact on the NFR and if the lighting strategies and the capacities are not optimised, it can result in negative NFR despite low investment costs, as is apparent during extended season in our study, for which the lighting capacities were not varied.

The study also showed that adding a night and day screen increased the economic performance of all selected designs across all locations for the two different production seasons. With regards to the CO_2 emissions from fossil fuel and electricity use, the design with the two thermal screens, fogging and mechanical heating and cooling with LED light had the most positive outcome. This implies that investing in high-tech energy saving equipment could be a better option than the standard greenhouses for greenhouse tomato production especially in the colder regions, since they not only help in saving energy but also yield in better NFR. Of the two different production seasons, the year-round production was more sensitive to variations in the prices of tomato and energy. The results of the study are useful for growers in order to select appropriate greenhouse designs according to the production season and local climatic conditions and can help facilitate future research in order to maximise the advantage of greenhouse technology that is both economically efficient and energy efficient. The results can also assist policy makers in formulating appropriate policies that can encourage growers to increase local tomato production while also keeping the production environmentally sound.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix C

Paper 3

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Life cycle assessment of tomato production for different production strategies in Norway

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ABSTRACT

The availability of fresh vegetables grown in greenhouses under controlled conditions throughout the year has given rise to concerns about their impact on the environment. In high latitude countries such as Norway, greenhouse vegetable production requires large amounts of energy for heat and light, especially during the winter. The use of renewable energy such as hydroelectricity and its effect on the environment has not been well documented. Neither has the effect of different production strategies on the environment been studied to a large extent. We conducted a life cycle assessment (LCA) of greenhouse tomato production for mid-March to mid-October (seasonal production), 20th January to 20th November (extended seasonal) production, and year-round production including the processes from raw material extraction to farm gate. Three production seasons and six greenhouse designs were included, at one location in southwestern and one in northern Norway. The SimaPro software was used to calculate the environmental impact. Across the three production seasons, the lowest global warming (GW) potential (600 g CO_2-eq per 1 kg tomatoes) was observed during year-round production in southwestern Norway for the design $NDSFML_{LED + LED}$, while the highest GW potential (3100 g CO_2-eq per 1 kg tomatoes) was observed during seasonal production in northern Norway for the design NS. The choice of artificial lighting (HPS (High Pressure Sodium) or LED (Light Emitting Diodes)), heating system and the production season was found to have had a considerable effect on the environmental impact. Moreover, there was a significant reduction in most of the impact categories including GW potential, terrestrial acidification, and fossil resource scarcity from seasonal to year-round production. Overall, year-round production in southwestern Norway had the lowest environmental impact of the evaluated production types. Heating of the greenhouse using natural gas and electricity was the biggest contributor to most of the impact categories. The use of an electric heat pump and LED lights during extended seasonal and year-round production both decreased the environmental impact. However, while replacing natural gas with electricity resulted in decreased GW potential, it increased the ecotoxicity potential.

1. Introduction

The availability of fresh agricultural products throughout the year is common in many developed countries. These products include off-season vegetables, which are domestically grown in greenhouses with controlled heating, cooling and supplemental lighting systems, and imported vegetables. There is, however, a growing concern regarding the effects of fresh vegetable production on the environment (Torrellas et al., 2012b). In Norway, tomatoes are a major greenhouse crop. The Norwegian market has seen a significant preference for locally produced tomatoes compared to imported ones (Bremnes et al., 2019). According to Rebnes and Angelsen (2021), Norway imported a total of 24113 tonnes of tomatoes in 2021, of which around 88% were imported from Spain and the Netherlands, and 12720 tonnes were produced domestically.

Greenhouses in northern latitude countries, such as Norway, consume great amounts of heat, often generated from fossil fuels, and electricity for lighting, particularly due to the shortage of light and heat during the winter season. In 2018, the Norwegian commercial greenhouses consumed a total of around 0.56 TWh energy (Statistics Norway,

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2019) mostly for heating and light. Several studies have shown that in greenhouse production, heating, which to a large extent is supplied by natural gas, has the highest environmental impact, and is the main contributor to global warming (Halberg and Rasmussen, 2006; Davis et al., 2011). The latest available study for Norway, showed that around 95% of greenhouse gas (GHG) emissions from commercial greenhouse tomato production were related to energy use. In addition, smaller emissions originated from artificial CO_2 fertilization. In total, the use of gas, including natural gas and propane for heating and CO_2 fertilization, accounted for almost 93% of GHG emissions while only 2% of GHG emissions were due to the use of hydroelectric energy (Verheul and Thorsen, 2010).

There is an increasing understanding of the effects of climate change among states and citizens alike in Europe, with around 92% of European citizens being of the view that GHG emissions ought to be reduced and the EU economy be made carbon neutral by 2050 (European Commission, 2019). In Norway, around 69.4% Norwegians are of the view that human activity is affecting the climate (Aasen et al., 2019). This view agrees to the Norwegian government's plan to reduce GHG emissions by at least 40% by 2030 compared to 1990 levels (*Rapport fra partssammensatt arbeidsgruppe* 1.7.2019) under the targets set by the Paris agreement (2015). Moreover, Norway produces some of the world's highest amounts of renewable electricity, primarily hydroelectricity, which emits only small amounts of greenhouse gases (The Norwegian Water Resources and Energy Directorate, 2020), creating a possibility to replace fossil fuel in the greenhouse sector with hydroelectricity.

