Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

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

Muhammad Naseer [a,*], *Tomas Persson* [a], *Isabella Righini* [b], *Cecilia Stanghellini* [b], *Henk Maessen* [a], *Michel J. Verheul* [a]

[a] *NIBIO, Norwegian Institute of Bio-economy Research, Division of Food Production and Society, Postvegen 213, 4353, Klepp Stasjon, Norway*

[b] *Wageningen UR Greenhouse Horticulture, P.O. Box 644, 6700 AP Wageningen, the Netherlands*

A R T I C L E I N F O

Article history:
Received 20 January 2021
Received in revised form
18 September 2021
Accepted 3 November 2021
Published online 20 November 2021

Keywords:
Climate
Design elements
Economic model
Energy use
Growers' profit

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.

* Corresponding author.
E-mail address: Na.seer@hotmail.com (M. Naseer).

https://doi.org/10.1016/j.biosystemseng.2021.11.005

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

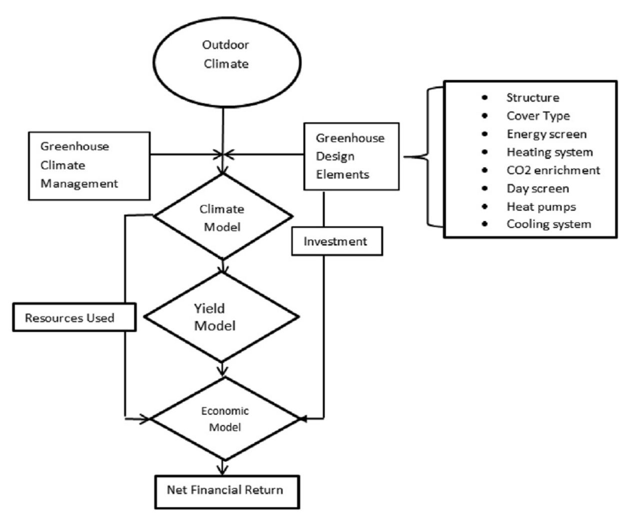

Fig. 1 – An overview of the model-based greenhouse design method used in this study. The climate model predicts the indoor climate of the greenhouse based on the outdoor climate management and design elements. The yield model predicts the fresh-mass harvest based on the climate model. The economic model 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:

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

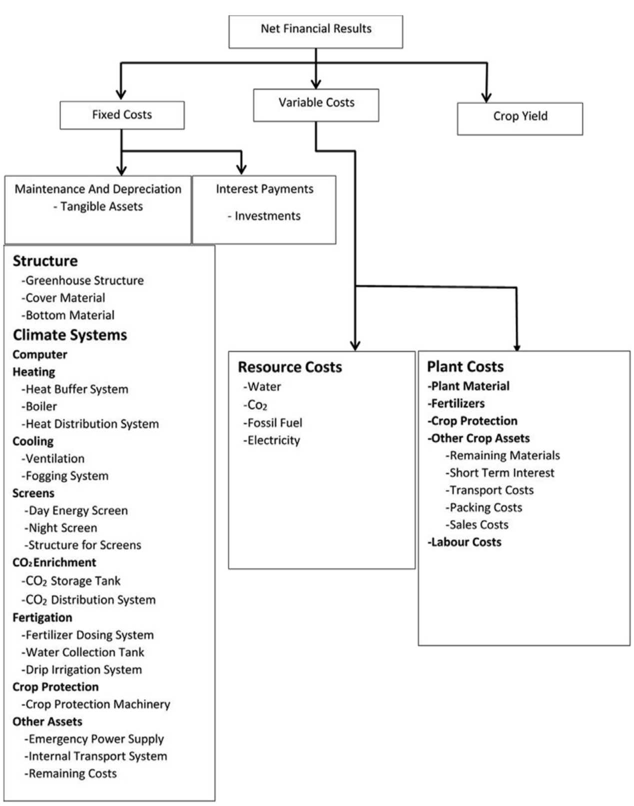

Fig. 2 – An overview of the costs associated with the Net Financial Return (NFR) of the grower. The costs are divided into fixed and variable costs and include the costs occurred as a result of using different design elements. Adapted from Vanthoor et al. (2011b).

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.

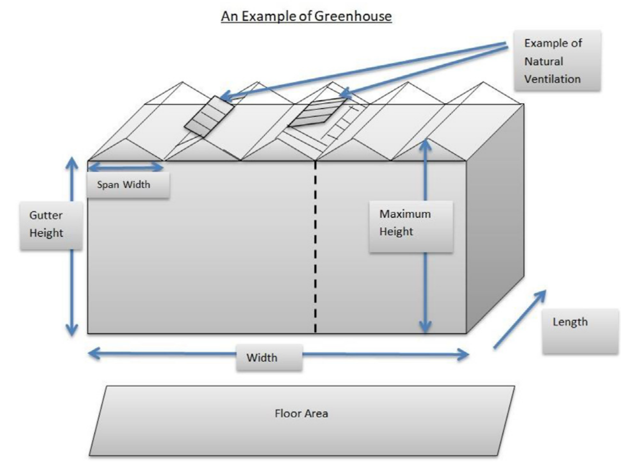

Fig. 5 – The shape and natural ventilation system in Venlo type greenhouses used in Norway.

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).

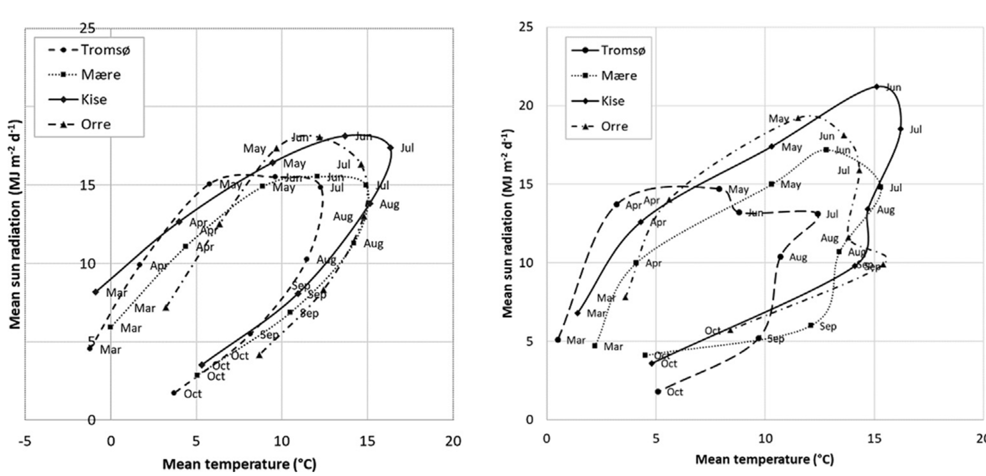

Fig. 4 – The mean temperature and radiation recorded in the four locations during the last 30 years (1989–2019) (left) and for the year 2016 (right).

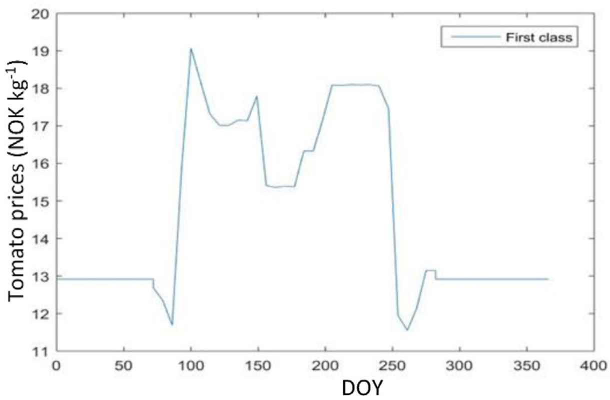

Fig. 6 – Price trajectory used for the tomatoes for year 2016 in Norway. Only the first-class yield is taken into account and so only the first-class yield was registered for this study. DOY: Day of the Year.

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^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	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

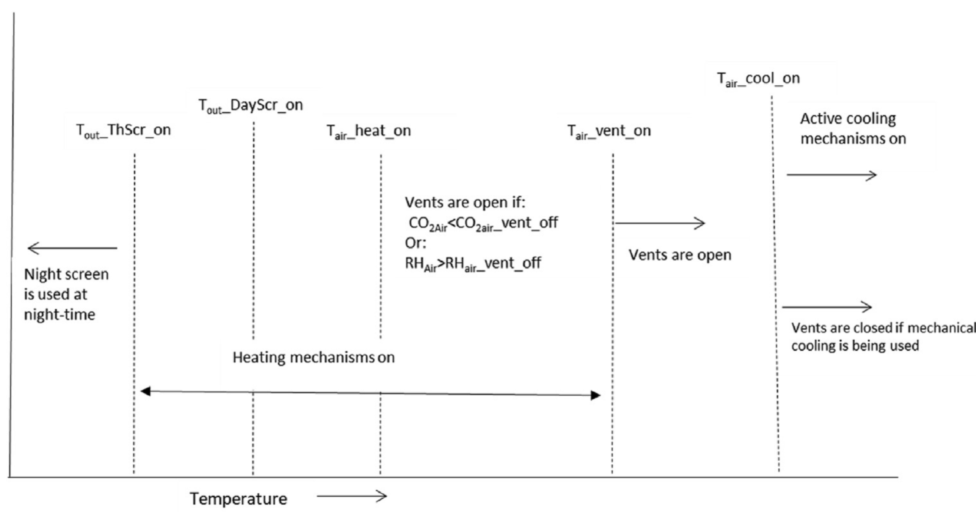

Fig. 7 – Strategy for managing the greenhouse climate. The average set points for climate control are shown in Table 4. Adapted from Vanthoor et al. (2011b).

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
$Tair_{\_vent\_on}$	23	(°C)	Temperature set point, measured inside the greenhouse, for opening of roof ventilation during daytime
$RHair_{\_vent\_on}$	84	(%)	Relative humidity set point, measured inside the greenhouse, for opening of roof ventilation
$CO_2air_{\_vent\_min}$	390	(ppm)	Set point for CO_2 dosage at maximum ventilation
$Tair_{\_heat\_on}$ (night/day)	17/19	(°C)	Temperature set point for turning on the heating system for night and day respectively
$Tair_{\_fog\_on}$	24	(°C)	Set point for fogging if the indoor air temperature was above this
$Tout_{\_NightScr\_on}$	14	(°C)	Set point for using night screen if temperature is below this
$Tout_{\_Day\_EnScr\_on}$	10	(°C)	Set point for using day energy screen if temperature is below this
$Iglob_{\_Day\_EnScr\_on}$	150	(W m^{-2})	Set point for day energy screen if Iglob is below this
CO_{2Air_ExtMin}	390	(ppm)	The CO_2 concentration below which the air is enriched with CO_2
CO_{2Air_ExtMax}	1000	(ppm)	Maximum CO_2 set point if Iglob ≥650 Wm-2 and temperature Tair ≥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