Multiple studies have evaluated effects on the environment and trade-offs in greenhouse and field tomato production by using life cycle assessment (LCA) techniques (Martínez-Blanco et al., 2011). Some of these works have focused on calculating the environmental impact, including abiotic depletion, acidification, eutrophication, global warming and photochemical oxidation, of indoor year-round tomato production in multi-tunnels (Khoshnevisan et al., 2014), while others study the environmental impact of tomato production in both open-fields and greenhouses with a comparison of different types of fertilizers (Martínez-Blanco et al., 2011). Antón et al. (2005) in his study has conducted an environmental impact assessment of three different tomato production systems including soil cultivation and open and closed hydroponic systems and analysed three different waste management scenarios to concluded that composting of biodegradable matter was the best way to manage the waste of biomass. Interest has also grown on the effect of heating systems on the environment (Torrellas et al., 2012b, 2013) some works also focus on the analysing the use of energy and the related greenhouse gas emissions of greenhouse organic farming (Baptista et al., 2017). Other local specific studies including under Spanish (Torrellas et al., 2012a), French (Boulard et al., 2011), Italian conditions (Cellura et al., 2012) have showed that high-tech, soil-less heated greenhouse production have a higher impact than unheated tunnels and greenhouses. Other works focusing on different types of greenhouses under Italian conditions (Russo and Scarascia Mugnozza, 2005) and on studying the carbon and water footprints trade-offs in Sydney, Australia also found similar results (Page et al., 2012). In unheated greenhouses, especially in the Mediterranean region, it has been shown that the structure, auxiliary equipment, fertilizers (Romero-Gámez et al., 2009) packaging and transportation (Hueso-Kortekaas et al., 2021) that contributed to the largest environmental impacts. Verheul and Thorsen (2010) found that heating requirements of greenhouses accounted for almost 93% of the total GHG emissions in greenhouses in Norway. Gjessing (2018) concluded that although GWP from the greenhouse structure was higher due to the higher use of steel and reinforced concrete in greenhouse systems using biogas than the GWP from standard greenhouse during seasonal and year-round production, low emissions associated with the production phase meant that the former system had lower cumulative emissions than standard production systems. However, there is a need to study other impact categories than GWP in order to get a better understanding of greenhouse tomato production in high latitude regions. In addition, LCA of tomato production in greenhouses heated by hydropower are missing.

Previously it has been shown that even within the same location, there is a large difference in the economic performance and resource use between production strategies in seasonal production (Naseer et al., 2021) as well as in extended seasonal and year-round production (Naseer et al., 2022). These studies also showed that greenhouse production with a high economic performance and low energy use was possible for Orre in southwestern Norway with a comparably mild climate, but such an economically favourable and energy-efficient production could not be identified for Tromsø in northern Norway. Therefore, it can be expected that the environmental impact may also differ between production strategies. The present study is aimed at examining the environmental impact of seasonal and off-season greenhouse tomato production in northern climatic conditions for greenhouse designs that have the potential for high economic performance or have a low fossil fuel use.

2. Materials and methods

2.1. Scope and system boundaries

Three production seasons: seasonal production (mid-March to mid-October); extended season (20th January to 20th November); and year-round production were evaluated at Orre in southwestern (SW) Norway (lat. 58.71, long. 5.56, alt. 18 m a.s.l.), and Tromsø in northern (N) Norway (lat. 69.65, long. 18.96, alt. 60 m a.s.l.) (Fig. 1) using a variation in greenhouse designs.

The system boundary included all stages of the products' life cycle from raw material extraction to farm gate (Fig. 2). Transport to the wholesaler and store was not within our boundaries, neither was the production or use of biological and chemical plant protections. Although biological pesticides, and to a relatively lesser extent also chemical pesticides, are used by most producers, previous studies related to heated greenhouses in Netherlands (Antón et al., 2012) and Norway (Verheul and Thorsen, 2010) have shown that pesticide contribution in greenhouse tomato production is negligible with regard to the total contribution of the tomato production. The functional unit (FU), which is the reference unit for expressing environmental interventions, was

Fig. 1. The two selected locations in Norway, for which the production strategies were evaluated.

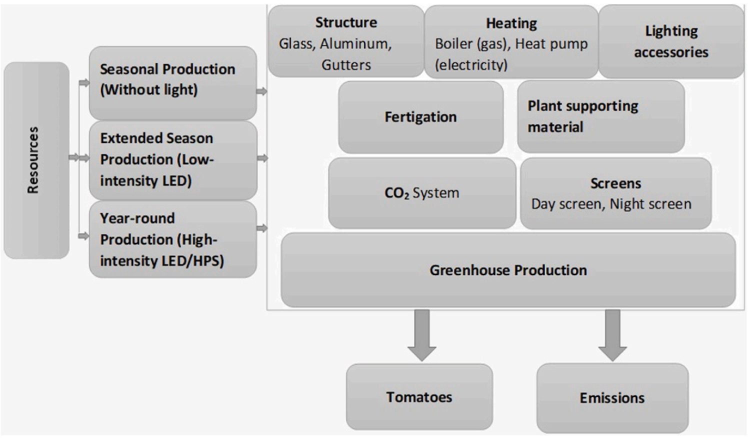

Fig. 2. System boundaries used in this study for greenhouse tomato production.

expressed as 1 kg fresh weight pre-packed 1st class tomatoes.

The marketable yield, i.e., 1st class fruits was considered to be 95% of the total fresh weight yield. Plants were transplanted to the greenhouse with the initial leaf area index (LAI) of 0.3, and the tomatoes were harvested at the light red ripening stage. For seasonal and extended seasonal production, young plants were transplanted in the greenhouse on standard Rockwool slabs with a density of 2.60 plants per m^2 and a row distance of 1.5 m. For year-round production, we considered two inter-plantings of tomato plants. The variable inputs included natural gas, electricity, fertilizer (that were supplied through water and is therefore referred to fertigation), cultivation medium, other production materials (tying hooks, nylon, etc.) and packaging and the fixed inputs included the greenhouse building and fixtures (cultivation slabs, gutters, shading systems, lighting systems etc.).

The seasonal production was carried out without the use of artificial lighting, whereas the extended production took place with fixed capacities of low intensity LED inter-lighting and in the year-round production we varied the type (HPS (High Pressure Sodium) and LED (Light Emitting Diodes)) and capacities of top lighting and constant LED-inter-lighting (see Naseer et al., 2022 for more details).

2.2. Scenarios

We evaluated two heating systems that comprised of a boiler heating system using natural gas, and a heat pump powered by electricity. To save energy within the greenhouse, we used night or day thermal energy screens. CO_2 fertilization was supplied to the greenhouse either by burning of natural gas in the boiler or as pure CO_2 from a tank.