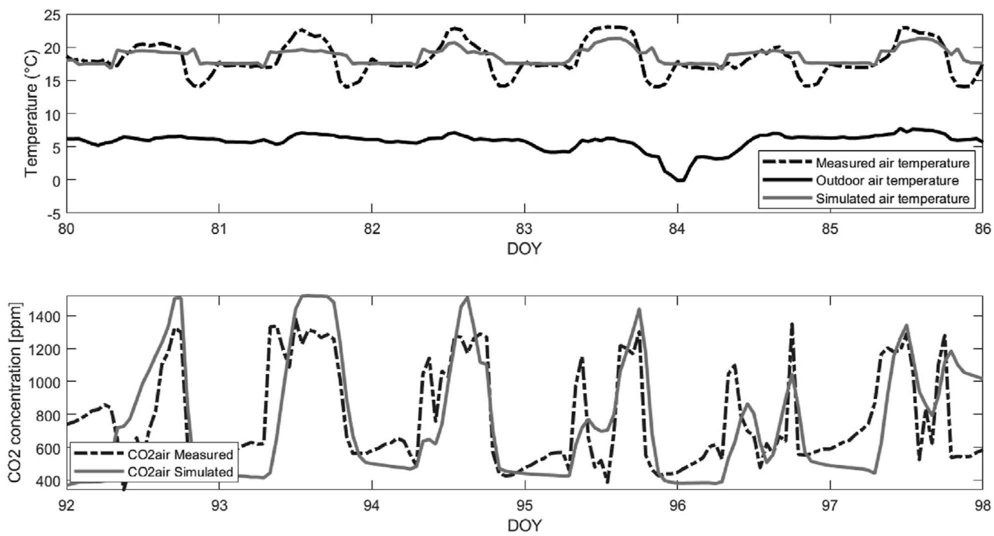

Fig. 8 – Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the start of the growing period. DOY: Day of the Year.

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

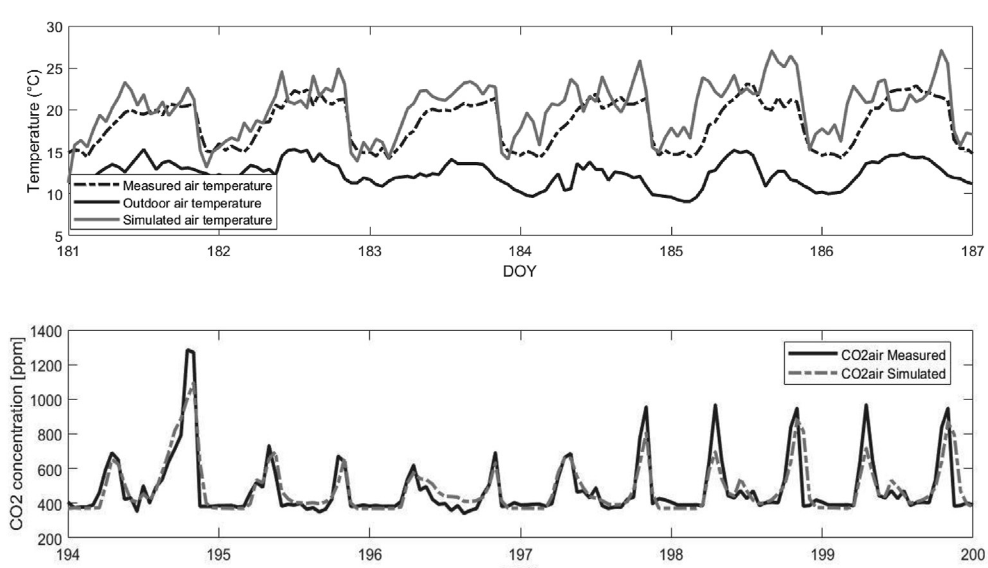

Fig. 9 – Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the mid-production period. DOY: Day of the Year.