The designs that previously were found to be the most profitable or that had the lowest energy use for seasonal previous (Naseer et al., 2021) and extended season and year-round production (Naseer et al., 2022) were evaluated. In doing so we aimed to assess whether designs that yield profit can also be sustainable considering other environmental loads than GHG emissions from energy use. A brief description of the selected greenhouse designs for the three production seasons is presented below:

2.2.1. Selected designs for seasonal production

1. **Night energy screen (NS):** This design consisted of a gas boiler with 1.16 MW capacity that was used for heating and CO_2 fertilization. A night energy screen consisting of 50% aluminum and 50% polyethylene, which was used for energy-saving purposes whenever the temperature was below 14 °C at night was included. No artificial cooling or fogging system was used. This design yielded the highest NFR for seasonal production out of several designs evaluated in Naseer et al. (2021).
2. **Day and night energy screens with fogging and mechanical cooling and heating (DNSFM)**: This design represents a production where the natural gas is partly replaced by hydroelectric energy. An electrical heat pump with a coefficient of performance (COP) of 3 was used for heating i.e., 1 kWh energy consumed would provide 3 kWh of output heat. There was an activation of mechanical cooling and heat harvest during the day when the temperature in the greenhouse exceeded 25 °C. In addition, CO_2-enrichment was provided by pure CO_2. All electricity was assumed to be generated in a hydro-electrical power plant. This design is a relatively closed design and had the lowest fossil fuel use (Naseer et al., 2021).

2.2.2. Selected designs for extended season production

1. **Night and day thermal screens + light ($NDSL_{LED}$):** This design consisted of the same design elements as NS described above, with the addition of a thermal screen, used during the day, when the temperature reached below 10 °C and the global radiation was below 150 Wm^{-2}, and an LED inter-lighting supplement with a capacity of 125 μmol.
2. **Night and day thermal screens + fogging + mechanical heating + lights ($NDSFML_{LED}$):** This design consisted of two thermal screens: one used during the day (like in design $NDSL_{LED}$) and the other at night (like in design NS), fogging, an electric heat pump with mechanical heating and cooling, and LED as inter-lighting with a capacity of 125 μmol.

2.2.3. Selected designs for year-round production season

1. **Night and day thermal screens + fogging + mechanical heating + lights ($NDSFML_{HPS\ +\ LED}$):** This design consisted of two thermal screens: one used during the day and the other at night, fogging, an electric heat pump with mechanical heating and cooling, and HPS with a capacity of 200 and 250 μmol as top light and LED as inter-lighting with a capacity of 125 μmol.
2. **Night and day thermal screens + fogging + mechanical heating + lights ($NDSFML_{LED\ +\ LED}$):** This design consisted of two thermal screens: one during the day and the other at night, fogging, an electric heat pump with mechanical heating and cooling, and LED with a capacity of 200 and 250 μmol as top light and LED as inter-lighting with a capacity of 125 μmol.

2.3. Impact assessment

This study used the SimaPro 9 software (www.simapro.com) to perform an LCA of greenhouse tomato production. LCA is well-established and standardized by the International Commission of Standardization ISO 14040 (2006a) and ISO 14044 (2006b). Data related to the background system, i.e., the production of fertilizers, electricity, constructions, etc. was taken from the Ecoinvent v.3 database. The ReCiPe 2016 Midpoint (H) V1.04 method (Huijbregts et al., 2017; Goedkoop et al., 2009) was used for impact assessment for a selection of impact categories (Table 1).

2.4. Data inventory

Values for greenhouse structure and building, fertilizer, culture medium, packaging, other production material, and waste management were taken from Verheul and Thorsen (2010), while values for fossil fuel and electricity use, pure CO_2 fertilization and yield in the seasonal production were taken from Naseer et al. (2021), and the corresponding values in the extended seasonal and year-round production from Naseer et al. (2022). We have chosen to use the values for basic greenhouse structure, fertilizer, culture medium, packaging, other production material, and waste management from 2010 since during the last 12 years, these have not changed significantly in the greenhouses we have evaluated in our study (Milford et al., 2021). The cultivation system was organised into these components: greenhouse structure, greenhouse equipment, climate control systems and fertilizers. Tables 2–4 provide an overview of yield and resources used for different designs, locations, and production seasons.

We used a Venlo type glasshouse with standard glass roofs and natural ventilation (Fernandez and Bailey, 1992). The greenhouse equipment included trolleys, cultivation gutters, shade systems and growing lights. A drip irrigation system was used to grow plants by irrigating standard Rockwool slabs. Bumblebees were used in the greenhouse for pollination. The material and equipment for greenhouse structure are listed in Table 5. CO_2 fertilization was supplied to the greenhouse through the boiler, by burning natural gas, or as pure CO_2 from a tank. The values for CO_2 supplied from the boiler was not recorded by the local growers, while values for pure CO_2 fertilization have been included. The total amounts of fertilizers used (Tables 2–4) were set according to recommendations by advisors at NIBIO. With regards to the waste management, we have assumed that metal and glass were 100% recycled, concrete was 50% recycled, and plastics 50% recycled and 50% incinerated. The estimated life spans of the different materials were: 20 years for metals, glass and concrete, 4–5 years for screens and other equipment, and 1 year for Rockwool.

Table 1
Selected impact categories, their abbreviations, and the measurement units.

Impact category	Abbreviation	Unit
Global warming	GW	g CO_2-eq
Ozone formation, Human health	OzHH	g NO_X-eq
Ozone formation, Terrestrial ecosystems	OzTE	g NO_X-eq
Terrestrial acidification	TA	g SO_2-eq
Freshwater eutrophication	FwEu	g P-eq
Marine eutrophication	MEu	g N-eq
Terrestrial ecotoxicity	TEco	g 1,4-DCB
Freshwater ecotoxicity	FwEco	g 1,4-DCB
Marine ecotoxicity	MEco	g 1,4-DCB
Land use	LU	m^2a crop-eq
Mineral resource scarcity	MiRes	g Cu-eq
Fossil resource scarcity	FRes	g oil-eq

Table 2
Overview of the crop yield and resources used for the selected greenhouse designs for the seasonal production in two Norwegian regions. For an explanation of the design abbreviations, see section 2.2.

Input data used in selected greenhouse designs for seasonal tomato production				
	Orre		Tromsø	
	NS	NDSFM	NS	NDSFM
Crop yield (kg m^{-2}) (Fresh weight)	41.4	40.2	37.2	35.6
Energy use natural gas (kWh m^{-2})	293.9	157.4	380.5	217.9
Electricity use (kWh m^{-2})	0.0	22.1	0.0	22.8
Plant fertilizers				
Nitrate Nitrogen (kg m^{-2})	0.5	0.4	0.4	0.4
Phosphorus (kg m^{-2})	0.1	0.1	0.1	0.1
Potassium (kg m^{-2})	0.8	0.7	0.7	0.7
Magnesium (kg m^{-2})	0.1	0.1	0.1	0.1
Calcium (kg m^{-2})	0.4	0.4	0.3	0.3
CO_2 (Pure) (kg m^{-2})	1.3	1.6	0.6	1.8

Table 3
Overview of the crop yield and resources used for the selected greenhouse designs for extended seasonal production in two Norwegian regions. For an explanation of the design abbreviations, see section 2.2.

Input data used in selected greenhouse designs for extended seasonal tomato production				
	Orre		Tromsø	
	$NDSL_{LED}$	$NDSFML_{LED}$	$NDSL_{LED}$	$NDSFML_{LED}$
Crop Yield (kg m^{-2}) (Fresh weight)	81.2	81.4	76.3	77.0
Energy use natural gas (kWh m^{-2})	550.2	269.3	644.5	340.5
Electricity use (kWh m^{-2})	199.2	272.5	215.7	288.9
Plant fertilizers				
Nitrate Nitrogen (kg m^{-2})	0.9	0.9	0.8	0.8
Phosphorus (kg m^{-2})	0.2	0.2	0.2	0.2
Potassium (kg m^{-2})	1.5	1.5	1.4	1.4
Magnesium (kg m^{-2})	0.2	0.2	0.2	0.2
Calcium (kg m^{-2})	0.7	0.7	0.7	0.7
CO_2 (Pure) (kg m^{-2})	2.8	4.5	2.5	4.7

3. Results

3.1. Seasonal production

The results showed that seasonal greenhouse production had high values for global warming potential and terrestrial ecotoxicity (Table 6). Of the two locations, Tromsø had higher values due to higher energy use. Replacing natural gas with electricity for an electric heat pump reduced most impact categories in both locations, however more so in Tromsø, but increased terrestrial ecotoxicity, while land use potential remained the same. Of the various input factors, natural gas and greenhouse structure had the highest contribution to most impact categories, while packaging had a high contribution to land use potential (Fig. 3). The design NS in Orre was associated with global warming potential of approximately 2200 g CO_2-eq. for 1 kg tomatoes, while the design with the lowest fossil fuel used, NDSFML, had the lowest global warming potential (approx. 1300 g CO_2-eq. for 1 kg tomatoes). Meanwhile, the highest global warming potential was observed in Tromsø (about 3100 g CO_2-eq. for 1 kg tomatoes for the design NS) and of about 1700 g CO_2-eq. for 1 kg tomatoes for the design NDSFML.

3.2. Extended seasonal production

The results showed that extended season production had relatively lower global warming potential and mineral and fossil resource scarcity

Table 4
Overview of crop yield and the resources used for the selected greenhouse designs for the year-round production in two Norwegian regions. For an explanation of the design abbreviations, see section 2.2.

Input factors used in selected greenhouse designs for year-round tomato production

	Orre		Tromsø	
	$NDSFML_{HPS + LED}$	$NDSFML_{LED + LED}$	$NDSFML_{HPS + LED}$	$NDSFML_{LED + LED}$
Energy use for HPS 250 μmol				
Natural gas (kWh m^{-2})	129.6	131.9	166.7	166.2
Electricity (kWh m^{-2})	1279.0	955.8	1352	1006
Crop Yield (kg m^{-2}) (Fresh weight)	129.7	129.8	126.6	126.9
Energy use for HPS 200 μmol				
Natural gas (kWh m^{-2})	140.1	140.7	178.4	177
Electricity (kWh m^{-2})	1116.0	857.6	1177	901
Crop Yield (kg m^{-2}) (Fresh weight)	122.6	123.8	119.2	120.4
Plant fertilizers used for both capacities				
Nitrate Nitrogen (kg m^{-2})	1.4	1.4	1.4	1.4
Phosphorus (kg m^{-2})	0.3	0.3	0.3	0.3
Potassium (kg m^{-2})	2.4	2.4	2.3	2.3
Magnesium (kg m^{-2})	0.4	0.4	0.4	0.4
Calcium (kg m^{-2})	1.2	1.2	1.2	1.2
CO_2 (Pure) (kg m^{-2})	5.6	5.9	6.3	6.5

than seasonal production but higher impact for terrestrial, freshwater and marine ecotoxicity and terrestrial acidification (Table 7). Tromsø continued to have higher impact for all categories in this season than Orre for both designs. The greater use of hydroelectricity had a greater contribution to some of the impact categories while the reduction in natural gas use reduced most impact categories. Of the various input factors, natural gas and greenhouse structure had the highest contribution to most impact categories, while electricity had a high contribution to terrestrial, freshwater and marine ecotoxicity and land use potential (Fig. 4). The global warming potential for the design $NDSL_{LED}$ in Orre was about 2100 g CO_2-eq. for 1 kg tomatoes and was highest for the same design in Tromsø (about 2600 g CO_2-eq. for 1 kg tomatoes). However, global warming potential was lowest for the design $NDSFML_{LED}$ in Orre, of about 1100 g CO_2-eq. for 1 kg tomatoes, which was the most energy efficient design in this season (Table 3).