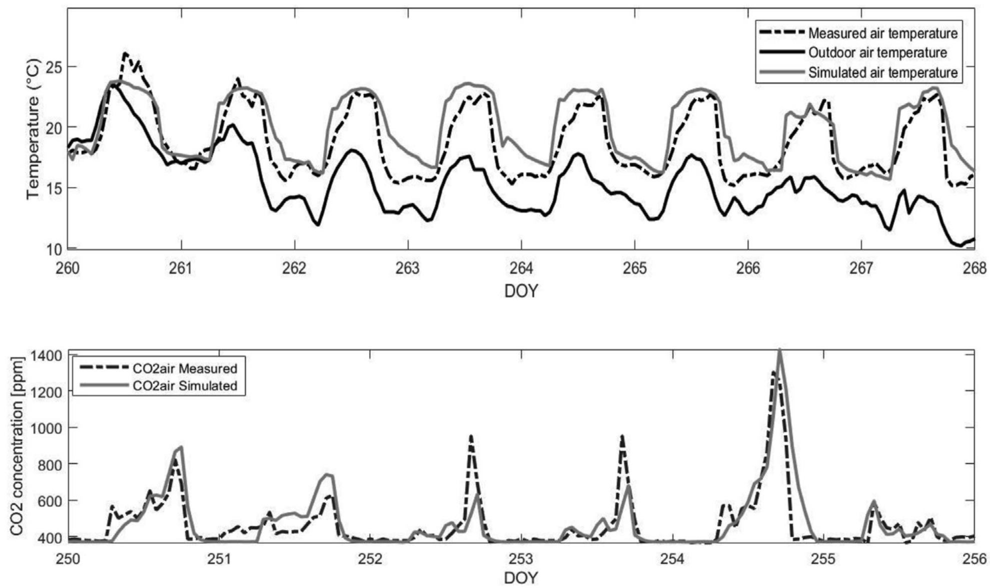

Fig. 10 – Prediction of temperature and CO_2 concentration for the greenhouse in Orre (SW Norway) at the end of the growing period. DOY: Day of the Year.

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.

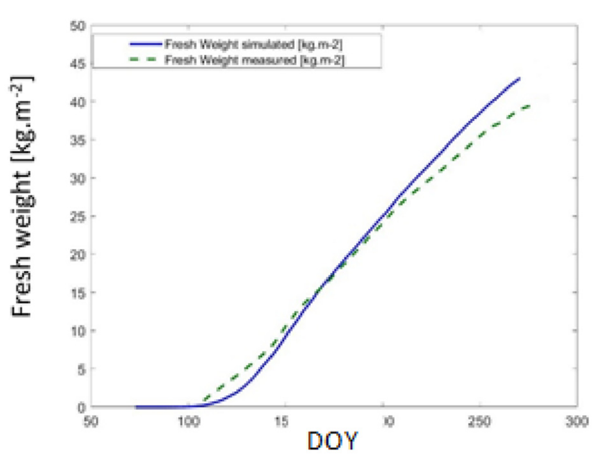

Fig. 11 – Measured (dashed line) and predicted (solid line) yield for SW Norway (Orre) greenhouse during the growing period from mid-March to mid-October in the Orre greenhouse. DOY: day of the year.

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; Aș;chilean, Răsoi, Raboaca, Filote & Culcer, 2018). In some studies, the model used was not validated against existing conditions and instead used data from

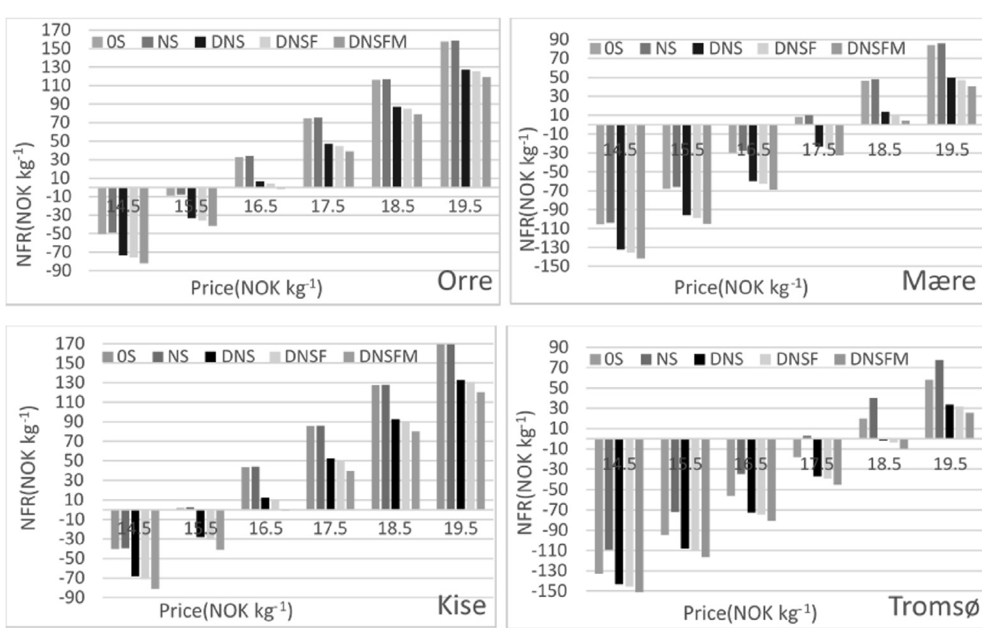

Fig. 12 – The relationship between NFR and tomato price trajectory for the four locations. This figure shows the prices which may yield an economically viable greenhouse design at each of the selected locations.