3.3. *Year-round production*

For the year-round production, the global warming potential for the design NDSFML with 200 μmol HPS as top light and 125 μmol interlighting capacities was about 640 g CO_2-eq. for 1 kg tomatoes in Orre (Table 8). When lighting capacities and types of lighting was varied for the same location, the lowest global warming potential was observed for the combination 250 μmol LED as top light and 125 μmol LED as interlighting, which was the lowest throughout the two locations (616 g CO_2-eq. for 1 kg tomatoes) (Table 9). Highest global warming potential was observed for the combination HPS as top light with capacity of 200 μmol in Tromsø (766 g CO_2-eq. for 1 kg tomatoes). Electricity, followed by natural gas, had the highest share in almost all impact categories in the two locations except global warming potential and fossil resource scarcity, while the other factors had significantly lower impact (Figs. 5 and 6). When HPS was replaced by LED as top light, regardless of the capacities, an overall decrease in all impact categories was observed at both locations, pointing toward the LED as a better choice for supplemental lighting for year-round greenhouse tomato production in Norway.

Table 5
Materials and quantities for greenhouse structure, auxiliary equipment, lighting equipment and climate system equipment for the Venlo greenhouse.

Greenhouse size	Shape	Type		Reference
5760 (m^2)	90*64 (m)	Venlo		Fernandez & Bailey (1992)
Structure				Verheul and Thorsen (2010) and Antón et al. (2012)
Material	Quantity	Unit	Explanation	
Aluminium	16022	kg	Gutters, ridges, bars, ventilation opening mechanism, screens	
Steel	62601	kg	Roof bars, rails, ventilation opening mechanism, wire system	
Concrete	26.3	m^3	Foundation, side paths	
Glass	67789	kg	Roof, walls	
Polyester	828.2	kg	Screens, floor material	
Greenhouse equipment				Verheul and Thorsen (2010) and Antón et al. (2012)
Polystyrene	523	kg	Substrate layers	
Polyvinyl Chloride	203	kg	Distribution system, distribution equipment	
Steel	46378	kg	Boiler, condensers, pumps, pipes, CO_2 systems equipment	
LDPE	450	kg	Drippers, microtubes, pipes, benches	
Aluminium	4869	kg	Heating pipes, rail pipes	
Polyethylene	32	kg	Tubes, screens	
Nylon	102	kg	Rope, clips	
Polyester	22	kg	Inside tanks	
Lighting equipment				Verheul and Thorsen (2010); Zhang et al. (2017); Dale et al. (2011) and Tuenge et al. (2013)
Aluminium	25650	kg	HPS fixture, LED, fitting parts, brackets, blocks	
Cords	8550	m	power cords	
Copper	239	kg	Wiring	
Diodes	132	kg	LED	
Glass	712	kg	LED glass	

4. Discussion

This study aimed at conducting an LCA of tomato production under different production strategies at two different locations in Norway. The designs have previously been shown to be economically profitable or associated with low energy use in seasonal (Naseer et al., 2021), and extended seasonal and year-round production (Naseer et al., 2022). Our results showed that, even within one country, the choice of production strategy, including the use of supplemental lighting, choice of heating system and the production season, had a huge influence on the environmental impact of the final production. Moreover, the fact that certain designs that yielded high NFR also resulted in low environmental impact across the three production seasons and selected locations shows that

Table 6
LCA results for seasonal greenhouse tomato production per FU, in Orre and Tromsø in Norway for NS (Night Screen) and NDSFM (Night and Day Screen with Mechanical Heat Pump and Fogging).

		Orre		Tromsø	
Impact category	Unit	NS	NDSFM	NS	NDSFM
Global warming	g CO_2-eq	2203.10	1315.46	3096.97	1757.06
Ozone formation, Human health	g NO_X-eq	1.78	1.23	2.40	1.53
Ozone formation, Terrestrial ecosystems	g NO_X-eq	1.86	1.29	2.51	1.60
Terrestrial acidification	g SO_2-eq	2.06	1.54	2.70	1.86
Freshwater eutrophication	g P-eq	0.14	0.12	0.17	0.14
Marine eutrophication	g N-eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	1791.84	1896.96	2093.48	2144.22
Freshwater ecotoxicity	g 1,4-DCB	57.33	70.38	67.96	75.12
Marine ecotoxicity	g 1,4-DCB	74.03	88.51	88.46	95.01
Land use	m2a crop-eq	0.01	0.01	0.01	0.01
Mineral resource scarcity	g Cu-eq	6.32	6.23	7.35	6.53
Fossil resource scarcity	g oil-eq	758.57	442.28	1075.00	595.79

economic profitability can be combined, and achieved, together with low environmental impact.

As expected, our results indicate that the greatest environmental burden from the production of greenhouse tomatoes in typical Norwegian systems arises from the large amounts of natural gas used for heating the greenhouse. Other components such as electricity use, structure, fertilizers, and packaging were also significant contributors, yet they were to a relative extent surpassed by heating in most environmental impact categories. This is comparable to findings from similar studies on greenhouse tomato production in Norway (Verheul and Thorsen, 2010; Gjessing, 2018) and other high latitude regions including Canada (Dias et al., 2017a, 2017b; Hendricks, 2012) and Sweden (Bosona and Gebresenbet, 2018).

This study chose 1 kg tomatoes as FU, which is a common unit for measuring tomato yield. A reason for selecting this FU is the possibility of easy comparison with other studies related to greenhouse production. Nonetheless, choosing 1 kg of tomato can be problematic in case tomatoes of different sizes are produced. Tomato types with smaller sizes, for instance cherry tomatoes, often have a lower yield but a higher market value than larger tomatoes. In such cases, it may be relevant to calculate the environmental impact per unit of turnover (Verheul and Thorsen, 2010). This study assumes the production of ordinary round tomatoes. There is a considerable production of this type of tomatoes in greenhouses across Europe. The fact that there is such a large geographical production range, including several European countries (Högberg, 2010) as well as other world regions (Hendricks, 2012), of this type of tomatoes means that results of this study are highly relevant from an international perspective. Comparisons of the results from our study with those from other study designs can help identify environmental advantages and disadvantages with different allocations of greenhouse tomato production across climate conditions, regions, and greenhouse types.