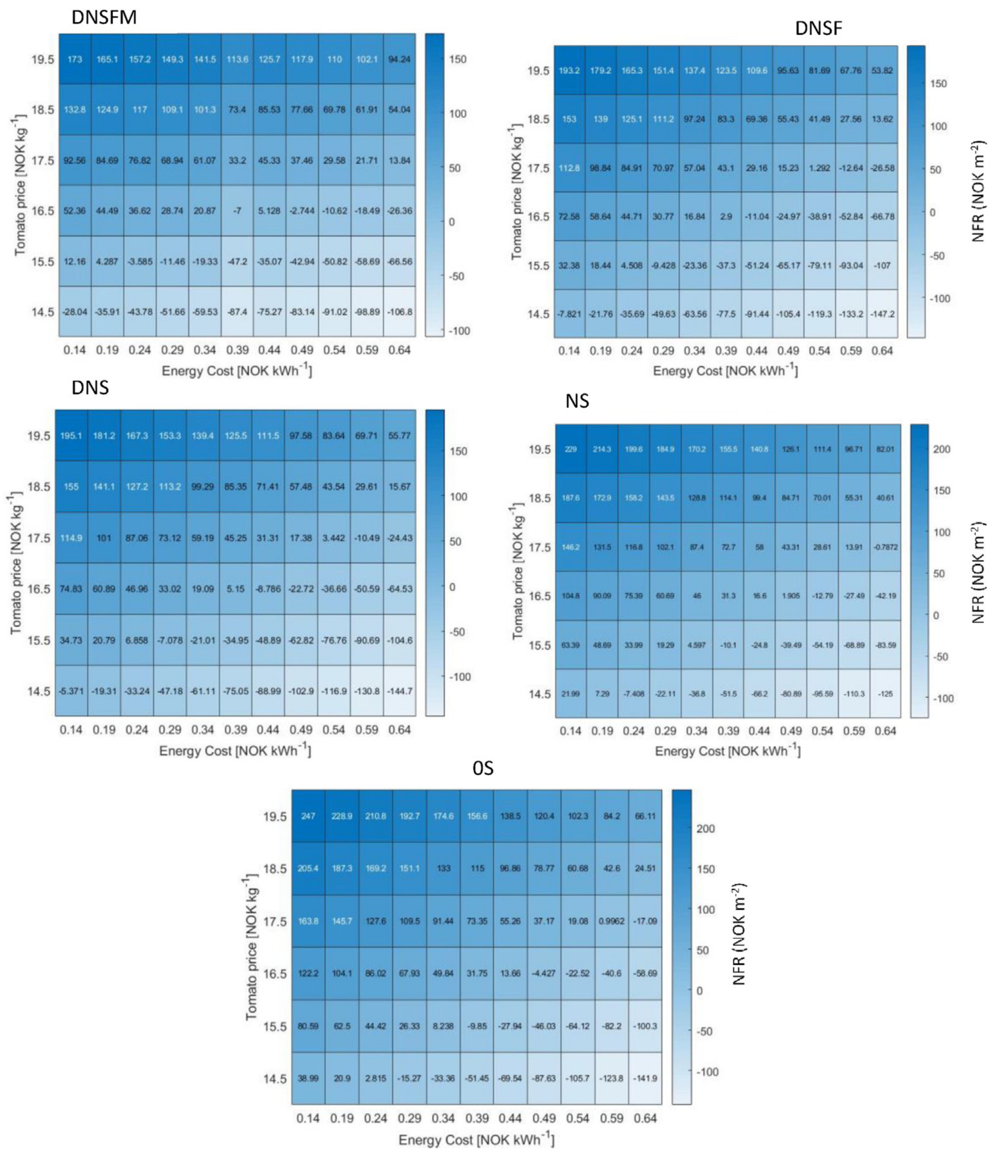

Fig. 13 – The effect of tomato price and energy costs on the NFR for the greenhouse in Orre (SW Norway). The figure shows that if the energy prices increase, the design with energy-saving elements results in higher NFR as compared to the standard greenhouse in Norway.

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 pay-back 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.

Acknowledgement

This study is a part of the research project 'Bio-economic production of fresh greenhouse vegetables in Norway (Bio-Fresh)', which is financially supported by the Bionær program of the Research Council of Norway, project number 255613/E50.

REFERENCES

Acosta-Silva, Y. J., Torres-Pacheco, I., Matsumoto, Y., Toledano-Ayala, M., Soto-Zarazúa, G. M., Zelaya-Ángel, O., et al. (2019). Applications of solar and wind renewable energy in agriculture: A review. *Science Progress, 102*, 127–140.

Ahamed, M. S., Guo, H., & Tanino, K. (2018). Sensitivity analysis of CSGHEAT model for estimation of heating consumption in a Chinese-style solar greenhouse. *Computers and Electronics in Agriculture, 154*, 99–111. https://doi.org/10.1016/j.compag.2018.08.040

Ahamed, M. S., Guo, H., Taylor, L., & Tanino, K. (2019). Heating demand and economic feasibility analysis for year-round vegetable production in Canadian Prairies greenhouses. *Information Processing in Agriculture, 6*(1), 81–90. https://doi.org/10.1016/j.inpa.2018.08.005

Aşchilean, I., Răsoi, G., Raboaca, M., Filote, C., & Culcer, M. (2018). Design and concept of an energy system based on renewable sources for greenhouse sustainable agriculture. *Energies, 11*, 1201.

Bambara, J., & Athienitis, A. K. (2018). Energy and economic analysis for greenhouse ground insulation design. *Energies, 11*(11), 3218, 1-15.

Bartzanas, T., Tchamitchian, M., & Kittas, C. (2005). Influence of the heating method on greenhouse microclimate and energy consumption. *Biosystems Engineering, 91*(4), 487–499.

Bremnes, E., Hansen, J. S., Slimestad, R., & Verheul, M. (2019). *Gartneryrket*. NIBIO, NOFIMA. https://nofima.no/publikasjon/1807024/.