Such comparisons of results also need to consider the system boundaries that have been considered in the LCA calculations. For this study, a system boundary including all processes from raw material extraction to farm gate was set. Hence, the transport from the farm to the consumer has not been considered and the subsequent losses that may occur during the transport phase are also not included. A recent study of greenhouse tomato production in Southern Spain considering the entire production stages, from processing of input materials to the disposal stage, reported that around 77% of its energy demand and carbon emissions arise due to packaging and transport (Hueso-Kortekaas et al., 2021). A previous study assessing the environmental impact of tomato crop in a multi-tunnel greenhouse, with the system boundary from raw materials extraction to farm gate including material disposal showed that under Mediterranean conditions, in the absence of heating requirements for the greenhouse, the structure, auxiliary equipment and fertilizers contributed the most to the environmental impacts (Torrellas et al., 2012a).

Another related aspect to the system boundary is that of the cut-off criteria for the types of emissions that were considered. For instance, in our study, we have not included the biogenic emissions related to the use of irrigation water since water is not a limited resource in Norway and the drainage water is usually recycled. Our study also omits biogenic emissions, including potential nutrient leaching and N2O and NH3 emissions from substrate (Rockwool) to air since N2O emissions from rockwool wrapped in plastic are significantly different from N2O emissions from managed soils. In addition, the nitrogen source is only synthetic (sodium nitrate) and consist of only 5% NH4+ and 95% of the

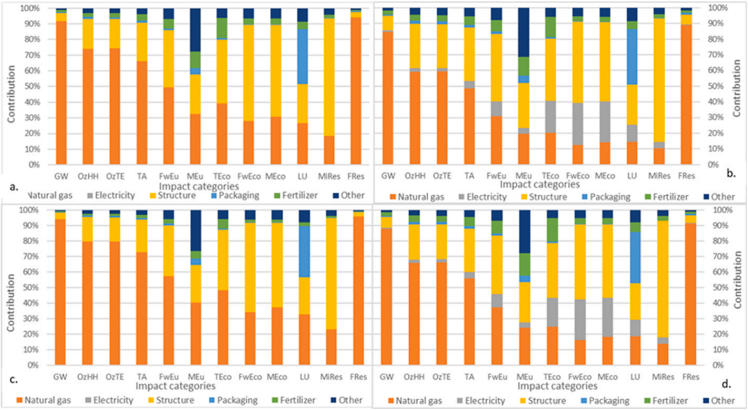

Fig. 3. Relative contribution to different impact categories for seasonal greenhouse tomato production for NS (Night Screen) (a and c) and NDSFM (Night and Day Screen with Mechanical Heat Pump and Fogging) (b and d), in Orre (a and b) and Tromsø (c and d). The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

Table 7

LCA results for extended season greenhouse tomato production per FU in Orre and Tromsø in Norway for NDSL$_{LED}$ (Night and Day Screens and LED inter-lighting) and NDSFML$_{LED}$ (Night and Day Screens with Mechanical Heat Pump and Fogging and LED inter-lighting) using 125 μmol LED as inter-lighting.

		Orre		Tromsø	
Impact category	Unit	NDSL	NDSFML	NDSL	NDSFML
Global warming	g CO_2-eq	2127.17	1173.25	2619.99	1510.68
Ozone formation, Human health	g NO_X-eq	1.73	1.15	2.09	1.40
Ozone formation, Terrestrial ecosystems	g NO_X-eq	1.81	1.20	2.18	1.46
Terrestrial acidification	g SO_2-eq	2.25	1.73	2.66	2.03
Freshwater eutrophication	g P-eq	0.19	0.18	0.22	0.21
Marine eutrophication	g N-eq	0.02	0.02	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	4188.23	4549.90	4732.22	5051.11
Freshwater ecotoxicity	g 1,4-DCB	145.27	168.82	164.96	187.95
Marine ecotoxicity	g 1,4-DCB	181.95	209.10	206.83	233.02
Land use	m2a crop-eq	0.01	0.01	0.01	0.02
Mineral resource scarcity	g Cu-eq	5.82	5.71	6.50	6.29
Fossil resource scarcity	g oil-eq	723.45	380.62	894.48	496.71

fertilizer NO3-. Therefore, similar to the findings of Hosono and Hosoi (2008) the indirect N2O emissions will be much less than in a conventional tomato soil-based culture. The indirect N2O emissions are included due to the production of Sodium nitrate.

Our results show that while there was a substantial reduction in most impact categories when natural gas was replaced with electricity in the seasonal and extended seasonal production cycles, an increase in the terrestrial, freshwater and marine ecotoxicity was detected. However, during year-round production season, moving from NDSFML$_{HPS + LED}$ to NDSFML$_{LED + LED}$, changed the trend of an increase in terrestrial, freshwater and marine ecotoxicity to an overall reduction for all impact categories. This could be explained by the fact that during seasonal and extended season production and within designs in each season, the use of electricity and natural gas increased, causing an increase in the potential for terrestrial, freshwater and marine ecotoxicity for which electricity was the biggest contributor.

Yet in year-round production, when LED replaced the traditional HPS as top lights and combined with the use of an electric heat pump, a reduction in the terrestrial, freshwater and marine ecotoxicity potential was seen. This could be explained by the fact that in typical glass greenhouses, heating requirements contribute to around 76–82% of terrestrial ecotoxicity potential (Boulard et al., 2011). Moreover, the mercury in HPS lights has also been shown to be a significant contributor to terrestrial ecotoxicity. However, the use of LED lights in design NDSFML$_{LED + LED}$ had lower environmental impacts than HPS and contributed to saving energy, as has also been shown in other studies (Tähkämö and Halonen, 2015). This puts further weight in the suggestion that in cold climate zones such as Norway, switching to year-round production of greenhouse tomatoes can yield better results, both in terms of economic profitability and environmental sustainability (Milford et al., 2021). The reduction in the environmental impact from seasonal to extended and year-round seasons can be further explained by the following reasons: 1. For the seasonal production, the design with the night screen, which used higher levels of energy, had higher yield. In extended and year-round seasons, the design having the night and day screens and electric heat pump had higher levels of energy saved and high levels of yield; 2. The use of artificial lighting and electric heat pump during extended and year-round seasons had the double effect of not only increasing the yield but also reducing the use of fossil fuel due to the heat produced from the lights (Naseer et al., 2021, 2022). These positive results of using an electric heat pump are a new and important empirical contribution of this study to existing research, especially related to high latitude regions such as Norway, and those which use energy from renewable sources.