Çakır, U., & Şahin, E. (2015). Using solar greenhouses in cold climates and evaluating optimum type according to sizing, position and location: A case study. *Computers and Electronics in Agriculture, 117*, 245–257. https://doi.org/10.1016/j.compag.2015.08.005

Campiotti, C., Belmonte, A., Catanese, V., Dicarlo, F., Dondi, F., Scoccianti, M., et al. (2010). Renewable energy for greenhouse agriculture. *Journal of Sustainable Energy, 1*(2).

Dansk Gartneri. https://danskgartneri.dk/. (Accessed 4 March 2019).

De Zwart, H. (1996). *Analysing energy-saving options in greenhouse cultivation using a simulation model*. PhD thesis. The Netherlands: Agriculture University of Wageningen https://edepot.wur.nl/195238.

Diakosavvas, D. (2017). *Improving energy efficiency in the agro-food chain*. Paris, France: Organisation for Economic Co-operation and Development (OECD).

Farquhar, G. D., Von Caemmerer, S., & Berry, J. A. (2001). Models of photosynthesis. *Plant Physiology, 125*(1), 42–45.

Fernandez, J. E., & Bailey, B. J. (1992). Measurement and prediction of greenhouse ventilation rates. *Agricultural and Forest Meteorology, 58*(3–4), 229–245. https://doi.org/10.1016/0168-1923(92)90063-A

Flores-Velazquez, J., Montero, J. I., Baeza, E. J., & Lopez, J. C. (2014). Mechanical and natural ventilation systems in a greenhouse designed using computational fluid dynamics. *International Journal of Agricultural and Biological Engineering, 7*(1), 1.

Flores-Velázquez, J., Montero, J. I., Baeza, E. J., Lopez, J. C., Pérez-Parra, J. J., & Bonachela, S. (2009). Analysis of mechanical ventilation in a three-span greenhouse using computational fluid dynamics (CFD). In *International Symposium on High Technology for Greenhouse Systems: GreenSys2009, 893* pp. 653–660). https://doi.org/10.17660/ActaHortic.2011.893.69

Flores-Velázquez, J., & Vega-García, M. (2019). Regional management of the environment in a zenith greenhouse with computational fluid dynamics (CFD). *Ingeniería agrícola y biosistemas, 11*(1), 3–20.

Fremstad, J. J. (2020). *Agriculture must reduce greenhouse gas emissions*. https://ruralis.no/en/2020/02/25/landbruket-ma-redusere-utslipp-av-klimagasser/. (Accessed 10 September 2021).

Fuller, R. J., Aye, L., Zahnd, A., & Thakuri, S. (2009). Thermal evaluation of a greenhouse in a remote high altitude area of Nepal. *International Energy Journal, 10*(2).

Gázquez, J. C., López, J. C., Pérez-Parra, J. J., Baeza, E. J., Saéz, M., & Parra, A. (2007). Greenhouse cooling strategies for Mediterranean climate areas. In *International Symposium on High Technology for Greenhouse System Management: Greensys 2007* (Vol. 801, pp. 425–432). https://doi.org/10.17660/ActaHortic.2008.801.45

Gupta, M. J., & Chandra, P. (2002). Effect of greenhouse design parameters on conservation of energy for greenhouse environmental control. *Energy, 27*(8), 777–794.

Hatirli, S. A., Ozkan, B., & Fert, C. (2006). Energy inputs and crop yield relationship in greenhouse tomato production. *Renewable Energy, 31*(4), 427–438. https://doi.org/10.1016/j.renene.2005.04.007

Hemming, S., Sapounas, A., de Zwart, H. F., Ruijs, M. N. A., & Maaswinkel, R. H. M. (2010). Design of a sustainable innovation greenhouse system for Turkey *(No. GTB-1009)*. The Netherlands: Wageningen UR Greenhouse Horticulture. https://edepot.wur.nl/173505.

Henshaw, P. (2017). Modelling changes to an unheated greenhouse in the Canadian subarctic to lengthen the growing season. *Sustainable Energy Technologies and Assessments, 24*, 31–38.

Hovland, I. (2018). Dekningsbidragskalkyler for hagebruk. In *Hovland I.,* Handbok far driftsplanlegging (pp. 45–71). Oslo: NIBIO. https://nibio.brage.unit.no/nibio-xmlui/bitstream/handle/11250/2569688/NIBIO_BOK_2018_4_10.pdf?sequence=2&isAllowed=y.

Impron, I., Hemming, S., & Bot, G. P. A. (2007). Simple greenhouse climate model as a design tool for greenhouses in tropical lowland. *Biosystems Engineering, 98*(1), 79–89. https://doi.org/10.1016/j.biosystemseng.2007.03.028

Incrocci, L., Stanghellini, C., & Kempkes, F. L. K. (2008). Carbon dioxide fertilisation in mediterranean greenhouses: When and how is it economical?. In *International Symposium on Strategies towards Sustainability of Protected Cultivation in Mild Winter Climate* (Vol. 807, pp. 135–142). https://doi.org/10.17660/ActaHortic.2009.807.16

IRENA. (2021). *Renewable Energy Statistics 2021*. Abu Dhabi: The International Renewable Energy Agency.

Joudi, K. A., & Farhan, A. A. (2015). A dynamic model and an experimental study for the internal air and soil temperatures in an innovative greenhouse. *Energy Conversion and Management, 91*, 76–82. https://doi.org/10.1016/j.enconman.2014.11.052

Karim, M. F., Hao, P., Nordin, N., Qiu, C., Zeeshan, M., Khan, A., et al. (2020). CO_2 enrichment using CRAM fermentation improves growth, physiological traits and yield of cherry tomato (Solanum lycopersicum L.). *Saudi Journal of Biological Sciences, 27*, 1041–1048.

Kläring, H., Hauschild, C., Heißner, A., & Bar-yosef, B. (2007). Model-based control of CO_2 concentration in greenhouses at ambient levels increases cucumber yield. *Agricultural and Forest Meteorology, 143*, 208–216.

Kondili, E., & Kaldellis, J. K. (2006). Optimal design of geothermal–solar greenhouses for the minimisation of fossil fuel consumption. *Applied Thermal Engineering, 26*(8–9), 905–915. https://doi.org/10.1016/j.applthermaleng.2005.09.015

Lamb, A., Green, R., Bateman, I., Broadmeadow, M., Bruce, T., Burney, J., et al. (2016). The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nature Climate Change, 6*, 488–492. https://doi.org/10.1038/nclimate2910

Lanoue, J. (2020). From Lab to Greenhouse: Shedding Light on the Role of Spectral Quality and CO_2 Concentration in Tomato (Solanum lycopersicum L.) Production (Doctoral dissertation).

Longo, S., Mistretta, M., Guarino, F., & Cellura, M. (2017). Life Cycle Assessment of organic and conventional apple supply chains in the North of Italy. *Journal of Cleaner Production, 140*, 654–663. https://doi.org/10.1016/j.jclepro.2016.02.049

Lopez-Marin, J., Rodriguez, M., Del Amor, F. M., Galvez, A., & Brotons-Martinez, J. M. (2019). Cost-benefit analysis of tomato crops under different greenhouse covers. *Journal of Agricultural Science and Technology A, 21*(2), 235–248. http://journals.modares.ac.ir/article-23-16418-en.html.

Luo, W., de Zwart, H. F., DaiI, J., Wang, X., Stanghellini, C., & Bu, C. (2005a). Simulation of greenhouse management in the subtropics, Part I: Model validation and scenario study for the winter season. *Biosystems Engineering, 90*(3), 307–318. https://doi.org/10.1016/j.biosystemseng.2004.11.008

Luo, W., Stanghellini, C., Dai, J., Wang, X., de Zwart, H. F., & Bu, C. (2005b). Simulation of greenhouse management in the subtropics, Part II: Scenario study for the summer season. *Biosystems Engineering, 90*(4), 433–441. https://doi.org/10.1016/j.biosystemseng.2004.12.002

Magán, J. J., López, A. B., Pérez-Parra, J. J., & López, J. C. (2008). *Invernaderos con cubierta de plástico y cristal en el sureste espan ol* (p. 54). Cuadernos de investigación.

Milford, A. B., Verheul, M., Sivertsen, T., & Kaufmann, L. (2021). Klimagassreduksjon i veksthusnæringen: Muligheter, barrierer og tiltak. *NIBIO Rapport*.

Miljødirektoratet. (2019). *Klimakur 2030: Tiltak og virkemidler mot 2030*. https://www.miljodirektoratet.no/globalassets/publikasjoner/m1625/m1625.pdf. (Accessed 12 September 2021).

Ministry of Petroleum and Energy. (2020). *Electricity disclosure*. https://www.nve.no/energy-supply/electricity-disclosure/. (Accessed 12 September 2021).

Mobtaker, H. G., Ajabshirchi, Y., Ranjbar, S. F., & Matloobi, M. (2016). Solar energy conservation in greenhouse: Thermal analysis and experimental validation. *Renewable Energy, 96*, 509–519.

Moe, R., Grimstad, S. O., & Gislerod, H. R. (2005). The use of artificial light in year round production of greenhouse crops in Norway. In *V International Symposium on Artificial Lighting in Horticulture* (Vol. 711, pp. 35–42). https://doi.org/10.17660/ActaHortic.2006.711.2

Mohammadi, A., & Omid, M. (2010). Economical analysis and relation between energy inputs and yield of greenhouse cucumber production in Iran. *Applied Energy, 87*(1), 191–196. https://doi.org/10.1016/j.apenergy.2009.07.021

Mussard, M. (2017). Solar energy under cold climatic conditions: A review. *Renewable and Sustainable Energy Reviews, 74*, 733–745.

Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., Ruoff, P. Verheul, M.J. (Submitted). Bio-economic evaluation of extended season and year-round tomato production in Norway using supplemental light.

Notarnicola, B., Salomone, R., Petti, L., Renzulli, P. A., Roma, R., & Cerutti, A. K. (Eds.). (2015). *Life cycle assessment in the agri-food sector: Case studies, methodological issues and best practices*. Springer.

Pakari, A., & Ghani, S. (2019). Evaluation of a novel greenhouse design for reduced cooling loads during the hot season in subtropical regions. *Solar Energy, 181*, 234–242. https://doi.org/10.1016/j.solener.2019.02.006

Pretty, J. N., Ball, A. S., Xiaoyun, L., & Ravindranath, N. H. (2013). The role of sustainable agriculture and renewable-resource management in reducing greenhouse-gas emissions and increasing sinks in China and India. In *Capturing Carbon and Conserving Biodiversity* (pp. 219–241). Routledge.

Raviv, M., Lieth, J. H., & Bar-Tal, A. (Eds.). (2019). *Soilless culture: Theory and practice*. Amsterdam: Elsevier.