Previous studies have shown that the necessity of heating greenhouses, especially in colder climates, and the subsequent reliance on fossil fuels, including oil and natural gas, make imported tomatoes a better choice than locally produced tomatoes (Keskitalo, 2009; Payen et al., 2014). However, the study by Payen et al. (2014) shows that under the conditions they studied, the imported tomatoes performed better with respect to the carbon and energy perspective but from a freshwater resource standpoint, local production of tomatoes under French conditions was better. One exception is the study by Nordenström et al. (2010), who found that bio-fuelled CHP heated greenhouse tomato production in central-Norway performed better environmentally in all impact categories studied including global warming potential, and potentials of abiotic depletion, acidification, eutrophication and ozone layer depletion than open-field tomatoes imported from Spain. While our study did not include a comparison with the environmental impact of imported tomatoes, our results have shown that for greenhouse tomato production in Norway, year-round production has much lower environmental impacts than seasonal and extended seasonal production. In total, our results indicate that the understanding of the difference

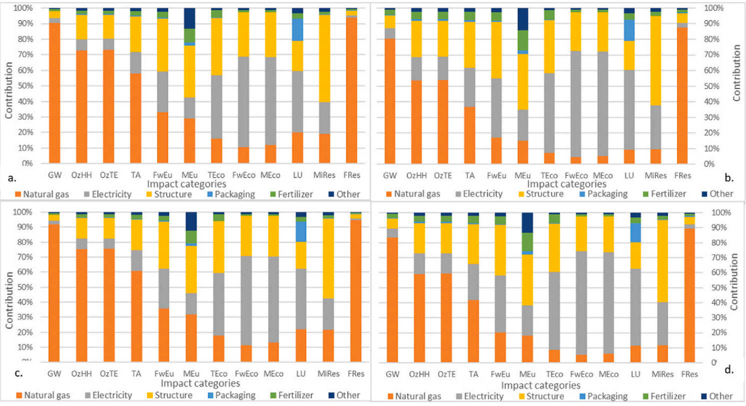

Fig. 4. Relative contribution to different impact categories for extended season greenhouse tomato production for NDSL$_{LED}$ (a and c) and NDSFML$_{LED}$ (b and d), in Orre (a and b) and Tromsø (c and d). NDSL denotes the design with the Night and Day Screens and LED inter-lighting, NDSFM denotes Night and Day Screens with Mechanical Heat Pump and Fogging and LED inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

Table 8

LCA results for year-round greenhouse tomato production per FU, in Orre and Tromsø in Norway for NDSFML$_{HPS + LED}$ and NDSFML$_{LED + LED}$ with 200 μmol top light and 125 μmol inter-lighting capacities. NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting.

		Orre		Tromsø	
Impact category	Unit	NDSFML_HPS_LED	NDSFML_LED_LED	NDSFML_HPS_LED	NDSFML_LED_LED
Global warming	g CO_2-eq	642.62	599.71	766.44	711.36
Ozone formation, Human health	g NO_X-eq	0.92	0.82	1.04	0.92
Ozone formation, Terrestrial ecosystems	g NO_X-eq	0.95	0.85	1.07	0.95
Terrestrial acidification	g SO_2-eq	1.85	1.57	2.04	1.72
Freshwater eutrophication	g P-eq	0.26	0.21	0.28	0.23
Marine eutrophication	g N-eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	7856.23	6250.60	8480.15	6711.44
Freshwater ecotoxicity	g 1,4-DCB	349.72	271.70	378.13	292.63
Marine ecotoxicity	g 1,4-DCB	428.10	332.89	462.93	358.58
Land use	m2a crop-eq	0.02	0.02	0.02	0.02
Mineral resource scarcity	g Cu-eq	7.01	5.88	7.52	6.27
Fossil resource scarcity	g oil-eq	172.39	165.15	211.75	201.45

Table 9

LCA results for year-round greenhouse tomato production per FU, in Orre and Tromsø in Norway for NDSFML$_{HPS + LED}$ and NDSFML$_{LED + LED}$ with 250 μmol top light and 125 μmol inter-lighting capacities. NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting.

		Orre		Tromsø	
Impact category	Unit	NDSFML$_{HPS + LED}$	NDSFML$_{LED + LED}$	NDSFML$_{HPS + LED}$	NDSFML$_{LED + LED}$
Global warming	g CO_2-eq	616.24	570.47	728.74	670.69
Ozone formation, Human health	g NO_X-eq	0.93	0.81	1.03	0.90
Ozone formation, Terrestrial ecosystems	g NO_X-eq	0.95	0.83	1.06	0.93
Terrestrial acidification	g SO_2-eq	1.90	1.58	2.08	1.72
Freshwater eutrophication	g P-eq	0.27	0.22	0.29	0.23
Marine eutrophication	g N-eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	8304.28	6476.35	8938.21	6935.62
Freshwater ecotoxicity	g 1,4-DCB	373.72	284.79	403.37	305.92
Marine ecotoxicity	g 1,4-DCB	457.22	348.72	493.53	374.63
Land use	m2a crop-eq	0.02	0.02	0.03	0.02
Mineral resource scarcity	g Cu-eq	7.22	5.95	7.72	6.33
Fossil resource scarcity	g oil-eq	159.73	153.38	195.22	185.66