Rebnes, G., & Angelsen, T. (2019). *Totaloversikten 2018*. https://www.frukt.no/globalassets/materiell/totaloversikten/totaloversikten-2018.pdf. (Accessed 10 September 2019).

Righini, I., Vanthoor, B., Verheul, M. J., Naseer, M., Maessen, H., Persson, T., et al. (2020). A greenhouse climate-yield model focussing on additional light, heat harvesting and its validation. *Biosystems Engineering, 194*, 1–15. https://doi.org/10.1016/j.biosystemseng.2020.03.009

Roy, J. C., Fatnassi, H., Boulard, T., Pouillard, J. B., & Grisey, A. (2015). CFD determination of the climate distribution in a semi closed greenhouse with air cooling. In *International Symposium on New Technologies and Management for Greenhouses-GreenSys2015* (Vol. 1170, pp. 103–110).

Sapounas, A. A., Hemming, S., & De Zwart, F. (2010). *Using computational fluid dynamics to optimise the design of a commercial scale greenhouse for Western Turkey weather conditions*. HEFAT 2010. http://hdl.handle.net/2263/44903.

Shukla, A., Tiwari, G., & Sodha, M. (2006). Thermal modeling for greenhouse heating by using thermal curtain and an earth–air heat exchanger. *Building and Environment, 41*, 843–850.

Singh, H., Poudel, M. R., Dunn, B., Fontanier, C., & Kakani, G. V. (2020). Effect of greenhouse CO_2 supplementation on yield and mineral element concentrations of leafy greens grown using nutrient film technique. *Agronomy, 10*, 323.

Singh, R. D., & Tiwari, G. N. (2010). Energy conservation in the greenhouse system: A steady state analysis. *Energy, 35*(6), 2367–2373. https://doi.org/10.1016/j.energy.2010.02.003

Su, Y., & Xu, L. (2015). June). A greenhouse climate model for control design. In *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)* (pp. 47–53). IEEE.

Tamburini, E., Pedrini, P., Marchetti, M. G., Fano, E. A., & Castaldelli, G. (2015). Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean area. *Sustainability, 7*(3), 2915–2935. https://doi.org/10.3390/su7032915

Tap, F. (2000). *Economics-based optimal control of greenhouse tomato crop production*. PhD thesis. The Netherlands: Agriculture University of Wageningen https://library.wur.nl/WebQuery/wurpubs/fulltext/195235.

The Norwegian Water Resources and Energy Directorate. (2020). *Kraftproduksjon*. https://www.nve.no/energiforsyning/kraftproduksjon/?ref=mainmenu. (Accessed 22 March 2020).

Torrellas, M., Antón, A., Ruijs, M., Victoria, N. G., Stanghellini, C., & Montero, J. (2012). Environmental and economic assessment of protected crops in four European scenarios. *Journal of Cleaner Production, 28*, 45–55.

Vanthoor, B. H. (2011). *A model-based greenhouse design method*. PhD thesis. The Netherlands: Agriculture University of Wageningen https://edepot.wur.nl/170301.

Vanthoor, B. H., Gazquez, J. C., Magan, J. J., Ruijs, M. N., Baeza, E., Stanghellini, C., et al. (2012a). A methodology for model-based greenhouse design: Part 4, economic evaluation of different greenhouse designs: A Spanish case. *Biosystems Engineering, 111*(4), 336–349. https://doi.org/10.1016/j.biosystemseng.2011.12.008

Vanthoor, B., Stanghellini, C., van Henten, E., & De Visser, P. (2008). Optimal greenhouse design should take into account optimal climate management. In *IV International Symposium on Applications of Modelling as an Innovative Technology in the Agri-Food-Chain: Model-IT* (Vol. 802, pp. 97–104). https://doi.org/10.17660/ActaHortic.2008.802.10

Vanthoor, B. H. E., Stanghellini, C., Van Henten, E. J., & De Visser, P. H. B. (2011a). A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. *Biosystems Engineering, 110*(4), 363–377. https://doi.org/10.1016/j.biosystemseng.2011.06.001

Vanthoor, B. H. E., Stanghellini, C., Van Henten, E. J., & De Visser, P. H. B. (2011b). A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. *Biosystems Engineering, 110*(4), 378–395. https://doi.org/10.1016/j.biosystemseng.2011.08.005

Verheul, M., Grimstad, S. O., & Maessen, H. F. R. (2012). Optimising a year-round cultivation system of tomato under artificial light. In *VII International Symposium on Light in Horticultural Systems*, 956 pp. 389–394). https://doi.org/10.17660/ActaHortic.2012.956.45

Verheul, M. J., & Thorsen, S. M. (2010). Klimagassregnskap for norske veksthusprodukter. *Bioforsk Rapport, 5*(135).

Vermeulen, P. C. M. (2016). Kwantitatieve informatie voor de glastuinbouw 2016-2017: kengetallen voor groenten, snijbloemen, pot en perkplanten teelten *(No. 5121)*. Bleiswijk: Wageningen UR Glastuinbouw.

Von Elsner, B., Briassoulis, D., Waaijenberg, D., Mistriotis, A., Von Zabeltitz, C., Gratraud, Russo G., et al. (2000). Review of structural and functional characteristics of greenhouses in European union countries: Part I, design requirements. *Journal of Agricultural Engineering Research, 75*(1), 1–16. https://doi.org/10.1006/jaer.1999.0502