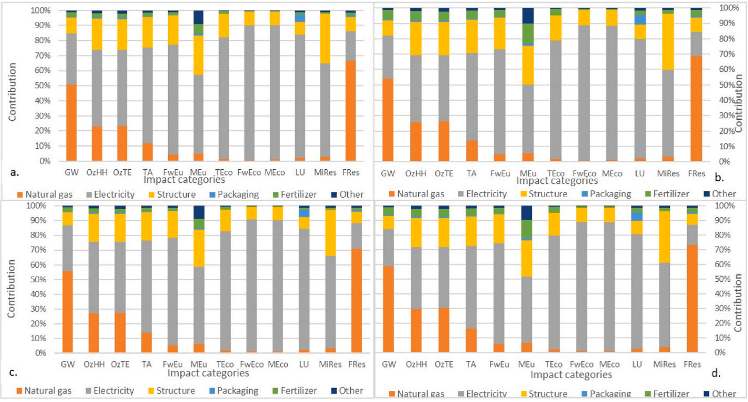

Fig. 5. Relative contribution to different impact categories for year-round greenhouse tomato production for NDSFML$_{HPS + LED}$ (a and c) and NDSFML$_{LED + LED}$ (b and d) respectively with 200 μmol top light and 125 μmol inter-lighting capacities in Orre (a and b) and Tromsø (c and d). NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

between imported and locally produced tomatoes, in Norway and in other countries, would benefit from further comparisons of imported and locally produced tomatoes where different designs and production cycles are included. Such comparisons should also include the same system boundaries for all included types of production, other inventory data and assumptions.

Nonetheless, the increased use of electricity resulted in a trade-off between the reduced potential for global warming and the increased potentials for terrestrial, freshwater and marine ecotoxicity during the three production seasons, even though there is an overall reduction in all other impact categories during the year-round production. Moreover, there was an overall reduction in all impact categories between different designs during the same production cycle. This presents a challenge in terms of assessing the environmental impact and economic performance of greenhouse tomato production and can be seen in LCAs of greenhouse tomato production using renewable energy resources in different

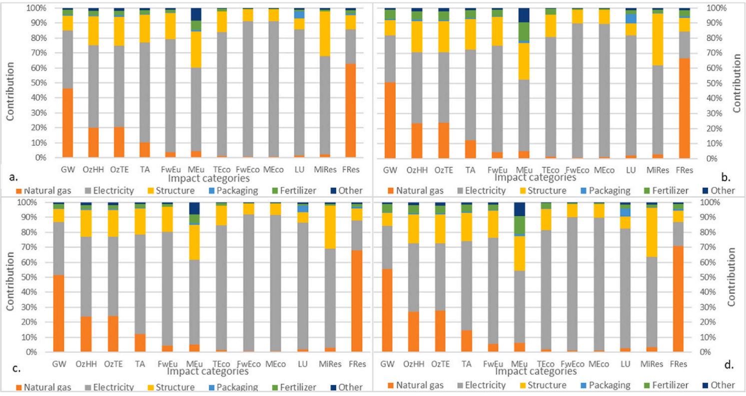

Fig. 6. Relative contribution to different impact categories for year-round greenhouse tomato production for NDSFML$_{HPS + LED}$ (a and c) and NDSFML$_{LED + LED}$ (b and d) respectively with 250 μmol top light and 125 μmol inter-lighting capacities, in Orre (a and b) and Tromsø (c and d). NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

regions. For instance, Dias et al. (2017a, 2017b) showed that when natural gas is substituted by wooden biomass for heating greenhouses in Ontario, Canada, although there was an almost 85% reduction in global warming potential relative to the fossil fuels, yet relative to global warming potential, its use had higher impacts in eutrophication and respiratory effects. Similarly, a study on the greenhouse tomato production in Hungary comparing the use of geothermal energy and natural gas for heating found that the former energy source had significantly lower environmental impact than the latter, however, geothermal energy had high financial costs (Torrellas et al., 2012b).

It will be difficult to say what the increase in terrestrial, freshwater and marine ecotoxicity means compared with an increase in greenhouse gas emissions or other categories, as no normalisation or weighting has been carried out (European Commission, 2010). Irrespective of the production cycle, questions related to the environmental impact of different energy sources and the environmental impact of vegetables is complex and highlights crucial issues related to the comparison of impact categories of food products. Payen et al. (2014) showed a trade-off between energy-related impact categories and freshwater use impacts. Their findings highlight the significance of selecting different impact categories and the preference one gives to them. Thus, it is not a simple matter of recommending a specific production strategy but the significance of the impact category one decides to give preference to. Nevertheless, further research is needed to know more about the selection criteria and the trade-offs between individual impact categories.

The study comprised of an LCA for several different greenhouse designs within each of three production cycles. The results for the assessment showed that variation in greenhouse management systems, especially climate control, has a significant impact on the environmental burden associated with the production of the same crop i.e., tomato and even within the same production region. This indicates the benefits of studying different production strategies to further reduce the environmental impact of greenhouse tomato production in Norway and could also benefit other regions with predominant production of greenhouse tomatoes or have similar climate conditions as that of Norway. Nonetheless, as pointed out by Milford et al. (2021), cooperation on measures to reduce the environmental impact among growers within different regions in Norway and elsewhere is necessary for these to achieve positive results.

5. Conclusion

In the present study, an LCA of greenhouse tomato production including processes from raw material extraction to farm gate as system boundary for three production cycles, a selected number of design strategies and two locations in Norway, was conducted. The study showed that there was a significant reduction in most impact categories from seasonal to extended and year-round production, indicating that year-round greenhouse tomato production in southwestern Norway has a lower impact from all evaluated categories than tomato production in northern Norway. Heating requirements of the greenhouse arising from the use of natural gas and electricity comprised the biggest contributor to most of the impact categories. Despite a reduction in most impact categories by using higher levels of electricity than fossil fuel in extended and year-round production, its contribution to terrestrial, freshwater, and marine ecotoxicity was significantly large.

CRediT authorship contribution statement

Muhammad Naseer: Conceptualization, Methodology, Data Acquisition, Software, Writing – original draft, and Subsequent Revisions, Editing. **Tomas Persson:** Conceptualization, Analysis and Interpretation, Drafting Manuscript and Revision. **Anne-Grete R. Hjelkrem:** Analysis and Interpretation, Revision. **Peter Ruoff:** Analysis and Interpretation, Revision. **Michel J. Verheul:** Conceptualization, Analysis and Interpretation, Drafting Manuscript and Revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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